Development of Emission Rates for Heavy-Duty Vehicles in the Motor Vehicle Emissions Simulator (Draft MOVES2009)

Draft Report

United States
Environmental Protection
Agency

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

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1 Heavy Duty Diesel Emissions

This main section details our analysis of data to develop emission rates for heavy-duty diesel trucks. 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 defined by 23 operating modes which will be discussed below. The 'extended idle' process occurs after 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.

1.1 Running Exhaust Emissions

MOVES running exhaust emissions analysis requires accuracy of second-by-second emission rates and parameters that can determine vehicle-specific power, vehicle tractive power normalized by weight (VSP). Heavy-duty emission rate analysis is no exception. However, compared the light-duty, the amount of data available is small. The VSP approach was developed with light-duty vehicles in mind, and as a result, the same approach needed to be applied for heavy-duty vehicles. While VSP is a good way to characterize emissions from light-duty vehicles, the range of running weights, coarseness of the VSP bin structure, and work-based (not distance-based) emissions standards make VSP-based analysis for heavy-duty diesel vehicles a challenge. Nevertheless, this report explains how we analyzed second-by-second heavy duty emission data to fit the VSP structure in MOVES.

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 long standing gross vehicle weight rating (GVWR) classifications and the model year groupings are differentiated by EPA emission standards.

Table 1 – MOVES stratifies HD emission rates into five regulatory classes

Regulatory Class name	MOVES Name	Gross Vehicle Weight Rating (GVWR) [lb]
2b Light-heavy duty [LHD2b]	Class 41	8500 – 14000
Light-heavy duty [LHD345]	Class 42	14000 – 19500
Medium-heavy duty [MHD]	Class 46	19500 – 33000
Heavy-heavy duty [HHD]	Class 47	> 33000
Urban Bus [BUS]	Class 48	N/A

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 which are used in the model are shown in Table 2.

Table 2 – MOVES Age Group Definitions

Age Group ID	Lower Age	Upper Age
3	0	3
405	4	5
607	6	7
809	8	9
1014	10	14
1519	15	19
2099	20	~

1.1.1 Nitrogen Oxides (NOx)

For NOx rates, we stratified heavy-duty vehicles into model year groups in Table 3. These groups were categorized based on changes in NOx emissions standards and the outcome of the Heavy Duty Diesel Consent Decree[1], which required additional control of NOx emissions during highway driving for model years 1999 and later. This 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/bhpr-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	

1.1.1.1 Data Sources

For NOx emissions from HHD, MHD, and urban buses, we relied on two data sources:

1. **ROVER PEMS (Portable Emissions Measurement System) testing conducted by U.S. Army Aberdeen Test Center on behalf of U.S. EPA[2]:** This ongoing program started in October 2000. Due to time constraints and quality of data, we only used data collected from October 2003 through September 2007. Data was compiled and reformatted for MOVES analysis by Sierra Research[3]. EPA performed the data analysis itself. The data we used consisted of 124 trucks and buses ranging from 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

2. **Consent Decree testing conducted by West Virginia University using their Mobile Emissions Measurement System (MEMS)[4,5]:** This program came 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 consisted of 188 trucks from 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 in 5-hz frequency, which we averaged around each second to convert the data to 1-hz.

From each data set, we used only tests we determined to be valid. For ROVER, 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. As our own high-level check on the quality of PEMS and ECU output, we further eliminated any trip where the pearson correlation coefficient between CO_2 (from PEMS) and engine power (from ECU) was less than 0.6. These filters led to a smaller and more conservative subset of the overall ROVER data, compared to if a more detailed quality check were performed (i.e. not all eliminated tests produced erroneous results). For the WVU MEMS data, WVU itself reported which tests were valid as part of the consent decree procedure. No additional detailed quality check was performed by EPA. Table 4 shows the total distribution of vehicles by model year group from both of the emissions test programs above.

Table 4 – Number of vehicles by model year group from the ROVER and WVU MEMS programs used for emission rate analysis

Regulatory class	1991-1997 MY	1998 MY	1999-2002 MY	2003-2006 MY
HHD	19	12	78	91
MHD	0	0	30	32
BUS	2	0	25	19

1.1.1.2 Calculating VSP from in 1-hz data

With on-road testing, using vehicle speed and acceleration to determine VSP is not accurate given the effect of road grade and wind speed. As a result, we needed to find a better way to calculate VSP. Therefore, we decided to derive VSP from engine data collected during testing. We first determined which seconds in the data that the truck was either idling or braking based on acceleration and speed criteria shown later 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 then engine was performing work.

$$P_{eng} = \omega_{eng} \tau_{eng}$$ **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 must 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 load map into VSP bins. The VSP bins 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

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 off of information from "The Technology Roadmap for the 21st Century Truck."[6]

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 VSP bin is equal to the sum of each accessory load. The calculations are included in Appendix *A.1 Calculation of Accessory Power Requirements for VSP bins.*

The total accessory loads $P_{loss,acc}$ listed below in Table 6 is subtracted from the engine power determined from Equation 1 to get net engine power available at the engine flywheel.

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. We performed a literature search[7,8,9,10,11,12,13,14,15] to determine an average value for driveline efficiency. Table 7 summarizes our findings.

Table 7 shows 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 our 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, to calculate VSP, we divided the axle power by the average weight for each regulatory class. We did not use the test weight because our test weights varied by truck or by test. Also, since running weights vary on a much broader range than light-duty vehicles and since we are characterizing NOx emissions by engine parameters, using the vehicles actual test weight would confound the results. Using an average running weight was the most appropriate. We did this by analyzing the Vehicle Inventory and Use Survey[16] data to establish a VMT-weighted average running weight for each regulatory class $m_{avg.regclass}$, shown in Table 8.

Table 8 – Average running weight by regulatory class in metric tons

Regulatory Class	Average running weight
HHD	27.7
MHD	11.4

LHD345	6.3
LHD2b	5.0
BUS	16.6

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

$$VSP = \frac{P_{axle}}{m_{avg,regclass}} \qquad \textbf{Equation 3}$$

Due to low power-to-weight ratios compared to light-duty vehicles, HHD trucks do not regularly reach VSP levels greater than 12 kW/metric ton, and MHD trucks greater than 18 kW/metric ton. To calculate VSP and emission rates for LHD trucks, engine and emissions data for MHD trucks were used, given the similarity in average engine size, to calculate engine power. We assume negligible accessory losses and the same 90% driveline loss. Then we divided the resulting axle power by the average weights in the LHD regulatory classes (listed in Table 8). We then constructed operating mode bins defined by VSP and vehicle speed according to the methodology outlined earlier in MOVES development[17] and described in Table 9.

Table 9 – Definition of the MOVES Operating Mode Attribute for Motor Vehicles (opModeID)

Operating Mode Bin	Operating Mode Description	Vehicle-Specific Power (VSP_t, kW/metric ton)	Vehicle Speed (v_t, mph)	Vehicle Acceleration (a, mph/sec)
0	Deceleration/Braking			$a_t \le -2.0$ OR ($a_t < -1.0$ AND $a_{t-1} < -1.0$ AND $a_{t-2} < -1.0$)
1	Idle		$-1.0 \le v_t < 1.0$	
11	Coast	$VSP_t < 0$	$0 \le v_t < 25$	
12	Cruise/Acceleration	$0 \le VSP_t < 3$	$0 \le v_t < 25$	
13	Cruise/Acceleration	$3 \le VSP_t < 6$	$0 \le v_t < 25$	
14	Cruise/Acceleration	$6 \le VSP_t < 9$	$0 \le v_t < 25$	
15	Cruise/Acceleration	$9 \le VSP_t < 12$	$0 \le v_t < 25$	
16	Cruise/Acceleration	$12 \le VSP_t$	$0 \le v_t < 25$	
21	Coast	$VSP_t < 0$	$25 \le v_t < 50$	
22	Cruise/Acceleration	$0 \le VSP_t < 3$	$25 \le v_t < 50$	
23	Cruise/Acceleration	$3 \le VSP_t < 6$	$25 \le v_t < 50$	
24	Cruise/Acceleration	$6 \le VSP_t < 9$	$25 \le v_t < 50$	
25	Cruise/Acceleration	$9 \le VSP_t < 12$	$25 \le v_t < 50$	
27	Cruise/Acceleration	$12 \le VSP_t < 18$	$25 \le v_t < 50$	
28	Cruise/Acceleration	$18 \le VSP_t < 24$	$25 \le v_t < 50$	
29	Cruise/Acceleration	$24 \le VSP_t < 30$	$25 \le v_t < 50$	
30	Cruise/Acceleration	$30 \le VSP_t$	$25 \le v_t < 50$	
33	Cruise/Acceleration	$VSP_t < 6$	$50 \le v_t$	
35	Cruise/Acceleration	$6 \le VSP_t < 12$	$50 \le v_t$	
37	Cruise/Acceleration	$12 \le VSP_t < 18$	$50 \le v_t$	

38	Cruise/Acceleration	$18 \le VSP_t < 24$	$50 \le v_t$	
39	Cruise/Acceleration	$24 \le VSP_t < 30$	$50 \le v_t$	
40	Cruise/Acceleration	$30 \le VSP_t$	$50 \le v_t$	

1.1.1.3 Calculating emission rates

1.1.1.3.1 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 bin. Then the emission rates were again averaged by regulatory class, 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).

$$\bar{r}_{pol} = \frac{\sum_{j=1}^{n_{veh}} \left(\sum_{i=1}^{n} \frac{r_{pol}}{n} \right)}{n_{veh}} \qquad \textbf{Equation 4}$$

where

n = the number of 1-hz data points for each vehicle,

n_{veh} = the total number of vehicles,

$\bar{r}_{pol}$ = the mean emission rate of pollutant *pol* for each stratification group (MOVES input),

$\bar{r}_{pol}$ = the emission rate of pollutant *pol* at second *i*

For NOx, we calculated a mean emission rate, called mean base rate in MOVES, for each regulatory class, model year group, and operating mode bin combination.

1.1.1.3.2 Statistics

Coefficients of variation (c_v) were calculated for all the emission rates. 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^2_{veh} = the variance within each vehicle, and

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

Then we calculated the between-vehicles variance s^2_{betw} (by source bin, age group, and operating mode) using the mean emission rates for each vehicle. Then, we determined the total variance by combining the within-vehicle and between-vehicle variances to get the standard error $s_{\bar{r}_{pol}}$

(Equation 6) and dividing the standard error by the mean emission rate to get the coefficient of variation $c_{v,\bar{r}_{pol}}$ (Equation 7).

$$s_{\bar{r}_{pol}} = \sqrt{\frac{s_{betw}^2}{n_{veh}} + \frac{s_{with}^2}{n_{tot}}} \qquad \textbf{Equation 6}$$

$$c_{v,pol} = \frac{s_{\bar{r}_{pol}}}{\bar{r}_{pol}} \qquad \textbf{Equation 7}$$

1.1.1.3.3 Hole Filling and forecasting

Since the data only covered model years 1994 through 2006, 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 (2007 and later), we decreased the emission rates for all operating mode bins by a ratio proportional to the decrease in the effective emissions standard. While the 2007 NOx standard is 0.2 g/bhp-hr, it is phased in through 2010 MY. Instead of phasing in aftertreatment technology, most manufacturers decided to meet a constant 1.2 g/bhp-hr standard, which did not require aftertreatment, from 2007 to 2009 MY (down from 2.4 g/bhp-hr in 2006). Therefore, we decreased the 2003-2006 emission rates by 50% for 2007-2009 MY. Starting in the 2010 MY, the NOx standard for all heavy-duty trucks will be 0.2 g/bhp-hr. Almost all of these trucks will be using SCR aftertreatment technology, which we are assuming to have a 90% NOx reduction efficiency from 2006 MY levels.

For model year 1990, we increased the 1991-1997 emission rates by 20% 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%, which is proportional the increase of the certification levels from the 1991 model year to the 1989 model year. The certification levels came from MOBILE6[18]. We assumed that emission levels did not change by model year for 1989 and earlier.

While we do not expect rates for high VSP for heavy- and medium-heavy duty vehicles, due to their power-to-weight ratios, we still need to have rates present in the model for completeness. Thus, we applied to those operating mode bins the rates calculated from data for the highest VSP level.

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

1.1.1.3.3.1 LNT-equipped pickup trucks

To meet the 2010 model year NOx emissions standards, the use of aftertreatment will likely be needed. Cummins decided to use aftertreatment starting in 2007 on their Dodge Ram pickup truck to meet the 2010 standards in 2007. The technology they used was a Lean NOx Trap (LNT). This technology allows for the storage of NOx during fuel-lean operation and conversion of this stored NOx into N_2 and H_2O during brief periods of fuel-rich operation. EPA's NVFEL acquired one of these trucks and performed local on-road PEMS testing in 2007. We used the PEMS and ECU output to determine VSP and emission rates in a similar way we did for the heavy-heavy-duty truck NOx rates. For heavy-duty vehicles in 2007 and later, a diesel particulate filter (DPF) is required to meet PM standards. Every so often, the DPF must be regenerated to remove and combust the PM from the filter to relieve backpressure and ensure proper engine exhaust function. This required that exhaust temperatures be high. However, these high temperatures adversely affect the LNT's NOx storage ability, causing tailpipe emission levels of NOx to increase. Therefore, while analyzing the 2007 Dodge Ram data, we separated regimes of PM regeneration from normal operation based on exhaust temperature. We performed the emission rate-VSP analysis separately for each regime, and weighted the two regimes together based on an assumed PM regeneration frequency of 10% of VMT. This is only an assumption based on the limited testing conducted. We will look to update this number based on any further data collection or research.

Since these LNT-equipped trucks are only about 25% of the LHDDT market, we again weighted the rates for the two LHD regulatory classes for model years 2007 and later. We assume that the remaining 75% of LHD diesel trucks from model year 2007 to 2009 will not have aftertreatment and exhibit the emission rates described in the hole filling section. We assume that the remaining 75% of LHD diesel trucks in model year 2010 and later will be equipped with SCR, and will exhibit 90% NOx reductions from 2006 levels, also described in the hole filling section.

Table 10 summarizes this and previous subsections regarding the methodology used to determine emission rates for each regulatory class-model year group combination.

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	LHD2b	LHD345
Pre-1988	Proportioned to certification levels	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	Proportioned to certification levels
1990	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels
1991-1997	Data analysis	Proportioned to HHD	Data analysis	Proportioned to HHD	Proportioned to HHD
1998	Data analysis	Proportioned to HHD	Proportioned to HHD	Proportioned to HHD	Proportioned to HHD
1999-2002	Data analysis	Data analysis	Data analysis	MHD engine data with LHD2b weight	MHD engine data with LHD345 weight
2003-2006	Data analysis	Data analysis	Data analysis	MHD engine data with LHD2b weight	MHD engine data with LHD345 weight
2007-2009	Proportioned to standards	Proportioned to standards	Proportioned to standards	Data (LNT), and proportioned to standards (non-LNT)	Proportioned to standards
2010 +	Proportioned to standards	Proportioned to standards	Proportioned to standards	Proportioned to standards	Proportioned to standards

An important point to note is that we did not make a stratification based on age for vehicles not equipped with NOx aftertreament 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) before and after useful life[19]. 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% increase in NOx over the useful life of the engine. Our tampering and mal-maintenance estimation methodology is discussed in detail in *Appendix*

A.2 Tampering and Mal-maintenance.

1.1.1.3.4 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 analysis. 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 through 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+ SCR	87	87
2010+ LNT	72	72

As described in *Appendix*

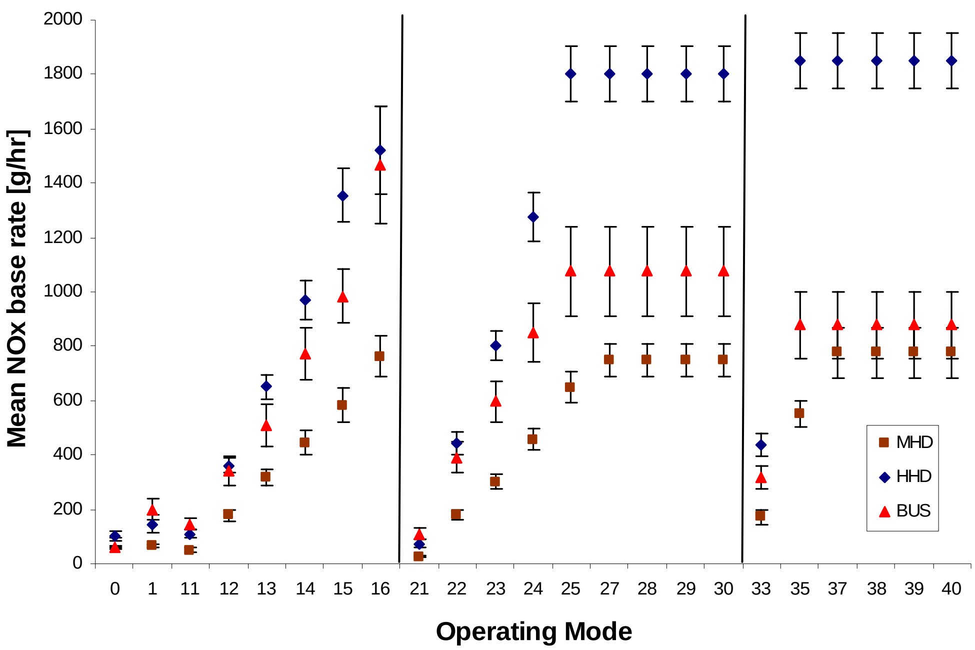
A.2 Tampering and Mal-maintenance, these emissions increases are combined with Table 35 to determine the emissions increase for each age group prior to the end of useful life for each regulatory class. With the introduction of aftertreatment systems to meet regulatory requirements for 2010 model year and later, EPA expects tampering and mal-maintenance to significantly increase emissions over time compared to the zero-mile level. Though 87% may appear to be a large increase of fleet-average emissions over time, it should be noted that the 2010 model year standard (0.2 g/bhp-hr) is about 83% lower than the 2009 model year effective standard (1.2 g/bhp-hr). This still yields a substantial reduction of about 69% from 2009 zero-mile levels to 2010 fully deteriorated levels. As more data becomes available for future model years, we will look to update these tampering and mal-maintenance and overall aging effects.

1.1.1.4 Sample results

The charts in this sub-section will show examples of the emission rates that resulted from the analysis. Not all rates are shown, but enough are shown to reveal the most common data trends and hole-filling results. The light-heavy duty regulatory classes are not shown for simplicity, 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.

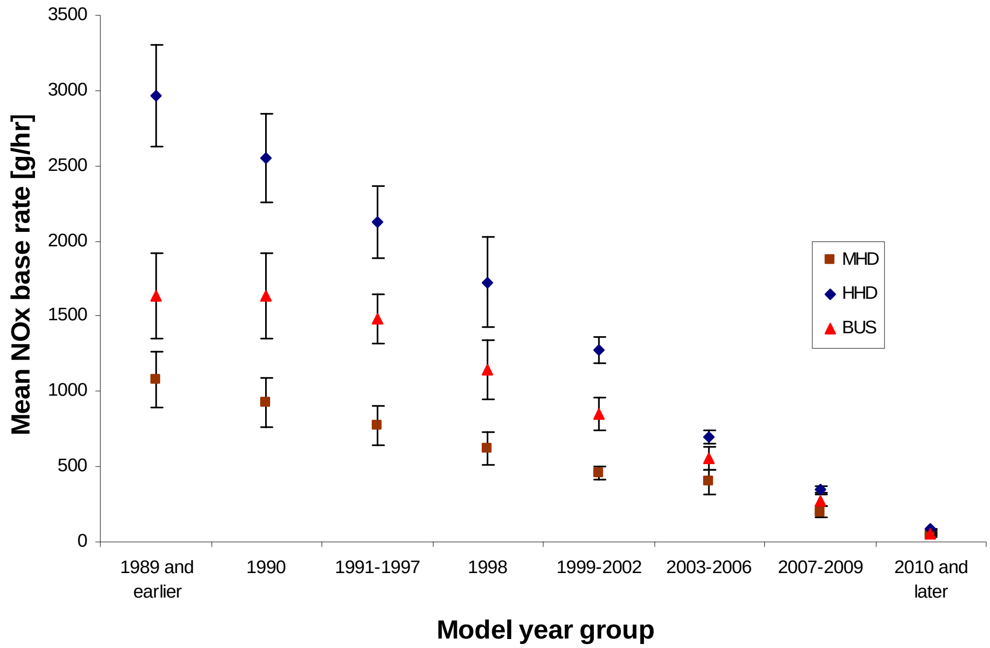
In Figure 1, we see that NOx emission rates increase with VSP. Also, the leveling of emission rates at high VSP/operating modes can be seen. This is strictly a matter of hole filling for completeness in the model; the high operating modes will not be reached given the low power-to-weight ratio of heavy-duty vehicles. For light-heavy duty trucks, which run lighter but have similar engine sizes as medium-heavy duty trucks, leveling off for high VSP in not required since those VSP levels can be attained in normal operation (similar to light-duty trucks).

Figure 1 shows NOx trends by operating mode for MHD, HHD, and Transit bus regulatory classes for model year 2002.



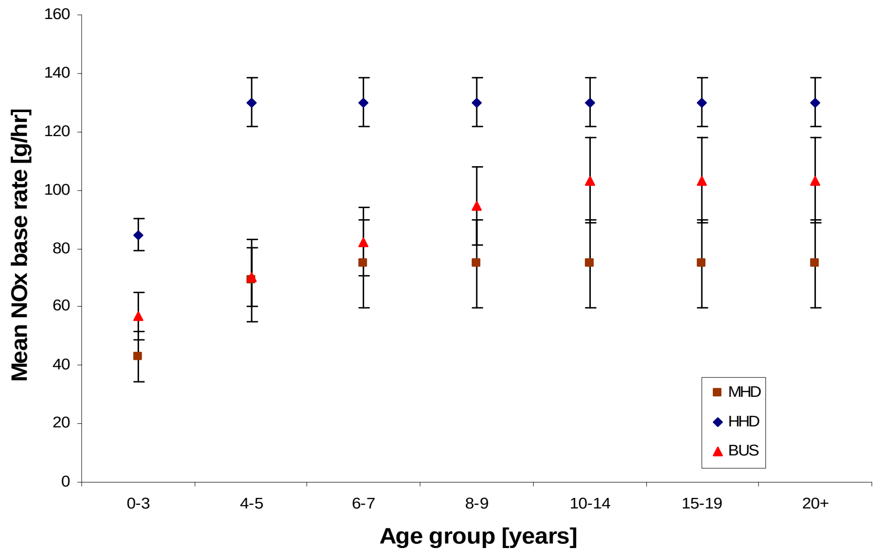
The effects of model year can be seen in Figure 2, which shows decreasing NOx rates by model year group for a sample operating mode (# 24). This chart is a combination of data analysis (model years 1991 through 2006) and hole filling. The trends in the data are expected, since model year groups were formed on the basis of NOx standards.

Figure 2 shows NOx trends by model year for operating mode 24. Stricter EPA standards have caused NOx emissions to decrease.



Age effects were only implemented for aftertreatment-equipped trucks (mostly model year 2010 and later) using our tampering and mal-maintenance analysis. Due to faster accumulation of miles, the heavy-heavy duty trucks reach their maximum emission rates the fastest, as shown in Figure 3. Coefficients of variation from previous model year groups were used to determine uncertainties for MY 2010.

Figure 3 shows NOx trends by age for model year 2010 for operating mode 24.



1.1.2 Particulate Matter (PM)

In this section particulate matter emissions are defined as particles emitted from heavy-duty engines which have a mean diameter less than 2.5 microns. Such particles consist of three subtypes. These are (1) elemental carbon (EC) which is the usually black colored soot that is emitted from combustion, (2) organic carbon (OC) which consists of particles of organic matter which is formed during the combustion process or immediately after in the tailpipe. It does not include particle formed in secondary reactions in the atmosphere, (3) sulfate particulate which consists of particles of sulfur emitted from engines as the result of fuel sulfur. These subtypes are the actual inputs in MOVES.

As mentioned for NOx, the heavy-duty diesel PM emission rates in MOVES also are a function of: (1) source bin, (2) operating mode, and (3) age group.

We stratified the data in the following model year groups in MOVES. These are generally based on the introduction of EPA emission 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 emission standards in units of gram per brake horsepower-hour (g/bhp-hr). The EPA standard was in terms of engine 'work' and was applied to all classes of heavy-duty engines.

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

Model Year Group Range	EPA PM Engine 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

The MOVES model has the capability of differentiating heavy duty trucks according the engine size, vehicle weight, and injection type (direct and indirect) as was done for the total energy rate inputs[20]. However, for PM emissions the data was just too sparse to consider such fine stratification, and it was not done.

1.1.2.1 Data Source

All of the data used to develop the MOVES PM2.5 emission rates comes from the CRC E-55/59 test program[21]. The following description by Dr. Ying Hsu and Maureen Mullen of E. H. Pechan, "Compilation of Diesel Emissions Speciation Data – Final Report" provides a good summary of the test 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, seven 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

Test counts are provided by test cycle in Table 14.

Table 14 – Vehicle Test Counts by Test Cycle

Test Cycle Name	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

1.1.2.2 Analysis

1.1.2.2.1 Calculate VSP in 1-hz data

Within source bins, data was further sub-classified on the basis of "operating mode," designated as the MOVES attribute "opModeID." For motor vehicles, operating mode is defined in terms of 23 bins defined in terms of vehicle-specific power (VSP), vehicle speed and vehicle acceleration. These are the same bins as were defined in Table 9 in the NOx discussion.

The first step in assigning operating mode is to calculate vehicle-specific power (VSP) for each emissions measurement. At a given time *t*, the instantaneous VSP_t (kW/metric ton), at a frequency of 1.0 Hz) represents the vehicle's tractive power normalized to its weight. The VSP parameter is expressed 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 VSP using the equation below:

$$VSP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{m_{avg,regclass}} \qquad \textbf{Equation 8}$$

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 [kg],
$m_{avg.regclass}$ = average running mass for regulatory class [metric ton] (*see Table 8*)
v_t = instantaneous vehicle velocity at time *t* [m/s], and
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[22] as determined through previous analyses for EPA's Physical Emission Rate Estimator (PERE). This method of calculating VSP is similar to how VSP was calculated for the light-duty vehicle emission rate analysis for MOVES, except that the average regulatory class weight is used in the denominator, instead of the actual test weight of the vehicle.

This is different from the way VSP was calculated for the NOx emission rate analysis since the data PM was collected on a chassis dynamometer instead of an onboard emission measurement system. For PM, the power portion (numerator) of the VSP equation was determined through vehicle speed and acceleration measurements from the chassis testing, whereas for NOx, the power was determined through engine control unit broadcasts. Grade effects are not included in any equations because grade does not come into play on chassis dynamometer tests, and it is already accounted for if VSP is calculated through engine speed and torque from the engine control unit. Operating mode bins were determined using the same method for NOx and all other pollutants (Table 9).

1.1.2.2.2 Normalize the TEOM Readings

Only heavy-duty diesel vehicles and tests in the E-55/59 test program that received both real time one hertz TEOM data and full cycle filter particulate data were utilized in the development of the emission rates. Since the development of MOVES emission rates is cycle independent, all available cycles / tests which met the above requirement were utilized. As a result, 488,881 seconds of TEOM data were utilized. The process required that each individual second by second TEOM rate be normalized using its overall cycle filter PM measurement (each combination of vehicle and test received a filter PM test). This was necessary because individual TEOM measurements are highly uncertain and vary widely in terms of magnitude (extreme positive and negative absolute readings can occur). Thus, only the relative contribution of a given one second measurement was used in the computation of the MOVES emission rates. The equation below shows the normalization process for a particular one second TEOM measurement.

$$PM_{normalized,i,j} = \frac{PM_{filter,j}}{\sum^{j} PM_{TEOM,i}} PM_{TEOM,i,j} \qquad \textbf{Equation 9}$$

Where

i is the individual one second measurement,

j is the particular test cycle (resultID – combination of vehicle and test),

$PM_{TEOM,i,j}$ is the TEOM measurement at second i during cycle j,

$PM_{filter,j}$ is the Total PM2.5 emissions collected on a filter over cycle j,

$PM_{normalized,i,j}$ is the Total PM2.5 emission result for second i and cycle j average, according the source bin, operating mode bin, model year group and age group.

1.1.2.2.3 Compute Total PM2.5 Mean Emission Results by MOVES Bin

After normalization, the data were stratified by regulatory class, model year group and the 23 operating mode bins (i.e., collectively called "MOVES bins"). Mean average results, count and standard deviation statistics for PM2.5 emission values were computed in terms of grams of PM2.5 per hour for each MOVES bin. In cases where the vehicle and TEOM test counts were sufficient for a given MOVES bin, these mean values became the MOVES basic emission rates for total PM2.5. In cases of no data or insufficient data for particular MOVES bin, a regression technique was utilized to fill 'holes'.

1.1.2.2.4 Hole filling and Forecasting

1.1.2.2.4.1 Missing operating mode bins

Detailed in *Appendix A.4 Regression to develop PM emission rates for missing operating mode bins*, a log-linear regression was performed on the existing PM data against VSP to fill in emission rates for missing operating mode bins. Similar to the NOx rates, emission rates were leveled off for the highest VSP bins.

1.1.2.2.4.2 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. These rates 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 are a ratio of the MHD emission rates, and bus (class 48) emission rates are proportioned to HHD rates. The emission rates of LHD2b are assumed to be equal to 0.46 * MHD emission rates. The emission rate of LHD345 is assumed to be 0.60 * MHD emission rate.

LHD2b emission rate	=	0.46 * MHD emission rate
LHD345 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[23] (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. The basis for this assumption is that the certification standards in terms of brake horsepower-hour (bhp-hr) are the same for all of the heavy-duty engines.

Urban Bus (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:

1991 – 1993 model years	Bus Emissions = (0.10/0.25) * HHD emissions
1994 – 1995 model years	Bus Emissions = 0.70 * HHD emissions
1996 – 2006 model years	Bus Emissions = 0.50 * HHD emissions

1.1.2.2.4.3 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 ten in the level of regulatory stringency required the use of particulate trap systems on heavy-duty diesels. As a result, the emission performance of diesel vehicles has likely changed dramatically.

Unfortunately, no second-by-second TEOM data were available for analysis on the 2007 and later model year vehicles. As a result, the emission factors for this most important group of vehicles was assumed to be a ratio of the 1998-2006 model year vehicles for each respective regulatory class and operating mode. After adjusting for age effects, we decreased the 2006 MY PM emission rates by 90% for the 2007 MY and later PM emission rates.

Since the vehicles of 2007 and later model year are the most critical group for future inventories, EPA will likely re-evaluate, and if necessary, update this assumption when sufficient data have been collected on in-use and fully 'seasoned' vehicles. EPA will also look at recent certification data to assess the zero-mile PM emission levels, as DPF effectiveness may be higher than the 90% stated here.

1.1.2.2.5 Tampering and Mal-maintenance

The MOVES model now 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.

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 15 were used to forecast or back-cast the basic PM emission rates to model model year group-age group combinations that were not part of 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. No historical data is available on these model years. However, for completeness, MOVES must have emission rates for these model years at age 3, 4 to 5, 6 to 7, etc. As a result, unless the assumption that the higher emission rates which are currently prevailing on the older model year vehicles have always prevailed – even when they were young, a modeling approach such as the T&M must be employed. Likewise, younger model years were tested only at lower age levels. No data has yet been collected on younger model year vehicles at high ages. The T&M methodology used in the MOVES analysis allows for the filling of age – model year group bins for which no data is available.

One criticism of the MOVES T&M methodology 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 which during the testing period may have had some maintenance problems. This issue would be most acute for the 2007 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 Tampering and Mal-maintenance. The overall MOVES tampering and mal-maintenance effects on PM emissions over the fleet's useful life are shown in Table 15.

Table 15 shows tampering and mal-maintenance emissions increase estimates for HC and CO over the useful life of trucks.

Model Year Group	Percent increase in PM due to T&M
Pre-1998	85
1998 - 2002	74
2003 – 2006	48
2007 – 2009	50
2010 +	50

1.1.2.2.6 Compute Elemental Carbon and Organic Carbon Emission Factors

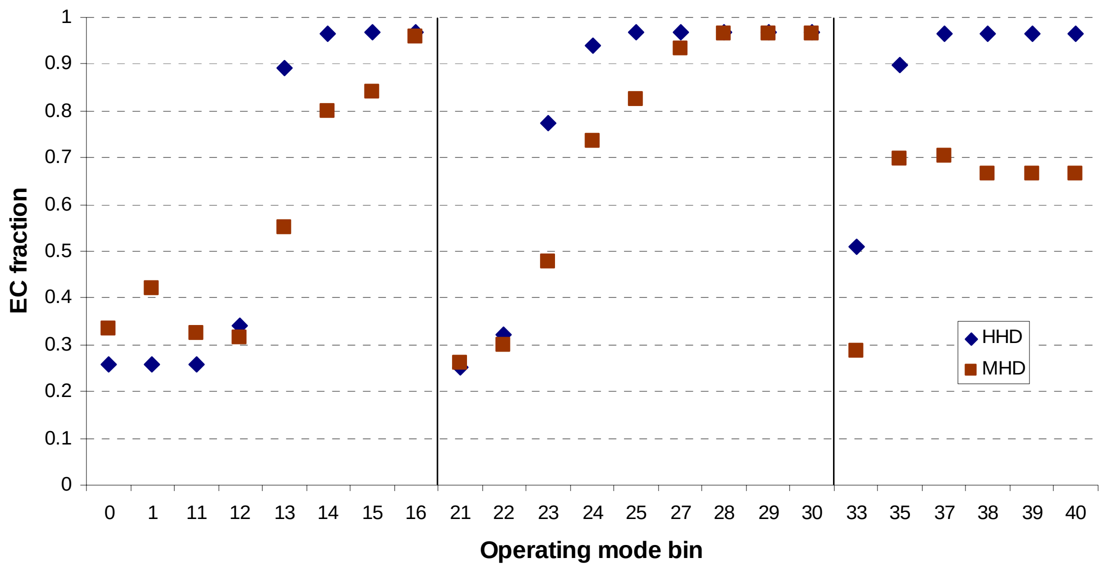
The MOVES model reports PM2.5 emissions according to three sub types. These are Elemental Carbon (EC), Organic Carbon (OC) and sulfate. Both EC and OC are computed directly from the total PM2.5 emissions using multiplicative factors. Sulfate is computed using a fuel sulfur balance (see MOVES Sulfate report for details). Since the fuel sulfur levels in the underlying study were not generally known, but believed to be small, sulfate emissions were ignored in the total PM2.5 emission levels. As a result, total PM2.5 was assumed to be comprised of only EC and OCarbon *(In the final version of MOVES a generic sulfate emission factor will be subtracted from the Total PM and the equation below will not be used).*

Total PM2.5 = EC + OC

Thus, OCarbon Fraction = 1.0 – EC Fraction

The final EC Fractions used in MOVES for pre-2007 model year trucks (i.e. before diesel particulate filters (DPFs) were standard) are shown in Figure 4. These vary according to regulatory class and MOVES operating mode bin. They typically range from 25 percent at low loads (low VSP) to over 90 percent at highly loaded modes. All of the EC fractions were developed by Chad Bailey and are documented in *Appendix A.5 Heavy-duty Diesel EC/OC Fraction Calculation*. 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 4 shows the Elemental Carbon fraction by operating mode bin for pre-DPF-equipped trucks.



A different methodology was used to compute EC factors for 2007 and later model year, DPF-equipped vehicles. For these vehicles it is believed that virtually all of the particulate that is emitted from the tailpipe will be OC and that only a modest fraction will be EC. The traps are designed to capture virtually all of the carbon. Potentially, small amounts of OC and sulfate may escape. This is essentially the opposite of the non-trap equipped heavy-duty diesel vehicles where the total PM2.5 is dominated by EC. Unfortunately, only limited particulate data exists on trap equipped vehicles. These data are based on particulate matter bound ionic species and EC/OC emissions data from a few trap equipped buses and a heavy-duty tractor. The data were extracted and a simple average computed from the SAE paper 2002-01-0432 "Chemical Speciation of Exhaust Emissions from Trucks and Buses Fueled on Ultra-Low Sulfur Diesel and CNG"[24]. Based on the date of the paper, it is likely that all of the diesel vehicle / trap systems were prototypes. Extraction of data from the paper yielded only a single factor which will be applied to all regulatory types and operating modes for 2007 and later diesel trucks and buses. This factor is the elemental carbon fraction. Table 16 summarizes the EC and OC fractions determined from the paper. These fractions were used for all operating mode bins for model years 2007 and later heavy-duty vehicles.

Table 16 shows EC and OC fractions used for DPF-equipped heavy-duty diesel vehicles.

EC fraction	0.0861
OC fraction	1 – ECfraction = 0.9139

As additional data becomes available, EPA will likely revise the EC Fraction used in MOVES.

Temperature Correction Factors

The MOVES model draft release of March, 2009 will not contain any temperature correction factors for PM2.5 emissions from heavy-duty diesel vehicles. This absence of temperature correction factors does not imply that EPA believes that heavy-duty diesel vehicle PM emissions are insensitive to temperature effects. In fact, it is quite likely that the inverse is true. Both running and start PM emissions from at least non-trap equipped vehicles are sensitive to temperature. However, EPA at this time cannot adequately quantify such emission effects, and is currently using a multiplicative placeholder value of unity as the temperature correction factor. EPA will update the MOVES model when sufficient data on diesel temperature correction factors is available for analysis and inclusion in the model.

1.1.2.3 Sample results

Figure 5 shows how PM rates increase with VSP. Also, the EC fraction of the PM rate increases with VSP as well. The leveling off at high VSP is due to our manual hole filling. At high speeds (greater than 50 mph; operating modes ≥ 30), the overall PM rates are lower than the other speed ranges.

Figure 5 shows PM rates by operating mode bin for model year 2002 age 0-3 for HHD trucks.

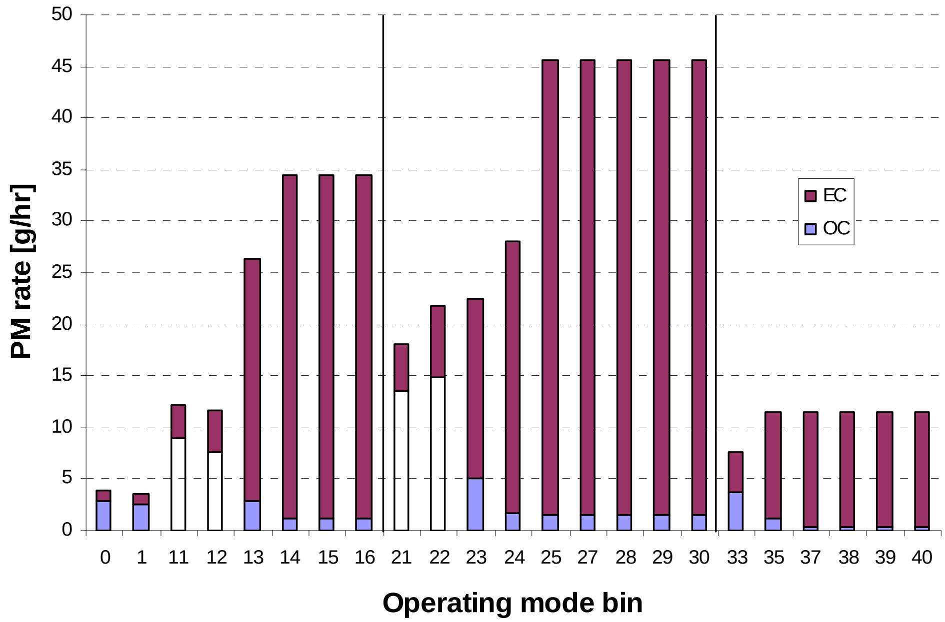


Figure 6 shows an example of how our tampering and mal-maintenance estimates increase PM with age. The EC fraction does not change by age, but the overall rate increases and levels off after the end of useful life. This figure shows the age effect for MHD. The rate at which emissions increase toward their maximum depends on regulatory class.

Figure 6 shows PM rates by age group for model year 2002 in operating mode 24 for MHD trucks.

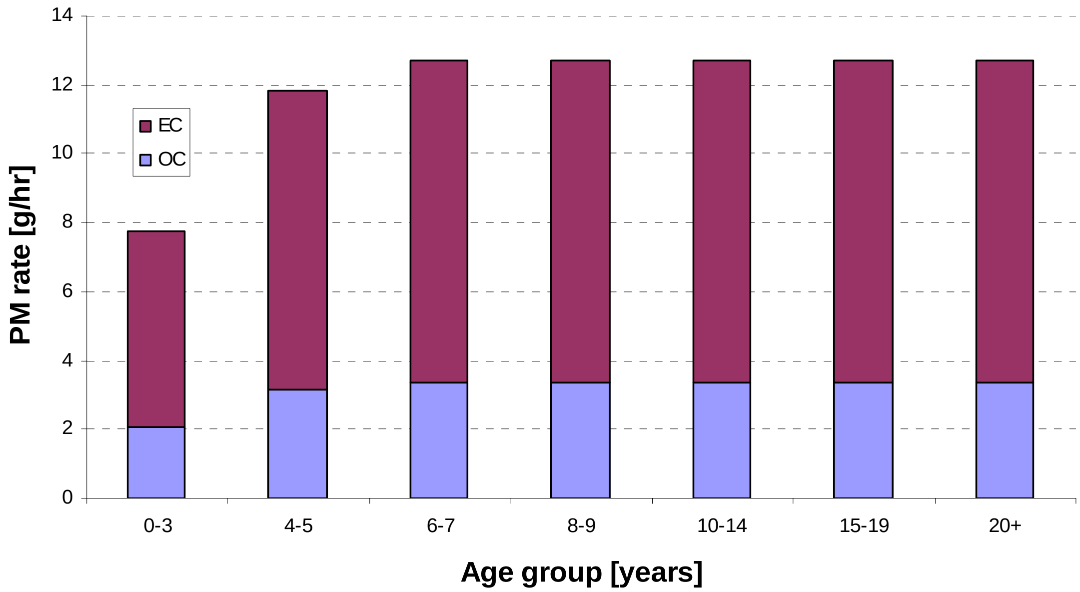
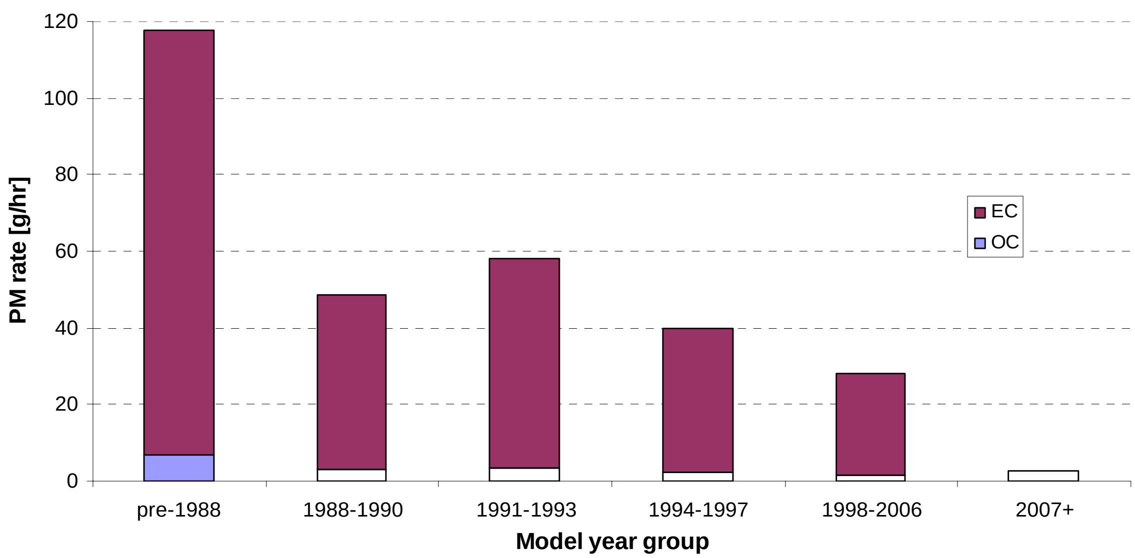


Figure 7 shows the effect of model year on emission rates. Emissions generally decrease with new PM standards. The EC fraction stays constant until model year 2007, when it is nearly zero due to widespread DPF use. The overall PM level is substantially lower starting in model year 2007. The earlier model years' emission rates represented here 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 7 shows PM rates by model year group for age 0-3 in operating mode 24 for HHD trucks.



1.1.3 Hydrocarbons (HC) and Carbon Monoxide (CO)

Diesel engines are not known to be a significant portion of the mobile source HC or CO emission inventories. Recent regulations on non-methane HC (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:

- 1960-1989
- 1990-2006
- 2007+

1.1.3.1 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[21]:** Mentioned earlier, this program represents the largest amount 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, and testing was conducted by West Virginia University from 2001 to 2005.
2. **Northern Front Range Air Quality Study (NFRAQ)[25]:** 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 designed 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)[26]:** 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 testing:** We have in our MSOD other historical HD chassis testing performed by WVU.

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 alignment was performed using the method similar to light-duty chassis test data time alignment. The quantities of vehicles in the data sets are shown in Table 17.

Table 17 shows the number of vehicles by model year group, regulatory class, and age group that were tested in the programs above.

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		
	LHD345	2			1			
	LHD2b	6						
2003-2006	HHD	6						

1.1.3.2 Analysis

Like for PM, VSP was calculated like in light-duty but normalized with average regulatory class weight instead of test weight, as described by Equation 10.

$$VSP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{m_{avg,regclass}}$$ **Equation 10**

Coefficients A, B, and C are road load coefficients pertaining to the heavy-duty vehicles[22] determined through previous analyses for EPA's Physical Emission Rate Estimator (PERE).

Using a similar method to the NOx analysis, we averaged emissions by vehicle and operating mode bin. We then averaged across all vehicles by model year group, age group, and operating mode. Statistics calculations followed the same equations and methodology as the NOx analysis.

Instead of populating all the emission rates directly into the model, 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 18.

Table 18 shows base 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 our tampering and mal-maintenance effects through that age point, either lower through younger ages or higher through older ages, using the methodology described in *Appendix*

A.2 Tampering and Mal-maintenance. The tampering and mal-maintenance effects for HC and CO are shown in
Table 19.

Table 19 shows tampering and mal-maintenance emissions increase estimates for HC and CO over the useful life of trucks.

Model years	Percent increase in HC and CO due to T&M
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 35 in section *A.2.3 Analysis* to get the emissions by age group.

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

1.1.3.3 Sample results

The charts in this sub-section will show examples of the emission rates that resulted from the analysis. Not all rates are shown, but enough are shown to reveal the most common data trends and hole-filling results. The light-heavy duty regulatory classes are not shown for simplicity, 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 just as for NOx.

In Figure 8 and Figure 9, we see that HC and CO mean emission rates increase with VSP, though there is much higher uncertainty than for the NOx rates. This could be due to the smaller data set or generally less significant with VSP. Also, the leveling of emission rates (hole filling) at high VSP/operating modes can be seen.

Figure 8 shows HC emission rates [g/hr] by operating mode bin for model year 2002.

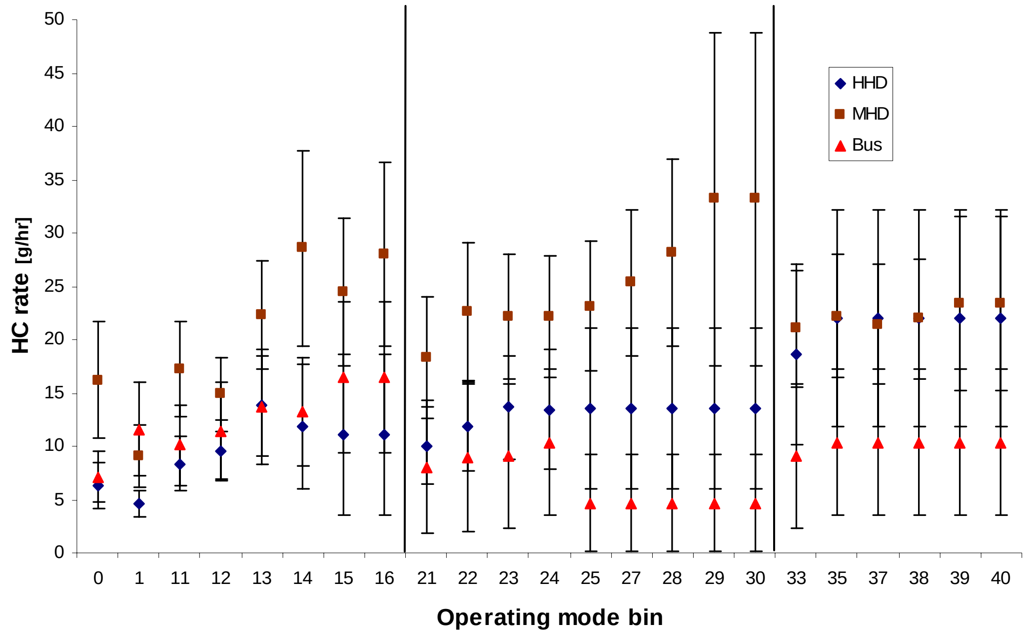


Figure 9 shows CO emission rates [g/hr] by operating mode bin for model year 2002.

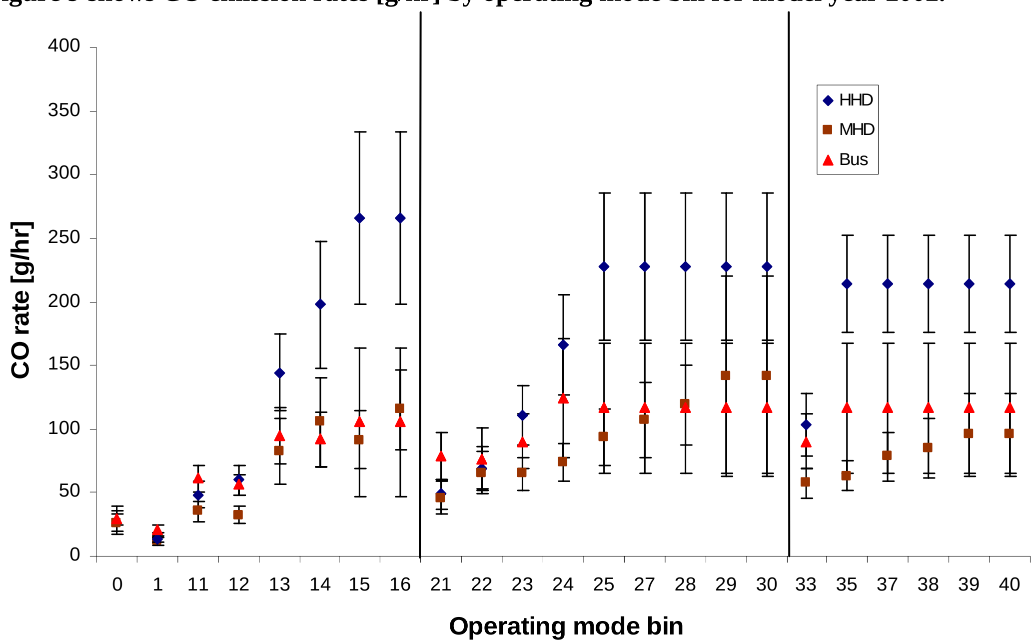


Figure 10 and Figure 11 show HC and CO emission rates by age group. These trends reflect entirely the T&M analysis, as the age effect for HC and CO were only modeled. Due to the T&M effect, there are large increases as a function of age. Since the age effect is a model, more in-use data if collected could help determine any real-world deterioration, especially in model years where diesel oxidation catalysts are most prevalent (2007 and later).

Figure 10 shows HC emission rates [g/hr] by age group for model year 2002 and operating mode bin 24.
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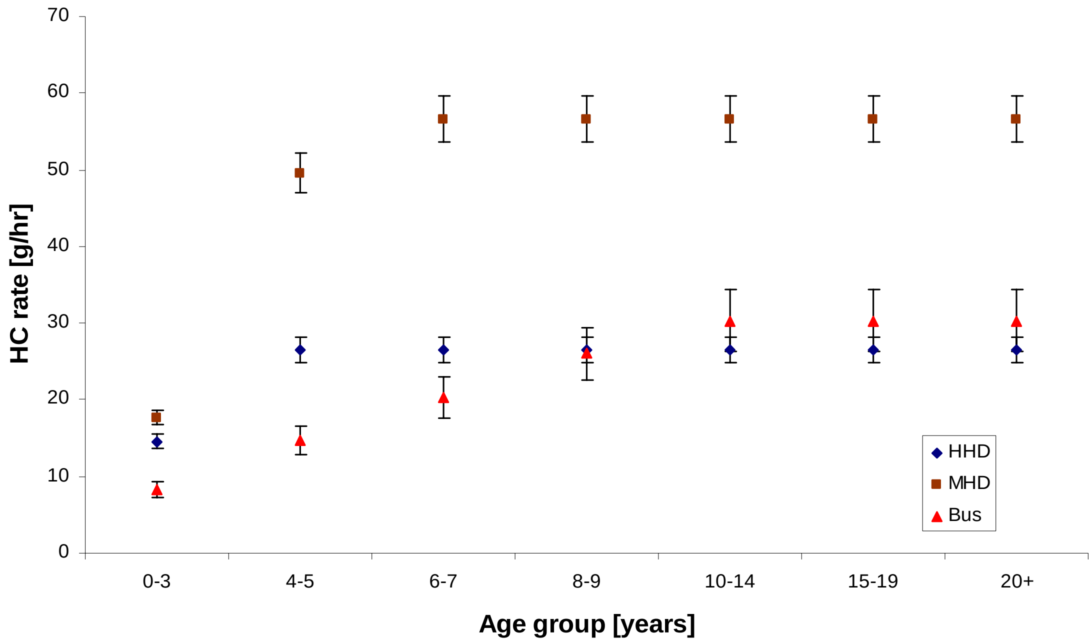


Figure 11 shows CO emission rates [g/hr] by age group for model year 2002 and operating mode bin 24.

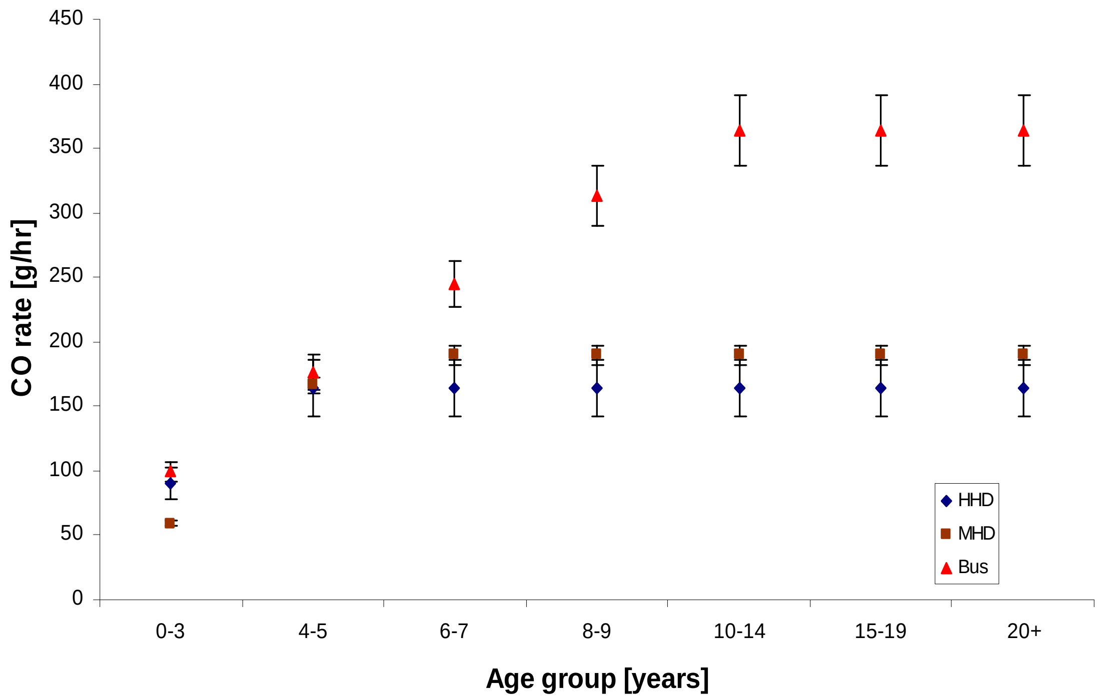


Figure 12 and Figure 13 show sample HC and CO emission rates by model year group. The two earlier model year groups are closer together, as we reduced the latest model year group due to the use of diesel oxidation catalysts. Due to the sparseness of the data and that HC and CO emission do not track as well with VSP (or power) as NOx or PM, uncertainties are much greater.

Figure 12 shows HC emission rates by model year group for operating mode bin 24 and ages 0-3.

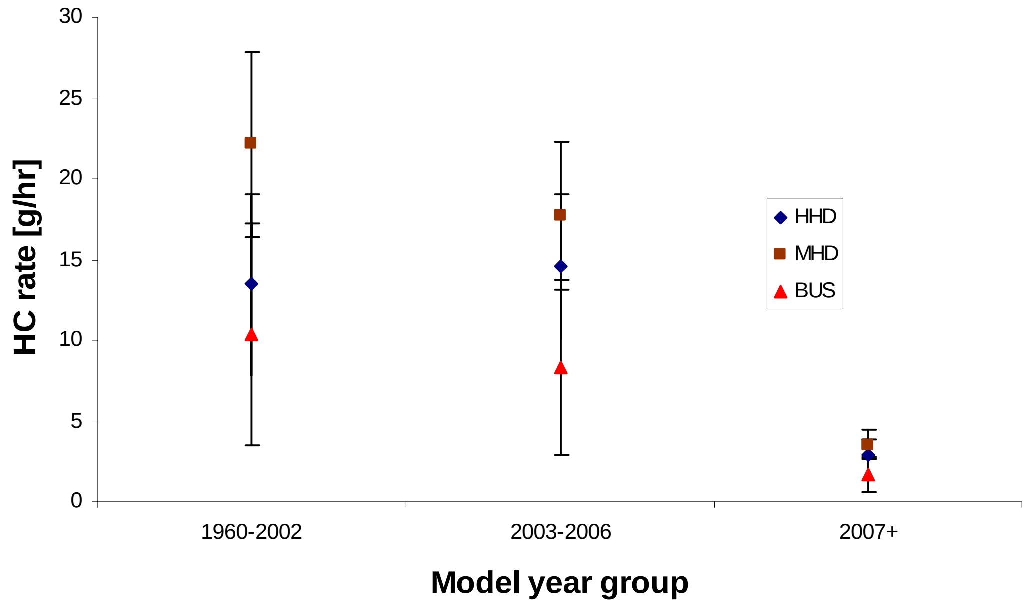
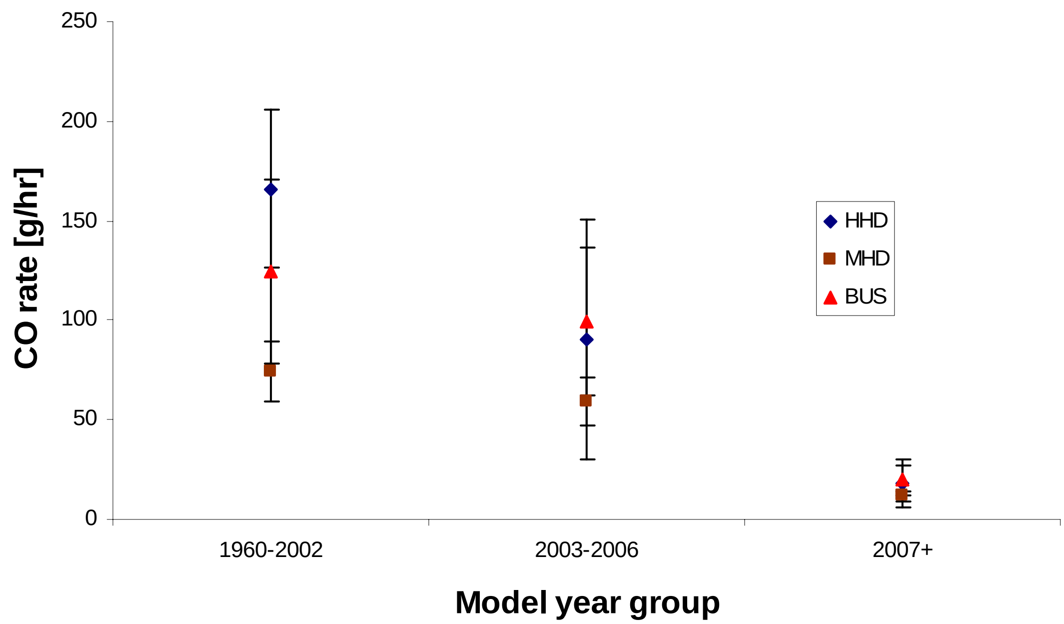


Figure 13 shows CO emission rates by model year group for operating mode bin 24 and ages 0-3.



1.1.4 Updates for final MOVES release

The methodology and results described in this document reflect the analysis performed for the draft release of MOVES. For the final release, we have planned a few changes to the heavy-duty diesel running exhaust emissions rates.

i. We plan to calculate VSP differently. Instead of using the average weight in each regulatory class to calculate VSP for a vehicle in that regulatory class, we will use one average weight for all heavy-duty vehicles to calculate VSP for each vehicle. Since emissions regulations are based on engine power regardless of regulatory class, normalizing this power by different masses destroys the relation between emissions and power across regulatory classes. This is especially true for NOx and PM, the two most significant pollutant emissions from diesel engines. This is also important because several source use types in MOVES are in multiple heavy-duty regulatory classes, and their VSP and operating mode distribution must be allocated to each regulatory class adequately. Using a uniform heavy-duty average mass preserves the relation of NOx and power by way of VSP. Indeed, vehicle-specific power would be a misnomer for the new calculation. Rather, it can be thought of as power scaled by a constant factor.

ii. We plan to incorporate NOx benefits resulting from reflashing heavy-duty engines from mid-1990's model years. Reflashing refers to the reprogramming of heavy-duty diesel engines' engine control units to lower NOx, as required under the consent decree that ruled against the so-called "emission defeat devices". The motivation for the change is to ensure that MOVES recognizes proactive steps taken by states to reflash to appropriate engines above and beyond the latent number of reflashes in the fleet. Benefits will likely be realized only in operating modes where the emission defeat devices were believed to have been most operational.

iii. We plan to incorporate emissions impacts of the recently promulgated heavy-duty onboard diagnostic (OBD) rule. This rule takes fully into effect in model year 2013 and is designed to lower the number of failure of aftertreament systems in the emerging fleet of heavy-duty vehicles.

iv. In light of i), our method of filling holes for missing regulatory classes will change. Since VSP will be essentially a scaled power, and heavy-duty engine emissions are generally a function of engine power, we will not adjust or modify rates for missing regulatory classes. The differences in overall emissions between classes can then be seen by the larger classes (e.g. HHD or Bus) reaching higher VSP levels compared to the smaller classes.

1.2 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 MOVES analysis, 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 distributed as a function of soak time can be found in subsection *1.2.3 Adjusting Start Rates for Soak Time* and in the MOVES light-duty emission rate counterpart document *Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator*.

1.2.1 HC, CO, and NOx

For light-duty vehicles, this is determined 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. This similar analysis was performed for LHD vehicles tested on the FTP and ST01, which also has 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 stratifications 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 20:

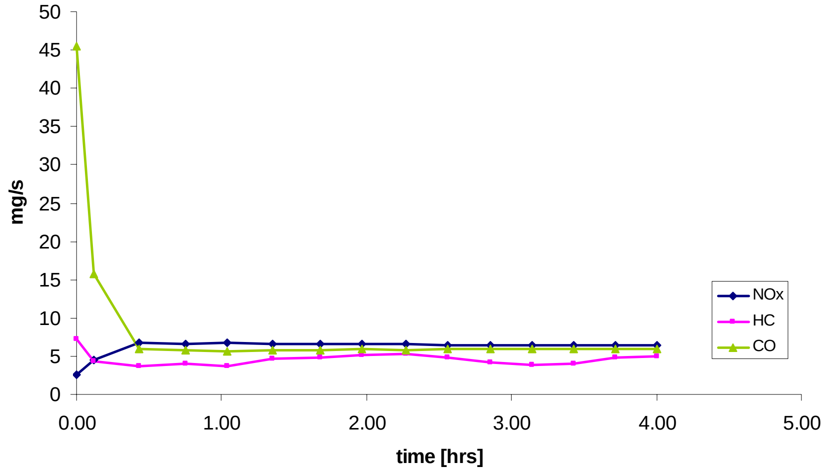
Table 20 shows average start emissions increases in grams for light-heavy duty vehicles

HC	CO	NOx
0.13	1.38	1.68

For HHD and MHD trucks, data was much more scant. We tested a 2007 Cummins ISB on an engine dynamometer at EPA's National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan. Among other idle tests, we performed a cold start idle test at 1100 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 14. 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 14 shows the stabilization of emissions from a cold start idle engine dynamometer test on an in-house 2007 MY Cummins ISB



We calculated the area under each curve for the first 25 minutes and divided by 25 minutes to get the average emission rate during the cold start idle portion. Then, we averaged the data for the remaining portion of the test, or the warm idle portion. The difference between cold start and warm start is in Table 21. The NOx increment is negative since cold start emissions are lower than warm start emissions.

Table 21 shows 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[27], 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 determined 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 get the cold start increment to be used in MOVES. We found that several trucks produced lower NOx emissions during cold start (including EPA's test), 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 our cold start increment to zero, pending any future data that may be collected. Table 22 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 22 shows MOVES inputs for HHD and MHD start emissions increases in grams.

HC	CO	NOx
0.0	16.0	0.0

1.2.2 Particulate Matter

Heavy-duty truck PM2.5 emissions for the start process have not been collected in any significance. No such rates were available from the MOBILE6.2 model for use in MOVES. Typically, heavy-duty vehicle emission measurements begin on fully warmed up vehicles. This test procedure bypasses the engine crank and early operating periods when the vehicle is not fully warmed up.

For the MOVES Draft version data one heavy-heavy-duty engine with six FTP tests using a filter PM measurement was available from EPA engine dynamometer testing. The engine was a 2004 model year engine.

The engine was tested at 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 = 1.9314 g – 1.8215 g = **0.1099 g PM2.5**

We applied this value of 0.10985 g of Total PM2.5 per start for 1960 through 2006 model year vehicles. A corresponding value of 0.01099 g was used for 2007 and later model year vehicles (90% reduction due to DPFs). We will look to update these numbers if more data is collected. For now, this one engine is our only data point.

1.2.3 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. The value at 720 min (12 hours) represents cold start, and each successive value represents a shorter soak time, representing operating modes 107 – 101, respectively. These bins are not related to the bins in Table 9, which deals with running exhaust emissions. Table 23 describes the different start-related operating mode bins in MOVES as a function of soak time.

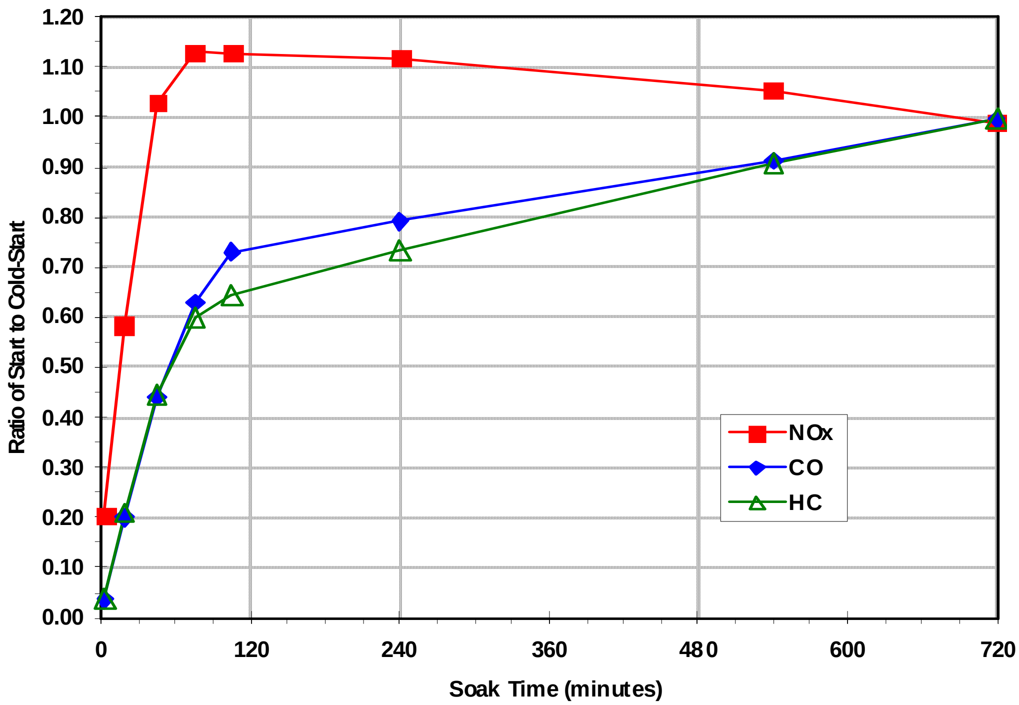
Table 23 – MOVES operating mode bins for start emissions (as a function of soak time)

Operating Mode Bin	MOVES Operating Mode Bin 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 15 below.

Figure 15 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 bin are given in Table 24 below.

Table 24 – MOVES Start PM Emission Rate by Operating Mode Bin (soak fraction)

Operating Mode Bin	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

1.3 Extended Idling Emissions

In the MOVES model, extended idling is "discretionary" idle operation characterized by extending idle periods that are several hours in duration, 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 cause 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.

For MOVES model, only diesel long-haul combination trucks are 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.

1.3.1 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)[28]. 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 range was 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)[29]. 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)[30]. 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)[31]. 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)[32].

The National Cooperative Highway Research Program (NCHRP)[33] 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)[34]. 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 testing using EPA's on-road emissions testing trailer based in Research Triangle Park, North Carolina (Broderick)[35]. 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)[36]. 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)[27].

1.3.2 Analysis

EPA performed an analysis of the emission impacts of extended idling for particulate matter (PM), oxides of nitrogen (NOx), hydrocarbons (HC), and carbon monoxide (CO) for populating the MOVES model. This analysis used all of the data sources referenced in this document. 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 EPA 2003 analysis is that factors that affect 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 years 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 (A/C, 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, or low engine speed (<1000 rpm) and no air conditioning. The second is representative of an extended idle condition with higher engine speed (>1000 rpm) and no air conditioning. The third represents an extended idle condition with higher engine speed (>1000 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 increased NOx emission rates due to 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, PM, and NOx emissions after hours of idling due to cool-down effects on EGR and the aftertreatment systems. As a result, idle NOx emissions will be reduced 12%, PM emissions will be reduced 11%, and HC emissions will be reduced 9% 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. Detailed equations are included in the Appendix.

1.3.3 Results

Table 25 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 25 shows extended idle emission rate inputs in g/hour.

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

The PM rates in the draft version of MOVES do not yet reflect the analysis detailed in the previous subsection. For the time being, the regular curb idle emission rates have been substituted (i.e., MOVES opmodeid = 1) for use in MOVES as extended idle rates. This is likely an understatement of the "true" and currently unknown extended idle rates. We expect the rates in the final version to increase at least marginally based on the increased use of accessories and, for current and future model years, a reduction of aftertreatment effectiveness during extended idling.

2 <u>Heavy-Duty Gasoline Truck emissions</u>

2.1 Running Exhaust Emissions

2.1.1 HC, CO, and NOx

2.1.1.1 Data and Analysis

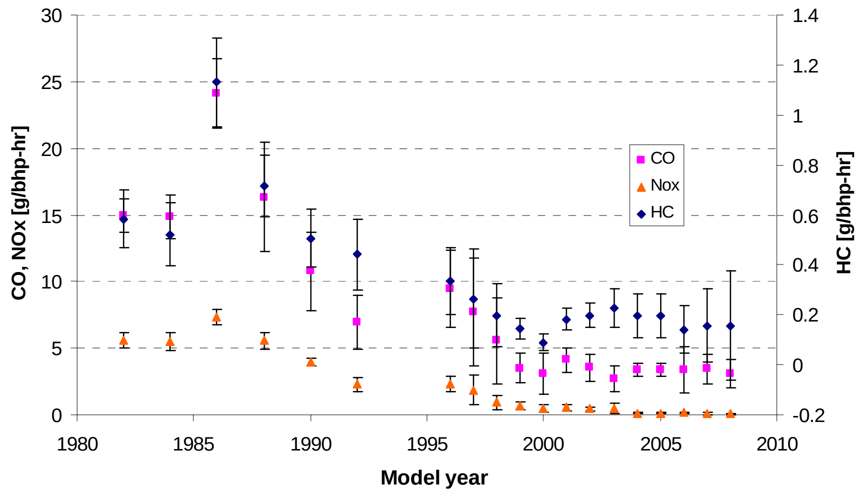
As gasoline-fueled vehicles are a small percentage of the heavy-duty vehicle fleet, the amount of data available for analysis was small. We relied on four medium-heavy duty gasoline trucks from the CRC E-55 program and historical data from EPA's Mobile Source Observation Database (MSOD), which has records of chassis tests performed by both EPA and outside parties or contractors. The heavy-duty gasoline data the MSOD contains is mostly of pickup trucks which fall mainly in the LHD2b regulatory class. Table 26 shows the number of vehicles in cumulative data sets. In the real world, most heavy-duty gasoline vehicles fall in either the LHD2b or LHD345 class, with a smaller percentage in the MHD class. There are nearly zero HHD gasoline trucks.

Table 26 shows the 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
	LHD2b		10
1990-1997	MHD		1
	LHD2b	33	19
1998-2002	MHD	1	
	LHD2b	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 VSP (Equation 8). Since heavy-duty emissions regulations are not usually focused on gasoline engines, we decided to look at certification data as a guide to developing model year groups for analysis. Figure 16 shows averages of certification results by model year.

Figure 16 shows brake-specific certification emission rates by model year for heavy-duty gasoline engines.



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

- 1960-1989
- 1990-1997
- 1998-2002
- 2003-2006
- 2007 and later

We chose to make an extra 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% from 2003-2006 MY levels.

Unlike our HD diesel analysis, we used the age effects present in the data itself. We did not incorporate an external tampering and mal-maintenance model into the HD gasoline rates. Due to sparseness of data we used only the two age groups listed in Table 26. We also did not stratify by regulatory class since there was only one regulatory class (LHD2b) predominantly represented in the data.

2.1.1.2 Sample Results

As for the heavy-duty diesel analysis, a few sample results graphs are shown. The first (Figure 17) shows all three pollutants against operating mode bin for the LHD2b regulatory class. In general, emissions follow the common trend with VSP. As expected, NOx emissions for heavy-duty gasoline vehicles are much lower than for heavy-duty diesel vehicles.

Figure 17 shows emissions by operating mode bin for MY 2002 age 0-3.

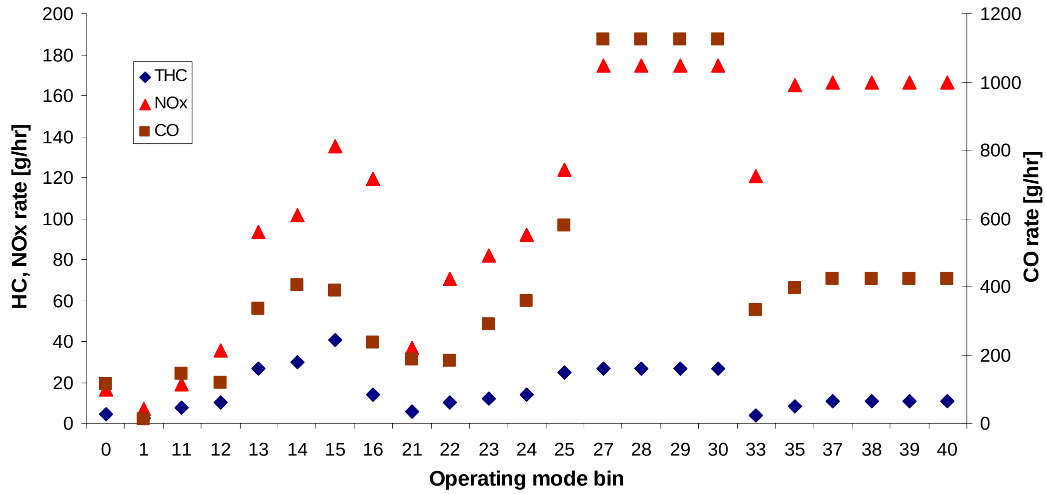


Figure 18 shows the emissions trends by age group. Since we did not use the tampering and mal-maintenance methodology as we did for diesels, the age trends reflect our coarse binning with age. For each pollutant, only two distinct rates exist – one for ages 0-5 and another for 6 and older

Figure 18 shows emissions by age group for MY 2002 in operating mode bin 24.

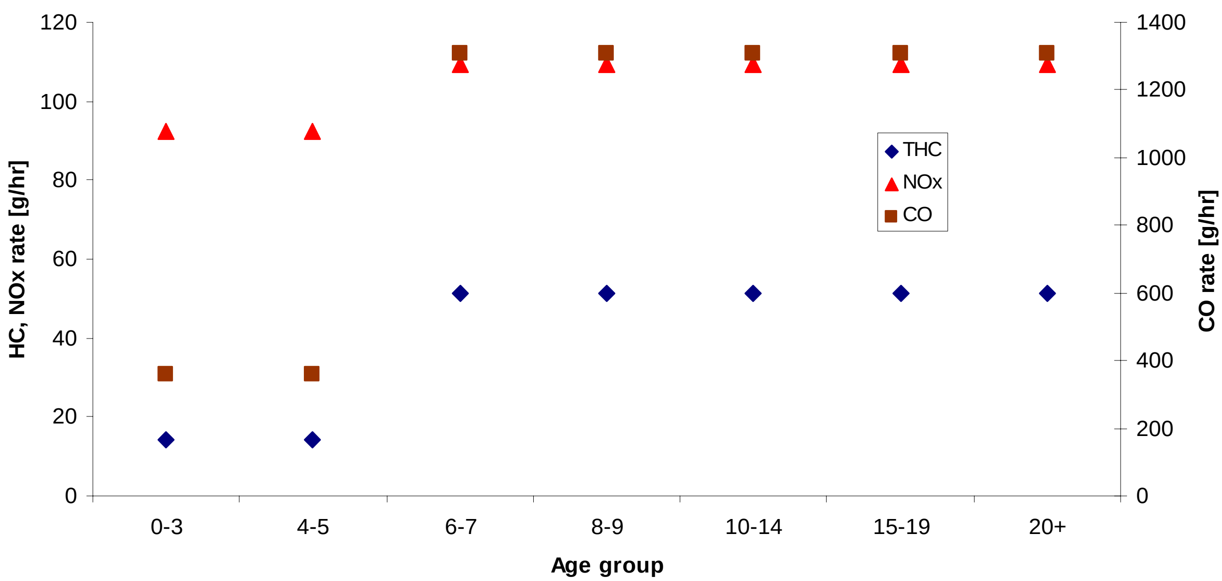
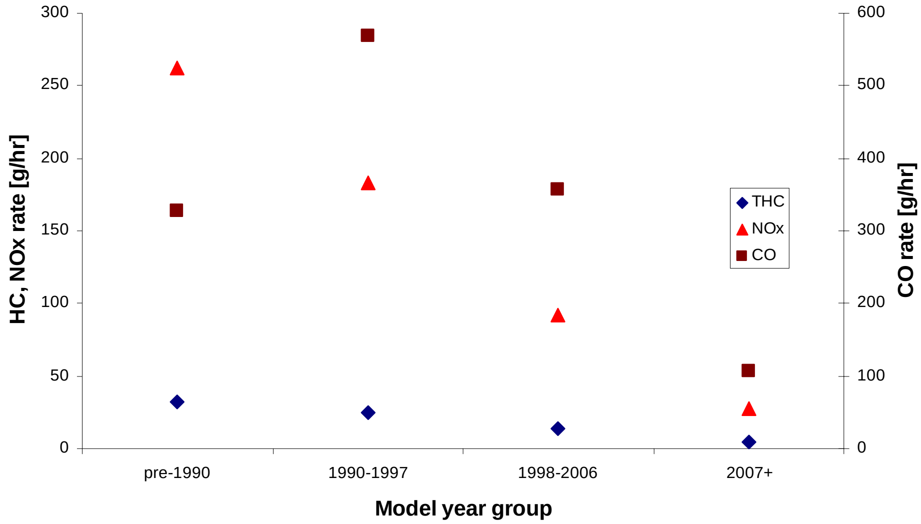


Figure 19 shows emissions by model year group. Except for CO, emissions consistently decrease with model year group. Our assumptions regarding implementation of increased effectiveness of catalysts substantially reduce emissions estimates for 2007 model year and later.

Figure 19 shows emissions by model year group for age 0-3 in operating mode 24.



2.1.2 PM

Unfortunately, the PM2.5 emission data from heavy-duty gasoline trucks are too sparse to develop the broad and detailed emission factors expected by the MOVES model. As a result, only a very limited analysis could be done, and 'placeholder' emission rates developed for the model. As such, EPA will likely revisit and update these emission rates, when sufficient data on PM2.5 emissions from heavy-duty gasoline vehicles become available.

The principal result from this analysis is that for the Draft MOVES2009 model, 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. Since the MOVES light-duty gasoline PM2.5 emission rates are a complete set of factors - stratified by particulate sub-type (elemental and organic carbon), operating mode, model year and regulatory class, the heavy-duty PM2.5 emission factors will also be a complete set.

2.1.2.1 Data Source

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 which were used are the UDDS test cycle data. 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 27.

Table 27 – Summary of data used in HD gasoline PM emission rate analysis

Vehicle	MY	Age	Test cycle	GVWR	PM2.5 mg/mi
1	2001	3	UDDS	12975	1.8115942
	2001	3	UDDS	19463	3.6101083
2	1983	21	UDDS	9850	43.3212996
	1983	21	UDDS	14775	54.3478261

3	1993	12	UDDS	13000	67.0949972
	1993	12	UDDS	19500	108.336719
4	1987	18	UDDS	10600	96.7349998
	1987	18	UDDS	15900	21.5098555

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.

2.1.2.2 Analysis

Examination of the heavy-duty data shows two distinct strata of data – 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:	0.06522 g/mi	Older Group
Mean for Vehicle 1:	0.00271 g/mi	Newer Group

For comparison with the heavy-duty gas PM rates tested over the UDDS cycle, <u>simulated</u> UDDS cycle emission rates were developed based on MOVES light-duty gas PM2.5 emission rates (normal deterioration assumptions) for light-duty gasoline trucks. The UDDS cycle represents standardized operation for the heavy-duty vehicles.

To make the comparisons fair, the simulated light-duty UDDS results were matched by model year and age to the model year and age of 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> model year light duty gas truck group are 0.0362 g/mi for MOVES organic carbon PM2.5 emissions and 0.002641 g/mi for elemental carbon. Ignoring sulfate emissions (which are in the order of 1×10^{-7} g/mile for low sulfur fuels) sum to 0.03884 g/mile.

This value leads to the computation of the ratio: $\frac{0.06522 \frac{g}{mile}}{0.03884 \frac{g}{mile}} = 1.679$.

The simulated UDDS emission factors for the <u>newer</u> model year light duty gas truck group are 0.004368 g/mi for MOVES organic carbon PM2.5 emissions and 0.0003187 g/mi for elemental carbon. Ignoring sulfate emissions (which are in the order of 1×10^{-8} g/mile for low sulfur fuels) sum to 0.004687 g/mi

This value leads to the computation of the ratio: $\frac{0.00271 \frac{g}{mile}}{0.004687 \frac{g}{mile}} = 0.578$.

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

$$Ratio_{final} = Ratio_{older} WtFrac + Ratio_{newer} (1 - WtFrac)$$
$$= 1.679 \times 0.75 + 0.578 \times 0.25 = \mathbf{1.40}$$

We 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.

2.2 Start Emissions

2.2.1 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 LHD2b regulatory class.

Table 28 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 28. 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

2.2.2 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 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.

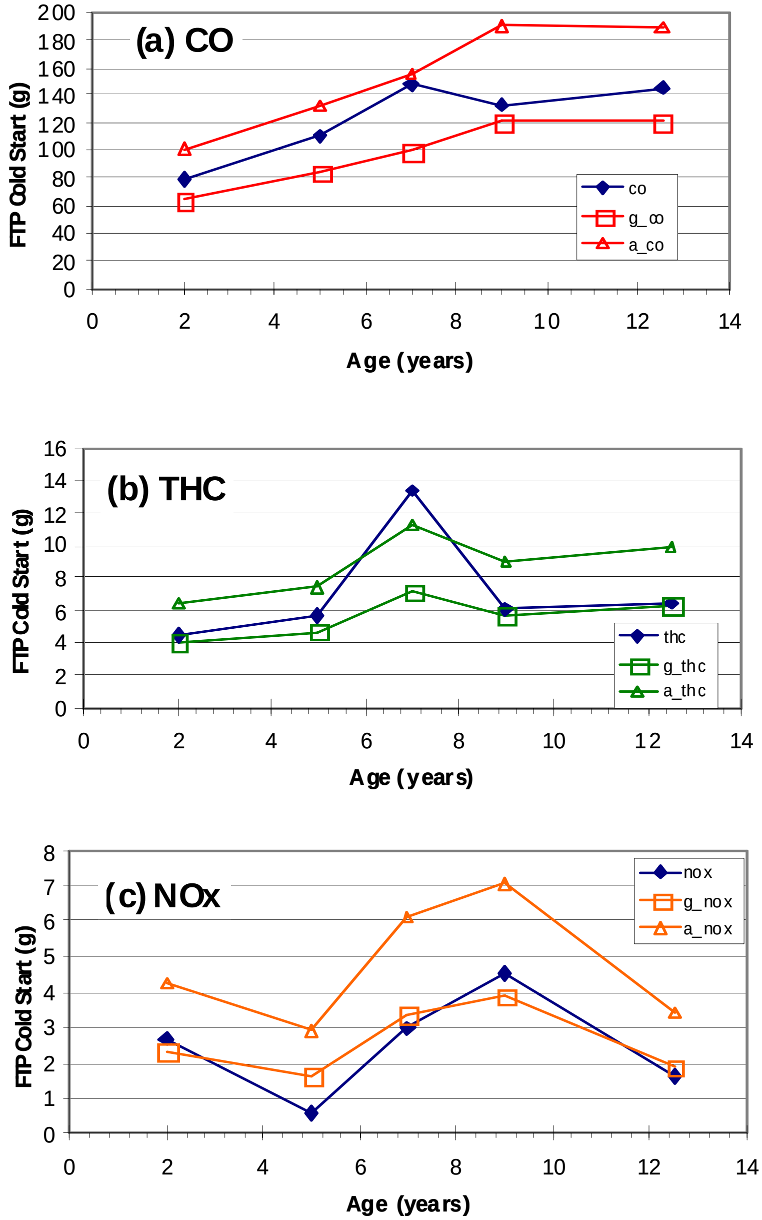
If we assume that the underlying population distributions are approximately lognormal, we can visualize the data in ways that illustrate underlying relationships. As a first step, we calculated geometric mean emissions, for purposes of comparison to the arithmetic means calculated by simply averaging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

$$\bar{x}_g = e^{\ln \bar{x}_l}$$ **Equation 11**

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 Heavy-duty Gasoline Start Emissions Analysis Figures*. 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 25 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) in . 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 lognormal 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.

Figure 20. 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).



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 26 above.

$$\bar{x}_a = \bar{x}_g \mathrm{e}^{\frac{s_l^2}{2}}$$ **Equation 12**

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 20 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.

2.2.3 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 13.

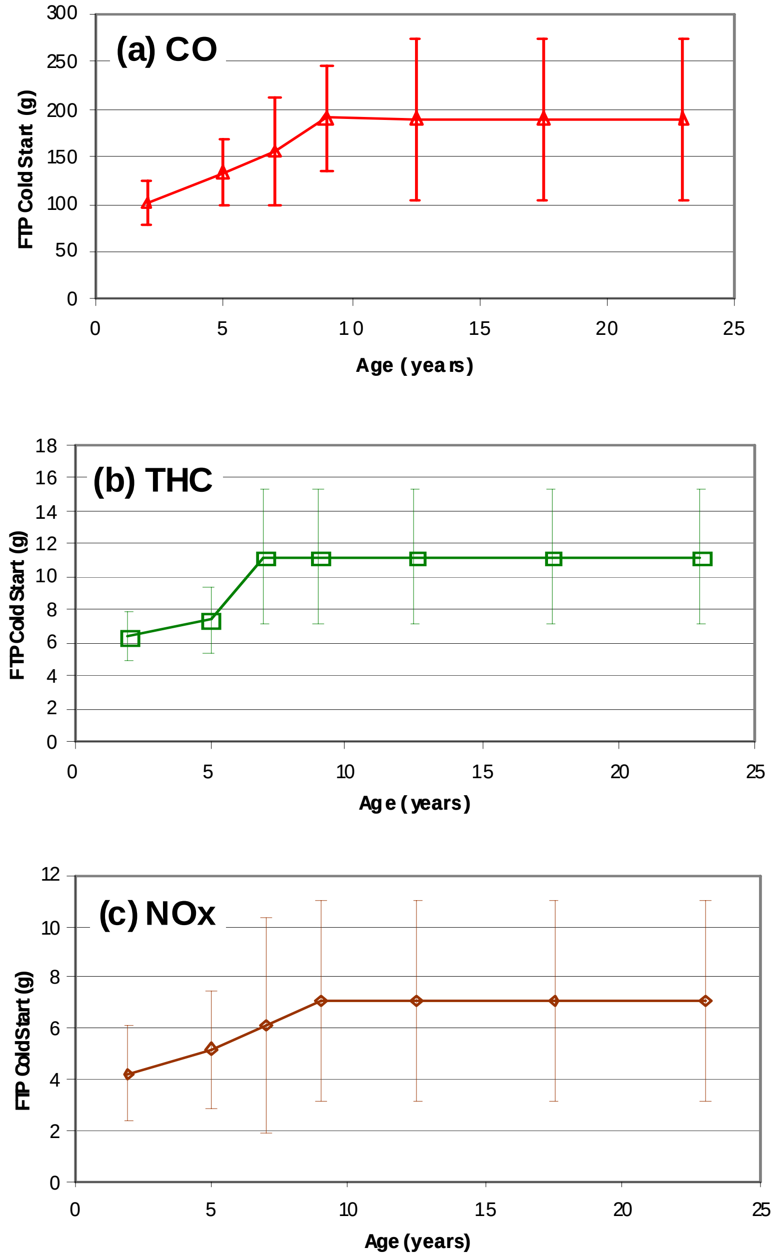
$$s = \sqrt{x_g^2 \, e^{s^2} (e^{s^2} - 1)} \qquad \textbf{Equation 13}$$

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 29 and in Figure 21. Note that these results represent only "cold-start" rates (opModeID 108).

Table 29. 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 21. Cold-start Emission Rates for Heavy-Duty Gasoline Trucks, with 95% Confidence Intervals



2.2.4 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.

2.2.4.1 Regulatory class LHD2b

For CO the approach was simple. We applied the values in Table 29 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 29 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

$$f_{\mathrm{HC}} = \left(\frac{0.14\ \mathrm{g/hp-hr}}{(0.14 + 0.20)\ \mathrm{g/hp-hr}} \right) \left(1.0\ \mathrm{g/hp\text{-}hr} \right) = 0.412 \qquad \textbf{Equation 14}$$

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

ERRATUM: the expression in Equation 14 above is in error, in that it does not relate the future standard (numerator) to the past standard (denominator). The following corrected value is to be used in revised rates for final MOVES.

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

We calculated the corresponding value for NOx as

$$f_{\mathrm{NOx}} = \left(\frac{0.20\ \mathrm{g/hp-hr}}{(0.14 + 0.20)\ \mathrm{g/hp-hr}} \right) = 0.588 \qquad \textbf{Equation 15}$$

ERRATUM: as for HC, the value in Equation 15 is erroneous, for similar reasons. Whereas the error was small, for HC, it is more substantial for NOx. The corrected value to be used for final MOVES, is

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

The error for HC is small but for NOx it is substantial. For these rates we neglected the THC/NMHC conversions, which we gave attention to 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

$$f_{\mathrm{HC}} = \frac{0.14\ \mathrm{g/hp \cdot hr}}{1.1\ \mathrm{g/hp \cdot hr}} = 0.127 \qquad \textbf{Equation 16}$$

$$f_{\mathrm{NOx}} = \frac{0.20\ \mathrm{g/hp \cdot hr}}{4.0\ \mathrm{g/hp \cdot hr}} = 0.05 \qquad \textbf{Equation 17}$$

2.2.4.2 Regulatory classes LHD345 and MHD

For LHD345 and MHD, we estimated values in terms of the values calculated for LHD2b.

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

$$f_{\mathrm{CO}} = \frac{37.1\ \mathrm{g/hp\text{-}hr}}{14.4\ \mathrm{g/hp\text{-}hr}} = 2.58 \qquad \textbf{Equation 18}$$

and the corresponding value for HC is1.73.

$$f_{\mathrm{HC}} = \frac{1.9\ \mathrm{g/hp\text{-}hr}}{1.1\ \mathrm{g/hp\text{-}hr}} = 1.73 \qquad \textbf{Equation 19}$$

We applied this ratio in all three model-year groups, as shown in Table 30.

ERRATUM: the ratios in Equation 18 and Equation 19 were erroneously applied to the 2005-2007 model-year groups for LHD345 and MHD vehicles. In final MOVES, values for these model-year groups will set be equal to those for the LHD2b vehicles, with the rationale that the standards converge for both groups.

For NOx, all values are equal to those for LHD2b, because the same standards apply to both classes throughout. The approaches for both regulatory classes in all three model years are shown in Table 30.

Table 30. Methods used to Calculate and Start Emission Rates for Heavy-Duty Spark-Ignition Engines

Regulatory Class	Model-year Group	Method		
		CO	THC	NOx
LHD2b	1960-2004	Values from Table 29	Values from Table 29	Values from Table 29
	2005-2007	Values from Table 29	Reduce in proportion To standards	Reduce in proportion To standards
	2008 +	Values from Table 29	Reduce in proportion To standards	Reduce in proportion To standards
LHD345, MHD	1960-2004	Increase in proportion	Increase	Same values as

		To standards	in proportion To standards	LHD2b
	2005-2007	Increase in proportion To standards	Increase in proportion To standards	Same values as LHD2b
	2008 +	Increase in proportion To standards	Increase in proportion To standards	Same values as LHD2b

As for heavy-duty diesel and light-duty vehicles we applied the curve in Figure 15 to adjust the start emission rates for varying soak times. The rates described in this section were for fully cold starts (soak time > 720 minutes).

2.2.4.3 Particulate Matter

We did not have data on PM from heavy-duty gasoline vehicles. As a result, we used the multiplication factor from the running exhaust emissions analysis of 1.40 to scale up the light-duty truck start emission rates.

A. Appendices

A.1 Calculation of Accessory Power Requirements for VSP bins

Table 31 – 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 32 – 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 33 – 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

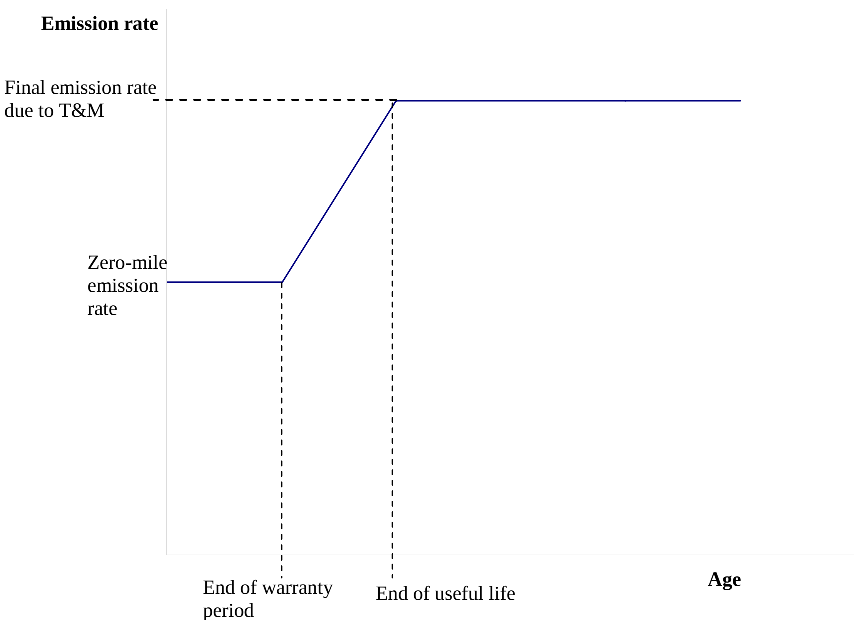
A.2 Tampering and Mal-maintenance

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 and test cells often yield very small rates of emissions deterioration through time. However, in real-world use, tampering and mal-maintenance yield higher rates of emissions deterioration through 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 affect emissions through age, we developed a simple function of emission deterioration through age. We applied the zero-age rates through emissions warranty period (5 years/100,000 miles), then increased the rates linearly up to useful life. Then we assumed that all the rates level off beyond the useful life age. Figure 22 shows this relationship.

Figure 22 qualitatively shows the implementation of age effects in MOVES.



The useful life refers to the length of time that engines are required to meet emissions standards. We incorporated this age relationship through the age groups in MOVES by averaging emissions rates for all ages in each age group. Mileage was converted to age with VIUS[37] (Vehicle Inventory and Use Survey) data, which contains data on how quickly trucks of different regulatory classes accumulate mileage. Table 34 shows the emissions warranty period and approximate useful life requirement period for each of the regulatory classes.

Table 34 – Warranty and useful life requirements by regulatory class

Regulatory class	Warranty age (Requirement: 100,000 miles/5 years)	Useful life mileage/age requirement	Useful life age
HHD	1	435,000/10	4
MHD	2	185,000/10	5
LHD345	4	110,000/10	4
LHD2b	4	110,000/10	4
BUS	2	435,000/10	10

While both an age and a mileage metric are given for these periods, whichever comes first is what determines the applicability of the warranty. As a result, since MOVES deals with age and not mileage, we need to convert all the mileage numbers to age numbers, as the mileage limit usually is 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 their emissions will happen more quickly than 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 proper 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 within 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 35 shows the multiplicative T&M adjustment factor by age. We determined this factor using the mileage-age data from Table 34 and the emissions-age relationship that we described in Figure 22. 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 35 shows the T&M multiplicative adjustment factor by age.

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), and a value of 1 indicates a fully deteriorated engine (or maximum emissions level). The calculation of emission rate by age group is described in the equation below.

$$\bar{r}_{pol,agegrp} = \bar{r}_{ZML}(1 + f_{pol,agegrp}TM_{pol})$$

A.2.2 Data Sources

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

- California's ARB EMFAC2007 Modeling Change Technical Memo[38] (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 EMAFAC 2007
- University of California –Riverside "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

T & M Categories

EPA generally agreed with 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 groups into EGR Stuck Open and EGR 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.

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 begins the use of EGR.
- 2007 and 2010 contain significant PM and NOx regulation changes.
- EPA issued a NPRM to require OBD phase-in beginning in 2010 model year for heavy duty trucks with complete phase-in by 2013. However, we will not be applying OBD to the frequency rates at this time because we have not issued a final rulemaking.

T &M Occurrence Rates

EPA T &M Occurrence Rate Differences from EMFAC2007

EPA agreed with the CARB EMFAC2007 occurrence rates, except as noted below.

Clogged Air Filter: EPA reduced the frequency rate from CARB's 15% to 8%. 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 CARB's 8% to 6% based on the UCR results.

Electronics Failed: EPA will continue to use the 3% frequency rate for all model years beyond 2010. CARB increased the rate to 30% 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 occurrence rates. We believe that the hardware will experience an evolution through 2010, not 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%. 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 20% EGR failure rate is too high and reduced the rate to 10%. All but one major engine manufacturer had EGR previous to the 2007 model year and all have it after 2007. Therefore, CARB'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[39] so it cannot be ignored.

NOX Aftertreatment malfunction: EPA developed the NOx aftertreatment malfunction rate 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% 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% occurrence rate in EMFAC2007 is too high and will use 10%. 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% 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% PM filter leak and system failure rate. CARB used 14% failure rate. They discounted high failure rates currently seen in the field.

PM Filter Disable: EPA agrees with CARB's 2% tamper rate of the PM filter. The filter causes is 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% failure rate. This rate consists of an approximate 2% tampering rate and 3% 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% of the time.

MOVES Tamper & 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%

Emission Effects

NOx Emission Effect of Tampering and Mal-maintenance

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% efficient and the selective catalyst reduction (SCR) systems in HHDD are 90% 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. MECA states 75-90% NOX reduction with open loop control and >95% reduction with closed loop control.[40] Visteon reports 60-80% NOX reduction with open loop control.[41]

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% increase in NOx during a complete failure, therefore we estimated a 500% increase as a midpoint between normal operation and a complete failure. The LHDD vehicles with LNT systems would experience a 500% increase in NOx during a complete failure. We estimated a 300% increase as a value between a complete failure and normal system operation.

The values with 0% 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 Effect of Tampering and Mal-maintenance

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% effectiveness. Many of the tampering and mal-maintenance items that impact PM also have a fuel efficiency and driveability impact. Therefore, operators will have an incentive to fix the issue.

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%; however this value is reduced by 95% due to the PM filter affectivity. 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% 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 Effect of Tampering and Mal-maintenance

EPA estimated oxidation catalysts are 80% effective at reducing hydrocarbons. All manufacturers will utilize oxidation catalysts in 2007, but only a negligible amount installed one 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% based on internal experience. We increased the HC emission effect of high fuel pressure to 10% 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% 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. The same effects were assumed 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 15 (PM), and
Table 19 (HC and CO).

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, PM filter, and NOx aftertreatment, are still active for the first hour.
- PM emissions standards:
  - Pre-2007: 0.1 g/bhp-hr
  - 2007: 0.1 g/bhp-hr
- 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 PM Rate Reduction = 1 - [(1/8 * 0.01 g/bhp-hr + 7/8 * 0.1 g/bhp-hr) / 0.1 g/bhp-hr] = 11%

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 Regression to develop PM emission rates for missing operating mode bins

The regression technique that was used was a log-linear least squares procedure. Regulatory class, model year group and speed bin (0 – 25 mph, 25-50 mph and 50+ mph bins) were represented by dummy variables in the regression. Natural log of emissions was regressed versus vehicle specific power (VSP) to represent the operating mode bins. The regression assumed a constant slope versus VSP for each regulatory class. Log 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 equation Eq-2 shows the form of the resulting regression equation.

Regression Coefficients for PM Emission Factor Model				
Regulatory Class 46			**Regulatory Class 47**	
Regclass Code	**Coefficient**		**Regclass Code**	**Coefficient**
464410	-5.419		474410	-5.143
464420	-4.942		474420	-4.564
464430	-4.765		474430	-4.678
464510	-5.366		474510	-5.847
464520	-4.929		474520	-5.287
464530	-4.785		474530	-5.480
464610	-5.936		474610	-5.494
464620	-5.504		474620	-5.269
464630	-5.574		474630	-5.133
464710	-5.927		474710	-6.242
464720	-5.708		474720	-5.923
464730	-5.933		474730	-6.368
464810	-6.608		474810	-6.067
464820	-6.369		474820	-5.754
464830	-6.305		474830	-6.154
VSP	0.02821		VSP	0.0968
Transformation Coefficient	0.5864		Transformation Coefficient	0.84035

The Regclass Code shown in the Table has the following explanation. The first two digits from the left indicate the regulatory class – either 46 or 47. Class 46 is the medium heavy-duty diesel vehicle class, and Class 47 is the heavy heavy-duty diesel vehicle class. The MOVES model also contains lighter diesel vehicle classes 41 and 42 and the transit bus class 48, but no data were available for these. The second two digits represent the model year group. Where the value of 44 maps to 1960-1987, 45 maps to 1988-1990, 46 maps to 1991-1993, 47 maps to 1994 - 1997 and 48 maps to 1998 – 2006. A final code value of 49 was also mapped to the 2007+ model years for use in MOVES. However, there were no data associated with this group. The final two digits represent the speed divisions of the operating mode bins. The value of 10 represents 0 to 25 mph, 20 represents 25 to 50 mph and 30 represents 50 mph and higher. The VSP is an independent variable within each of the speed divisions.

Log emissions = Coefficient + VSPCoefficient * Avg VSP + Log Trans Coeff

Where :

The variable 'Coefficient' are the coefficients found in the above table. VSPCoefficient is the VSP Coefficient at the bottom of the table, and Log Trans Coeff is the log transformation coefficient in the table. Avg VSP is the average VSP utilized by MOVES for each of the 23 operating mode bins in units of kW/metric ton (i.e., bin11 = 0, bin12 = 1.5, bin13 = 4.5, etc.).

A.5 Heavy-duty Diesel EC/OC 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 University of California Riverside's "Mobile Emission Laboratory."

The subsequent sections of the memo describe the following:

- the extension of PERE for heavy-duty diesel vehicles, developed by Nam and Giannelli, 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

PERE (Physical Emission Rate Estimator) is a model employed by EPA in earlier developmental phases of MOVES.[42] In particular, the MOVES team employed it in "hole filling" greenhouse gas emission rates for unlikely SourceBin/OpModeBin combinations in MOVES2004.[43]

The underlying theory behind PERE and its comparison with measured fuel consumption data is described by Nam and Giannelli (2005).[42] 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 described by Nam and Giannelli (hereafter, "PERE-HD", accessory loads were described by a single estimate of the power demand of accessories.

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 and OC 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, resistive force coefficients, transmission type, class [MDT/HDT/bus]);

- engine parameters (fuel type, displacement); and
- driving cycle.

The specification of these inputs allows a 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 would using a small number of averages alone.

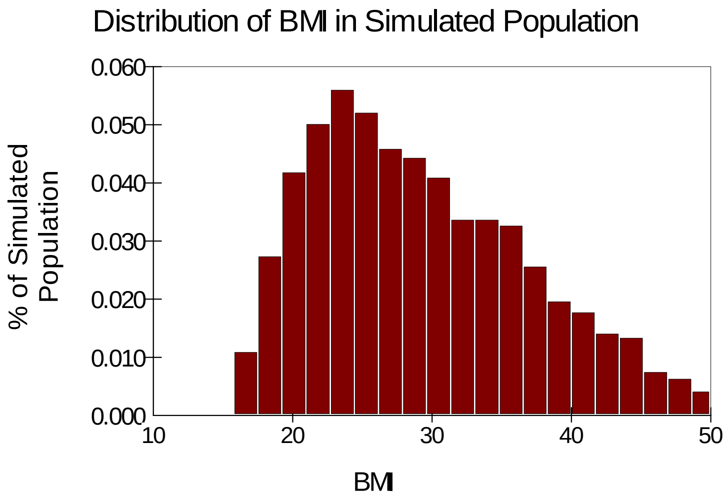
For the current application, PERE-HD, a model built within Microsoft Excel was expanded to allow for a representative sample of [running weight] * [engine displacement] * [model year] combinations. A third-party add-on package to Excel, @Risk 4.5 (Palisade Corporation, 2004) allows fixed inputs within spreadsheet models to be substituted with probability distributions, sample an input value from each input distribution, and re-run the spreadsheet model many times. This type of procedure is commonly referred to as "Monte Carlo" simulation.

A.5.2.1.1 Monte Carlo Simulation in PERE-HD

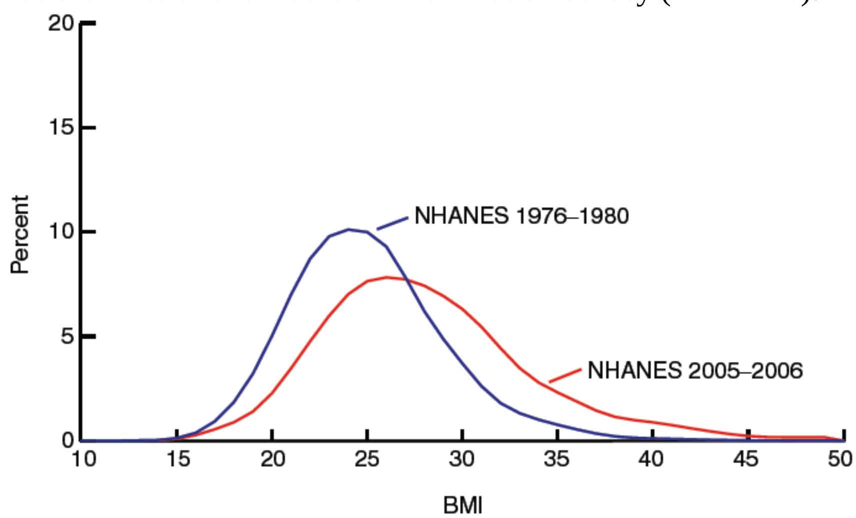
To illustrate how @Risk performs this process, compare the results of the following equation when using fixed inputs versus distributions of inputs:

$$BMI = M / L^2$$

This is the equation for body mass index in humans, a simple surrogate for overweight and underweight. 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 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 (5000 iterations) using @Risk, we would predict a probability distribution of BMI in the population as follows:



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



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

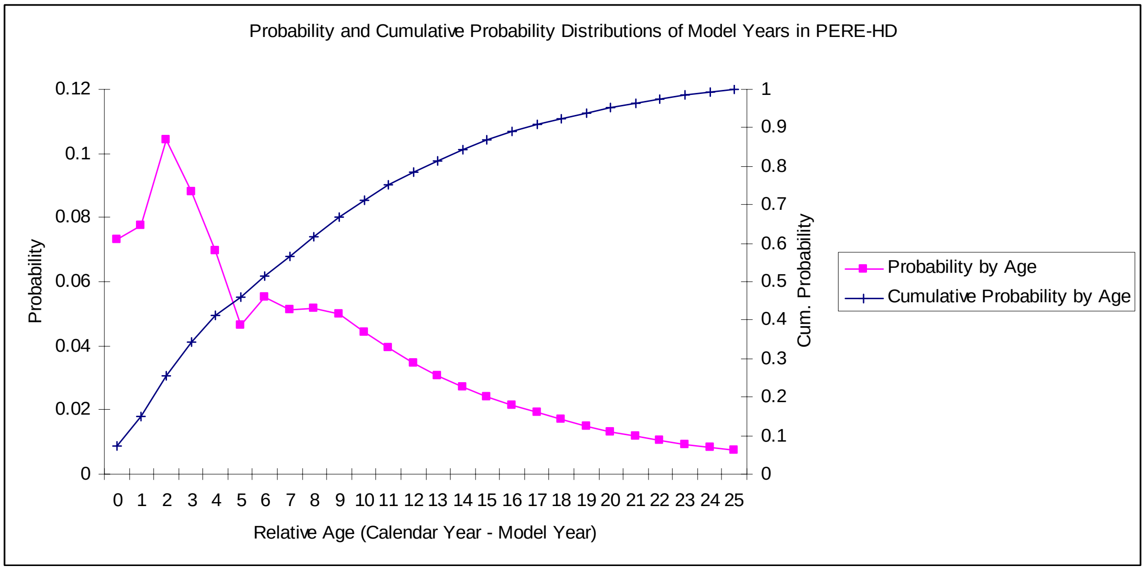
These graphs illustrate how Monte Carlo simulation can be used to provide meaningful information about the variability in a population. Although the model example is very simple, it illustrates the point that a model with "average" inputs provides much less information than does Monte Carlo simulation of 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 (FMEP) vary by model year, improving with later model years. As such, model year was simulated as a probability distribution, using data from the Census Bureau's 1997 Vehicle Inventory and Use Survey (VIUS) VIUS reports VMT by model year, so these data were normalized total VMT to develop a probability distribution. Model year distributions in 1997 were normalized to the current calendar year (2008).[1] 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:

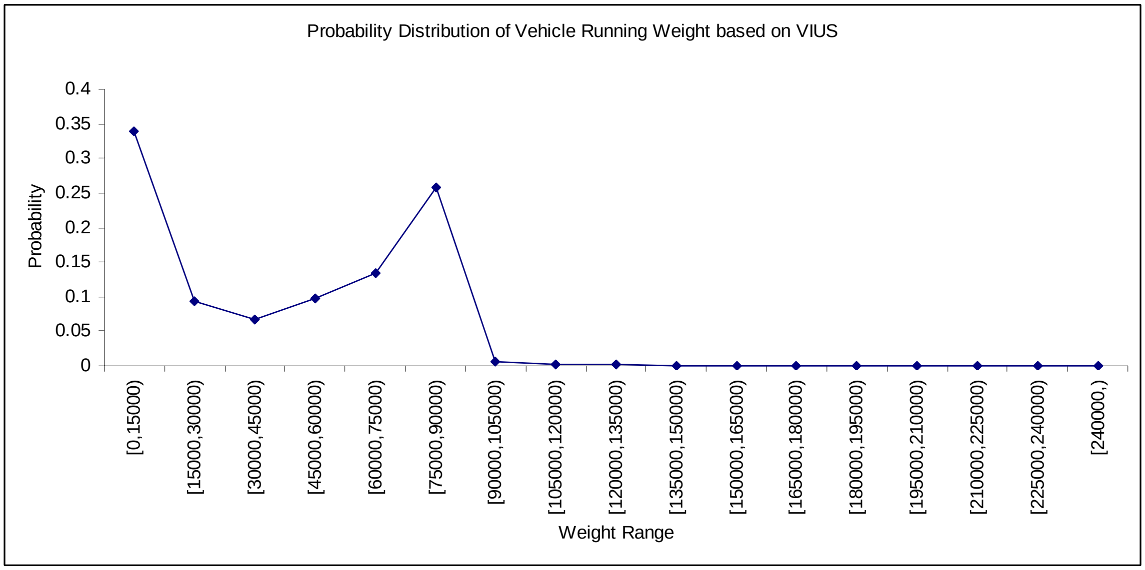


A.5.2.1.3 Vehicle Weight and Engine Displacement

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 microdata obtained from the Census Bureau.[44] A two-way table was constructed to estimate VMT broken out as [weight class] * [displacement class]. Analyses were restricted to diesel-powered trucks only.

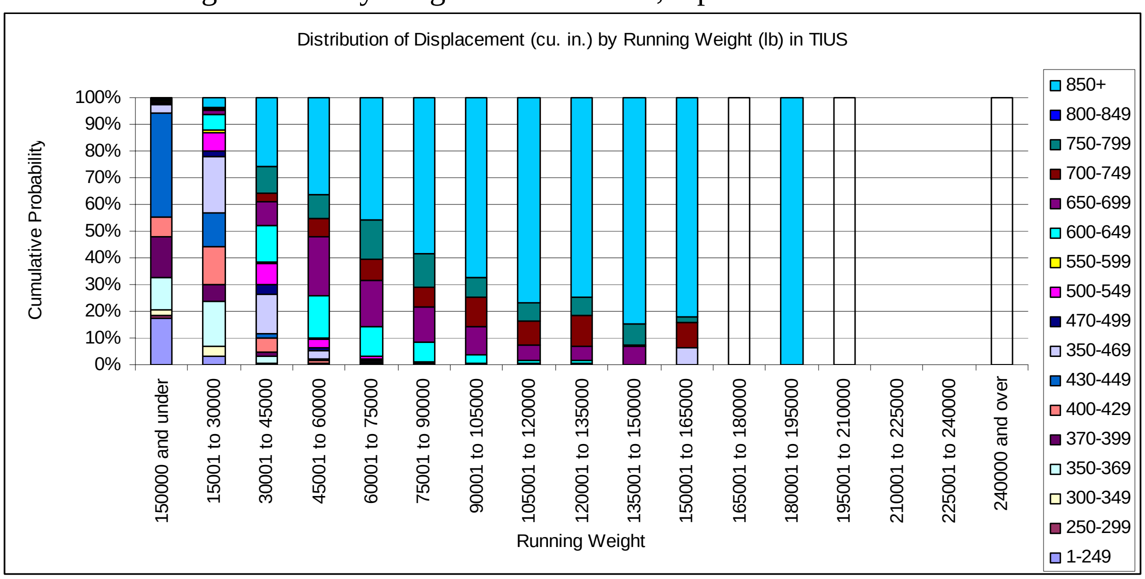
First, @Risk selects a running weight from a probability distribution representing the fraction of truck VMT occurring at a given running weight:

[1] 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)]. A and B parameters were determined 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 TIUS reports ranges of running weight, any value of running within the TIUS-specified ranges were considered equally likely and modeled as uniform probability distributions. For the upper and lower ends 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, 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 bins, 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 values based in surveyed truck operator responses. This allows plausible variability in weight-engine pairings, which translates into differences in engine BMEP. As described later, IMEP is a key variable in predicting EC and OC emission rates.

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

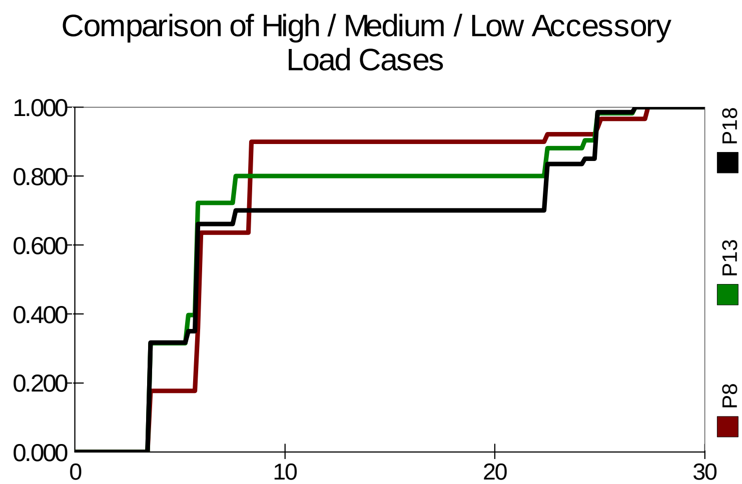
A.5.2.1.4 Accessory Load

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, Gururaja and Cullen (2008) developed a more detailed set of accessory load estimates based on several accessories' power demand while in use and the fraction of time that an accessory is in use.[45] Gururaja and Cullen estimated "high," "medium," and "low" accessory use categories 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. The 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 prior to the final version of MOVES, though the limited sensitivity of total results limits the importance of the accessory terms within the current exercise.

Within @Risk, the variable in PERE-HD, "Pacc" 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 powering 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. [NEEDS REFERENCE]

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. These technologies are promoted by EPA's Smartway Transport Partnership.

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 a 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 that 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, lube 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 memo, 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:

- Thermooptical 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:
  - Thermooptical 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.
  - Thermooptical 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 other techniques also exist within published literature, but the above techniques have been most applied in emissions and routine ambient PM sampling.

Among the available techniques, it has been a point of controversy among academics as to what analysis 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. It should be noted that different emission researchers employ different analysis techniques. Desert Research Institute (DRI) employed TOR in analyzing the Kansas City gasoline PM emission study samples, 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. Research of all of these groups is employed throughout this study, so an inter-comparison of the methods of TOT/TOR is necessary to be able to "recalibrate" one set of data to another.

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. EC and OM inventories sit between these to "columns."

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.[46] That standard operating procedure defines thermooptical reflectance (TOR) as the method for analysis of ambient carbon PM.

A.5.2.2.3 TOR – TOR Calibration Curve

As part 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. 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.[47]

Both EC and OC were analyzed using the same approach. All data from all vehicles were compiled together into tabular spreadsheets.

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) in the range [0,1). Those cases with RAND $\geq$ 0.95 were set aside as a cross-validation data set, and excluded from any further regression analyses done.

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.

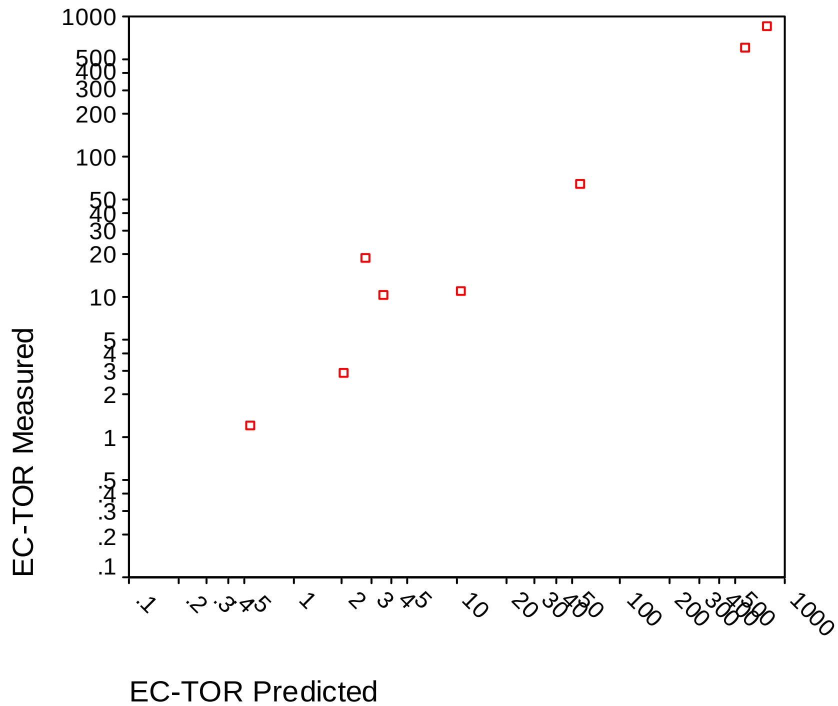
It should be noted that for each regression, the intercept term was set to zero. Models including intercepts did not have intercept terms that reached statistical significance. As such, R^2 values are not considered valid.

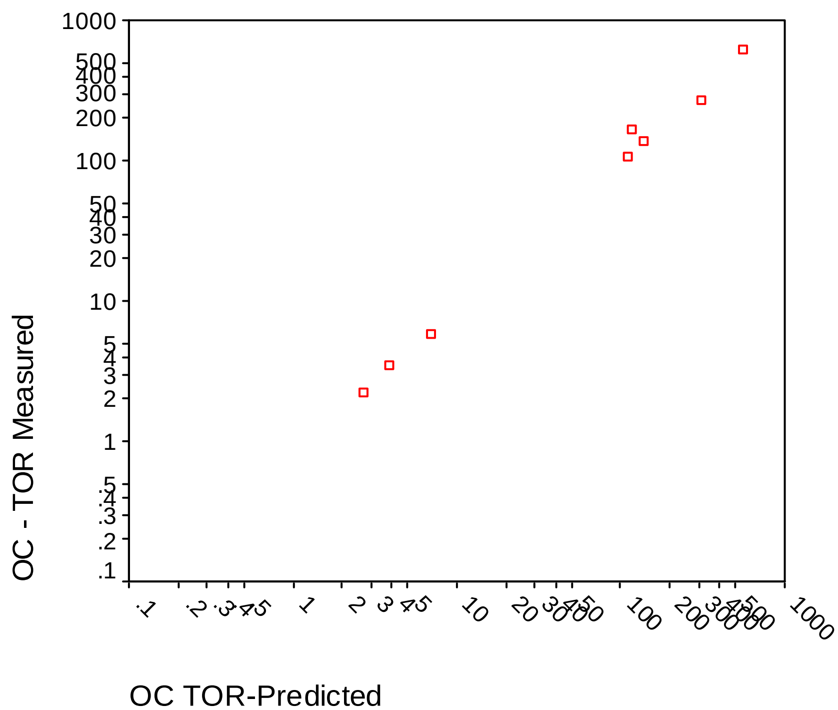
The coefficients from the weighted regression for EC and OC are reported below:

Slope	Beta	Std. Error	t-value	Sig.
EC-TOR	1.047	0.011	91.331	<0.001

OC-TOR	1.014	0.007	153.923	<0.001

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 emission 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 Parameter 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 bin (OpModeBin).

It should be noted that the “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, might be applicable to the extrapolation of the observed rates to other vehicles or driving conditions. As a result, identifying an engine parameter that explains the observed variation in driving cycle-based emission rates for EC and OM is desirable. Such a parameter will assist in estimating emission associated with short-term variations in driving.

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

$$MEP = P*n_R / V_d*N$$

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.

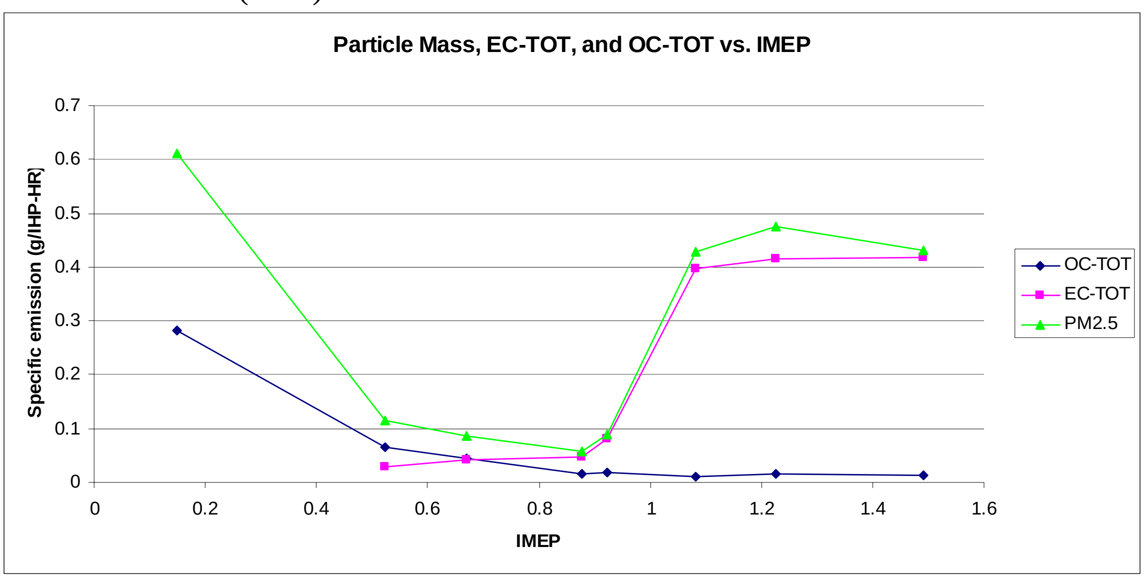
MEP can be broken into various components. “Indicated MEP” or IMEP refers to the sum of BMEP (brake MEP) and FMEP (friction MEP). Heywood (1988) writes that maximum BMEP is an indicator of good engine design and “essentially constant over a wide range of engine sizes.” Nam and Giannelli (2004) note that 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 Gianelli’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

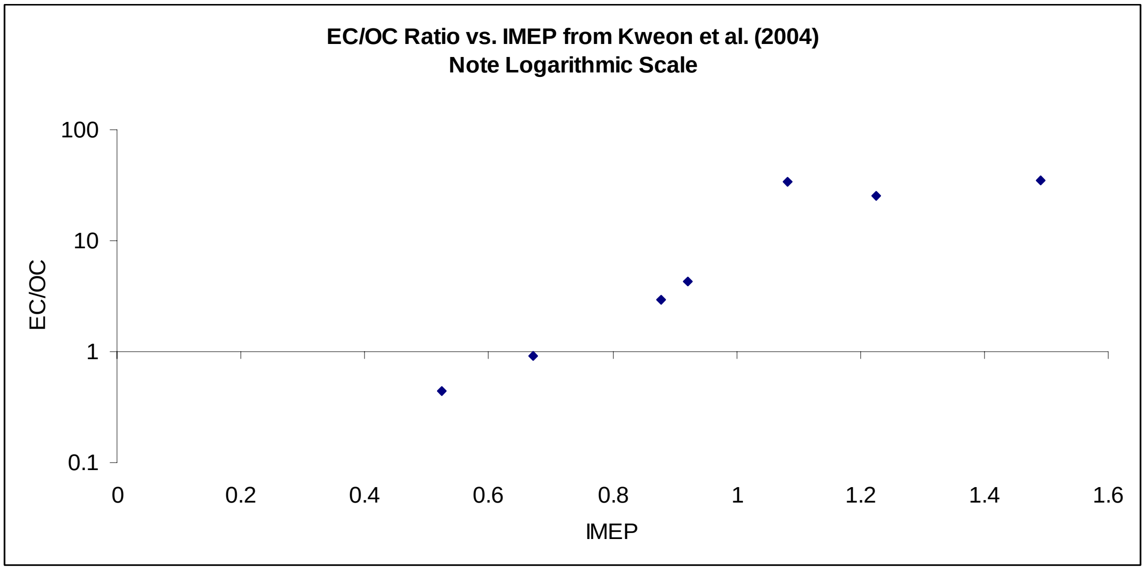
The study reports exhaust mass composition, including PM2.5, EC, and organic mass (OM, estimated as 1.2 x OC) measured with TOT (denoted here as EC-TOT and OC-TOT). In the main study, the authors report that EC and OC are highly sensitive to the equivalence ratio. However, IMEP is highly correlated with 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 paper 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:

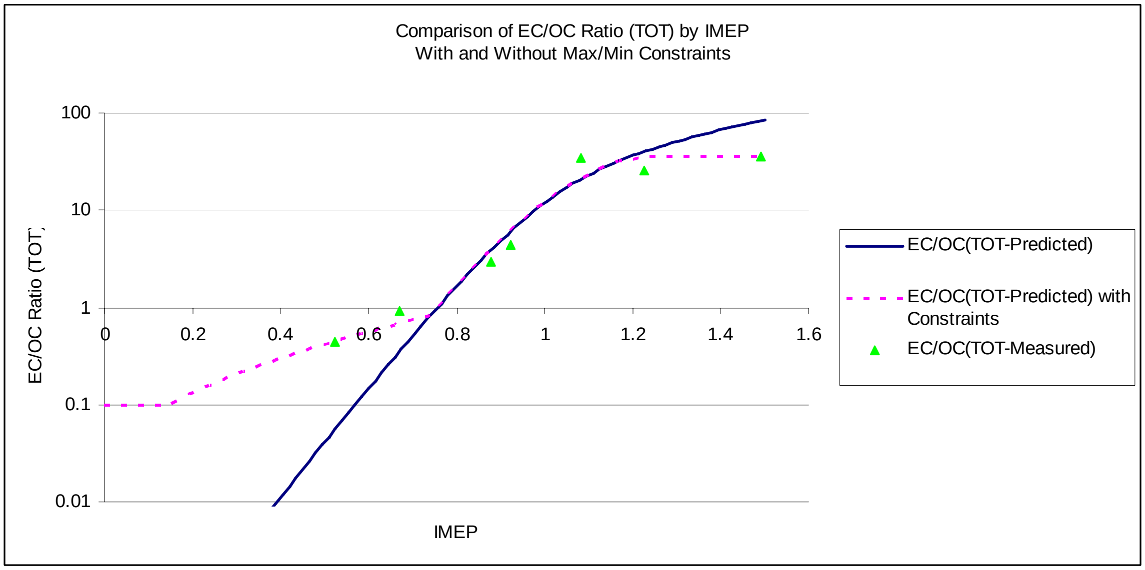
Y	A	B	C
EC-TOT	2.12×10^{-5}	-9.79	4.67×10^{-5}
OC-TOT	0.155	-2.275	-0.859

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 will 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 atomically part 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.[48] 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 be 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.5.2 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.[49] 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 likely 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.

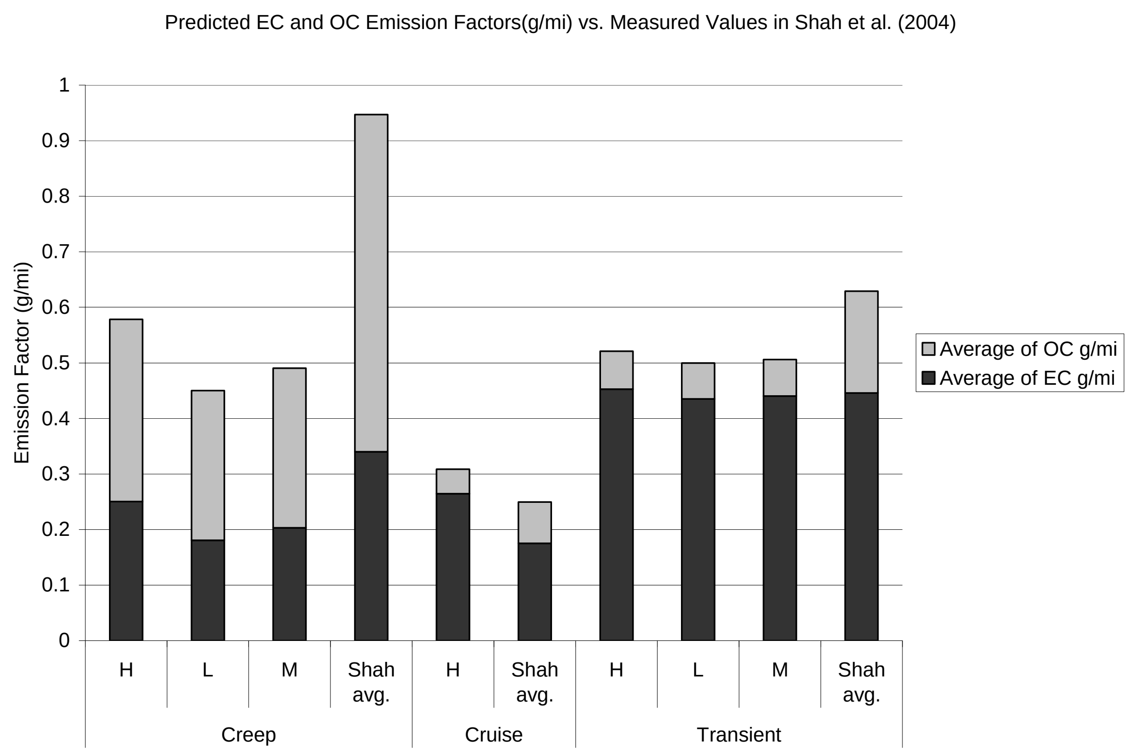
Cycle	**Distance (mi)**	**Duration (s)**	**Average Speed (mph)**	**Maximum Speed (mph)**	**Maximum Acceleration (mph/s)**
Cold start/idle	0	600	0	0	0
Creep	0.124	253	1.77	8.24	2.3
Transient	2.85	668	15.4	47.5	3.0

Cruise	23.1	2083	39.9	59.3	2.3

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

Rate/Factor	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

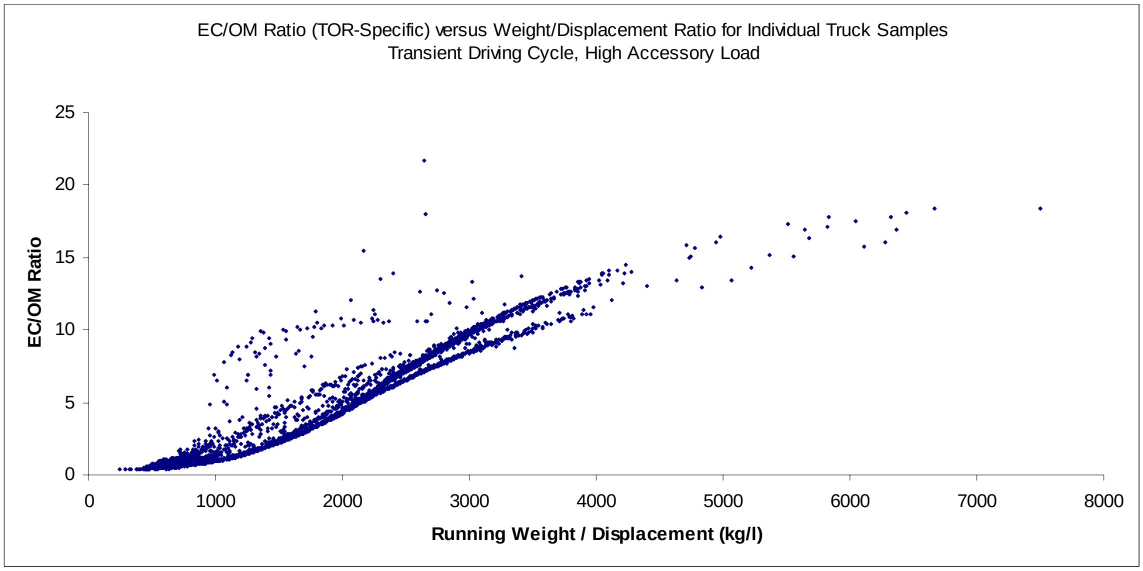
The following graph illustrates the comparison between predicted EC-TOT and OC-TOT emission factors predicted by PERE-HD and those reported by Shah et al. (2004). The letters "H," "M," and "L" refer to high, medium, and low accessory loads employed in the PERE-HD runs with IMEP-based emission rates.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



A.5.3 Variability in Predicted EC and OC Emission Rates

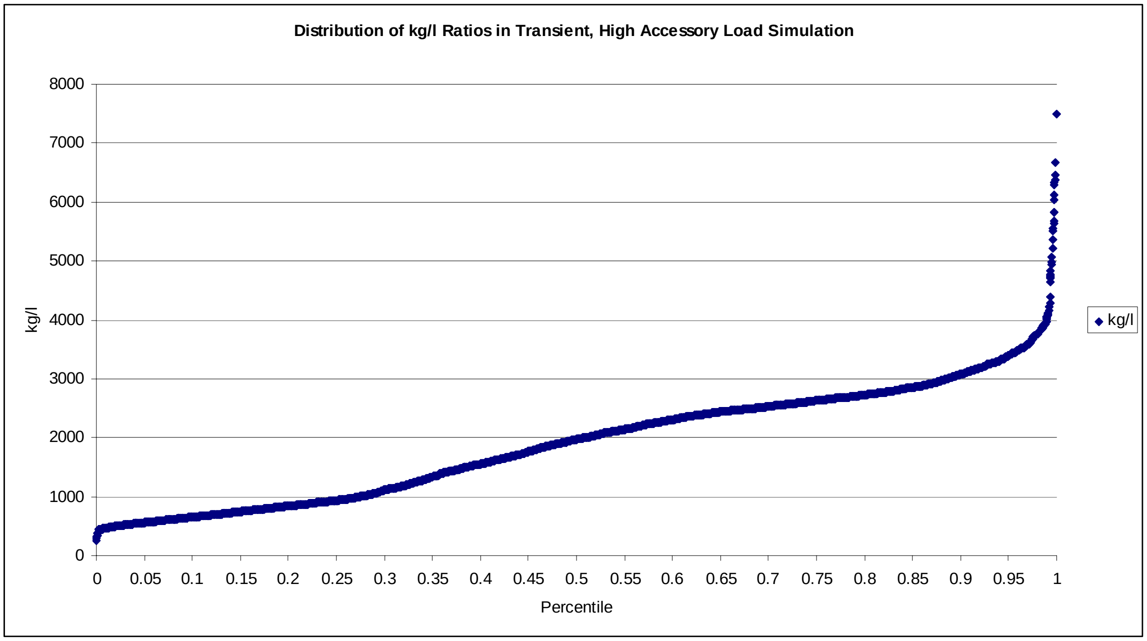
Through the modeling approach used here the influence of variable vehicle weight and engine displacement on HDDV EC and OC emission rates can be assessed. It should be noted that these relationships are contingent on the particular algorithms employed in PERE-HD for estimating power and IMEP, as well 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.

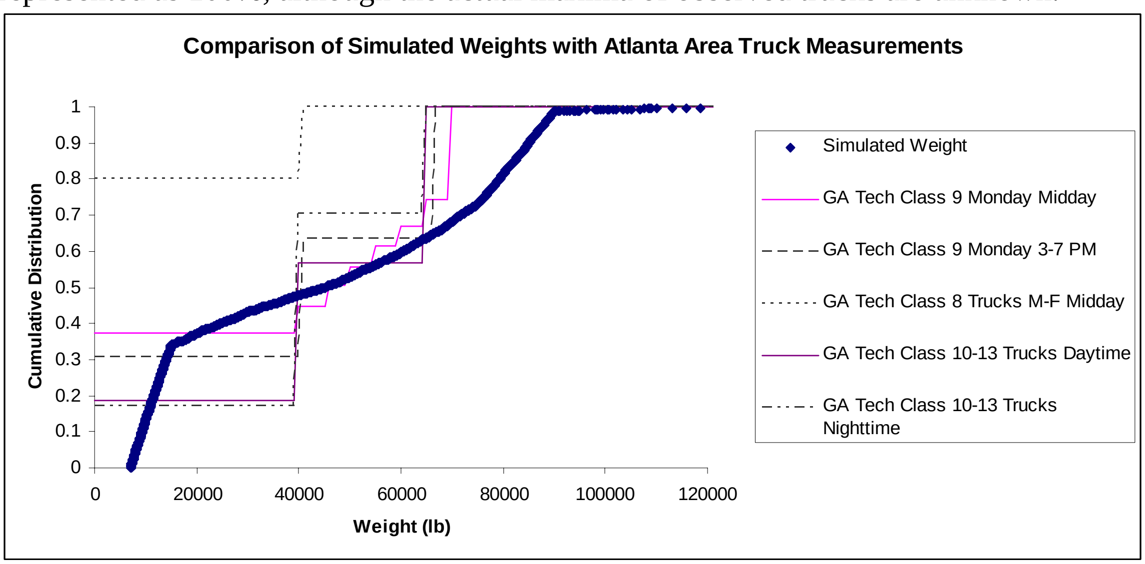


In general, these results reflect the role that running weight has on IMEP in a truck. Since IMEP correlates highly with the air/fuel ratio (or equivalence ratio φ), the data suggest that EC/OC partitioning is driven by the pyrolysis that occurs in engines under load.

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.[50] 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.5.4 Calculating EC/OC fraction by MOVES operating mode bin

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 MOVES. The next step of analysis for MOVES consists of appropriately binning the outputs to fit the MOVES operating mode structure. EC and OC emission rates, as opposed to total PM, 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 OC rates, we must calculate EC and OC fractions by MOVES operating mode. Then, the total PM rate can be multiplied by the EC and OC fractions to obtain EC and OC input emission rates.

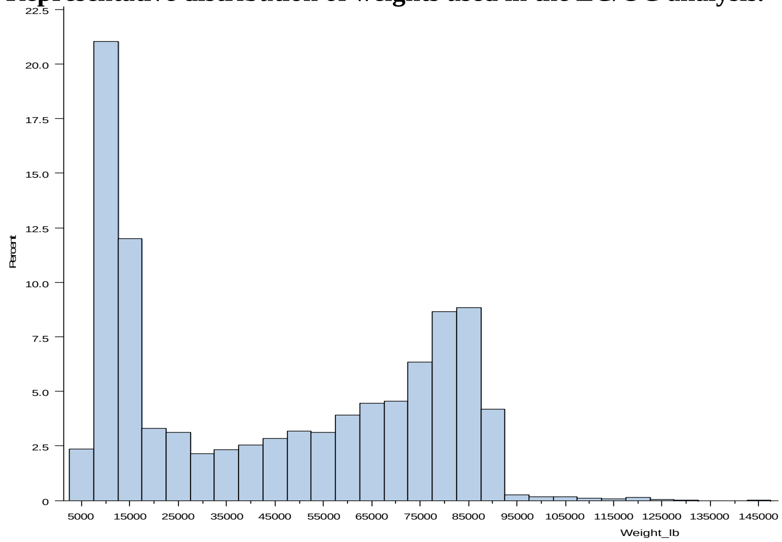
One of PERE's outputs for heavy-duty vehicles is road load coefficients. For each individual weight in the distribution, PERE outputs a set of A/B/C coefficients similar to the ones used to calculate VSP in the HC, CO, and PM emission rate analysis. We used these coefficients and weights to calculate 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 OC 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 relation 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 OC rates were also computed for each second during each cycle, we were able to average the EC and OC rates by operating mode bin. Then, we calculated the fractions of EC and OC for each operating mode bin. For the LHD classes, we used the MHD fractions, and for buses, we used the HHD fractions.

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

The resulting EC fractions by operating mode bin are shown in Figure 4 in the main body of this report.

A.6 Heavy-duty Gasoline Start Emissions Analysis Figures

Figure 23. Cold-Start Emissions (FTP, g) for Heavy-Duty Gasoline Vehicles, averaged by Model-year and Age Groups

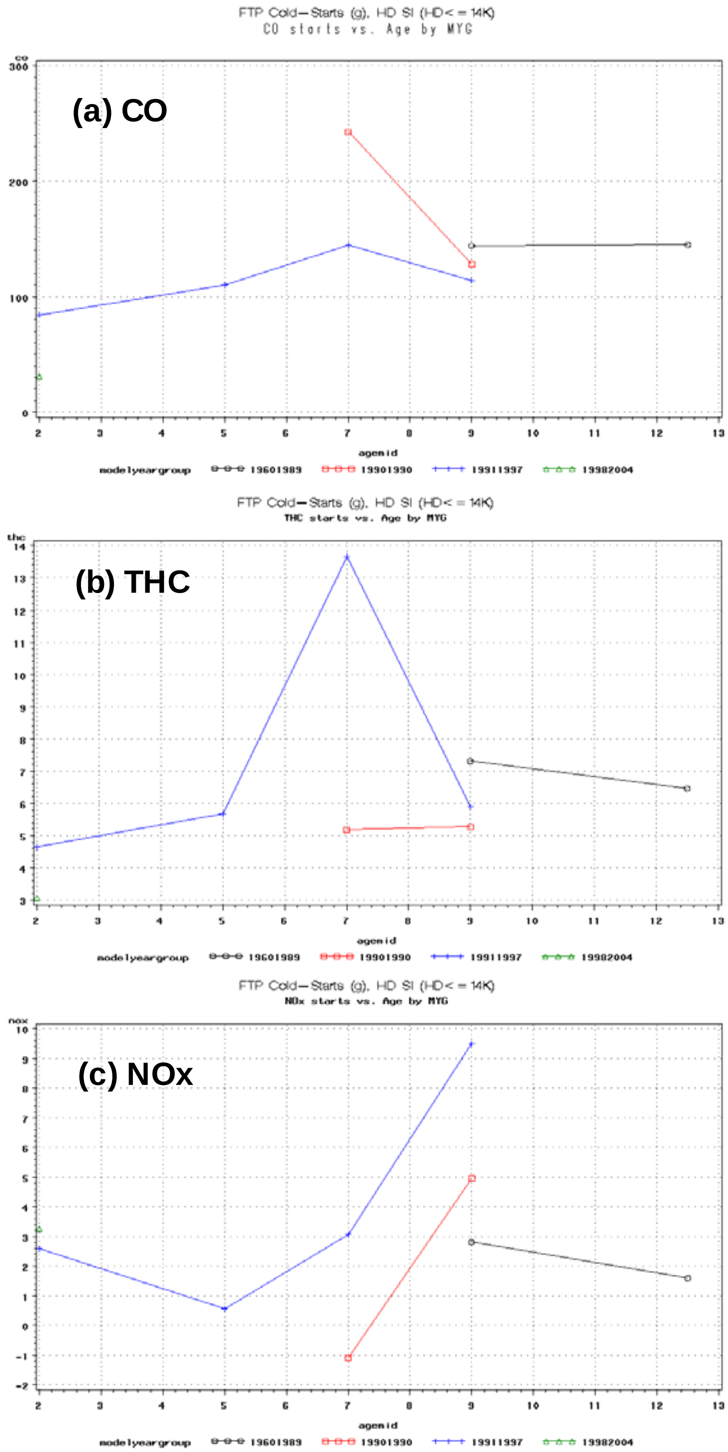


Figure 24. Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, GEOMETRIC MEANS by Model-year and Age Groups

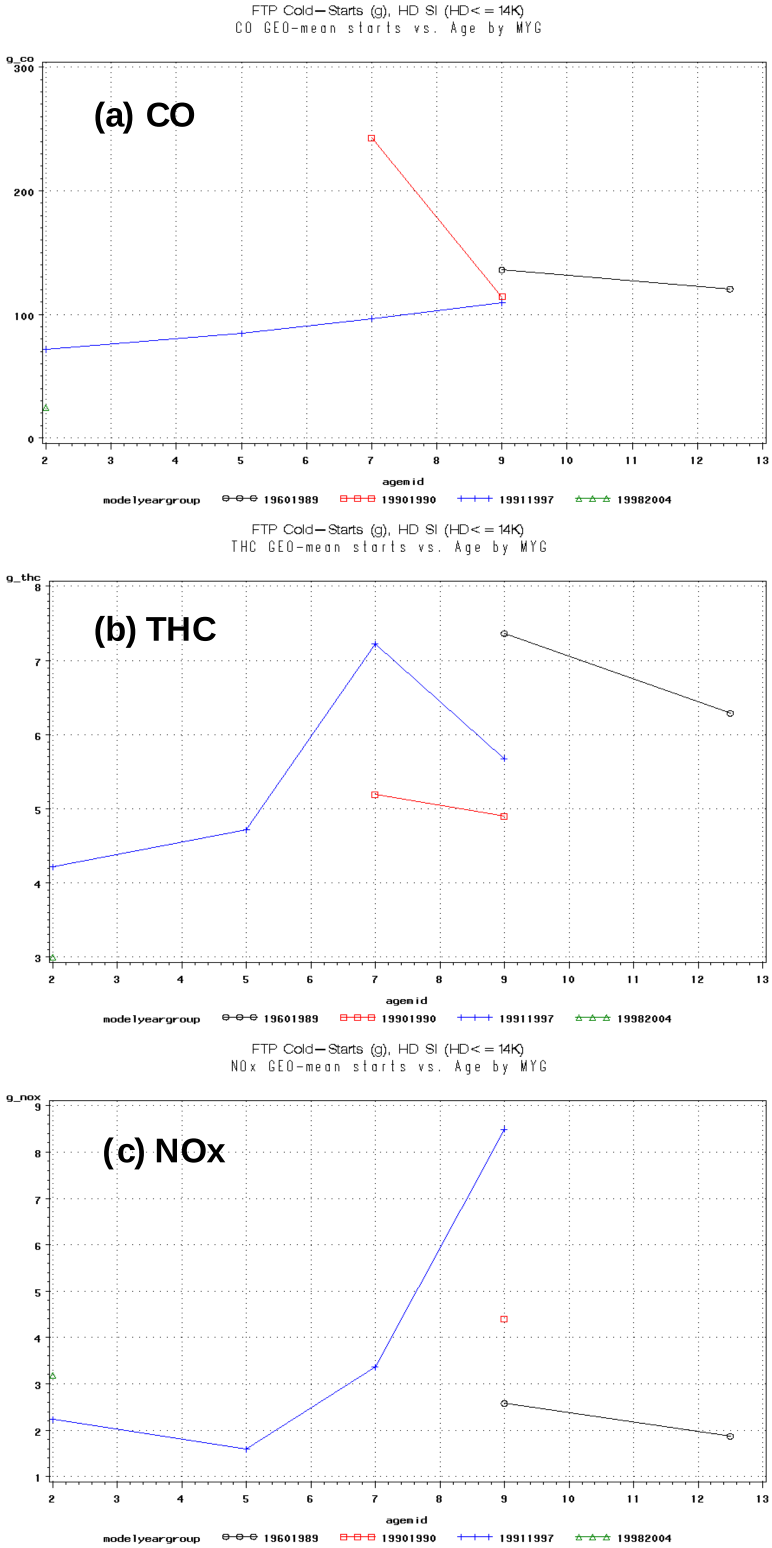


Figure 25. Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks: LOGARITHMIC STANDARD DEVIATION by Model-year and Age Groups.

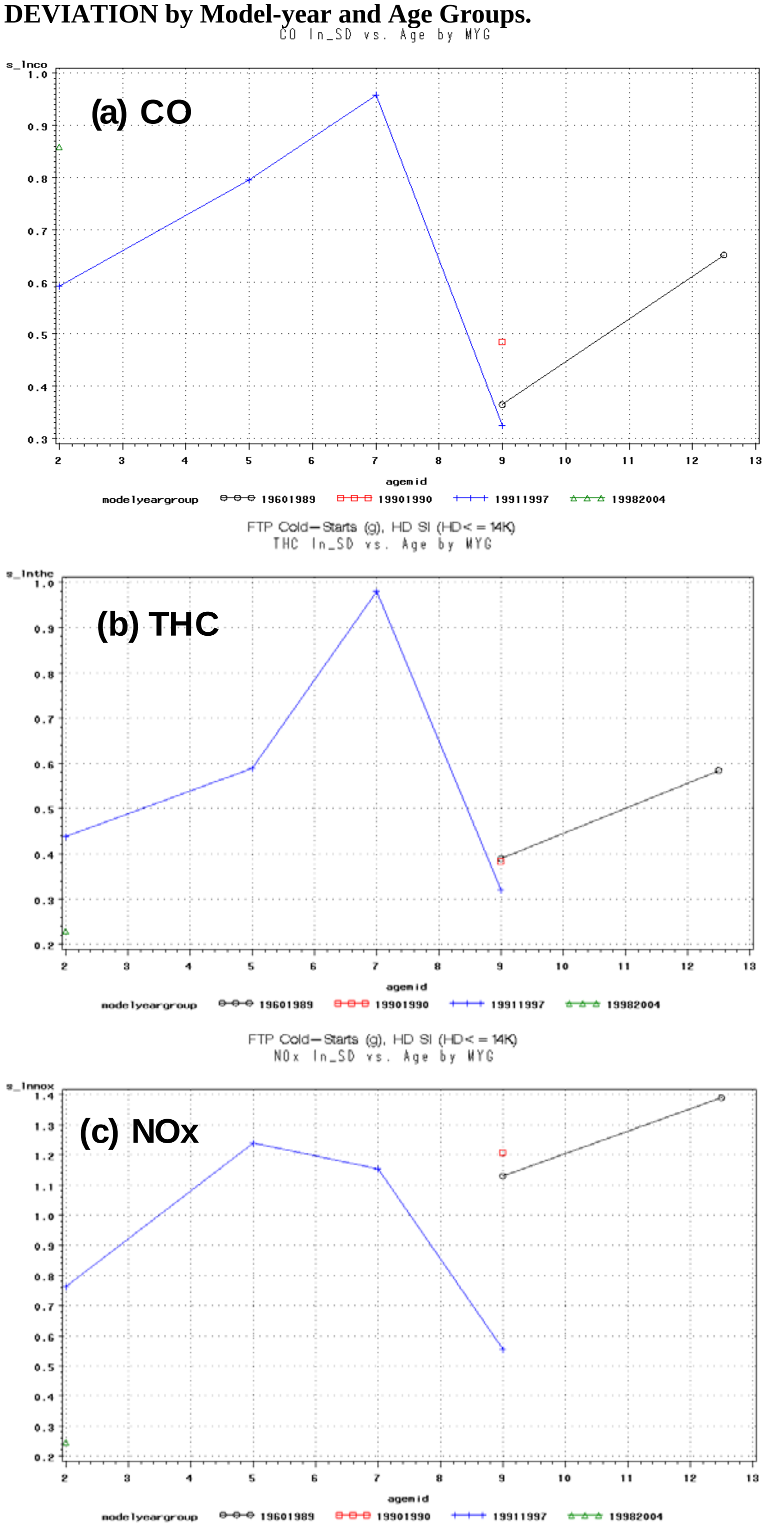


Figure 26. Cold-Start Emissions for Heavy-Duty Gasoline Trucks: RECALCULATED ARITHMETIC MEANS by Model-year and Age Groups.

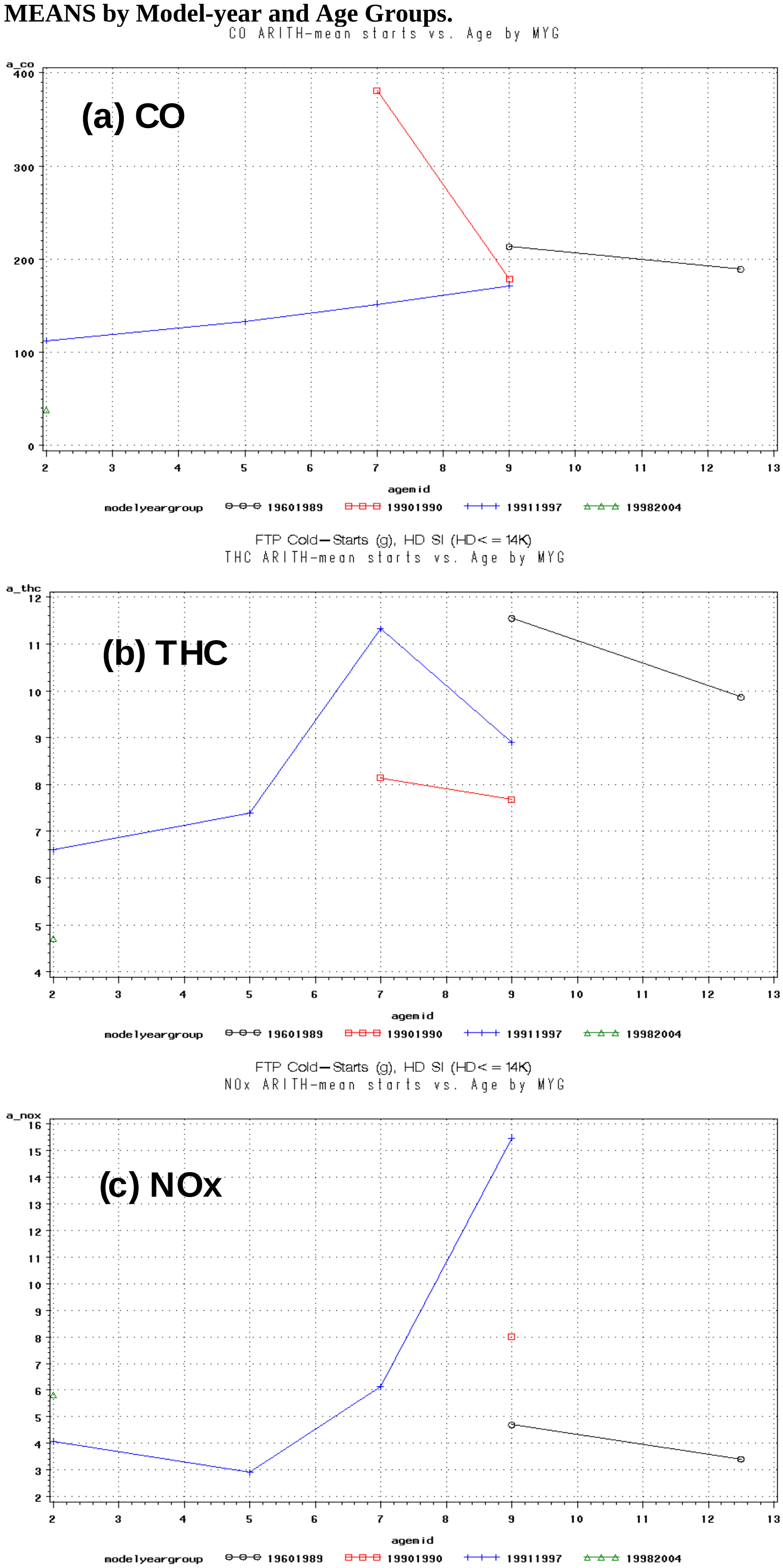


Table 36 - Emission Standards for Heavy-Duty Spark-Ignition On-road Engines

Regulatory Class	Model Year	Emissions Standards (g/hp-hr)				
		CO	**THC**	**NMHC**	**NOx**	**NMHC + NOx**
LHD2b	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	
LHD345, 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	

[1] Heavy Duty Diesel Engine Settlement Information. EPA website. http://www.epa.gov/compliance/resources/cases/civil/caa/diesel/

[2] Jack, J. "U.S. Army Aberdeen Test Center Support of Heavy Duty Diesel Engine Emissions Testing." http://www.epa.gov/ttn/chief/conference/ei15/session1/jack.pdf

[3] D. McClement. "Reformatting On-Road In-Use Heavy-Duty Emissions Test Data". Sierra Research, prepared for US EPA, April 2008.

[4] Diesel Engine Consent Decree: HD In-Use Testing. EPA website. http://www.epa.gov/compliance/resources/cases/civil/caa/diesel/test.html

[5] Gautam, M., et al. "Evaluation of In-Use Heavy-Duty Vehicle Emissions Using the Mobile Emissions Measurement System (MEMS) for Engine Model Years 2001 to 2003." Final Data Reports present to engine manufacturers to fulfill testing requirements documented in Phases III and IV of the Heavy Duty Diesel Engine consent decree. West Virginia University. 2002 & 2007.

[6] Oak Ridge National Lab, "Technology Roadmap for the 21st Century Truck Program" December 2000. Bradley, Ron. http://roadmap.itap.purdue.edu/ctr/documents/21stcenturytruck.pdf

[7] Rakha, Hesham. "Variable Power Vehicle Dynamics Model for Estimating Truck Accelerations". Rakha, Hesham, Lucic, Ivana. Page 6. http://filebox.vt.edu/users/hrakha/Publications/Variable%20Power%20Truck%20Acceleration%20-%20Ver%202.0.pdf

[8] Development of LNG-Powered heavy-Duty Trucks in Commercial Hauling, National Renewable Energy Lab, December 1998, NREL/SR-540-25154

[9] Goodyear. "Factors Affecting Truck Fuel Economy – Section 9" Page 5. http://goodyear.com.ve/truck/pdf/radialretserv/Retread_S9_V.pdf

[10] Ramsay, Euan and Bunker, Jonathan. "Acceleration of Multi-Combination Vehicles in Urban Arterial Traffic Corridors" August 2003 Queensland University of Technology PhD Project. Page 11 http://eprints.qut.edu.au/archive/00002359/01/RS&ETechForum2003_Ramsay&Bunker_2.pdf

[11] SAE J2188 Revised OCT2003:Commerical Truck and Bus SAE Recommended Procedure for Vehicle Performance Prediction and Charting.

[12] "Technology Roadmap for the 21st Century Truck Program" December 2000. Page 32 http://roadmap.itap.purdue.edu/ctr/documents/21stcenturytruck.pdf

[13] Pritchard, Ewan. "Hybrid Electric School Bus Preliminary Technical Feasibility Report" Advanced Energy Corporation. September 14, 2004. Page 25. http://www.odyne.com/pdf/Pritchard-report.pdf

[14] Hedrick, J.K., Ni, A. "Vehicle Modeling and Verification of CNG-Powered Transit Buses" University of California, Berkeley. California Partners for Advanced Transit and Highways. 2004. Page 21. http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1169&context=its/path

[15] "Hybrid Theory: Hybrid Vehicle engineering for economy, the environment, and customer delight" MIRA. Page 2. http://www.mira.co.uk/Case_Studies/documents/ProjectChoiceHybridBus.pdf

[16] Vehicle Inventory and Use Survey. http://www.census.gov/svsd/www/vius/products.html

[17] Koupal, et al. "MOVES2004 Energy and Emissions Inputs - Draft Report February, 2005." EPA420-P-05-003, March 2005.

[18] Lindhjem, C. & Tracie Jackson. "Update of Heavy-Duty Emission Levels (Model Years 1988-2004+) for Use in MOBILE6" (M6.HDE.001). EPA420-R-99-010, April 1999.

[19] Darlington, T., Dennis Kahlbaum, Gregory Thompson. "On-Road NOx Emission Rates from 1994-2003 Heavy-Duty Diesel Trucks." SAE 2008-01-1299, April 2008.

[20] Koupal, John et al. MOVES2004 Energy and Emissions Inputs - Draft Report February, 2005 www.epa.gov/otaq/models/ngm/may04/crc0304a.pdf

[21] Clark, et al. "California Heavy Heavy-Duty Diesel Truck Emissions Characterization for Program E-55/59." West Virginia University Research Corporation. November 2005.

[22] Nam, Ed and Robert Giannelli. "Fuel Consumption Modeling of Conventional and Advanced Technology Vehicles in the Physical Emission Rate Estimator (PERE)," US EPA Office of Transportation and Air Quality, EPA420-P-05-001. http://www.epa.gov/otaq/models/ngm/420p05001.pdf. February 2005.

[23] "Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6 Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors" (EPA420-R-02-005). http://www.epa.gov/otaq/models/mobile6/r02005.pdf

[24] Lev-On, Miriam, et al. "Chemical Speciation of Exhaust Emissions from Trucks and Buses Fueled on Ultra-Low Sulfur Diesel and CNG", SAE 2002-01-00432, March 2002.
[25] Graboski, et al. "Heavy-Duty Diesel Vehicle Testing for the Northern Front Range Air Quality Study." Colorado Institute for Fuels and High-Altitude Engine Research, Colorado School of Mines. Prepared for Colorado State University, February 1998.
[26] Energy and Environmental Analysis, Inc. "Documentation and Analysis of Heavy-Duty Diesel Vehicle Emission Test Data." Prepared for New York Department of Environmental Conservation, December 2000.
[27] Calcagno, James A. "Evaluation of Heavy-Duty Diesel Vehicle Emissions During Cold-Start and Steady-State Idling Conditions and Reduction of Emissions from a Truck-Stop Electrification Program." Dissertation Presented for the Doctor of Philosophy Degree, University of Tennessee, Knoxville, December 2005.
[28]McCormick, et al (2000), "Idle Emissions from Heavy-Duty Diesel and Natural Gas Vehicles at High Altitude," Robert McCormick, et al, Colorado Institute for Fuels and Engine Research, Colorado School of Mines, Journal of the Air and Waste Management Association, Revised May 3, 2000.
[29]Lim (2002), "Study of Exhaust Emissions from Idling Heavy-duty Diesel Trucks and Commercially Available Idle Reducing Devices," Han Lim, US EPA Office of Transportation and Air Quality, September 2002.
[30]Lambert, et al (2002), "Preliminary Results for Stationary and On-Road Testing of Diesel Trucks in Tulare, California," Douglas Lambert, et al, Clean Air Technologies Inc., May 15, 2002.
[31]Irick (2002), "NOx Emissions and Fuel Consumption of HDDVs during Extended Idle," David K. Irick, University of Tennessee, Bob Wilson, IdleAire Technologies Inc., Coordinated Research Council 12th Annual On-Road Vehicle Emission Workshop, San Diego, California, April 15-17, 2002.
[32]Gautam, Clark, et al (2002), "Heavy-duty Vehicle Chassis Dynamometer Testing for Emissions Inventory, Air Quality Modeling, Source Apportionment and Air Toxics Emissions Inventory," Phase I Interim Report, CRC Project No. E-55/E-59, Mridul Gautam and Nigel N. Clark, et al, West Virginia University Research Corporation, July 2002.
[33]NCHRP (2002), "Heavy-duty Vehicle Emissions," National Cooperative Highway Research Program Project 25-14, Cambridge Systematics, Inc., with Battelle, Sierra Research and West Virginia University. October 2002.
[34]Tang and Munn (2001), "Internal Report – Idle Emissions from Heavy-Duty Diesel Trucks in the New Your Metropolitan Area," Tang and Munn, New York State Dept of Environmental Conservation, November 9, 2001.
[35]Broderick, Dwyer, et al (2001), "Potential Benefits of Utilizing Fuel Cell Auxiliary Power Units in Lieu of Heavy-Duty Truck Engine Idling," Broderick, Dwyer, et al. Institute of Transportation Studies, University of California - Davis. Paper UCD-ITS-REP-01-01
[36]Storey, et al (2003), "Particulate Matter and Aldehyde Emissions from Idling Heavy-Duty Diesel Trucks," John M.E. Storey, John F. Thomas, Samuel A. Lewis, Sr., Thang Q. Dam, K. Dean Edwards. Oak Ridge National Laboratory. Gerald L. DeVault, Y-12 National Security Complex. Dominic J. Retrossa, Aberdeen Test Center. SAE Paper 2003-01-0289.
[37] Vehicle Inventory and Use Survey, U.S. Census Bureau http://www.census.gov/svsd/www/vius/products.html
[38] Zhou, Lei. "Revision of Heavy Heavy-Duty Diesel Truck Emission Factors and Speed Correction Factors." California Air Resources Board, October 2006.
[39] Illinois Environmental Protection Agency. "Effectiveness of On-Board Diagnostic I/M Testing" September 2003. Page 21. www.epa.state.il.us/air/publications/obd-report-final.pdf
[40] Manufacturers of Emission Controls Association. www.meca.org
[41] Song, Qingwen. (2002). "Model-based Closed-loop Control of Urea SCR Exhaust Aftertreatment System for Diesel Engine." Song, Q. and Zhu, George. SAE 2002-01-287. Page 1. http://www.visteon.com/utils/whitepapers/2002_01_0287.pdf
[42] Nam, E.K.; Giannelli, R. (2005) Fuel Consumption Modeling of Conventional and Advanced Technology Vehicles in the Physical Emission Rate Estimator (PERE). EPA Office of Transportation and Air Quality. Draft document EPA420-P-05-001.
[43] http://www.epa.gov/otaq/models/ngm/420s05002.htm#pere
[44] U.S. Census Bureau. (2000) Vehicle Inventory and Use Survey 1997 Microdata File [CD-ROM]. U.S. Department of Commerce Economics and Statistics Administration
[45] Gururaja, P.; Cullen, A. (2008) "Accessory requirement" tab on Microsoft Excel spreadsheet, "VSP Weights 2008-Feb.xls". Personal communication.
[46] Desert Research Institute, Atmospheric Sciences Division. (2005) DRI STANDARD OPERATING PROCEDURE. DRI Model 2001 Thermal/Optical Carbon Analysis (TOR/TOT) of Aerosol Filter Samples – Method IMPROVE_A. DRI SOP #2-216.1. [Online at http://www.epa.gov/ttn/amtic/specsop.html]
[47] http://www.nrel.gov/vehiclesandfuels/nfti/feat_split_study.html

[48] Heywood, J.B. Internal Combustion Engine Fundamentals. McGraw-Hill: New York, 1988. Data from Table 11.8, page 629.
[49] Shah, S.D.; Cocker, D.R.; Miller, J.W.; Norbeck, J.M. (2004) Emission rates of particulate matter and elemental and organic carbon from in-use diesel engines. Environ Sci Technol 38: 2544-2550.
[50] Ahanotu, D.N. (1999) Heavy-duty vehicle weight and horsepower distributions: measurement of class-specific temporal and spatial variability. PhD Dissertation, Georgia Institute of Technology.

Additional Extended Idling References

EPA (2004), "Guidance for Quantifying and Using Long-Duration Truck Idling Emission Reductions in State Implementation Plans and Transportation Conformity." (EPA420-B-04-001, January 2004) (http://www.epa.gov/smartway/idle-guid.htm)

EPA (2003), "Draft Analysis of Heavy-Duty Diesel Vehicle Idle Emission Rates," (EPA420-D-03-001, November 2003)

Additions:

Clark, Khan, Thompson, Wayne, Gautam, Lyons (2005), "Idle Emissions from Heavy-Duty Diesel Vehicles" Presentation by the Center for Alternative Fuels, Engines, and Emissions at West Virginia University.

CRC (2007), "Heavy-Duty Vehicle Chassis Dynamometer Testing for Emissions Inventory, air Quality Modeling, Source Apportionment, and Air Toxics Emissions Inventory" CRC Report No. E55/59. August 2007.

California Air Resource Board (2006), EMFAC Modeling Change Technical Memo: "Revision of Heavy Heavy-Duty Diesel Truck Emission Factors and Speed Correction Factors" Zhou, Lei. October 20, 2006.

Lutsey et al (2004) "Heavy-Duty Truck Idling Characteristics – Results from a Nationwide Truck Survey" Lutsey, Nicholas, Brodrick, Christie-Joy, Sperling, Daniel, Oblesby, Carollyn. Transportation Research Record 1880. Pages 30-38. http://www.its.ucdavis.edu/publications/2004/UCD-ITS-RP-04-38.pdf

Wallace (2003) "Modeling of Line-Haul Truck Auxiliary Power Units in ADVISOR 2002" Wallace, John Paul, Thesis August 2003, University of California- Davis. http://www.its.ucdavis.edu/publications/2003/UCD-ITS-RR-03-07.pdf