Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator (MOVES2010)

Final 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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This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

United States
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1. Gaseous Exhaust Emissions from Light-Duty Gasoline Vehicles (THC, CO, NOx)

1.1 Introduction

1.1.1 MOVES Background

The material presented in this document is a component of a much larger effort, including the estimation of emission rates for heavy-duty vehicles, estimation of evaporation emissions, estimation of usage and activity patterns for vehicles, the compilation and storage of all types of input data in the MOVES database, and the algorithms that combine and process input information during model runs, translating inputs and modeling assumptions into inventory estimates.

Readers not familiar with MOVES may find it useful to access additional documentation providing a broader view of MOVES, the rationale for its development as a replacement for MOBILE6, and broad overviews of its design.

- The "*Initial Proposal*" for MOVES describes the impetus behind the effort to design a new inventory model from the ground up, with the goal of developing a tool both more comprehensive and flexible than its predecessor[1].
- A subsequent "*Draft Design and Implementation Plan*" describes the MOVES design and introduces the reader to concepts and terminology developed for the new model[2].
- Readers wishing to further understand the development of the modal design for running emissions can consult the "*Methodology for Developing Modal Emission Rates,*"[3] as well as the "*Shoot Out*"[4] conducted among several candidate approaches.
- This document focuses on development of inputs to the MOVES Database. Readers interested in further understanding the processes used by the model to process inputs into inventory estimates can consult the MOVES Software Design Reference Manual (SDRM)[5].

A large volume of additional documentary and supporting materials can be obtained at http://www.epa.gov/otaq/models/moves/movesback.htm. In general, the most recent and relevant materials are at the top of the page, with older material located further down. However, as the previous references show, references posted throughout the page are still relevant to the MOVES model and database in its most recent versions.

1.1.2 Light-Duty Vehicles

This chapter describes the technical development of emission rates for gaseous exhaust pollutants for light-duty vehicles. These pollutants include total hydrocarbons (THC), carbon monoxide (CO) and oxides of nitrogen (NOx). The resulting model inputs are included in the MySQL database supporting the MOVES2010 model.

Light-duty vehicles are defined as cars and trucks with gross vehicle weight ratings (GVWR) of less than 8,500 lbs. For purposes of emissions standards "cars" are designated as "LDV" or "passenger cars" (PC), and are distinguished from "trucks" which are further subclassified as "light light-duty trucks" (LLDT) and "heavy light-duty trucks" (HLDT), on the basis of GVWR ≤ 6000 lbs and GVWR > 6000 lbs, respectively. The two broad classes, LLDT and HLDT, are further subdivided into LDT1/LDT2, and LDT3/LDT4. As these subdivisions are highly specific and technical, we do not describe them here. Interested readers can find more information at http://www.epa.gov/otaq/standards/weights.htm. As MOVES pools all truck classes for purposes of inventory estimation, we will refer to "cars" and "trucks" throughout.

Exhaust emissions from light-duty vehicles have contributed substantially to urban air pollution, and have received a great deal of scientific, political and regulatory attention over the past forty years. The Clean Air Act (CAA), passed in 1970 (and amended in 1977 and 1990), set "National Ambient Air-Quality Standards" (NAAQS) for HC, CO and NOx. Carbon monoxide is targeted for its respiratory toxicity, and HC and NOx largely for their roles in production of ground-level ozone, another pollutant targeted under the CAA. Regulations designed to reduce automobile emissions to facilitate achievement of compliance with the NAAQS include Tier-1 standards introduced in the mid 1990's, followed by National Low-Emission Vehicle (NLEV) standards starting in 2001, and Tier-2 standards starting in 2004. Concurrently, the state of California and additional states electing to adopt "California" in lieu of "Federal" standards have implemented the "LEV-I" and "LEV-II" standards. In addition to introducing more stringent tailpipe standards, requiring introduction of oxygenated gasolines, and modifying test procedures, the 1990 CAA Amendments expanded requirements for Inspection-and-Maintenance programs (I/M). The role played by I/M programs in many urban areas over the past twenty years means that accounting for the existence of such programs is a primary consideration in modeling tailpipe emissions from light-duty vehicles.

Through a combination of regulation and improved technology, gaseous tailpipe emissions from light-duty vehicles have declined substantially over the past several decades. Important milestones in engine and emissions control technology have included the introduction of fuel injection (replacing carburetion), positive crankcase ventilation (PCV), exhaust gas recirculation (EGR), catalytic converters, electronic engine controls, and on-board diagnostic systems (OBD). Development of emission rates thus largely involves constructing a "numerical" account of this history. However, a detailed account of these developments is beyond the scope of this document which will focus on the development of emission rates as inputs to the MOVES database. However, this history has been well described elsewhere, and we refer interested readers to the EPA website[6,7], as well as to the peer-reviewed literature[8,9,10,11,12,13].

1.1.3 Differences between MOVES and MOBILE

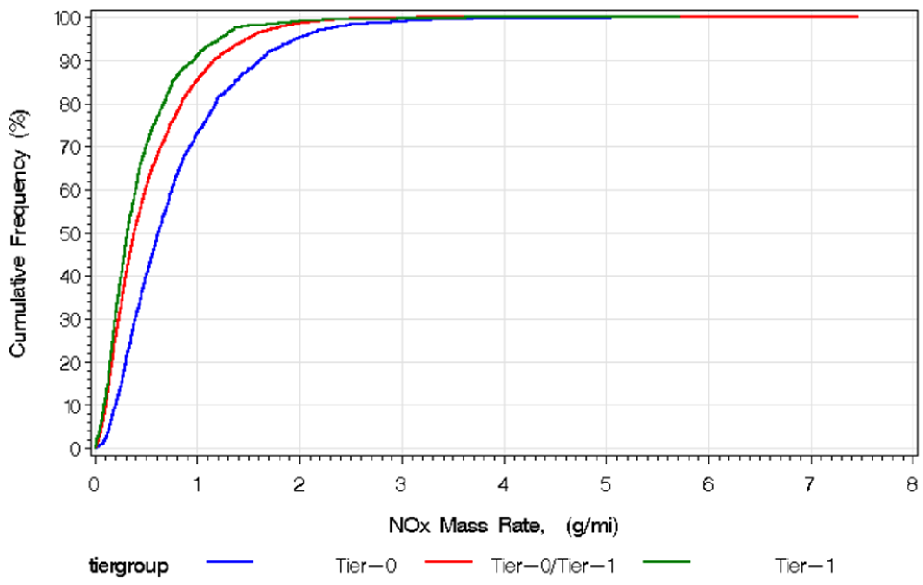
At the outset, it is useful to highlight four important different between MOVES and MOBILE. (1) While intending to estimate average emissions across the entire vehicle fleet, MOVES does not distinguish between “normal” and “high emitters,” (2) MOVES inverts MOBILE’s approach to inspection and maintenance, (3) MOVES is a “modal” model, whereas MOBILE is “non-modal,” and (4) emission rates developed for MOVES are expressed in time-specific, rather than distance specific terms, i.e., mass/time (g/hr), rather than mass/distance (g/mi, g/km).

1. A fundamental difference between MOVES and MOBILE is that MOVES does not classify vehicles into “emitter classes.” The MOBILE model(s) provided different sets of emission rates for “normal” and “high” emitters. While arbitrary, this distinction made qualitative and practical sense because the emission rates were themselves averages of FTP test results.

We didn’t attempt a similar approach in MOVES for several reasons, some conceptual, some practical. The main conceptual reason is that in review of data, we did not see clear evidence of distinct “high emitter” subpopulations. Rather, review of emissions data seems to show highly skewed but continuous distributions with long tails, which we treat as log-normal for modeling purposes. Clearly, the vehicles in the upper percentiles of the distributions make disproportionate contributions to the inventory, assuming similar driving patterns to cleaner vehicles in the lower percentiles. Based on these observations, our approach has been to capture the mean of the entire distribution, including the upper tail. We illustrate these concepts using two examples, based on aggregate cycle means from the Phoenix I/M program, measured on the IM147 cycle.

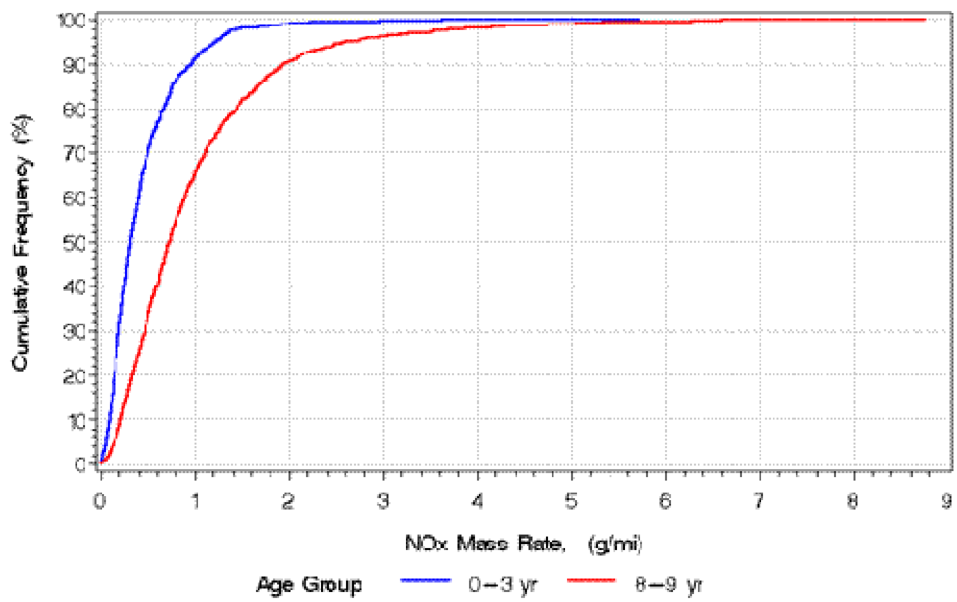
Figure 1 shows cumulative distributions of NOx emissions for “young” cars, aged 0-3 years, representing two sets of emissions standards. The blue distribution represents “Tier 0” vehicles, manufactured prior to 1994; the green represents “Tier 1” vehicles, manufactured in 1996-97, and the red represents a mix of the two, during the Tier-1 phase-in period (1994-95). Note that the combination of reduced standards and improved technology pushes the entire distribution “leftward” or towards lower emission levels.

Figure 1. Cumulative distributions of running NOx for cars, Age 0-3, measured on the IM147 cycle (Source: Phoenix I/M program).



A similar example, Figure 2, shows NOx distributions for Tier-1 vehicles (MY1996-97) at two different age levels, 0-3 and 8-9 years old, shown in blue and red, respectively. Qualitatively, the picture looks very similar to Figure 1, except that in this case we can see the effect of age in pushing the entire distribution "rightwards," towards higher emission levels. Note that the entire distribution shifts, including the lower percentiles, not only the "high emitters" in the upper percentiles.

Figure 2. Cumulative distributions of running NOx for Tier-1 cars, at two age levels, measured on the IM147 cycle (Source: Phoenix I/M program).



A pattern not necessarily apparent in Figure 1 emerges if we view the same distributions on a logarithmic scale, as shown in Figure 3. In the logarithmic view, we can see that the distribution at 8-9 years is the same is that at 0-3 years, but shifted to the right; that is, the shapes (variances) of the two distributions are very similar, but the means are shifted. These figures illustrate the "logarithmic" or "multiplicative" scaling typical in emissions data. The utility of logarithms in modeling follows from the fact that multiplicative patterns representing actual changes can be represented and projected very conveniently as additive changes in logarithmic space. These patterns obtain whether the data are analyzed with respect to technology, age or power. The development of emission rates, as described in this chapter (and for PM in Chapter 2), relies heavily on these concepts. Figure 4 shows a similar picture to Figure 2, except for THC; what is notable is that the THC distributions are even more skewed than the NOx distributions.

Figure 3. Cumulative distributions of running NOx for Tier-1 cars, at two age levels, measured on the IM147 cycle (LOGARITHMIC SCALE) (Source: Phoenix I/M program).

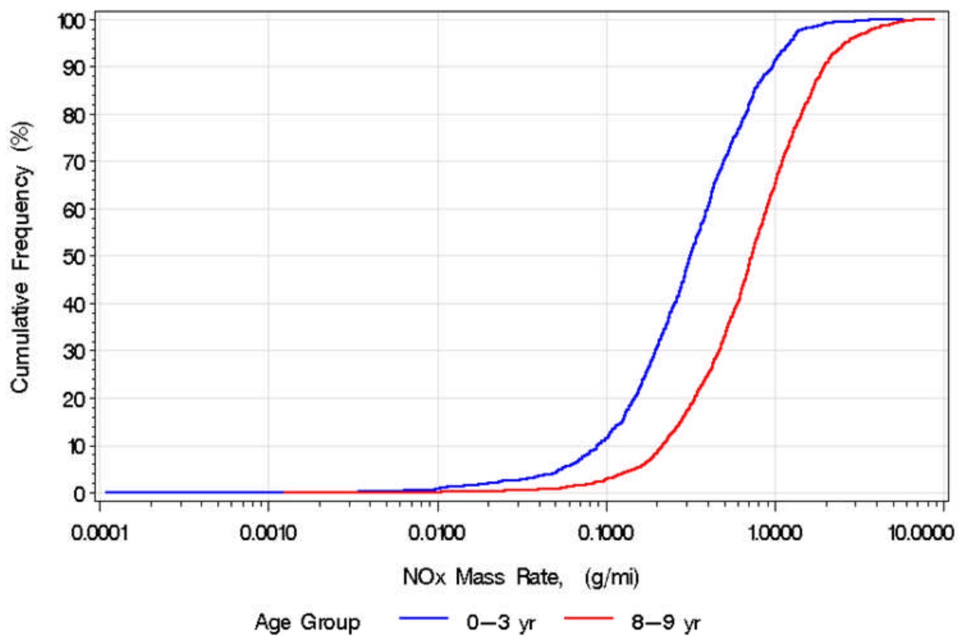
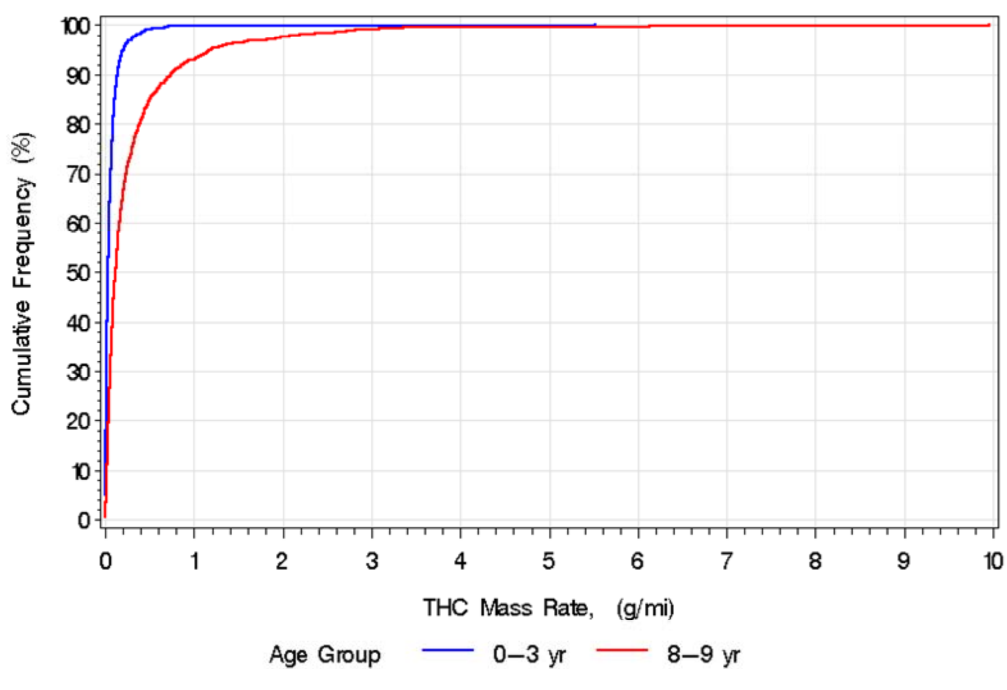


Figure 4. Cumulative distributions of running THC for Tier-1 cars, at two age levels, measured on the IM147 cycle (Source: Phoenix I/M program).



In addition to the conceptual reason just illustrated, there were practical reasons for not creating one or more “high-emitter” classes: (1) a vehicle or test showing high emissions for one pollutant need not show high emissions for other pollutants, (2) high emissions may be a transitory phenomenon in many cases, i.e., vehicles with high results for one set of measurements may not show similar results if re-measured; in such cases it is very difficult to determine whether the apparent change is due to an actual change in the vehicle or the notoriously high variability of emissions measurements, (3) given that rate development for MOVES operating modes is not coupled to the FTP (or any particular cycle), convenient and non-arbitrary definitions of “high emitter” are not readily available, and (4) distinction of emitter classes would require that the intensive process of rate development be repeated for each class, including the projection of emissions by age and power, and development of distinct adjustments for temperature and fuel (performed separately). The detailed data required for these analyses and their projection into the future is not available.

2. A second important difference between MOVES and MOBILE is that MOVES inverts MOBILE’s approach to inspection and maintenance. That is, the emission rates provided with MOBILE represented “non-I/M” conditions, and MOBILE represented I/M conditions by making adjustments during model runs. By contrast, the MOVES input table contains two sets of rates, representing “I/M reference” and “non-I/M” conditions, respectively. In development of these rates, “I/M conditions” were assigned as the default case, and rates representing “non-I/M” conditions were developed in relation to rates representing “I/M conditions.” During model runs, MOVES represents particular I/M programs as a function of both sets of rates, modified by adjustments calculated to represent the parameters of specific programs. These topics are discussed in greater detail in 1.3.3.6.

3. A third major difference between MOVES and MOBILE is that MOVES is modal, whereas MOBILE was not. This feature gives MOVES tremendous flexibility, allowing users to represent any driving pattern, across a range of temporal and spatial scales. The modal emission rates are applied consistently at the different analysis scales under which MOVES operates – national, county and project.

4. Finally, emission rates in MOVES are expressed as “time-specific” rates (mass/time, g/hr), as opposed to “distance-specific” rates (g/mi), as were rates in MOBILE. With respect to model design, the purpose for this change was to introduce a measurement basis that would be applicable to all emissions sources, processes, and operating modes, including those for which a distance-specific basis is not applicable. Examples include all emissions for nonroad equipment, which are expressed on a mass/work basis in the NONROAD model (g/hp-hr, g/kW-hr), and idle or “hotelling” emissions for all sources, which occur while the source is stationary.

1.1.4 Overview

Section 1 describes the structure of the MOVES emissionRateByAge table, as it applies to gaseous-pollutant emissions from gasoline-fueled light-duty vehicles. The values in this table describe the “base rates” (meanBaseRate). These values represent mean emissions on the MOVES reference fuel on a temperature range of 68-86 ºF, and unadjusted for the effects of temperature, humidity, air-conditioning and inspection-and-maintenance programs (I/M). The adjustments for these factors, applied during MOVES runs, are described in a separate report:

"*MOVES2010 Highway Vehicle Temperature, Humidity, Air Conditioning, and Inspection and Maintenance Adjustments.*" [34]

The emissionRateByAge table includes rates representing start and running operation, defined as distinct "processes" in MOVES. Rates representing "running operation" are described in Section 1.3, and those for "start operation" are described in section 1.4.

For running emissions, section 1.3.3 describes the development of emission rates for vehicles manufactured prior to model year 2000. Sub-sections 1.5.1 and 1.5.2 describe the process of data selection and quality assurance. Rates were generated either directly from available data (sub-section 1.3.3) or by development and application of statistical "hole-filling" models (sub-section 1.3.4). These rates were derived using data from the Phoenix I/M program and represent rates characteristic of a program with features similar to those in the Phoenix program[14].

Because the analyses described in sub-sections 1.3.3 and 1.3.4 relied on data collected on IM240 and IM147 cycles, we thought it appropriate to evaluate the extrapolation with power to high levels beyond those covered by the I/M cycles. The development and application of adjustments to rates in operating modes at high power is discussed in sub-section 1.3.3.5.

As mentioned, the rates described in 1.3.3 and 1.3.4 represent emission rates for vehicles under the requirements of an inspection-and-maintenance program, specifically the program in Phoenix, AZ, during calendar years 1995-2005. For this reason, we refer to these rates as "I/M reference rates." With respect to the I/M reference rates, we describe the approach taken to estimating rates in non-I/M areas, designated as the "non-I/M reference rates", in 1.3.3.6. For runs representing areas without an I/M program, MOVES uses the non-I/M reference rates. For runs representing areas with I/M programs, MOVES adjusts the I/M reference rates to account for the particular aspects of the program(s) represented. It is important to note the I/M reference rates assume full compliance with program requirements within the area. MOVES discounts estimated emissions for non-compliance during a model run, which is then represented in the results[34].

We have observed, as have other researchers, that emissions deterioration tends to follow exponential, or log-linear trends over the first 8-9 years. However, after this point, the trends enter a declining phase, during which increases in mean emissions continue at a reduced rate. For the I/M reference rates, we assume that rates stabilize between 12 and 15 years of age. For the non-I/M reference rates, we assume that they continue to increase at reduced rates through 20+ years of age. The analyses guiding these assumptions are described in 1.3.3.7.

For start emissions, we also applied different methods to different datasets to derive two sets of rates. For vehicles manufactured in 1995 and earlier, the process of rate development is described in 1.4.1. For vehicles manufactured in 1996 and later, the process of rate development is described in 1.4.2. We assume that emissions deterioration affects start as well as running emissions. Sub-section 1.4.3 describes how we estimate deterioration in start emissions in relation to deterioration in running emissions.

1.2 Emissions Sources (sourceBinID) and Processes (polProcessID)

In MOVES terminology, pollutants are emitted by "sources" via one or more "processes." Within processes, emissions may vary by operating mode, as well as by age Group. The relevant pollutants are the gaseous criteria pollutants: total hydrocarbons (THC), carbon monoxide (CO) and oxides of nitrogen (NOx). The relevant processes are exhaust emissions emitted during engine start and running processes, i.e., "exhaust start" and "exhaust running." Combinations of pollutant and process relevant to this chapter are shown in Table 1. For start emissions, the meanBaseRate is expressed in units of g/start, and for running emissions, the meanBaseRate is expressed in units of g/hr, which MOVES terminology designates more specifically as "g/SHO," where SHO denotes "source-hours operating."

Note that this document describes only emission rates for exhaust hydrocarbons. Modeling of emission rates for evaporative hydrocarbons is described in a separate report: *Development of Evaporative Emissions Calculations for the Motor Vehicle Emissions Simulator*[15].

For these pollutants and processes emissions sources include light-duty vehicles (cars and trucks). Note that the engine-size and weight-class attributes are not used to classify vehicles. For light-duty vehicles, these parameters are assumed not to influence emissions, as these vehicles are required to meet applicable standards irrespective of size and weight.

In the emissionRateByAge table, the emissions source is described by a label known as the "sourceBinID". This identifier is constructed as a pattern variable incorporating the attributes shown in Table 2. Assignment of the attributes just described allows assignment of the source-bin identifier. The identifier is a 19-digit numeric label, of the form "1*ffttteeyyssssswwww*00," where each component is defined as follows:

1 is the literal value "1," which serves as a leading value to set the magnitude of the entire label,
ff represents the fueltypeID,
tt represents the engTechID,
ee represents the regClassID,
yy represents the shortModYrGrpID,
ssss represents the engSizeID,
wwww represents the weightClassID, and
00 is the literal value "00," which serves to provide two trailing zeroes at the end of the label.

The individual attributes are assembled in the proper sequence by constructing the sourceBinID as a pattern variable, where

$$
\begin{aligned}
\text{sourcebinID} = 1\times10^{18} \\
&+ \text{fuelTypeID}\times10^{16} \\
&+ \text{engTechID}\ \times10^{14} \\
&+ \text{regClassID}\ \times10^{12} \\
&+ \text{shortModYrGroupID}\times10^{10} \\
&+ \text{engSizeID}\ \times10^{6} \\
&+ \text{weightClassID}\times10^{2}
\end{aligned}
\qquad \textbf{Equation 1}
$$

As an example, Table 3 shows the construction of sourceBin labels for light-duty gasoline vehicles, manufactured in model years 1998 and 2010.

Table 1. Combinations of pollants and processes for gaseous pollutant emissions.

pollutantName[1]	pollutantID[1]	processName[2]	processID[2]	polProcessID[3]	Section
HC	1	Running exhaust	1	101	
		Start exhaust	2	102	
CO	2	Running exhaust	1	201	
		Start exhaust	2	202	
NO_x	3	Running exhaust	1	301	
		Start exhaust	2	302	

[1] as shown in the database table "pollutant."
[2] as shown in the database table "emissionProcess."
[3] as shown in the database table "emissionRateByAge."

Table 2. Construction of sourceBins for Exhaust Emissions for light-duty vehicles.

Parameter	**MOVES Database Attribute[1]**	**Values**
Fuel type	fuelTypeID	Gasoline = 01 Diesel = 02 Ethanol = 05
Engine Technology	engtechid	01= "Conventional internal Combustion"
Regulatory Class	regClassID	20 = "Car" (LDV) 30 = "Truck" (LDT)
Model-Year group	shortModYrGroupID	Varies[2]
Engine Size Class	engSizeID	<not used>
Vehicle Test Weight	weightClassID	<not used>

[1] as used in the database table "emissionRateByAge."
[2] as defined in the database table "modelYearGroup."

Table 3 Examples of sourceBinID construction for cars and trucks in model years 1998 and 2010.

fuelTypeID	engTechID	regClassID	shortModYrGroupID	sourceBinID
1 (Gasoline)	1 (conventional)	20 (Car)	98 (MY 1998)	1 01 01 20 98 0000 0000 00
1	1	30 (Truck)	30 (MY 2010)	1 01 01 30 98 0000 0000 00
1	1	20 (Car)	98 (MY 1998)	1 01 01 20 30 0000 0000 00
1	1	30 (Truck)	30 (MY 2010)	1 01 01 30 30 0000 0000 00

1.2.1 The emissionRateByAge Table.

The rates described in this document are stored in the MOVES emissionRateByAge table. This table includes five fields, as shown in Table 4. Consistent with the MOVES modal approach, the table contains mean base emission rates (meanBaseRate) and associated estimates of uncertainty in these means for motor vehicles classified as “emissions sources” (sourceBinID), and by “operating mode” (opModeID). The table includes rates for vehicles inside and outside of Inspection-and-Maintenance Areas. The uncertainty estimates are expressed as coefficients of variation for the mean (meanBaseRateCV); this term is synonymous with the “relative standard error (RSE). In this section, we will describe the processes of data classification by source bin and operating mode, calculation of mean emission rates, and statistical evaluation of the results.

1.2.1.1 Age Groups (ageGroupID)

To account for emissions deterioration, MOVES estimates emission rates for vehicles in a series of age ranges, identified as age groups (ageGroupID). Seven groups are used, as follows: 0-3, 4-5, 6-7, 8-9, 10-14, 15-19, and 20+ years. The values of the attribute ageGroupID for these classes are 3, 405, 607, 809, 1014, 1519, and 2099, respectively. These groups assume that the most rapid change in emissions as vehicles age occurs between 4 and 9 years.

Table 4. Description of the EmissionRateByAge Table.

Field	Symbol	Description
SourceBinID	---	Source Bin identifier. See Table 2 and Table 3 and Equation 1.
PolProcessID	---	Combines pollutant and process. See Table 1.
opModeID		Operating mode: defined separately for running and start emissions. See Table 5.
ageGroupID		Indicates age range for specific emission rates. See 1.2.1.1.
meanBaseRate	$\overline{E}_{\text{cell}}$	Mean emission rates in areas not influenced by inspection and maintenance programs.
meanBaseRateCV	$\text{CV}_{\overline{E}}$	Coefficient of variation of the cell mean (relative standard error, RSE), for the meanBaseRate.
meanBaseRateIM		Mean emission rate in areas subject to an I/M program with features similar to the Phoenix program . See 1.3.7.
meanBaseRateIM CV		Coefficient of variation of the cell mean (relative standard error, RSE), for the meanBaseRateIM.
dataSourceID		Numeric label indicating the data source(s) and method(s) used to develop specific rates.

1.3 Exhaust Emissions for Running Operation

Running operation is defined as operation of internal-combustion engines after the engine and emission control systems have stabilized at operating temperature, i.e., “hot-stabilized” operation.

1.3.1 Operating Modes (opModeID)

For running emissions, the key concept underlying the definition of operating modes is “vehicle-specific power” (VSP, P_{V}). This parameter represents the tractive power exerted by a vehicle to move itself and its cargo or passengers[16]. It is estimated in terms of a vehicle’s speed and mass (commonly referred to as weight), as shown in Equation 2

$$P_{\mathrm{V},t} = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{m} \qquad \textbf{Equation 2}$$

In this form, VSP ($P_{\mathrm{V},t}$, kW/metric ton) is estimated in terms of vehicles’:

- speed at time t (v_t, m/sec),
- acceleration a_t (m/sec^2) ,
- - mass m (metric ton) (usually referred to as “weight, ”),
- - track-road load coefficients *A*, *B* and *C*[3], representing rolling resistance, rotational resistance and aerodynamic drag, in units of kW-sec/m, kW-sec^2/m^2 and kW-sec^3/m^3, respectively.

This version of the equation does not include the term accounting for effects of road grade, because the data used in this analysis was measured on chassis dynamometers. Note that during model operation, MOVES does account for grade when characterizing vehicle activity. For a description of this process, see the “*Vehicle Population and Activity*” report[17].

On the basis of VSP, speed and acceleration, a total of 23 operating modes are defined for the running-exhaust process (Table 5). Aside from deceleration/braking, which is defined in terms of acceleration, and idle, which is defined in terms of speed alone, the remaining 21 modes are defined in terms of VSP within broad speed classes. Two of the modes represent “coasting,” where VSP < 0. and the remainder represent “cruise/acceleration,” with VSP ranging from 0 to over 30 kW/metric ton. For reference, each mode is identified by a numeric label, the “opModeID.”

Table 5. Definition of MOVES Operating Modes for Running-Exhaust operation.

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

1.3.2 Scope

In estimation of energy consumption for MOVES2004, it was possible to combine data from various sources without regard for the residence locations for vehicles measured. In contrast, when turning attention to the regulated gaseous pollutants, it is essential to know with some degree of confidence whether vehicles had been subject to inspection-and-maintenance (I/M) requirements at or previous to the time of measurement. After reviewing data sources, it became clear that the volumes of data collected within I/M areas vastly exceeded those collected in non-I/M areas. We also concluded that I/M programs themselves could provide large and valuable sources of data. In consideration of the demanding analytic tasks posed by the ambitious MOVES design, we elected to estimate rates for vehicles in I/M areas first, as the "base-line" or "default" condition. Following construction of a set of rates representing I/M "reference" conditions, the plan was to estimate rates for non-I/M areas relative to those in I/M areas. This approach is an inversion of that used in MOBILE6, in which "non-I/M" is the "default condition" relative to which "I/M" emissions are calculated during a model run.

In addition, the rates described below represent emissions on the FTP temperature range (68 – 86 °F) to provide a baseline against which temperature adjustments would be applied during model runs.

1.3.3 Emission-Rate development: Subgroup 1 (Model years through 2000)

1.3.3.1 Data Sources

For emissions data to be eligible for use in MOVES development, several requirements were imposed:

- To derive rates for operating modes, it was essential to acquire data measured on transient tests.
- Data had to be measured at a frequency of approximately 1 Hz., e.g., continuous or "second-by-second" measurements.
- To make allowance for application of temperature adjustments (developed separately), it was necessary to know the temperature at the time of test.
- Vehicles were subject to I/M program requirements at the time of measurement.

1.3.3.1.1 Vehicle Descriptors

In addition to the requirements listed above, complete descriptive information for vehicles was required. Vehicle parameters required for incorporation into MOVES are shown in Table 6.

Table 6. Required Vehicle Parameters.

Parameter	Units	Purpose
VIN		Verify MY or other parameters
Fuel type		
Make		
Model		
Model year		Assign sourceBinID, calculate age-at-test
Vehicle class		Assign sourceBinID
GVWR	lb	Distinguish trucks from cars (LDV)
Track road-load power	hp	Calculate track road-load coefficients *A*, *B* and *C*

1.3.3.1.1.1 Track Road-Load Coefficients: Light-Duty Vehicles

For light-duty vehicles, we calculated the track load coefficients from the "track road load power at 50 mph" (TRLP, hp), based on Equation 3[18].

$$A = PF_A \cdot \left(\frac{\text{TRLHP} \cdot c_1}{v_{50} \cdot c_2} \right)$$
$$B = PF_B \cdot \left(\frac{\text{TRLHP} \cdot c_1}{(v_{50} \cdot c_2)^2} \right) \qquad \textbf{Equation 3}$$
$$C = PF_C \cdot \left(\frac{\text{TRLHP} \cdot c_1}{(v_{50} \cdot c_2)^3} \right)$$

where:

PF_A = default power fraction for coefficient *A* at 50 mi/hr (0.35),
PF_B = default power fraction for coefficient *B* at 50 mi/hr (0.10),
PF_C = default power fraction for coefficient *C* at 50 mi/hr (0.55),
c_1 = a constant, converting TRLP from hp to kW (0.74570 kW/hp),
v_{50} = a constant vehicle velocity (50 mi/hr),

c_2 = a constant, converting mi/hr to m/sec (0.447 m·hr/mi·sec)).

In the process of performing these calculations, we converted from English to metric units, in order to obtain values of the track road-load coefficients in SI units, as listed above. Values of TRLP were obtained from the Sierra I/M Look-up Table.[19]

1.3.3.1.2 Test Descriptors

In addition, a set of descriptive information was required for sets of emissions measurements on specific vehicles. Essential items for use in rate development are listed in Table 7.

Table 7. Required Test Parameters.

Parameter	Units	Purpose
Date		Determine vehicle age at test
Time of day		Establish sequence of replicates
Ambient temperature	°F	Identify tests on target temperature range
Test Number		Identify 1st and subsequent replicates
Test duration	sec	Verify full-duration of tests
Test result	pass/fail	Assign tests correctly to pass or fail categories
Test weight	lb	Calculate vehicle-specific power

1.3.3.1.3 Candidate Data Sources

In addition to the parameters listed in Table 6 and Table 7, datasets with historic depth and large sample sizes were highly desirable, to characterize the high variability typical of exhaust emissions as well as trends with vehicle age.

At the outset, a large volume of emissions data was available, representing over 500,000 vehicles when taken together (Table 8). In some cases they could be combined as broadly comparable pairs representing I/M and non-I/M conditions. While not all available data could receive detailed attention, due to limitations in time and resources, a selection of likely candidates was subjected to a high degree of scrutiny and quality-assurance, after which some were excluded from further consideration for specific reasons.

Table 8. Datasets available for use in estimating Running emissions from cars and trucks.

Dynamometer		Remote-Sensing (RSD)	
I/M	**non-I/M**	**I/M**	**non-I/M**
AZ (Phoenix)		AZ Phoenix	
IL (Chicago)		IL (Chicago)	
MO (St. Louis)		MO St. Louis	
NY (New York)		Maryland/N Virginia	VA (Richmond)
		GA (Atlanta)	GA (Augusta/Macon)
			NE (Omaha)
			OK (Tulsa)

Several remote-sensing datasets received consideration. However, we elected not to use remote-sensing data directly to estimate rates, for several reasons: (1) For the most part, the RSD datasets on hand had very restricted model-year by age coverage (historic depth), which severely limited their usefulness in assigning deterioration. (2) The measurement of hydrocarbons by RSD is highly uncertain. The instruments are known to underestimate the concentrations of many hydrocarbon species relative to other techniques, such as flame-ionization detectors. In inventory estimation, a multiplicative adjustment of 2.0-2.2 is often applied to allow comparison to HC measurements by other methods.[20] (3) In MOVES, emissions are expressed in terms of mass rates (mass/time). While fuel-specific rates (mass emissions/mass fuel) can be estimated readily from remote-sensing data[21], mass rates cannot be calculated without an independently estimated CO_2 mass rate. It followed that RSD would not provide rates for any MY×Age combinations where dynamometer data were not available. In these cases, RSD would be dependent on and to some extent redundant with dynamometer data. (4) Because remote-sensing measurements are typically sited to catch vehicles operating under light to moderate acceleration, results can describe emissions only selected cruise/acceleration operating modes. However, RSD cannot provide measurements for coasting, deceleration/braking or idle modes. For these reasons we reserved the RSD for additional roles, such as verification of results obtained from dynamometer data.

Table 9. Characteristics of candidate Datasets

	Chicago	**Phoenix**	**NYIPA**	**St. Louis**
Type	Enhanced	Enhanced	Basic/Enhanced	Enhanced
Network	Centralized	Centralized	De-centralized	Centralized
Exempt MY	4 most recent	4 most recent	2 most recent	2 most recent
Collects random sample?	YES	YES	n/a	NO
Program Tests	Idle, IM240, OBD-II	Idle/SS, IM240, IM147, OBD-II	IM240	IM240
Fast-pass/Fast-fail?	YES	YES	n/a	YES
Test type (for random sample)	IM240	IM240, IM147	IM240	n/a
Available CY	2000-2004	1995-1999 2002-2005	1999-2002	2002-2005
Size (no. tests)	8,900	62,500	8,100	2,200,000

Dynamometer datasets that received serious consideration are described below and summarized in Table 9.

Metropolitan Chicago. We acquired data collected over four calendar years (2000-04) in Chicago's centralized enhanced program. In addition to routine program tests, the program performed IM240 tests on two random vehicle samples. One is the "back-to-back" random sample. This sample is relatively small (n ~ 9,000 tests), but valuable because each selected vehicle received two full-duration IM240 tests in rapid succession, obviating concerns about conditioning prior to conduction of IM240 tests. A second is the "full-duration" random sample, in which selected vehicles received a single full-duration IM240. This sample is much larger (n > 800,000) but less valuable due to the lack of replication. Despite its size, the full-duration sample has no more historic depth than the back-to-back sample, and thus sheds little additional light on age trends in emissions. Both samples were simple random samples, indicating that in the use of the data, users must assume that the samples are self-weighting with respect to characteristics such as high emissions, passing/failing test results, etc.

St. Louis. Another large program dataset is available from the program in St. Louis. While a large sample of program tests is available, this program differed from the others in that no random evaluation sample was available. Because vehicles were allowed to "fast-pass" their routine tests, results contained many partial duration tests (31 – 240 seconds). At the same time, the lack of replication raised concerns about conditioning. Partial duration was a concern in itself in that the representation of passing vehicles declined with increasing test duration, and also because it compounded the issue of conditioning. In addition, while OBD-equipped vehicles failing a scan received IM240s, those passing their scans did not. Because addressing the interwoven issues of inadequate conditioning, "fast-pass bias" and "OBD-screening bias" proved intractable, we excluded this dataset from further consideration.

Phoenix. At the outset, the random samples from the Phoenix program appeared attractive in that they had over twice the historic depth of any other dataset, with model-year × age coverage spanning 11 calendar years. Usage of these samples is somewhat complicated by the fact that no random samples were collected for two years (2000-01) and by the fact that the sample design employed changed in the middle of the ten-year period. During the first four years, a simple "2% random sample" was employed. During the last four years, a stratified design was introduced which sampled passing and failing vehicles independently and at different rates. In the stratified sample, failures were over-sampled relative to passing vehicles. Thus, using these data to estimate representative rates and to combine them with the 2% sample, assumed to be self-weighting, required reconstruction of the actual stratified sampling rates, as described below.

New York Instrumentation/Protocol Assessment (NYIPA). This dataset differs from the others in that while it was collected within an I/M area in New York City, it is not an I/M program dataset as such. It is, rather, a large-scale research program designed to establish correlation between the IM240 and an alternative transient test. It is not entirely clear whether it can be considered a random sample, in part because estimation of representative averages was not a primary goal of the study. All data that we accessed and used was measured on full-duration IM240s during a four-year period. There was a high degree of replication in the conduction of tests, allowing fully-conditioned operation to be isolated by exclusion of the initial test in a series of replicates. While these data played a prominent role in development of energy consumption rates for MOVES2004, the four-year duration of the program limits its usefulness in analysis of age trends for gaseous pollutants.

1.3.3.2 Data Processing and Quality-assurance

We performed several quality-assurance steps to avoid known biases and issues in using I/M data to estimate mean emissions. One source of error, "inadequate conditioning" can occur when vehicles idle for long periods while waiting in line. To ensure that measurements used reflected fully-conditioned vehicles we excluded either portions of tests or entire tests, depending on test type and the availability of replicates. If back-to-back replication was performed, we discarded the first test in a series of replicates. If replication was not performed, we excluded the first 120 seconds of tests (for IM240s only).

Another problem occurs when calculation of fuel economy for tests yields values implausible enough to indicate that measurements of one or more exhaust constituents are invalid (e.g., 300 mpg). To identify and exclude such tests, we identified tests with outlying measurements for fuel economy, after grouping vehicles by vehicle make, model-year and displacement.

An issue in some continuous or second-by-second datasets is that cases occur in which the emissions time-series appears to be "frozen" or saturated at some level, not responding to changes in power. We found that the occurrence of such problems was more or less evenly distributed among the fleet regardless of age or model year, and that severe instances were rare. We excluded tests in which 25% or more of the measurements were "frozen."

For a modal analysis assuming that emissions respond to power on short time scales,
It is critical that the emissions time-series be aligned to the power time-series. Consequently, we examined alignment for all tests. As necessary, we re-aligned emissions time series to those for VSP by maximizing correlation coefficients, using parametric Pearson coefficients for CO_2 and NO_x, and non-parametric Spearman coefficients for CO and THC.

1.3.3.2.1 Sample-design reconstruction (Phoenix only)

For data collected in Phoenix during CY 2002-05, we constructed sampling weights to allow use of the tests to develop representative means. The program implemented a stratified sampling strategy, in which failing vehicles were sampled at higher rates than passing vehicles.
It is thus necessary to reconstruct the sample design to appropriately weight failing and passing vehicles in subsequent analyses. After selection into the random sample, vehicles were assigned to the "failing" or "passing" strata based on the result of their routine program test, with the specific test depending on model year, as shown in Figure 5. Within both strata, sample vehicles then received three replicate IM147 tests.

Based on test records, reconstructing sampling rates simply involved dividing the numbers of sampled vehicles by the total numbers of vehicles tested, by model year and calendar year, for failing (f) and passing (p) strata, as shown in Equation 4.

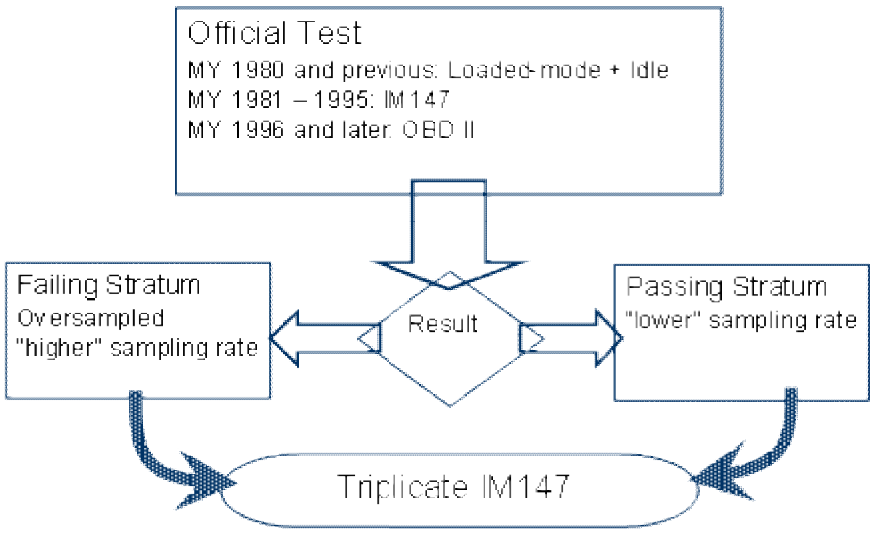
$$f_{\mathrm{f,MY,CY}} = \frac{n_{\mathrm{f,MY,CY}}}{N_{\mathrm{f,MY,CY}}} \qquad f_{\mathrm{p,MY,CY}} = \frac{n_{\mathrm{p,MY,CY}}}{N_{\mathrm{p,MY,CY}}}$$

Equation 4

Corresponding sampling weights indicate the numbers of vehicles in the general fleet represented by each sample vehicle. They were derived as the reciprocals of the sampling fractions, as shown in Equation 5.

$$w_{\text{f,MY,CY}} = \frac{1}{f_{\text{f,MY,CY}}} \qquad w_{\text{p,MY,CY}} = \frac{1}{f_{\text{p,MY,CY}}}$$ **Equation 5**

Figure 5. Stratified sampling as applied in selection of the random evaluation sample in the Phoenix I/M Program (CY 2002-05).



1.3.3.3 Source selection

After excluding the St. Louis dataset, and comparing the Phoenix, Chicago and NY datasets, analysis, we elected to rely on the Phoenix dataset for purposes of rate estimation and to use the other datasets, including selected remote-sensing data, for purposes of comparison. This course was chosen for several reasons.

For our purposes, the greater historic depth of the Phoenix data was a tremendous advantage. It was the only set deep enough to allow direct and independent assessment of deterioration. The limited depth of the other datasets would have meant that the subset of calendar years that could be covered by pooled data would have been relatively limited. Only a single calendar year, 2002, is covered by all three datasets. Several years would be covered by two out of three. Calendar 1999 is covered by Phoenix and NY; 2000 and 2001 would have been covered by NY and Chicago, and 2003 and 2004 by Chicago and Phoenix. The remaining years, 1996-98 and 2005 could have been covered only by Phoenix in any case.

In addition, pooling the three datasets would have raised several difficult technical issues that may not be apparent at first glance. Table 9 shows that the datasets were of greatly differing sizes. Thus, if the datasets were pooled without some type of relative weighting, Phoenix would have exerted much stronger influence than the others in most shared calendar years. To rectify disparities in influence by assigning the different datasets similar or proportional influence would have required development of some sort of a weighting scheme, but a rational basis for such relative weighting is not immediately apparent.

The question of pooling is further complicated by the fact that use of the Phoenix data collected in CY 2002 to 2005 requires use of sampling weights for passing and failing tests (as described) above), whereas the Chicago and NYIPA datasets are assumed to be self-weighting. Again, no rational basis for incorporating weighted and self-weighted tests from various programs in the same CY was immediately apparent.

Finally, the selection of the Phoenix data provided a relatively consistent basis for specification of a "reference fuel," and development of associated fuel adjustments[34].

1.3.3.4 Methods

1.3.3.4.1 Data-Driven Rates

Where data was present, the approach was simple. We calculated means and other summary statistics for each combination of sourceBinID, ageGroup and operating mode (i.e., table cell). We classified the data by regulatory class (LDV="cars", LDT="trucks"), model-year group, age group and operating mode (Table 5). The model-year groups used are shown in Table 7, along with corresponding samples of passing and failing tests.

Table 10. Test sample sizes for the Phoenix random evaluation sample (*n* = no. tests)

Model-year group[1]	**Cars**		**Trucks**	
	fail[2]	*pass*	*fail*	*pass*
1981-82	562	539	340	495
1983-85	1,776	2,078	1,124	1,606
1980-89	3,542	6,420	1,745	3,698
1990-93	2,897	8,457	1,152	4,629
1994-95	997	4,422	703	3,668
1996-98	1,330	3,773		
1996			526	1,196
1997-98			858	2,320
1999-2000	176	753	136	624
Total	11,285	26,478	6,589	18,254

[1] Note that these are the model-year groups used for analysis; NOT the model-year groups used in the MOVES database.
[2] Note that 'failure' can indicate failure for CO, HC or NOx, as applicable.

We calculated means and other summary statistics for each combination of sourceBinID, ageGroupID and opModeID. For simplicity, we will refer to a specific combination of sourceBinID, and opModeID as a "*cell*," to be denoted by label '*h*'.

1.3.3.4.1.1 Rates: Calculation of weighted means

The emission rate (meanBaseRate) in each cell is a (E_h) simple weighted mean

$$E_h = \frac{\sum_{i=1}^{n_{\text{test}}} w_i R_{i,t}}{\sum_{i=1}^{n_{\text{test}}} w_i} \qquad \textbf{Equation 6}$$

where w_i is a sampling weight for each vehicle in the cell, as described above, and $R_{i,t}$ is the "second-by-second" emission rate in the cell for a given vehicle at a given second t.

1.3.3.4.1.2 Estimation of Uncertainties for Cell Means:

A new feature of MOVES is its ability to estimate uncertainty in emissions projections. In the emissionRateByAge table, uncertainties for individual rates are stored in the "meanBaseRateCV" fields (Table 4).To estimate sampling error for each cell, we calculated standard-errors by weighted variance components. In estimating variances for cell means, we treated the data within cells as effective cluster samples, rather than simple random samples. This approach reflects the structure of the data, which is composed of sets of multiple measurements collected on individual vehicles. Thus, measurements on a specific vehicle are less independent of other measurements on the same vehicle than of measurements on other vehicles. Accordingly, means and variances for individual vehicle tests were calculated to allow derivation of between-test and within-test variance components. These components were used in turn to calculate the variance of the mean for each cell, using the appropriate degrees of freedom to reflect between-test variability[22]. To enable estimation of variances under this approach, we calculated a set of summary statistics, as listed below:

Test mean (E_i): the arithmetic mean of all measurements in a given test on a specific vehicle in a given cell.

Test sample size (n_h), the number of individual tests represented in a cell.

Measurement sample size (n_i): the number of measurements in a cell representing an individual test on an individual vehicle.

Cell sample size ($n_{h,i}$): the total number of individual measurements on all vehicles in a cell, where each count represents a measurement collected at an approximate frequency of 1.0 Hz, (i.e., "second-by-second").

Test variance (s_i^2): the variance of measurements for each test represented in a cell, calculated as the average squared deviation of measurements for a test about the mean for that test. Thus, we calculated a separate test variance for each test in each cell.

Weighted Between-Test variance component (s_b^2): the component of total variance due to variability among tests in a cell, or stated differently, the weighted variance of the test means about the cell mean, calculated as

$$s_\mathrm{b}^2 = \frac{\sum_{i=1}^{n_i} w_i \left(E_i - E_h\right)^2}{\sum_{i=1}^{n_i} w_i - 1} \qquad \textbf{Equation 7}$$

Weighted Within-Test Variance Component (s_w^2): the variance component due to variability within tests, or the variance of measurements within individual tests ($R_{i,t}$) about their respective test means, calculated in terms of the test variances, weighted and summed over all tests in the cell:

$$s_\mathrm{w}^2 = \frac{\sum_{i=1}^{n_h} w_i \left(n_i - 1\right) s_i^2}{\left(\sum_{i=1}^{n_h} w_i\right)\left(n_{h,i} - n_h\right)} \qquad \textbf{Equation 8}$$

Variance of the cell mean ($s_{\bar{E}}^2$): this parameter represents the uncertainty in the cell mean, and is calculated as the sum of the between-vehicle and within-test variance components, with each divided by the appropriate degrees of freedom.

$$s_{E_h}^2 = \frac{s_\mathrm{b}^2}{n_h} + \frac{s_\mathrm{w}^2}{n_{h,i}} \qquad \textbf{Equation 9}$$

Coefficient-of-Variation of the Mean (CV_{Eh}): this parameter gives a relative measure of the uncertainty in the cell mean, allowing comparisons among cells. It is calculated as the ratio of the cell standard error to the associated cell mean

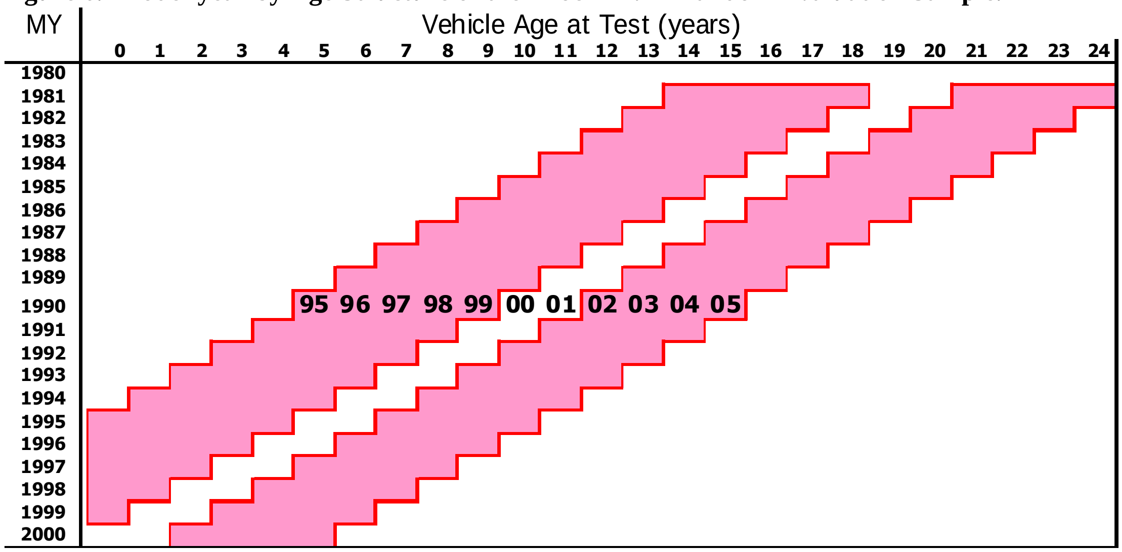
$$\mathrm{CV}_{E_h} = \frac{\sqrt{s_{E_h}^2}}{E_h} \qquad \textbf{Equation 10}$$

Note that the term CV_{Eh} is synonymous with the term “relative standard error” (RSE).

1.3.3.4.2 Model-generated Rates (hole-filling)

Following averaging of the data, it was necessary to impute rates for cells for which no data was available, i.e., “holes.” Empty cells occur for age Groups not covered by available data (Figure 6). In the figure, “age holes” are represented by un-shaded areas. Filling in these un-shaded areas required “hind-casting” emissions for younger vehicles for older model years, as well as “forecasting” deterioration of aging vehicles for more recent model years. Empty cells occur as well in high-power operating modes not covered by the IM147 or IM240, meaning operating modes with power greater than about 24 kW/metric ton.

Figure 6. Model-year by Age Structure of the Phoenix I/M Random Evaluation Sample.



1.3.3.4.2.2 Rates

To estimate rates in empty cells (holes), we constructed statistical models of emissions data to extrapolate trends in VSP and age. For this purpose, we generated a series of models based on the MOVES operating-mode/ageGroup structure. Note that the extrapolated values were modified on a case-by-case basis as described in section 1.5.5.

As a preliminary step, data were averaged for each test within a set of classes for VSP and speed. We averaged emissions by model-year-group, regClass, age, VSP class, speed class and test. Classes for VSP followed intervals of 3.0 kW/metric ton (e.g., 0-3, 3-6, … 27-30, 30+). Speed classes followed those used for the MOVES operating modes (e.g., 1-25 mph, 25-50 mph, 50+ mph). The resulting dataset had a single mean for each test in each 6-way cell. The purpose for this averaging was to give the resulting statistical model an appropriate number of degrees of freedom for each of the class variables, i.e., the d.f. would be determined by the number of tests rather than the number of individual “second-by-second” measurements. Note that the matrix used for this purpose was finer than that represented in Table 5.

We fit separate models in three groups of operating modes. For all operating modes except brake/deceleration and idle, we fit one model incorporating VSP. We call this group “coast/cruise/acceleration.” For braking/deceleration and idle, we fit two additional models not incorporating VSP, as these modes are not defined in other terms (Table 5). Overall, we fit three models for each combination of cars and trucks, for the model-year groups shown in Table 10, giving a total of 60 models.

Before fitting a model, we drew a sample of vehicle tests in each model-year group (n = 1,200 to 3,500, see Table 11). This sampling was performed to fit models on smaller volumes of data that a standard desktop computer could handle. The sample was stratified by test result (*pass*, *fail*) and age, with allocation proportional to that in the sample pool. Within each result age stratum, tests were drawn using simple random sampling, and sampling frequencies and weights, f_{strat} and w_{strat}, calculated as

$$f_{\text{strat}} = \frac{n_{\text{strat}}}{N_{\text{strat}}}, \qquad w_{\text{strat}} = \frac{1}{f_{\text{strat}}} = \frac{N_{\text{strat}}}{n_{\text{strat}}}$$ **Equation 11**

where n_{strat} and N_{strat} are the number of tests selected from a stratum and total number of tests in the stratum, respectively. Then, for each test selected, a final weight was calculated as the product of the stratum weight and the initial sampling weight ($w_{\text{result,MY,CY}}$), as shown in Equation 5.

$$w_{\text{final}} = w_{\text{result,MY,CY}} w_{\text{strat}}$$ **Equation 12**

Table 11. Sample sizes for statistical modeling, by regulatory class and test result.

Model-year group	LDV		LDT	
	fail	*pass*	*fail*	*pass*
1981-82	645	554	476	723
1983-85	569	631	508	691
1980-89	375	828	343	856
1990-93	260	944	209	991
1994-95	406	1,995	378	2,021
1996-98	663	1,738		
1996			346	854
1997-8			671	1,730

Each model included two sub-models, one to estimate means and one to estimate variances, as described below.

1.3.3.4.2.2.1 Coast/Cruise/Acceleration

Means model

For the means sub-model, the dependent variable was the natural logarithm of emissions

$$\ln E_h = \beta_0 + \beta_1 P_V + \beta_2 P_V^2 + \beta_3 P_V^3 + \beta_4 a + \beta_5 s + \beta_6 P_V s + \gamma_7 t_i + \varepsilon \qquad \textbf{Equation 13}$$

where :

- $\ln E_h$ = natural-logarithm transform of emissions (in cell *h*),
- P_V, P_V^2, P_V^3 = first-, second- and third-order terms for vehicle-specific power (VSP, kW/metric ton),
- a = vehicle age at time of test (years),
- s = speed class (1 -25 mph, 25-50 mph and 50+ mph),
- t = test identifier (random factor)
- ε = random or residual error

- β = regression coefficients for the intercept and fixed factors P_V, a and s.
- γ = regression coefficients for the random factor *test*.

The model includes first-, second- and third-order terms in P_V to describe curvature in the power trend, e.g., enrichment for CO and the corresponding decline in NOx at high power. The age term gives an ln-linear trend in age. The speed-class term allows for a modified intercept in each speed class, whereas the power/speed-class interaction allows slightly different power slopes in each speed class. The random factor term for test fits a random intercept for each test, which does not strongly affect the mean estimates but does affect the estimation of uncertainties in the coefficients.

After fitting models, we performed basic diagnostics. We plotted residuals against the two continuous predictors, VSP and age. We checked the normality of residuals across the range of VSP and age, and we plotted predicted vs. actual values.

Variances model

The purpose of this sub-model was to model the variance of lnE_h, i.e., the logarithmic variance s_l^2, in terms VSP and age. To obtain a dataset of replicate variance estimates, we drew sets of replicate test samples. Each replicate was stratified in the same manner as the larger samples (Table 11). To get replicate variances, we calculated ln-variance for each replicate within the VSP/age matrix described above.

Models were fit on set of replicate variances thus obtained. The dependent variable was logarithmic variance

$$s_l^2 = \alpha_0 + \alpha_1 a + \alpha_2 P_\mathrm{V} + \alpha_3 P_\mathrm{V} a + \varepsilon \qquad \textbf{Equation 14}$$

where P_V and a are VSP and age, as above, and α are regression coefficients. After fitting we examined similar diagnostics as for the means model.

Model application

Application of the model was simple. The first step was to construct a cell matrix including all emission rates to be calculated, as shown in Table 12.

Table 12. Construction of emission –rate matrix for light-duty gasoline vehicles.

	Count	Category	MOVES Database attribute
	1	Fuel (gasoline)	fuelTypeID = 01
×	2	Regulatory Classes (LDV, LDT)	regClassID = 20, 30
×	10	Model-year groups	As in Table 11
×	21	Operating modes	opModeID = 11-16, 21-30, 33-40
×	7	Age Groups	ageGroupID = 3, 405, 607, 809, 1014, 1519, 2099
×	3	Pollutant processes (running HC, CO, NOx)	polProcessID = 101, 201, 301
=	9,660	TOTAL cells	

Next, we constructed a vector of coefficients for the means sub-model (**β**) and merged it into the cell matrix.

$$\boldsymbol{\beta} = \lfloor \beta_0 \ \beta_1 \ \beta_2 \ \beta_3 \ \beta_4 \ \beta_{5(0-25)} \ \beta_{5(25-50)} \ \beta_{5(50+)} \ \beta_6 \rfloor$$ **Equation 15**

Then, for each table cell, we constructed a vector of predictors ($\mathbf{X}_h$). Equation 16 shows an example for an operating mode in the 1 – 25 mph speed class, e.g., the value for the 1-25 mph class is 1 and the values for the 25-50 and 50+ speed classes are 0. To supply values for VSP (P_{V}) and age group (a), cell midpoints were calculated and applied as shown in Table 13.

$$\mathbf{X}_h = \lfloor 1 \ \ P_{\mathrm{V}} \ \ P_{\mathrm{V}}^{\ 2} \ P_{\mathrm{V}}^{\ 3} \ a \ \ 1 \ \ 0 \ \ 0 \ \ P_{\mathrm{V}} \ \rfloor$$ **Equation 16**

Table 13. Values of VSP used to apply statistical models.

opModeID	Range	Midpoint
11, 21	< 0	-2.0
12, 22	0 - 3	-2.5
13, 23	3 - 6	4.5
14, 24	6 - 9	7.5
15, 25	9 - 12	10.5
16	12 +	14.5
27,37	12 - 18	15.0
28,38	18 - 24	21.0
29,39	24 - 30	27.0
30	30 +	34.0
40	30 +	34.0
33	< 6	0.5
35	6 - 12	9.0

The final step was to multiply coefficient and predictor vectors, which gives an estimated logarithmic mean ($\ln E_h$) for each cell h.

$$\ln E_h = \mathbf{X}_h^{'}\%$$ **Equation 17**

The application of the variances model is similar, except that the vectors have four rather than nine terms

$$\boldsymbol{\alpha} = [\ \alpha_0\ \alpha_1\ \alpha_2\ \alpha_3\ ]$$ **Equation 18**

$$\mathbf{X}_h = [1\ \ P_{\mathrm{V}}\ \ a\ \ P_{\mathrm{V}}a\ ]$$ **Equation 19**

Thus, the modeled logarithmic variance in each cell is given by

$$s^2_{l,h} = \mathbf{X}_h‡$$ **Equation 20**

In some model-year groups, it was not always possible to develop plausible estimates for the age slope β_4, because the data did not cover a wide enough range of calendar years. For example, in the 99-00 model-year group, the available data represented young vehicles without sufficient coverage of older vehicles. We considered it reasonable to adapt the age slope for the 96-98 model-year group for cars, and the 1997-98 model-year group for trucks.

In the groups 83-85 and 81-82, the data covered vehicles at ages of 10 years and older but not at younger ages. Simply deriving slopes from the available data would have given values that were much too low, resulting in very high emissions for young vehicles. In these cases we considered it more reasonable to adopt an age slope from a subsequent model year group. When making this assumption, it is necessary to recalculate the intercept, based on the assumed slope and the earliest available data point.

Intercepts, denoted as β_0*, were recalculated by rearranging Equation 13 to evaluate the model in operating mode 24, using the age slope from the previous model-year group (β_4*) and an estimate of ln-emissions from the available dataset at the earliest available age ($\ln E_{a*}$) at age a*. In operating mode 24, the midpoint of the VSP range (6-9) is 7.5 kW/metric ton and the speed class is 25-50 mph.

$$\beta_0^* = \ln E_{a*} - 7.5\beta_1 - 7.5^2\beta_2 - 7.5^3\beta_3 - \beta_4^* a* - \beta_{5(25-50)} - 7.5\beta_6$$ **Equation 21**

On a case by case basis, age slopes were adopted from earlier or later model-year groups. In a similar way, ln-variance models or estimates could be adopted from earlier or later model years.

1.3.3.4.2.2.2 Braking/Deceleration

Means model

We derived models similar to those used for coast/cruise/acceleration. For these operating modes, however, the models were much simpler, in that they did not include VSP or the speed classes used to define the coast/cruise/accel operating modes. Thus, emissions were predicted solely in terms of age, although random intercepts were fit for each test as before:

$$\ln E_h = \beta_0 + \beta_1 a + \gamma_7 t_i + \varepsilon \qquad \textbf{Equation 22}$$

Variances model

In addition, we fit variances models for these operating modes, which were also simple functions of age.

$$s_l^2 = \alpha_0 + \alpha_1 a + \varepsilon \qquad \textbf{Equation 23}$$

Model_application

In these operating modes, rates were to be modeled for a total of 840 cells. This total is calculated as in Table 12, except that the number of operating modes is 2, rather than 21. We set up coefficient and predictor vectors, as before.

For the means and variances sub-models the vectors are

$$\boldsymbol{\beta} = [\ \beta_0 \ \beta_1 \ ] \qquad \textbf{Equation 24}$$

and

$$\mathbf{X}_h = [1 \quad a\ ] \qquad \textbf{Equation 25}$$

respectively.

For the variances model the coefficients vector is

$$\ddagger = [\alpha_0 \ \alpha_1 \ ] \qquad \textbf{Equation 26}$$

and the predictor vector is identical to that for the means model.

As with coast/cruise/accel modes, we considered it reasonable in some model-year groups to adopt a slope or ln-variance from a previous or later model-year group. In model-year groups where the purpose was to hindcast rates for younger vehicles, rather than forecast rates for aging vehicles, it was again necessary to recalculate the intercept based on a borrowed age slope and an estimate of $\ln E_h$ calculated from the sample data for the youngest available age class. In this case, Equation 27 is a rearrangement of Equation 22.

$$\beta_0^* = \ln E_{a*} - \beta_4 a* \qquad \textbf{Equation 27}$$

After these steps, the imputed values of $\ln E_h$ were calculated, as in Equation 19.

1.3.3.4.2.3 Estimation of Model Uncertainties

We estimated the uncertainty for each estimated $\ln E_h$ in each cell. During each model run, we saved the covariance matrix of the model coefficients ($\boldsymbol{s_\beta}^2$). This matrix contains covariances of each of the nine coefficients in relation to the others, with the diagonal containing variances for each coefficient.

$$\mathbf{s}_{\boldsymbol{\beta}}^{2}=\begin{bmatrix} \sigma_0^2 & . & . & . & \sigma_{0,4}^2 & . & . & . & \sigma_{0,6}^2 \\ . & \sigma_1^2 & . & . & . & . & . & . & . \\ . & . & \sigma_2^2 & . & . & . & . & . & . \\ . & . & . & \sigma_3^2 & . & . & . & . & . \\ \sigma_{4,0}^2 & . & . & . & \sigma_4^2 & . & . & . & \sigma_{0,4}^2 \\ . & . & . & . & . & \sigma_{5(0-25)}^2 & . & . & . \\ . & . & . & . & . & . & \sigma_{5(25-50)}^2 & . & . \\ . & . & . & . & . & . & . & \sigma_{5(50+)}^2 & . \\ \sigma_{6,0}^2 & . & . & . & \sigma_{6,4}^2 & . & . & . & \sigma_6^2 \end{bmatrix} \qquad \textbf{Equation 28}$$

Using the parameter vectors $\mathbf{X}_{\boldsymbol{h}}$ and the covariance matrix $\boldsymbol{s_\beta}^2$, the standard of error of estimation for each cell was calculated as

$$s_{\ln E_h}^2 = \mathbf{X}_h^{'}\mathbf{s}_{\boldsymbol{\beta}}^{2}\mathbf{X}_h \qquad \textbf{Equation 29}$$

The standard error of estimation in each cell represents the uncertainty of the mean estimate in the cell, based on the particular values of the predictors defining the cell[23]. The pre- and post-multiplication of the covariance matrix by the parameter vectors represents the propagation of uncertainties, in which the parameters represent partial derivatives of each coefficient with respect to all others and the co-variances represent the uncertainties in each coefficient in relation to itself and the others.

1.3.3.4.2.4 Reverse transformation

To obtain an estimated emission rate E_h in each cell, the modeled means and variances are exponentiated as follows

$$E_h \ = \ \mathrm{e}^{\ln E_h}\mathrm{e}^{0.5 s_{l,h}^2} \qquad \textbf{Equation 30}$$

The two exponential terms use the results of the means and variances sub-models, respectively. The left-hand “means” term represents the geometric mean, or the center of the implied log-normal distribution, whereas the right-hand “variance” term reflects the influence of the “high-emitting” vehicles representing the tail of the distribution.

The estimate of ln-variance could be obtained in several different ways. The first and preferred option was to use the modeled variance as described above. A second option was to use an estimate of variance calculated from the available sample of ln-transformed data. A third option, also based on available data, was an estimate calculated from averaged emissions data and the mean and variance of ln-transformed emissions data. This process involves reversing Equation 30 to solve for s_l^2. If the mean of emissions data is x_a and mean of ln-transformed data is x_l, then the logarithmic variance can be estimated as

$$s_l^2 = 2\ln\left(\frac{\bar{x}_a}{e^{x_l}}\right) \quad \textbf{Equation 31}$$

In practice one of these options was selected based on which most successfully provided model estimates that matched corresponding means calculated from the data sample.

The uncertainties mentioned above represent uncertainties in $\ln E_h$. Corresponding standard errors for the reverse-transformed emission rate E_h were estimated numerically by means of a Monte-Carlo process. At the outset, we generated a pseudo-random set of 100 variates of $\ln E_h$, based on a normal distribution with a mean of 0.0 and variance equal to $s_{\ln E}^2$. We applied Equation 30 to reverse-transform each variate, and then calculated the variance of the reverse-transformed variates. This result represented the variance-of-the-mean for E_h ($s_{E_h}^2$), as in Equation 9. Finally, we calculated the CV-of-the-mean (CV_{Eh}) for each modeled emission rate, as in Equation 10.

1.3.3.4.3 Table Construction

After compilation of the modeling results, the subset of results obtained directly from the data (Equation 6 to Equation 10), shaded area in Figure 6) and the complete set generated through modeling (Equation 13 to Equation 31) were merged.   A final value was selected for use in the model data table. The value generated from data was retained if two criteria were met: (1) a subsample of three or more individual vehicles must be represented in a given cell ($n_h \geq 3$), and (2) the CV_{Eh} (relative standard error, RSE) of the data-driven E_h must be less than 50% (CV_{E_h} < 0.50). Failing these criteria, the model-generated value was substituted. For purposes of illustration, results of both methods are presented separately.

At this point, we mapped the analytic model-year groups onto the set of model-year groups used in the MOVES database. The groups used in the database are designed to mesh with heavy-duty standards and technologies, as well as those for light-duty vehicles. To achieve the mapping, we replicated records as necessary, in cases where the analytic group was broader than the database group. Both sets of groups are shown in Table 14.

Table 14. Mapping "Analytic" Model-year Groups onto MOVES database Model-year groups

"Analytic"		"MOVES database"	modelYearGroupID	shortModYrGroupID
Cars	*Trucks*			
1981-82	1981-82	1980 and previous	19601980	1
1981-82	1981-82	1981-82	19811982	61
1983-85	1983-85	1983-84	19831984	62
1983-85	1983-85	1985	1985	85
1986-89	1986-89	1986-87	19861987	63
1986-89	1986-89	1988-89	19881989	64
1990-93	1990-93	1990	1990	90
1990-93	1990-93	1991-1993	19911993	65
1994-95	1994-95	1994	1994	94
1994-95	1994-95	1995	1995	95
1996-98	1996	1996	1996	96
1996-98	1997-98	1997	1997	97
1996-98	1997-98	1998	1998	98
1996-98	1997-98	1999	1999	99
1996-98	1997-98	2000	2000	20

1.3.3.5 Verification and Adjustment for High-Power Operating modes

The rates described were derived from data measured on IM240 or IM147 cycles, which are limited in terms of the ranges of speed and vehicle-specific power that they cover. Specifically, these cycles range up to about 50 mph and 24 kW/metric ton for speed and VSP, respectively. Some coverage does exist outside these limits but can be sporadic and highly variable. The operating modes outside the I/M window include modes 28,29,30, 38, 39 and 40, which we'll refer to as the 'high-power' operating modes. For these modes, the statistical models described above were used to extrapolate up to about 34 kW/metric ton.

Based on initial review and comment on this aspect of the analysis, we thought it advisable to give additional scrutiny to the high power extrapolation. To obtain a framework for reference, we examined a set independently measured data, collected on drive cycles more aggressive than the IM cycles, namely, the US06 and the "Modal Emissions Cycle" or "MEC." Much of the data was collected in the course of the National Cooperative Highway Research Program (NCHRP)[24] and the remainder on selected EPA programs, all stored in OTAQ's Mobile-Source Observation Database (MSOD). Unlike the US06, which was designed specifically to capture speed and acceleration not captured by the FTP, the MEC is an "engineered" cycle, designed not to specific driving patterns, as does the FTP, but rather to exercise vehicles through the ranges of speed, acceleration and power comprising the performance of most light-duty vehicles. Several variants of the MEC were developed to provide a database to inform the development of the

Comprehensive Modal Emissions Model (CMEM)[24]. Driving traces for the US06 and MEC cycles are shown in Figure 7 and Figure 8. Both cycles range in speed up to over 70 mph and in VSP up to and exceeding 30 kW/metric ton.

Figure 7. Example Speed Traces for the US06 and MEC Drive Cycles.

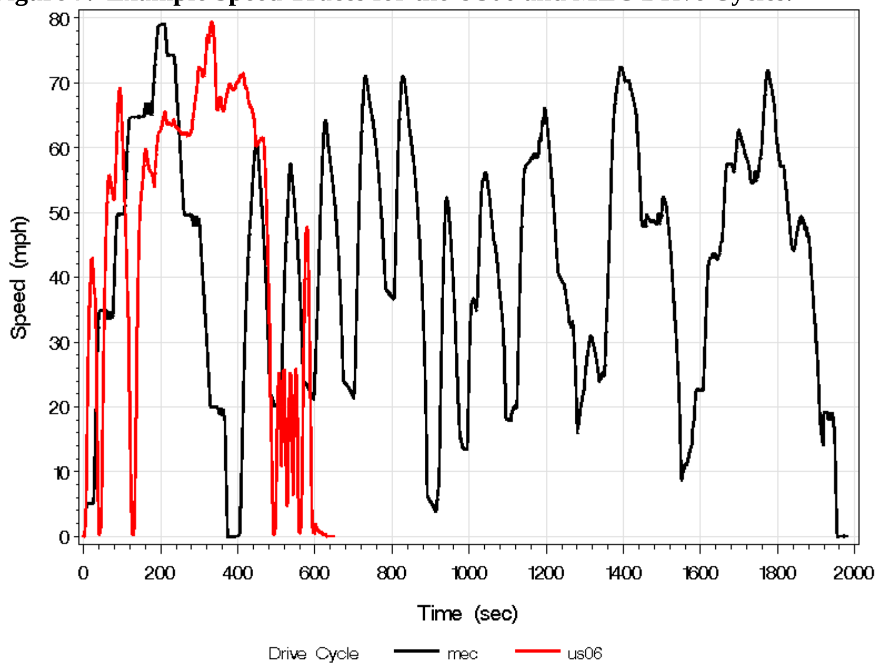


Figure 8. Example vehicle-specific power (VSP) traces for the US06 and MEC cycles.

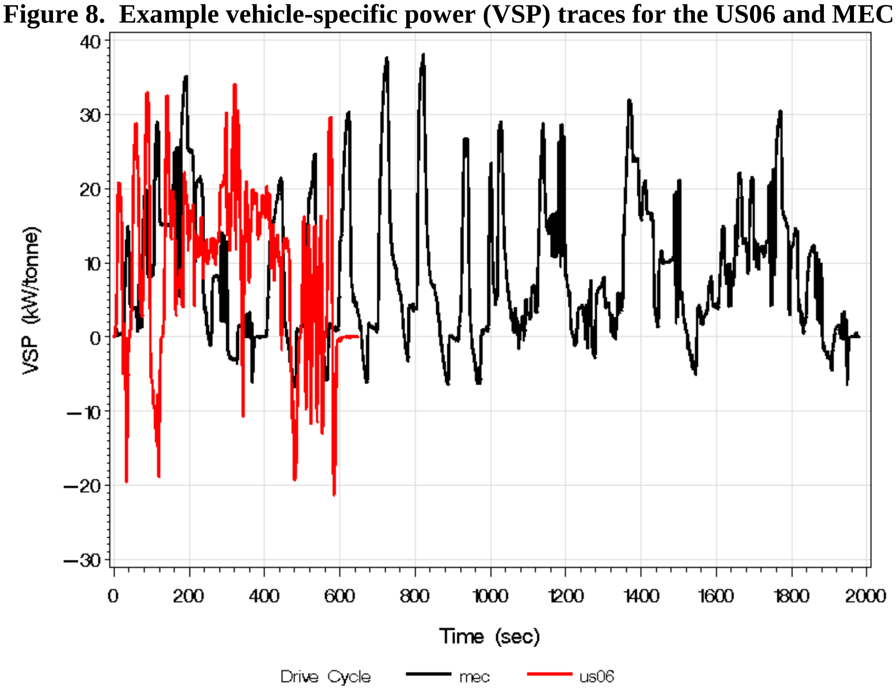


Table 15 summarizes the numbers of available tests by regulatory class, model-year group and drive cycle, with numbers of tests differing in each model-year group. Samples were somewhat larger for cars for both cycles, which represented a broad range of model-years.

Table 15. Sample sizes for US06 and MEC Samples (No. tests)

Model-year group	Car		Truck		Total
	US06	***MEC***	***US06***	***MEC***	
1980 & earlier	4	14		6	**24**
1981-85	15	23	8	19	**65**
1986-89	21	24	13	31	**89**
1990-93	54	57	22	36	**169**
1994-95	49	45	22	30	**146**
1996-99	58	28	56	17	**159**
Total	**201**	**191**	**121**	**139**	**652**

Figure 9, Figure 10 and Figure 11 show trends in emissions vs. VSP for CO, HC and NOx for LDV and LDT by model year group. Both cycles were averaged and plotted as aggregates.

Figure 9. CO emissions (g/sec) on aggressive cycles , vs. VSP, by regulatory class and model-year group.

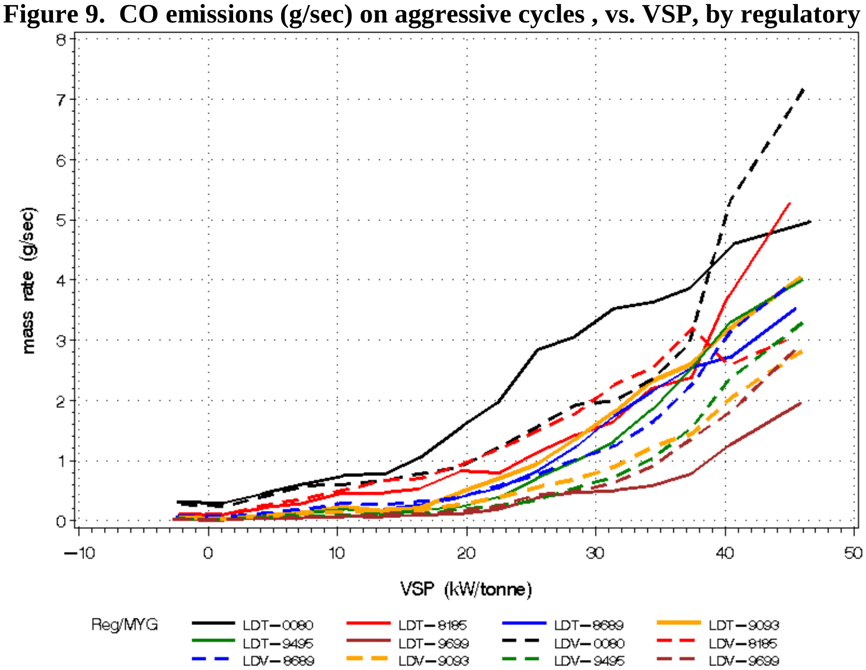


Figure 10. THC emissions (g/sec) on aggressive cycles , vs. VSP, by regulatory class and model-year group.

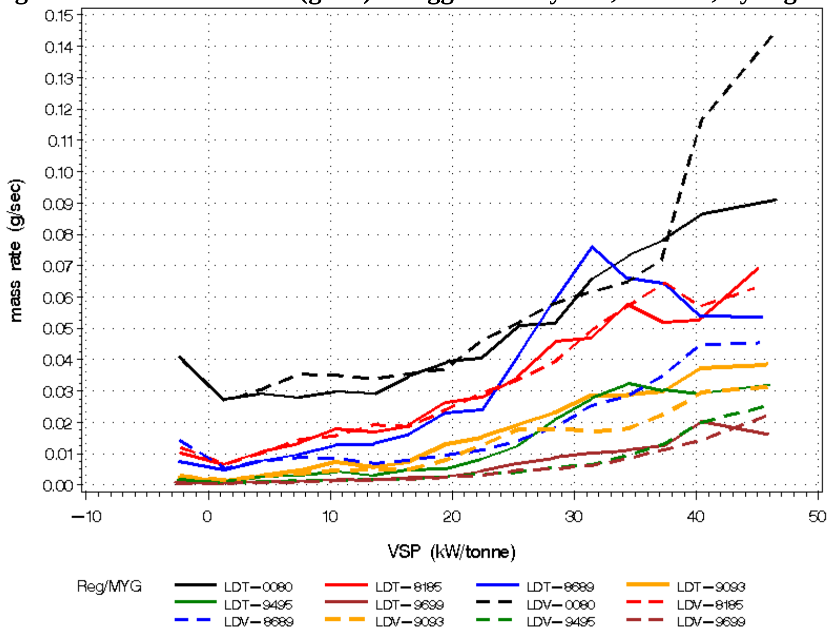
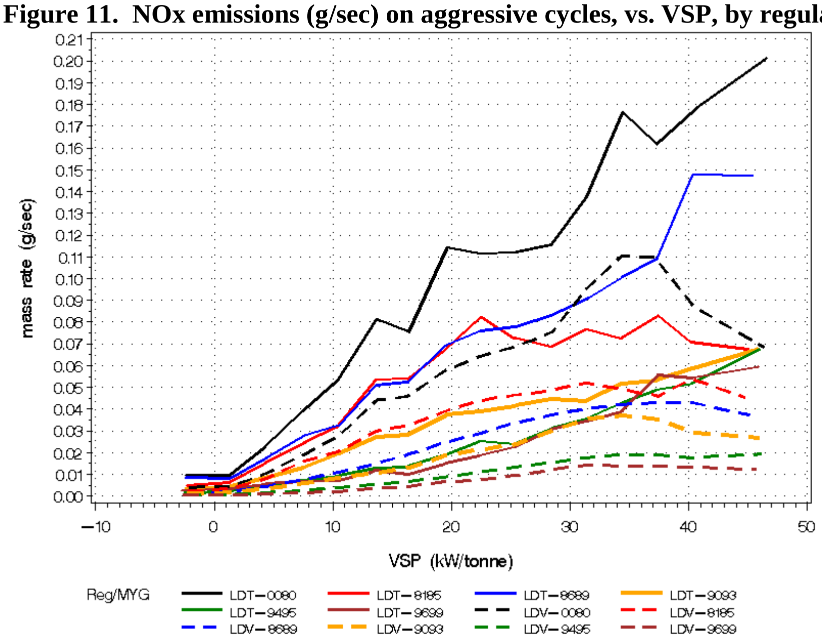


Figure 11. NOx emissions (g/sec) on aggressive cycles, vs. VSP, by regulatory class and model-year group.



To construct a basis for reference, we averaged the data by regulatory class, model-year group and operating mode, using the model-year groups shown in Table 15. After averaging, we calculated ratios from high-power operating modes to a selected reference mode. Specifically, we selected two modes covered by the IM cycles (27 and 37) to serve as reference points. The midpoint VSP for each is ~15 kW/metric ton. With mode 27 as a reference, we calculated ratios to modes 28, 29 and 30.

$$R_{i:27} = \frac{E_{h,i}}{E_{h,27}},\ \text{for } i = 28, 29, 30 \qquad \textbf{Equation 32}$$

and with mode 37 as a reference, we calculated ratios to modes 38, 39 and 40.

$$R_{i:37} = \frac{E_{h,i}}{E_{h,37}},\ \text{for } i = 38, 39, 40 \qquad \textbf{Equation 33}$$

After calculating the ratios, we calculated ratio-based emissions estimates (E^R) as the products of their respective ratios and the initial rate for modes 27 or 37

$$E^R_{h,i} = R_{i:27} E^{initial}_{h,27},\ \text{or}\ \ E^R_{h,i} = R_{i:37} E^{initial}_{h,37} \qquad \textbf{Equation 34}$$

respectively, where $E_h^{initial}$ is the initial data-driven or model-generated rate calculated as previously described.

The next step, the process by which ratio-based rates were selected as rates for particular operating modes on a case-by-case basis has changed substantially for the final rates. In the draft, we calculated upper and lower confidence limits for E^R and replaced the initial rate with E^R if it fell outside the confidence band, i.e., if the initial rate was greater than the upper bound or lower than the lower bound. Evaluation of the results of this approach showed, however, that it gave spurious results in many cases. We found it impossible to assign a confidence level for the band that would work in all cases, i.e., sufficiently sensitive to identify and correct problem cases, but not so sensitive so as to make unnecessary modifications.

For the final rates, we developed a different logic for applying the ratio-based rates. One change from the draft is that ratio-based rates were considered only for modes 29,30, 39 and 40, i.e., modes spanning the range of VSP beyond the IM147. Modes 28 and 38 are partially covered by the I/M cycles, and the differences among the data, model and ratios were generally much smaller than for the four highest modes. The steps in the revised process are:

1) Identify acceptable candidate values (data, model or ratio). The data values were considered acceptable if (1) a value was present, (2) it met the acceptability criteria (described above on page 33) and (3) it was greater than the value in the next lowest mode. Similarly, predicted values were acceptable if they exceeded the value for the preceding operating mode.

Following these evaluations, the final value was selected as the minimum of the acceptable candidates. These criteria were applied sequentially to prevent declining VSP trends with increasing power. As a first step, values were selected for operating modes 29 and 39, relative to modes 28 and 38. In a successive step, values were selected for 30 and 40, relative to those selected for 29 and 39, respectively. We present some examples below, showing differences between the draft and final rates.

In the THC example (Figure 12), the final values are substantially reduced, particularly for modes 29 and 30. In the draft (a), the initial rates fall outside the confidence intervals for the ratio-based rates for three out of six possible cases, i.e., in modes 30, 39 and 40. The resulting rate is higher for modes 30 and 40, but lower for 39. In the final rates, the results vary. For modes 29 and 30, the data values meet the criterion of the minimum value giving an increasing trend from mode 28 – 30. However, for modes 39 and 40, the ratio and the model give the values meeting the criterion, as shown in (c).

The example for CO shows different behavior in the draft, but a similar outcome in the final (Figure 13). In the draft (a), the initial values for modes 28-30 all fall within the confidence intervals for the ratio-based value and are thus retained. The values for 39 and 40, fall outside the band on the low side and are replaced by the ratio-based rates. For operating modes 29 and 30, the data is selected as the minimum option available, as with HC. For modes 39 and 40, the model is similarly selected. In the final rates, the ratio based values are not adopted for this example, as they had been in the draft, and the net result is a decrease in CO rates in the affected operating modes.

Finally, in the NOx example (Figure 14), the initial rates are replaced in five out of six cases in the draft (a). The initial values for 28-30 and 40 all fall below the lower confidence limit, whereas that for 30 falls above the upper confidence limit. In the final, the ratio is used more sparingly, as in the HC and CO examples. Model values are used in two cases (modes 30 and 40) and the ratio in one case (mode 39).

These examples highlight the uncertainty of projecting emissions at high power and of projecting beyond the range of the IM147. Uncertainties are much smaller for opModes 28 and 38 than for 29,30 , 39 and 40. This pattern may be due to the fact that, for modes 28 and 38, the power range for the IM147 overlaps somewhat the range of the aggressive cycles. For this reason, the degree of extrapolation is lower and the power trends are similar.

Figure 12. THC emission rates (g/hr), vs. VSP for MY 1998 cars at ages 4-5 years: (a) options for draft rates, (b) Options for final model (data, model and ratio) and (c) options selected for final rates.

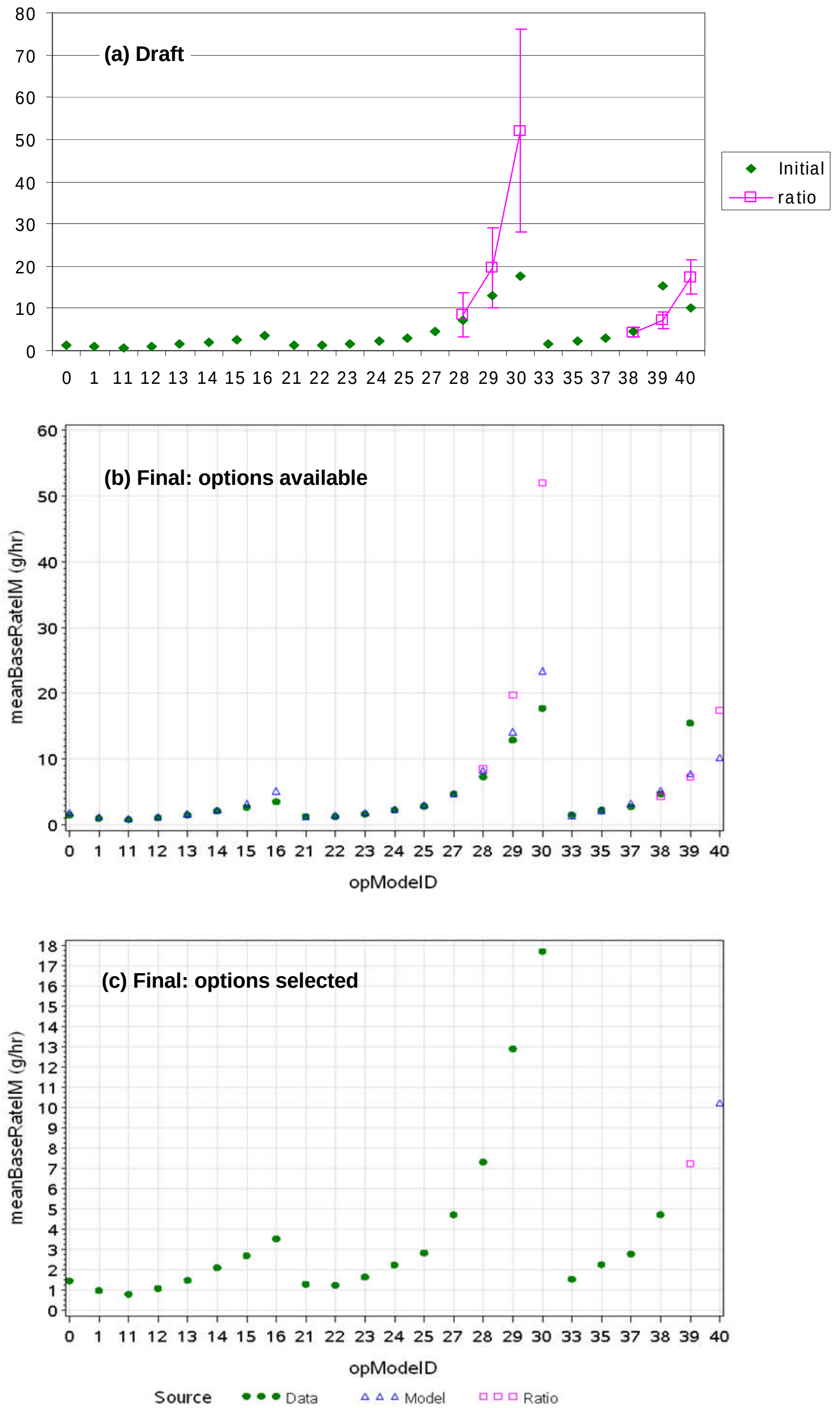
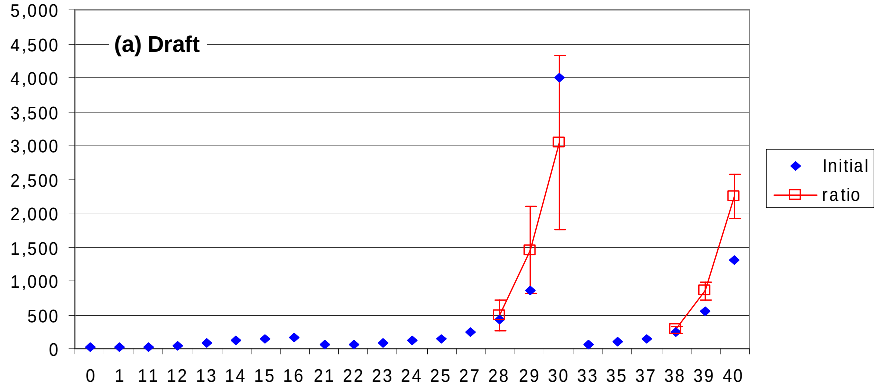
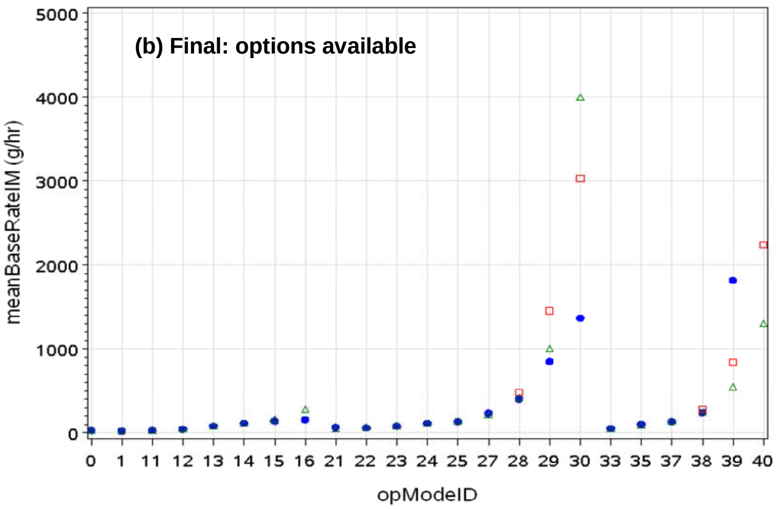


Figure 13. CO emission rates (g/hr), vs. operating mode for MY-1998 trucks at ages 6-7: (a) options for draft rates , (b) Options for final model (data, model and ratio and (c) options selected for final rates.





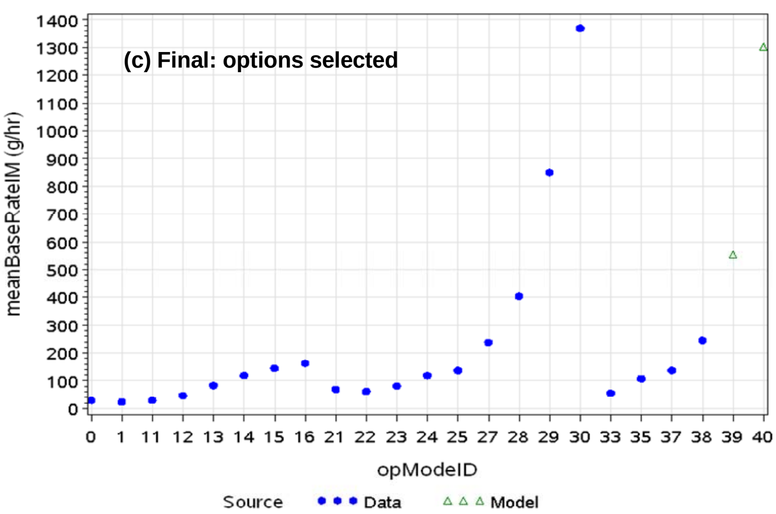
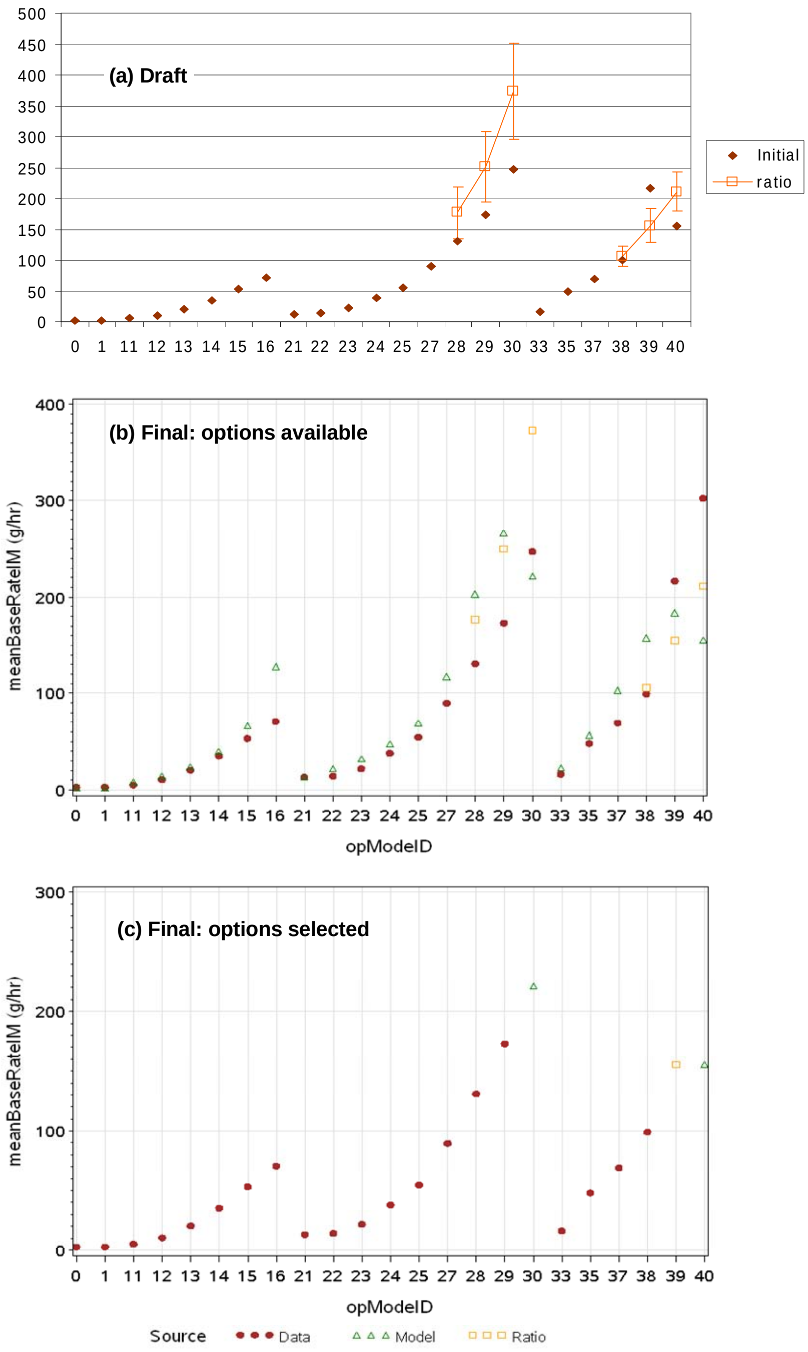


Figure 14. NOx emission rates (g/hr) vs. operating mode for MY-1995 Cars at ages 8-9: (a) options for draft rates , (b) Options for final model (data, model and ratio and (c) options selected for final rates.



1.3.3.6 Estimating Rates for non-I/M Areas

In modeling emission inventory for light-duty vehicles, it is necessary at the outset to consider the question of the influence of inspection-and-maintenance (I/M) programs. In this regard a fundamental difference between MOVES and MOBILE is that MOVES inverts MOBILE's approach to representing I/M. In MOBILE, the emission rates stored in the input data tables represent non-I/M conditions. During a model run, as required, emissions for I/M conditions are modeled relative to the original non-I/M rates.

In MOVES, however, two sets of rates are stored in the input table (emissionRateByAge). One set represents emissions under "I/M conditions" (meanBaseRateIM) and the other represents rates under "non-I/M conditions" (meanBaseRate). The first set, representing vehicles subject to I/M requirements, we call the "I/M reference rates". The second, representing vehicles not subject to I/M requirements, we call the "non-I/M reference rates."

For the I/M reference rates, the term "reference" is used because the rates represent a particular program, with a specific design characteristics, against which other programs with differing characteristics can be modeled. Thus, the I/M references are, strictly speaking, regional rates, and not intended to be (necessarily) nationally representative. Development of the I/M reference rates is discussed above in sections 1.3.3.2 and 1.3.3.3. As the I/M references represent Phoenix, the program characteristics implicitly reflected in them include:

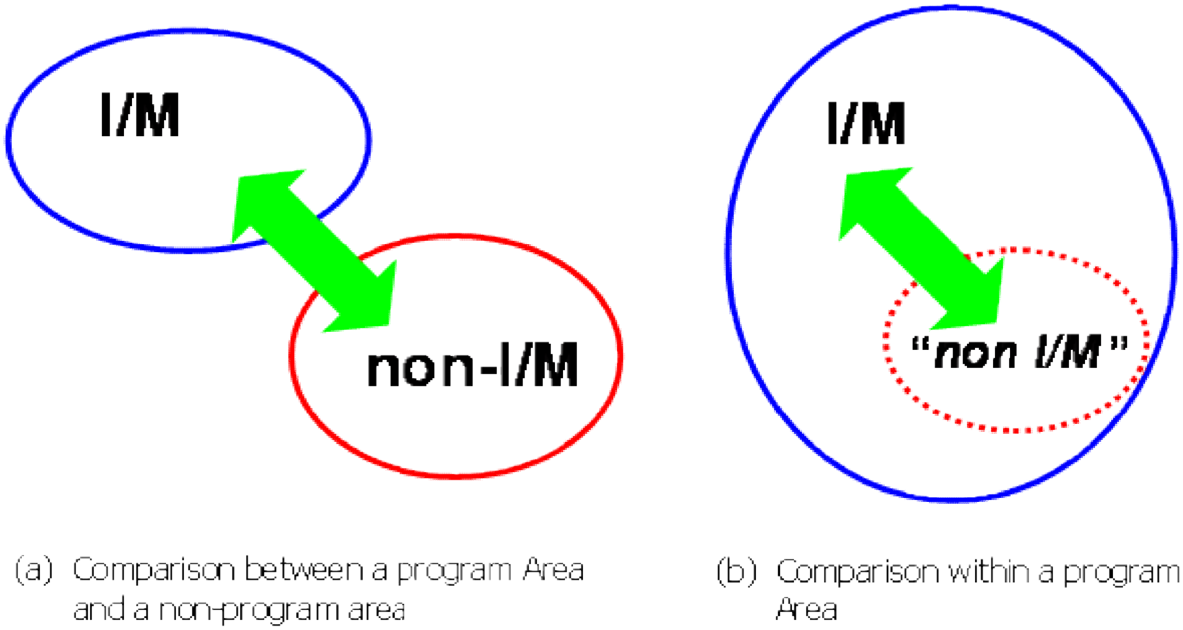
- A four-year exemption period,
- transient tailpipe tests for MY 81-95,
- OBD-II for MY 96+,
- Biennial test frequency.

In addition, the Phoenix program provides a relatively stable basis against which to represent other program designs and for application of fuel adjustments.

Our approach is to derive the non-I/M rates relative to the I/M references, by adjustment. One reason for adopting this approach is that, as mentioned, the volumes of data available in I/M areas vastly exceed those collected in non-I/M areas. An additional practical reason is that major work-intensive steps such as "hole-filling" and projection of deterioration need only be performed once.

In contrast to the I/M references, the non-I/M reference rates are designed to be nationally representative. Broadly speaking, they are intended to represent all areas in the country without I/M programs. In general, estimating the influence of I/M areas on mean emissions is not trivial, and efforts to do so commonly follow one of two broad approaches. One approach is to compare emissions for two geographic areas, one with and one without I/M Figure 15(a). A second and less common approach is to compare emissions between two groups of vehicles within the same I/M area, but with one group representing the main fleet ostensibly influenced by the program, and the second, far smaller, representing vehicles measured within the program but presumably not yet influenced by the program Figure 15(b).

Figure 15. General approaches to estimating differences attributable to I/M programs: (a) comparison of subsets of vehicles between two geographic areas, with and without I/M, and (b) comparison within a program area.



For convenience, we refer to the first approach as the "between-area" approach, and the second as the "within-area" approach. Neither approach attempts to measure the incremental difference attributable to a program from one cycle to the next.

The approach we adopted emphasizes the "within-area" approach, based on a sample of vehicles "migrating" into Phoenix. To lay the basis for comparison, the primary goal was to identify a set of vehicles that had been measured by the program after moving into the Phoenix area, but that had not yet been influenced by the program. The specific criteria to identify particular migrating vehicles are presented in Table 16.

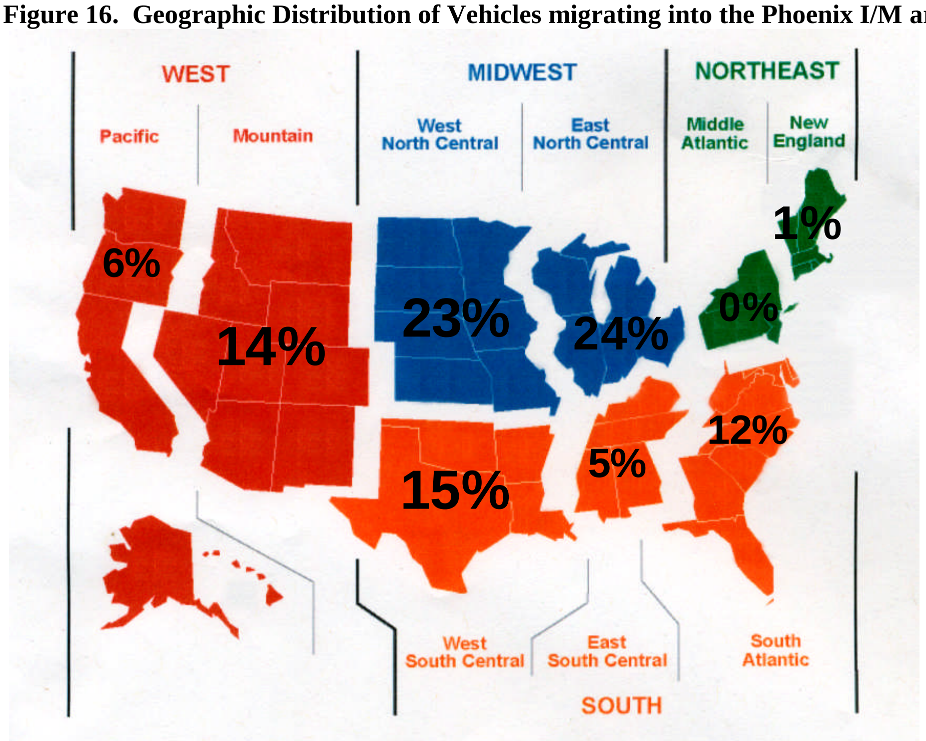
Table 16. Criteria used to identify vehicles migrating into the Phoenix Program.

logic	**Criterion**
	The vehicle comes from from out-of-state
OR	From a non-I/M county in AZ
AND NOT	From other I/M areas
AND	Receiving very first test in Phoenix program
AND	Selected for random evaluation sample

After applying these criteria, we identified a sample of approximately 1,400 vehicles. The origin of vehicles entering the Phoenix Area was traced by following registration histories of a set of approximately 10,000 candidate vehicles. The last registered location of vehicles was identified prior to registration in Phoenix or the vehicle's first test in the Phoenix program. Vehicles were excluded if their most recent registration location was in a state or city with an I/M program[25].

Figure 14 shows the distribution of incoming vehicles, by Census Region. Most vehicles migrating to Phoenix came from the Midwest (47%), followed by the South (32%), the West (20%) and the Northeast (1%). The low incidence from the NE may be attributable to the large number of I/M programs in that region.

Figure 16. Geographic Distribution of Vehicles migrating into the Phoenix I/M area, 1995-2005.



To assess the differences between migrating (non-I/M) and "local" (I/M) vehicles, we adopted a simple approach. We calculated ratios between means for the migrating and local groups, as shown in Equation 35. We used aggregate tests, after preliminary analyses suggested that the ratios did not vary significantly by VSP. Because the sample was not large in relation to the degree of variability involved, we also aggregated tests for cars and trucks in all model years. However, we did calculate ratios separately for three broad age groups (0-4, 5-9, and 10+) years.

$$\text{Ratio} = \frac{\overline{E}_{\text{non-I/M}}}{\overline{E}_{\text{I/M}}} \qquad \textbf{Equation 35}$$

For purposes of verification, we compared our results to previous work. An initial and obvious comparison was to previous work based on an out-of-state fleet migrating into Phoenix that provided a model for our own analysis[7]. This previous effort identified a migrating fleet, and analyzed differences between it and the program fleet for vehicles in model years 1984 – 1994 measured during calendar years 1995-2001. To adapt the previous results for our purposes, we translated averages for migrating and program fleets into ratios as in Equation 35.

Another valuable source for comparison was remote-sensing data collected in the course of the Continuous Atlanta Fleet Evaluation (CAFE) Program[26,27]. Unlike our own analysis, this program involves a comparison between two geographic areas. The "I/M area" is the thirteen-county Atlanta area, represented by measurements for approximately 129,000 vehicles. The other (the non-I/M area) is the twelve-county non-I/M area, surrounding Atlanta, represented by measurements for approximately 28,000 vehicles. Both areas have been under a low-sulfur fuel requirement since 1999. Results used for this analysis were collected during CY 2004. The non-I/M : I/M ratios calculated from the RSD are based on concentrations, rather than mass rates.

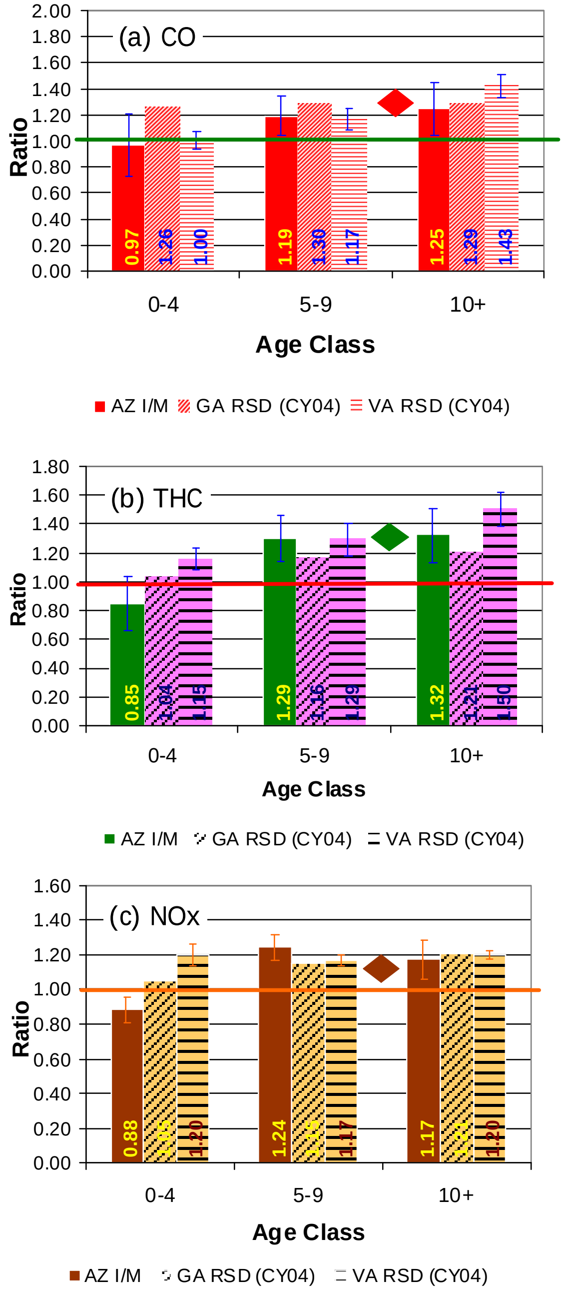
A third source was an additional remote-sensing dataset collected in N. Virginia/D.C. area. The I/M area was the "northern-Virginia" counties, and the non-I/M area was Richmond. The I/M and non-I/M areas were represented by about 94,000 and 61,000 vehicles, respectively, collected in CY 2004. In this case, the molar ratios were converted to mass rates, with use of fuel-consumption estimates derived from energy-consumption rates in MOVES2004. After this step, non-I/M : I/M ratios were calculated using the mass rates.

Results are shown in Figure 17. The charts show mean ratios for the three age groups for our migrating vehicle analysis, as well as the remote-sensing studies. The diamonds represent approximate values from Wenzel's earlier work with the Phoenix data. For our analyses (solid bars) the ratios are generally lower for the 0-4 year age Group, and larger for the 5-9 and 10+ age groups, but differences between the two older groups are small. The Atlanta results show a similar pattern for HC and NOx, but not for CO, for which the ratios are very similar for all three age groups. The Virginia results are the other hand, show increasing trends for CO and HC, but not for NOx. The ratios in Atlanta are slightly higher than those for Phoenix in the 0-4 year age group. This difference may be attributable to the shorter exemption period in Atlanta (2 years) vs. the four-year period in Phoenix, but it is not clear that these differences are statistically significant. In all three programs, ratios for the two older age classes generally appear to be statistically significant.

In interpreting the ratios derived from the Phoenix data, it is important to note that they assume full program compliance. In the migrating vehicle analysis this is the case because all emissions measurements were collected in I/M lanes. Thus, vehicle owners who evaded the program in one way or another would not be represented. On the whole, results from multiple datasets, using different methods, showed broad agreement.

If we calculate non-IM reference rates from the I/M references by ratio, with the ratios constant by model-year group and VSP, it follows that the absolute differences must increase with power. Similarly, absolute differences increase with age, for two reasons. The first reason is the same as that for VSP, that for a constant ratio, the absolute difference increases as emissions themselves increase, and on top of this, the second reason is that the ratios themselves increase with age (Figure 15). A third implication is the absolute differences would be smaller for successive model-year groups as tailpipe emissions decline with more stringent standards.

Figure 17. Non-I/M : I/M ratios for CO, HC and NOx for the Phoenix Area (this analysis) compared to remote-sensing results for Atlanta and N. Virginia, and previous work in Phoenix (diamonds).



A final practical step is to translate these results into terms corresponding to the MOVES age groups. As mentioned, the program in Phoenix has a four-year exemption period for new vehicles. However, it is not uncommon for other programs to have shorter exemptions; for example, both the Atlanta and N. VA programs have two-year exemptions.

An additional factor is that the coarser age groups used for the migrating-vehicle analysis don't mesh cleanly with the MOVES age groups. It was therefore necessary to impute values to the first two MOVES age groups (0-3 and 4-5 years). We achieved this step by linearly interpolating the value for the 5-9 year age Group to a value of 1.0 at 0 years of age, as shown in Figure 18. To anchor the interpolation, we associated the value of the ratio for the 5-9 year age group with the midpoint of the group (7.5 years). Then, based on a straight line interpolation, we imputed values for the 0-3 and 4-5 MOVES age groups, by taking the value on the line associated with the midpoint of each class, 1.5 and 5 years, respectively.

Figure 18. Imputation of Non-I/M Ratios for the 0-3 and 4-5 year MOVES AgeGroups by Linear Interpolation from the Midpoint of the 5-9 year Analysis Age Group.

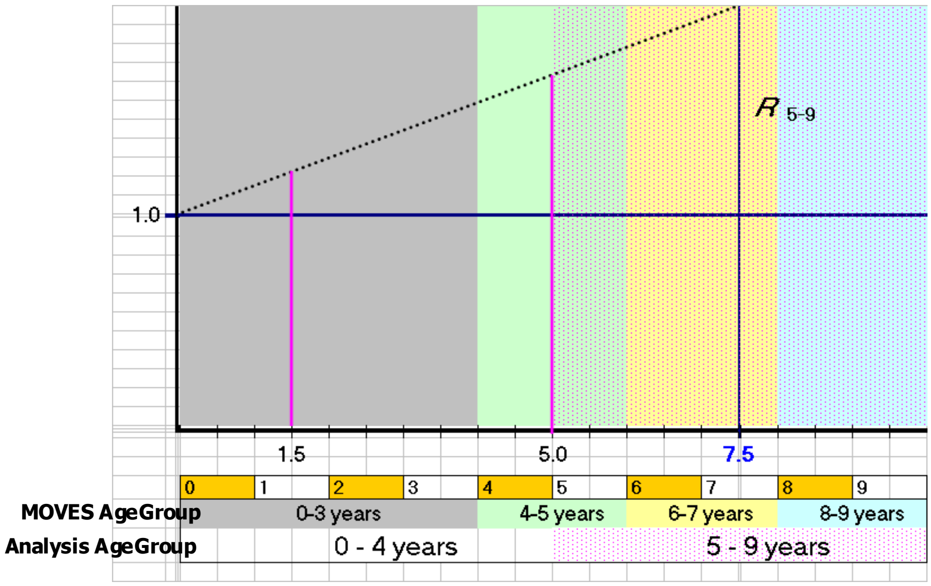
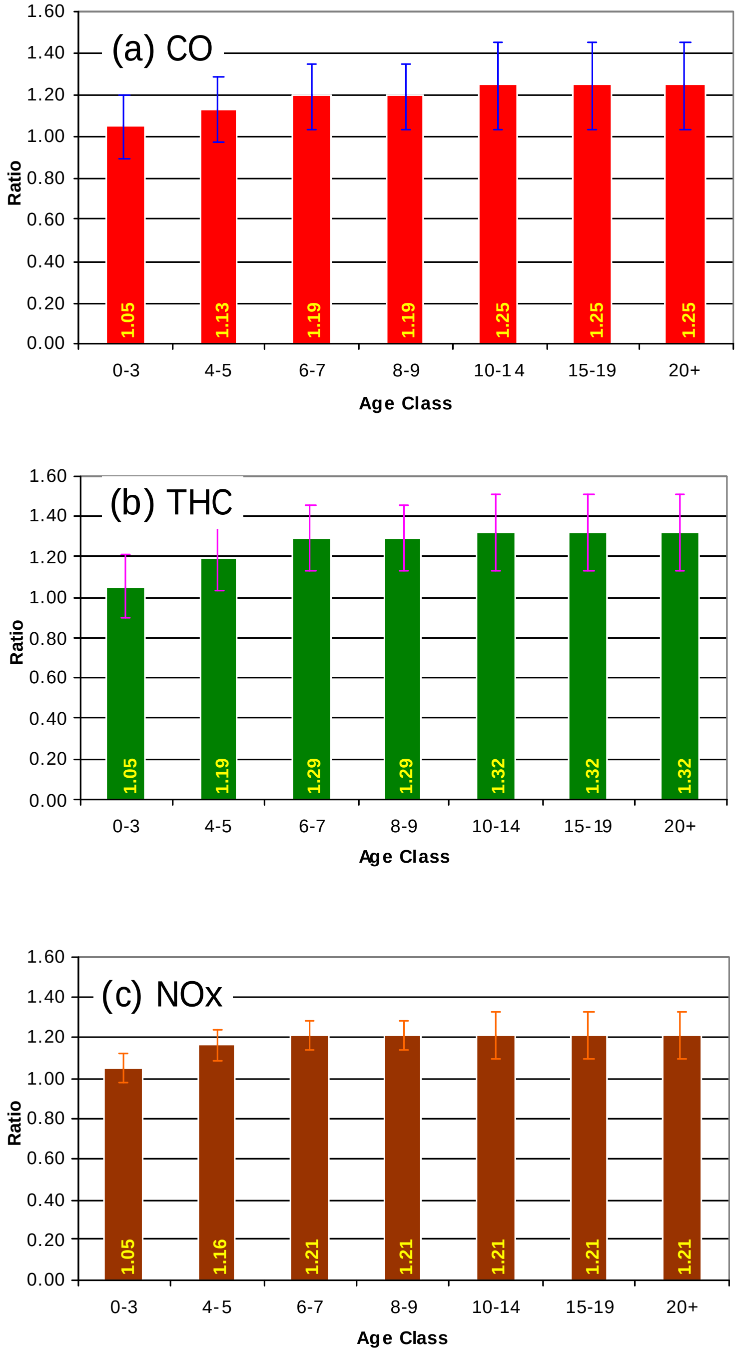


Figure 19 shows final values of the non-I/M ratios for CO, THC and NOx, with error-bars representing 95% confidence intervals. The values for each pollutant start at 5.0% and increase with age, stabilizing at maximum values at 6 years (for NOx) and 10 years (for HC and CO).

Figure 19. Final non-I/M ratios for CO, HC and NOx, by MOVES AgeGroups, with 95% confidence intervals.



The ratios shown in Figure 17 are applied to the I/M reference rates to derive non-I/M reference rates.

$$E_{h,\text{non-I/M}} = \text{Ratio} * E_{h,\text{I/M}} \qquad \textbf{Equation 36}$$

The uncertainty in $E_{h,\text{non-I/M}}$ was calculated by propagating the uncertainty in the Ratio with that of the corresponding I/M rate $E_{h\text{I/M}}$.

$$\begin{aligned} s^2_{E_{h,\text{non-I/M}}} &= \left(\frac{\partial E_{h,\text{non-I/M}}}{\partial R}\right)^2 s_R^2 + \left(\frac{\partial E_{h,\text{non-I/M}}}{\partial E_{h,\text{I/M}}}\right)^2 s^2_{E_{h,\text{I/M}}} \\ s^2_{E_{h,\text{non-I/M}}} &= E^2_{h,\text{I/M}} s_R^2 + R^2 s^2_{E_{h,\text{I/M}}} \end{aligned} \qquad \textbf{Equation 37}$$

Thus, for any given cell *h*, the uncertainty in the non-I/M reference rate is larger than that for the corresponding I/M reference rate, which is reasonable and appropriate given the additional assumptions involved in developing the non-I/M reference rate.

Figure 20 shows an example of the reference rates vs. operating mode, for all three pollutants. Note that not all the modes are shown, to allow examination of differences between non-I/M and I/M rates at lower VSP. Figure 21 shows corresponding trends by age for two operating modes. The first is opmode 11, (speed = 1-25 mph, VSP <0 kW/metric ton) and 27 (speed = 25-50 mph, VSP = 12-18 kW/metric ton). An clear observation from both plots is that the I/M difference is much larger in the more aggressive mode (27) than in the less aggressive one (11), with the inference that I/M differences will be more strongly expressed for more aggressive than less aggressive driving, in absolute (but not relative), terms.

Figure 20. Non-I/M and I/M Reference Rates by Operating Mode (Example: Cars, MY 1994, at 8-9 years of age)

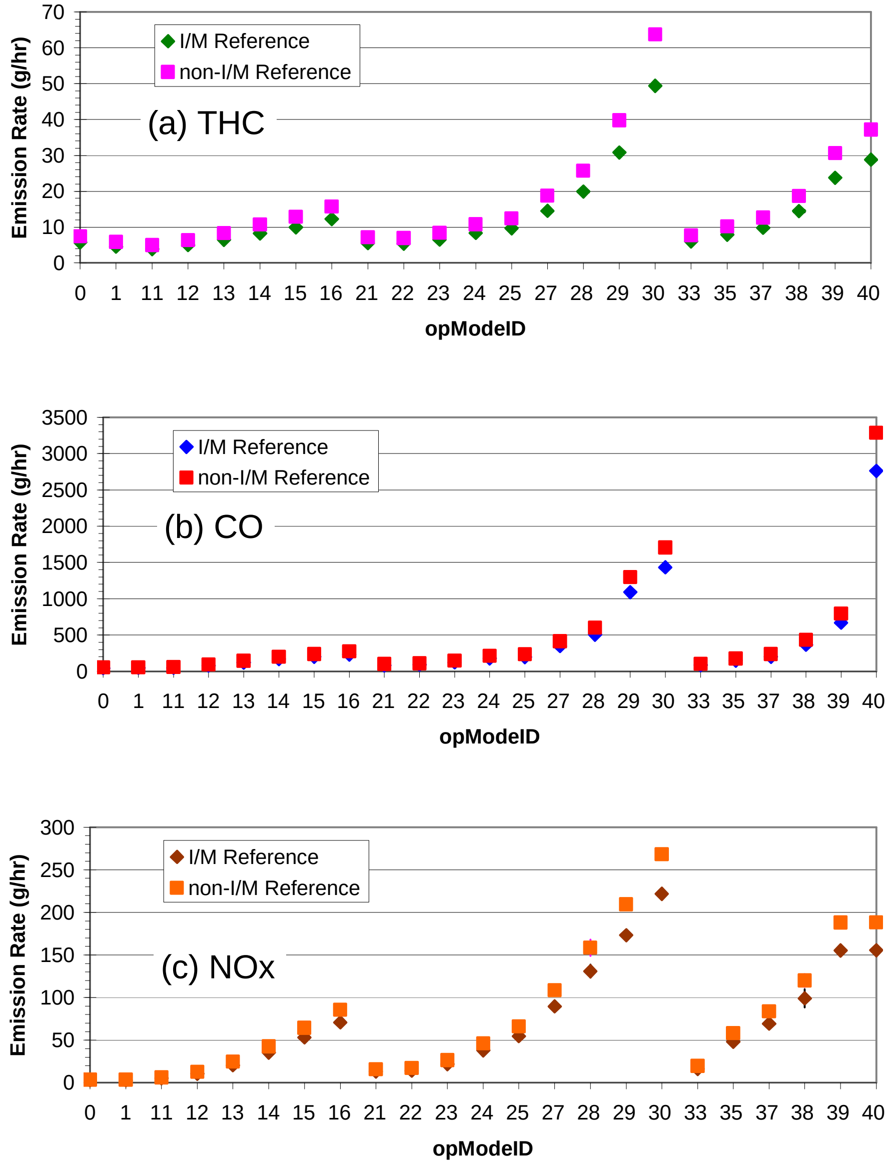
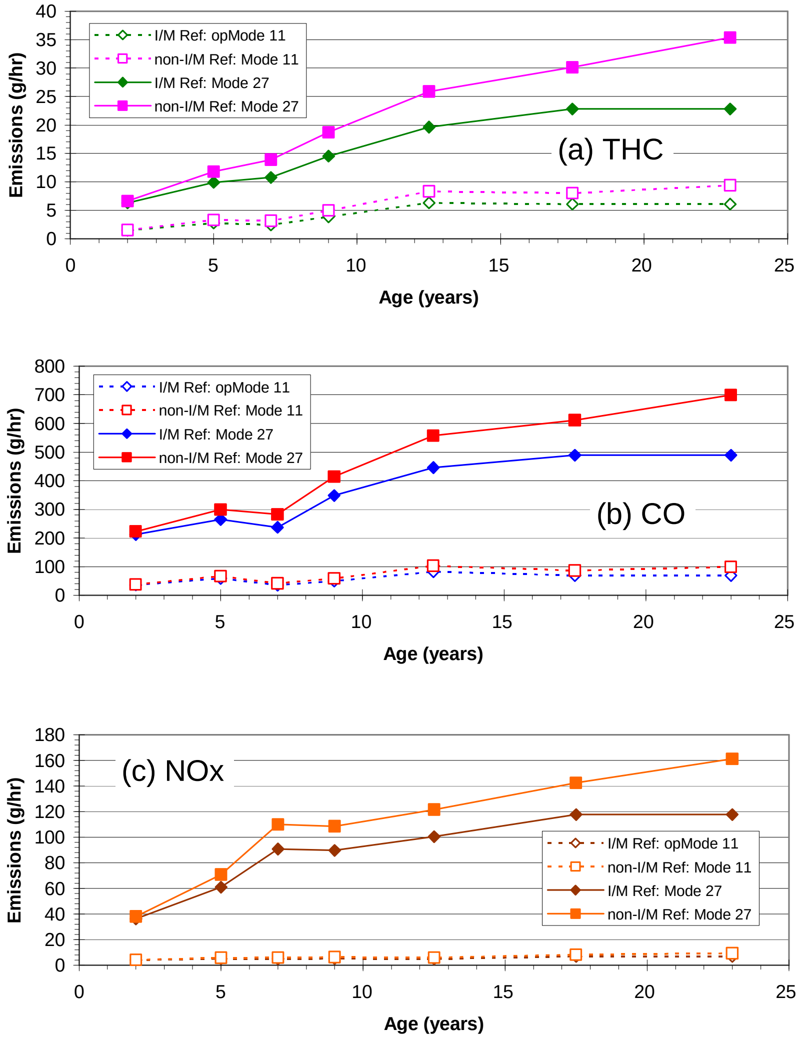


Figure 21. Non-I/M and I/M Reference Rates vs. Age for Two Operating Modes (Example: Cars, MYG 1994).



1.3.3.7 Stabilization of Emissions with Age

One characteristic of the data is that fleet-average emissions do not appear to increase indefinitely with age, but rather tend to stabilize at some point between 12 and 15 years of age. This behavior is visible in datasets with enough historical depth for age trends to be observable, including the Phoenix random sample and long-term remote-sensing studies[12]. Figure 22 and Figure 23 show age trends by model year for cars and trucks, respectively. The values shown are aggregate mass rates over the IM147 expressed as g/sec for CO, THC and NOx. Incorporating stabilization of emissions with age is another departure with the approach used on MOBILE, which allowed emissions to increase indefinitely.

From these figures, as well as Figure 1, it is clear that no data were available at ages older than 10 years of age for model years later than 1995, and that no data was available at ages older than 15 years for model years older than 1990. Thus for model years more recent than about 1995 it was necessary to project emissions for ages greater than 8-10 years.

However, it is not appropriate to simply extrapolate the statistical models past about 8-10 years. As described above, emissions were modeled as ln-linear with respect to age, which implies exponential trends for reverse-transformed values. However, exponential trends will increase indefinitely if extrapolated much beyond the range of available data, which obviously does not describe observed patterns of fleet emissions. To compensate for this limitation, we employed a simple approach to represent the decline and stabilization of the rates.

We calculated ratios of means between the 10-14 and 15-19 year ageGroups, each relative to the 8-9 year age group, using the 1986-89 and 1990-93 model-year groups, which contain data for vehicles as old as 19 years. For this purpose we used Phoenix data averaged by MOVES model-year and age groups, as shown in Figure 24. Data points in the figure represent aggregate tests (g/mi). After averaging by model-year group and ageGroup, we calculated ratios of means for the 10-14 and 15-19 ageGroups.

$$R_{\text{age}} = \frac{\overline{E}_{10-14}}{\overline{E}_{8-9}}, \quad R_{\text{age}} = \frac{\overline{E}_{15-19}}{\overline{E}_{8-9}} \qquad \textbf{Equation 38}$$

We calculated modified rates for the 10-14 and 15-19 year ageGroups as the product of the rate for the 8-9 year ageGroup and the corresponding ratio (R_{age}). Assuming that emissions would be fully stable by 20 years, we set the rate for the 20+ year ageGroup equal to that for the 15-19 year ageGroup. We calculated variances for the ratios as in Equation 37, but did not propagate the uncertainty through to the final result.

Table 17. Ratios used to stabilize emission rates for the 10-14 and 15-19 year ageGroups, calculated relative to the 8-9 year ageGroup.

Regulatory Class	ageGroup	Ratios (R_{age})			Variances (V_R)		
		THC	CO	NOx	THC	CO	NOx
Cars	10-14	1.338	1.226	1.156	0.000000032	0.000160	0.00000009
Cars	15-19	1.571	1.403	1.312	0.00000411	0.00268	0.00000261
Trucks	10-14	1.301	1.220	1.156	0.00000173	0.000758	0.00000138
Trucks	15-19	1.572	1.479	1.312	0.0000518	0.0666	0.0000499

Figure 22. Aggregate IM147 Emissions (g/sec) for Cars, by Model year and Age, for the Phoenix Random Sample.

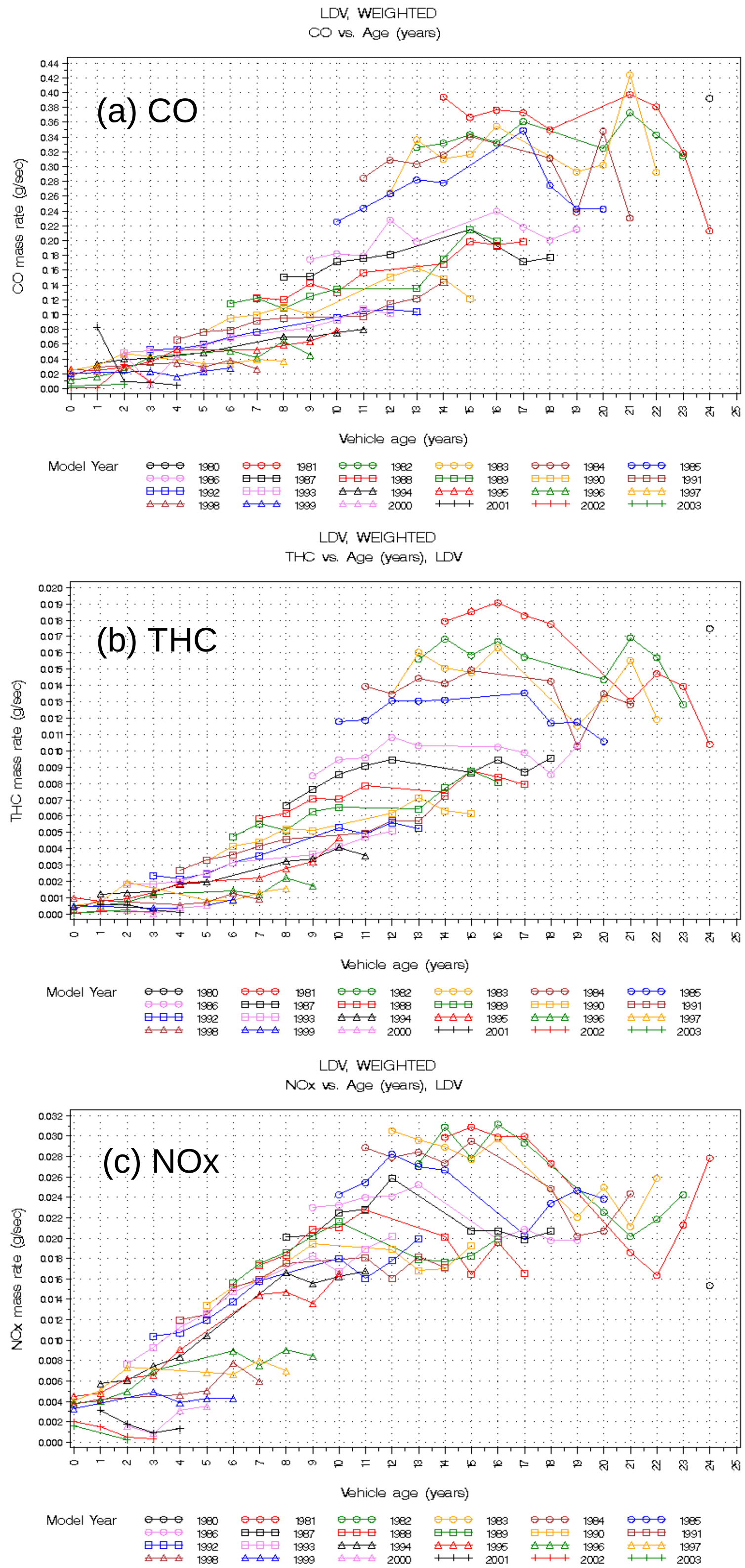


Figure 23. Aggregate IM147 Emissions (g/sec) for trucks, by Model year and Age, for the Phoenix Random Sample.

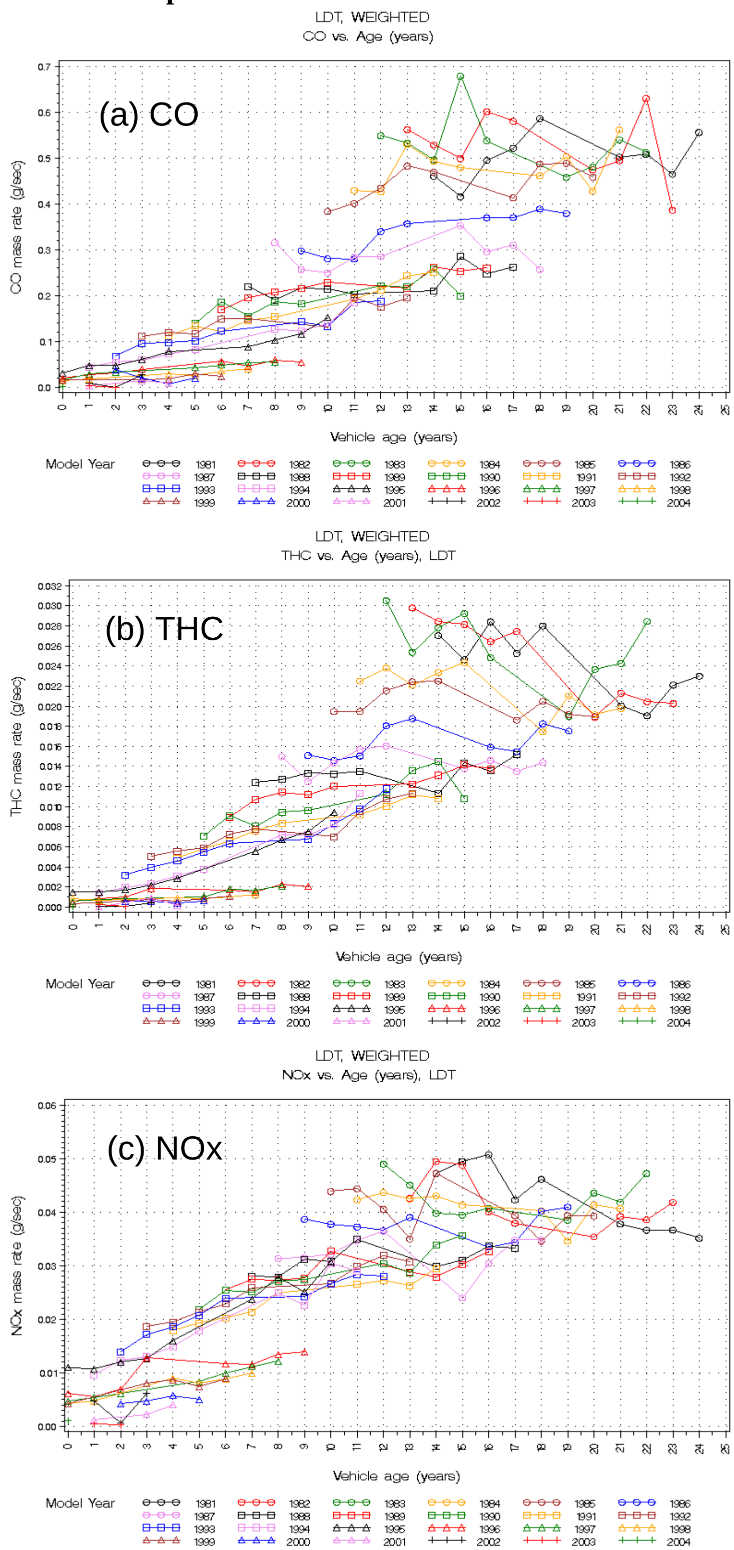
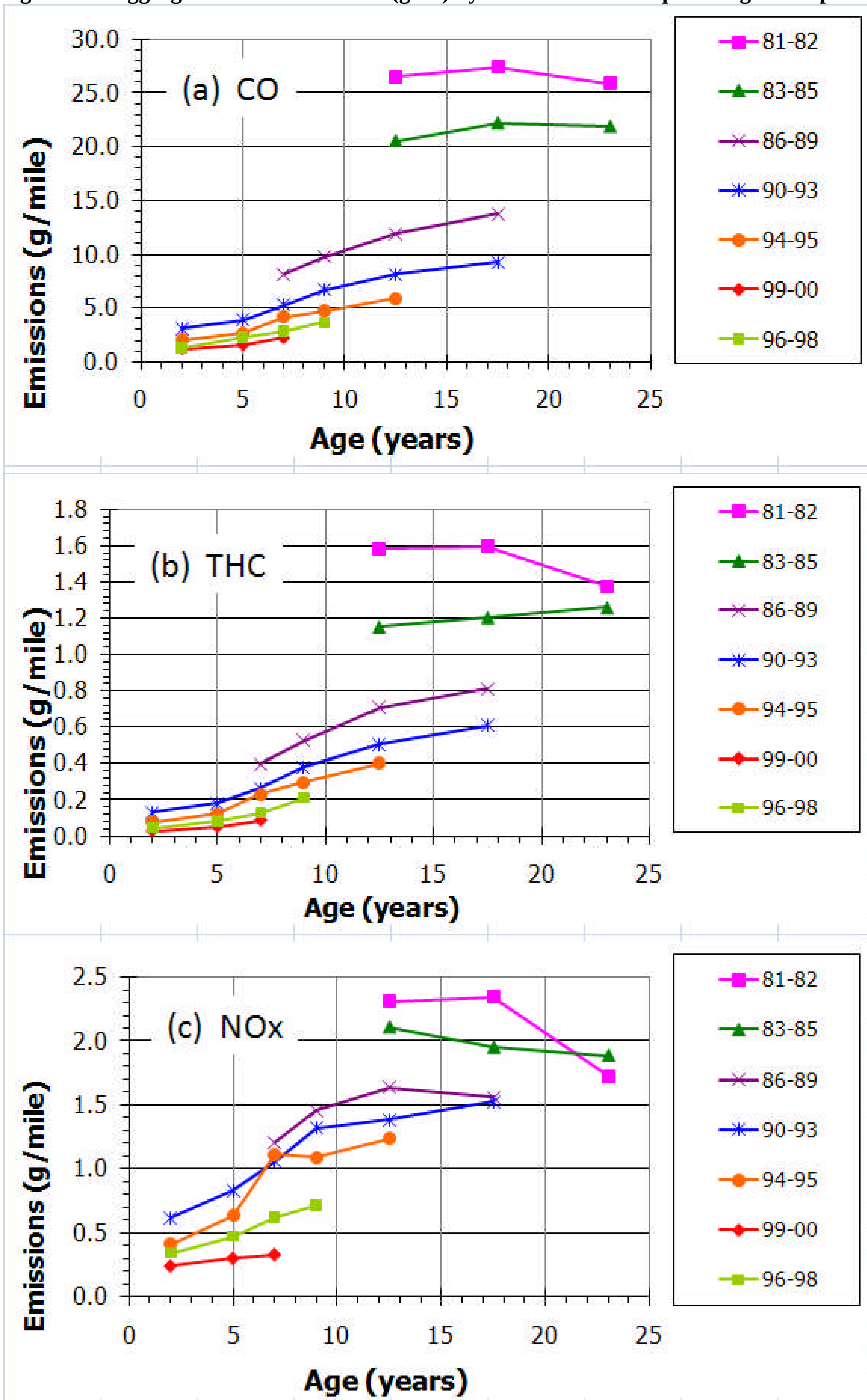


Figure 24. Aggregate IM147 Emissions (g/mi) by Model-Year Group and Age Group.



1.3.3.7.2 non-I/M Reference Rates

The ratios developed in 1.3.3.7.1 are assumed to apply in I/M areas, as the underlying data was collected in the Phoenix I/M area. It is therefore plausible that the patterns observed may be reflective of I/M areas. The program places some pressure on high-emitting vehicles to improve their emissions, leave the fleet, leave the area, or, it could be added, evade requirements in some way. However, in the absence of a program, high-emitting vehicles are not identified and owners have less incentive to repair or replace them. Thus, the question arises as to whether deterioration patterns would necessarily be identical in non-I/M as in I/M areas. Two plausible scenarios can be proposed. In the first, the pattern of deterioration followed by stabilization is similar in non-I/M as in I/M areas, but emissions stabilize at a higher level, and perhaps at a later age. In the second, emissions continue to increase in non-I/M areas, but at a slower rate after 10-15 years.

Data that sheds light on these questions are very limited, as the datasets with sufficient history were collected within I/M areas. Thus, given the absence of information, we adopted an assumption that, absent the existence of a program, emissions would increase after 19 years. We applied this assumption by assuming that the ratio observed between the 10-14 and 15-19 year ageGroups would persist in linear fashion from the 15-19 to the 20+ year ageGroups.

Table 18 shows the deterioration stabilization ratios for both the I/M and non-I/M references rates. As mentioned above, all ratios are applied by multiplication by values for the 8-9 year ageGroup in all operating modes. The ratios for I/M areas ($R_{\text{age,I/M}}$) are identical to those in Table 17. The center column shows the ratio of values of $R_{\text{age,I/M}}$ for the 15-19 to the 10-14 year ageGroups. Ratios for the non-I/M references ($R_{\text{age,non-I/M}}$) are identical to those for I/M in the 10-14 and 15-19 year ageGroups. In the 20+ year ageGroup, the non-I/M ratio is equal to the product of the 15-19 value and the ratio of the 15-19 and the 10-14 values.

Table 18. Deterioration-stabilization ratios as applied to I/M and non-I/M reference rates.

Pollutant	Regulatory Class	ageGroup	$R_{age,I/M}$[1]	Ratio (15-19:10-14)	$R_{age,non\text{-}I/M}$
THC	Cars	10-14	1.338		1.338
		15-19	1.571	1.174	1.571
		20+	1.571		1.845
	Trucks	10-14	1.301		1.301
		15-19	1.572	1.206	1.572
		20+	1.572		1.898
CO	Cars	10-14	1.226		1.226
		15-19	1.403	1.144	1.403
		20+	1.403		1.606
	Trucks	10-14	1.220		1.220
		15-19	1.479	1.213	1.479
		20+	1.479		1.795
NOx	Cars	10-14	1.159		1.159
		15-19	1.312	1.132	1.132
		20+	1.312		1.486
	Trucks	10-14	1.159		1.159
		15-19	1.312	1.132	1.132
		20+	1.312		1.486

[1] Values in this column are identical to those in Table 17.
[2]. Calculated as the ratio of the values in the current and previous rows.
[3] for 10-14 and 15-19 year ageGroups, values in this column identical to the I/M column; for the 20+ year ageGroup, values in this column equal the product of the value in the previous row (15-19) and the value in the center column.

1.3.4 Emission-Rate Development: Subgroup 2 (MY 2001 and later)

1.3.4.1 Data Sources

Data for vehicles in model years 2001 and later was acquired from results of tests conducted under the In-Use Verification Program. This program, initiated in 2003, is run by manufacturers and administered by EPA/OTAQ through the Compliance and Innovative Strategies Division (CISD).

To verify that in-use vehicles comply with applicable emissions standards, customer-owned vehicles at differing mileage levels are tested on an as-received basis with minimal screening. Emissions are measured on the Federal Test Procedure, US06 and other cycles. The FTP is most relevant to our purposes, but the US06 is also important.

1.3.4.1.1 Vehicle Descriptors

In addition to the parameters listed above in Table 7, the IUVP data provides engine-family information. Using engine family, the IUVP files can be merged with certification test records by model year. The certification test records provide information on standard level and specific emissions standards applicable to each vehicle. The standard level refers to the body of standards to which vehicles were certified (Tier 1, NLEV, LEV-I, LEV-II), and the standards refer to specific numeric standards for HC, CO or NOx, where HC are represented by non-methane hydrocarbons (NMHC) or non-methane organic gases (NMOG), depending on combinations of standard level and vehicle class (LDV, LDT1-4).

Table 19. Vehicle Descriptors available in IUVP files and certification test records.

Parameter	**Units**	**Source**		**Purpose**
		IUVP	*Cert. Records*	
VIN		Y		Verify MY or other parameters
Fuel type		Y		
Make		Y	Y	
Model		Y	Y	
Model year		Y	Y	Assign sourceBinID, calculate age-at-test
Engine Family		Y	Y	
Tier			Y	
Emissions Standard			Y	Assign Vehicle Class

Combining data from both sources allows individual test results to be associated with the correct standard level and emissions standard, which allows inference of the correct vehicle class.

1.3.4.2 Estimating I/M Reference Rates

The goal of this process is to represent I/M reference rates for young vehicles, i.e., the first ageGroup (0-3 years). The rates are estimated by Tier, model year and regulatory class. The process involves six steps, each of which is discussed in more detail in Section 1.3.4.2.1, below.

1. *Average IUVP results* by standard level and vehicle class.

2. *Develop phase-in assumptions* for MY 2001 – 2021, by standard level, vehicle class and model year

3. *Merge FTP results and Phase-in assumptions*. For running emissions, calculate weighted ratios of emissions in each model year to those for Tier 1 (MY2000). Then calculate emissions by operating mode in each model year by multiplying the MY2000 emission rates by the weighted ratio for each model year.

4. *Estimate Emissions by Operating Mode*. We assumed that the emissions control at high power (outside ranges of speed and acceleration covered by the FTP) would not be as effective as at lower power (within the range of speed and acceleration covered by the FTP).

5. *Apply Deterioration* to estimate emissions for three additional age Groups (4-5, 6-7 and 8-9). We assume that NLEV and Tier-2 vehicles will deteriorate similarly to Tier-1 vehicles, when viewed in logarithmic terms. We therefore apply ln-linear deterioration to the rates developed in steps 1-4. For the remaining three groups, emissions are assumed to stabilize as described above on page 53.

6. *Estimate non-I/M reference rates*. The rates in steps 1-6 represent I/M references. Corresponding non-I/M references are calculated by applying the ratios applied to the Tier-1 and pre-Tier-1 rates (Figure 19).

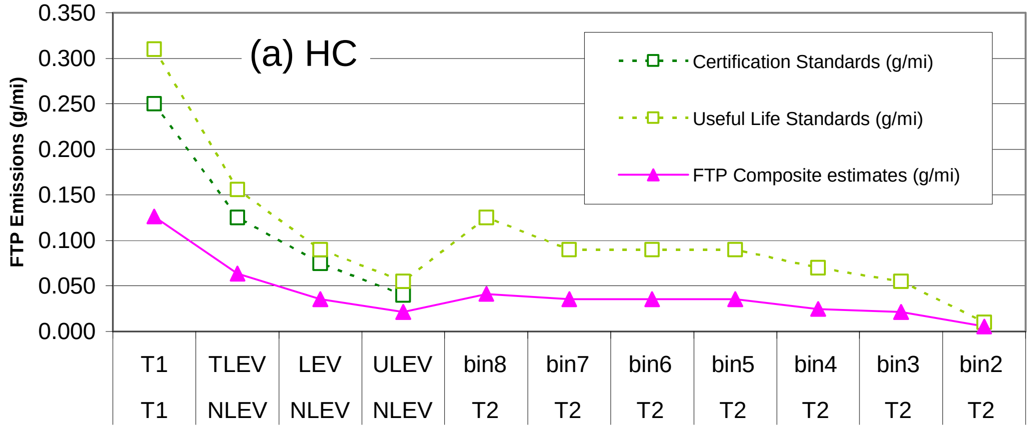
Each of these steps is described in greater detail in the sub-sections below.

1.3.4.2.1 Averaging IUVP Results

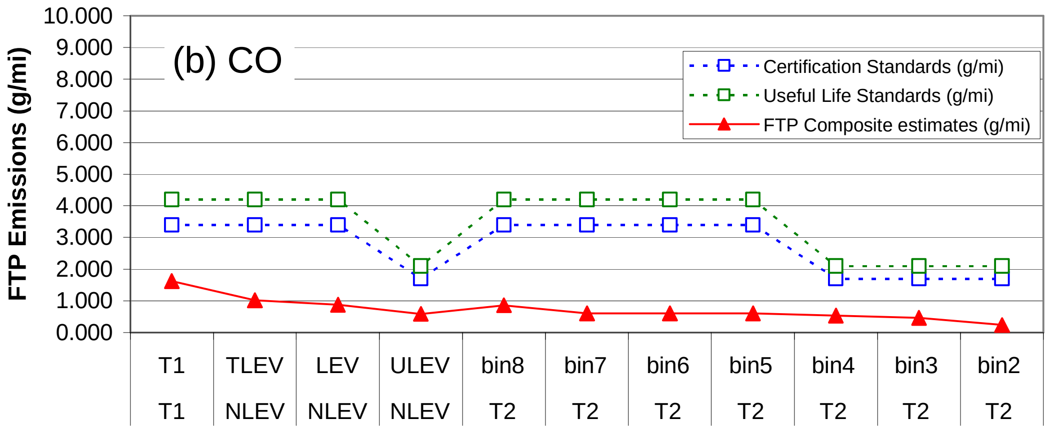
In using the IUVP results, “cold-start” emissions are represented as “Bag 1 – Bag 3” i.e., the mass from the cold-start phase less that from the corresponding hot-start phase. Similarly, “hot-running” emissions are represented by the “Bag 2,” or the “hot-stabilized” phase, after the initial cold-start phase has conditioned the engine.

The first step is to average the IUVP results by Tier and vehicle Class. Results of this process are shown below. In the figures, note that the HC values represent non-methane hydrocarbons (NMHC) for Tier 1 and non-methane organic gases (NMOG) for NLEV and Tier 2. Figure 25 shows FTP composite results in relation to applicable certification and useful-life standards. For THC and NOx, the data show expected compliance margins in the range of 40-60% in most cases. For CO, compliance margins are even larger, ostensibly reflecting the concomitant effects of HC or NOx control on CO emissions.

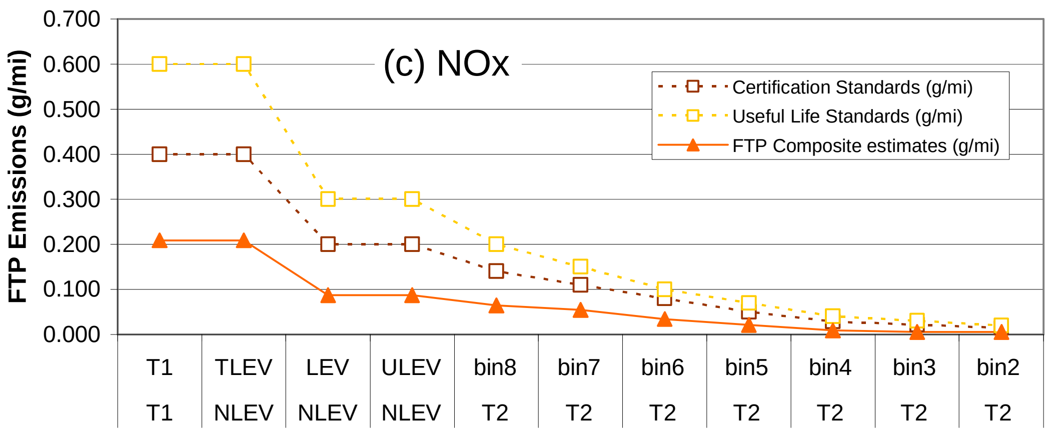
Figure 25. Composite FTP Results for Tier1, NLEV and Tier 2 Vehicles, as measured by IUVP, in relation to corresponding certification and useful-life standards.



(a) HC
FTP Emissions (g/mi)
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
Certification Standards (g/mi)
Useful Life Standards (g/mi)
FTP Composite estimates (g/mi)
T1 TLEV LEV ULEV bin8 bin7 bin6 bin5 bin4 bin3 bin2
T1 NLEV NLEV NLEV T2 T2 T2 T2 T2 T2 T2



(b) CO
FTP Emissions (g/mi)
10.000
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
Certification Standards (g/mi)
Useful Life Standards (g/mi)
FTP Composite estimates (g/mi)
T1 TLEV LEV ULEV bin8 bin7 bin6 bin5 bin4 bin3 bin2
T1 NLEV NLEV NLEV T2 T2 T2 T2 T2 T2 T2



(c) NOx
FTP Emissions (g/mi)
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Certification Standards (g/mi)
Useful Life Standards (g/mi)
FTP Composite estimates (g/mi)
T1 TLEV LEV ULEV bin8 bin7 bin6 bin5 bin4 bin3 bin2
T1 NLEV NLEV NLEV T2 T2 T2 T2 T2 T2 T2

Figure 26. Cold-start (Bag 1 – Bag 3) and Hot-running (Bag 2) FTP emissions for Tier 1, NLEV and Tier 2 vehicles, as measured by IUVP (g/mi).

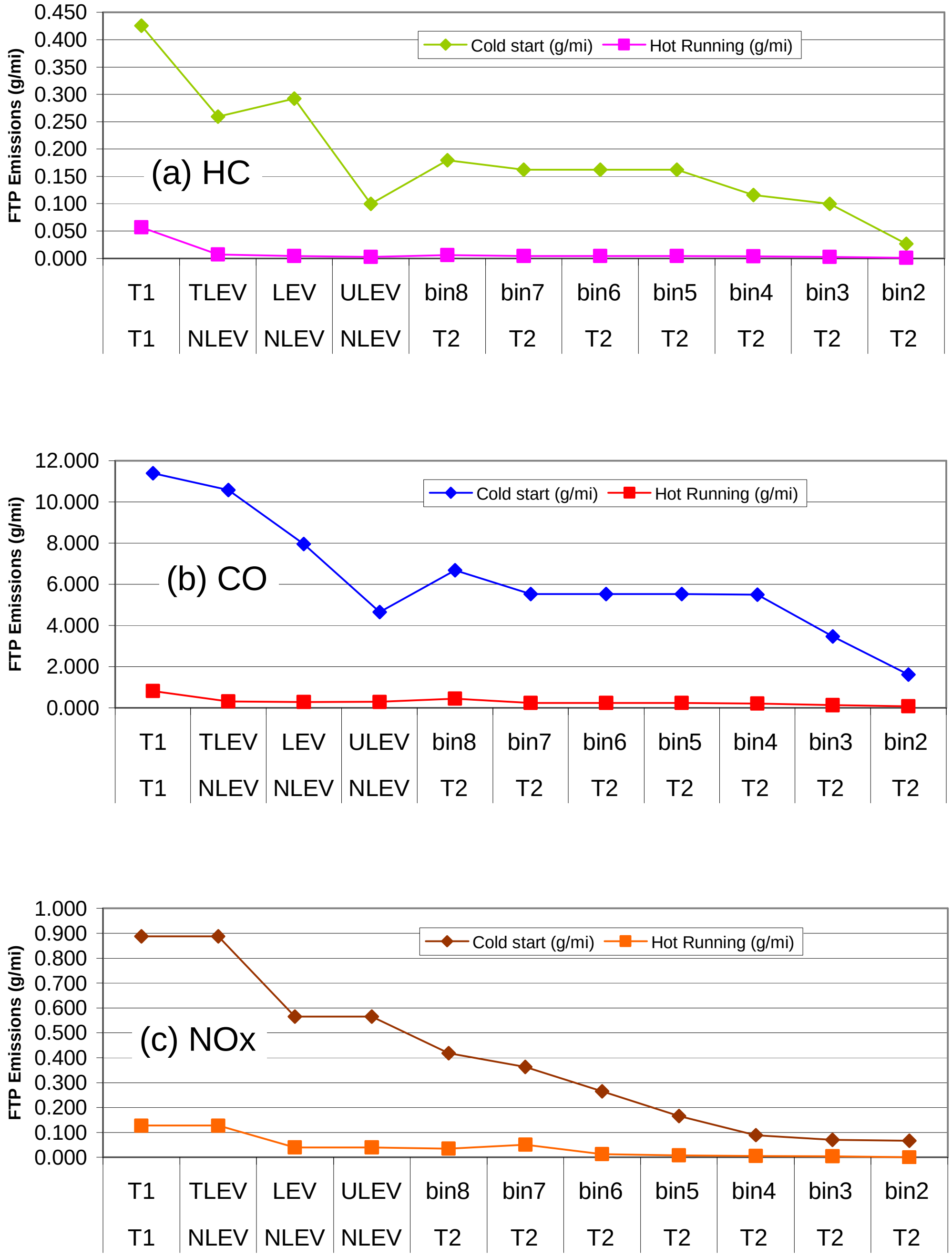


Figure 27 Composite, Cold-start (Bag 1 – Bag 3) and Hot-running (Bag 2) FTP emissions for Tier 1, NLEV and Tier 2 vehicles, as measured by IUVP, normalized to respective Tier-1 levels.

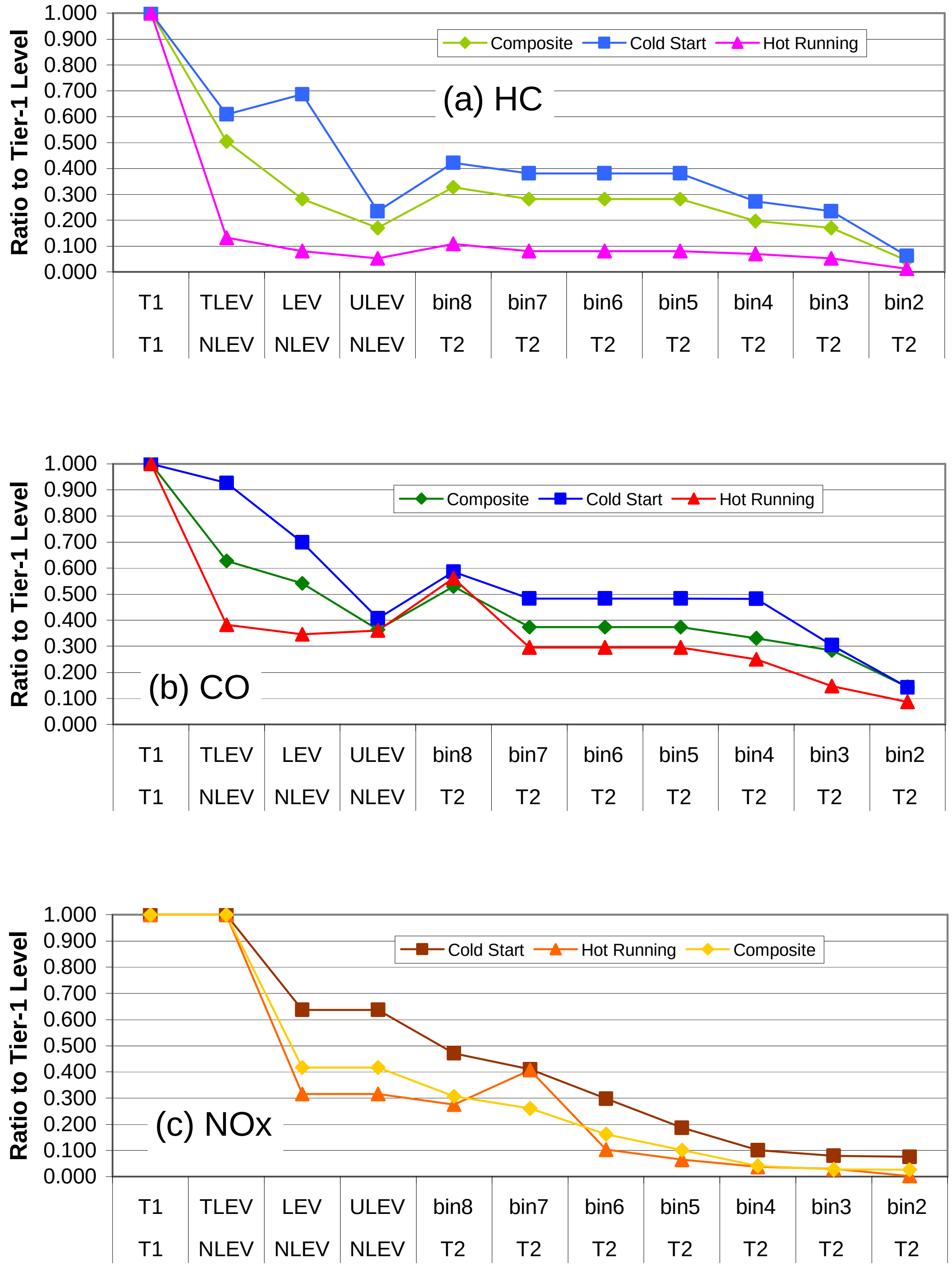


Figure 26 shows results for separate phases of the FTP, to examine differential effects of standards on start and running emissions. As mentioned, the "cold-start" emissions are represented by the difference between Bags 1 and 3, divided by the nominal bag distance (3.59 miles) which expresses the values as a "start rate" in g/mi. The "hot-running" emissions are represented by Bag 2 emissions, also divided by the appropriate distance to obtain an aggregate rate, in g/mi. Additionally, Figure 23 shows composite, start and running values normalized to their respective Tier-1 levels, which clearly displays the greater relative levels of control for running as opposed to start emissions. Not surprisingly then, distinguishing start and running emissions shows that composite FTP values for HC and CO are strongly influenced by start emissions. Starts are also important for NOx, but to a lesser degree. In any case, the results show that sole reliance on composite results in projecting future emissions declines would give misleading results in projecting either start or running emissions. Hence, the method described below emphasizes treating them separately.

1.3.4.2.2 Develop Phase-In Assumptions

To estimate emissions levels for specific model years, we developed assumptions describing the phase-in of new emissions standards after model year 2000. For rates stored in the MOVES default database, we developed assumptions intended to apply to vehicles sold in states where Federal, rather than California standards applied. Thus, the phase-is designed to represent the phase-in of National-Low-Emission-Vehicle (NLEV) and Tier-2 standards.

To achieve these steps, we obtained certification records and test results for a selection of model years[28]. These records contain information on certified vehicles, including model year, engine family, standard level (Tier-1, LEV, Bin 5, etc.), and sales area, as well as numerical standards used for certification on the Federal Test Procedure (e.g., 0.05 g NMOG/mile, etc.). For each engine family, we inferred the vehicle class (LDV, LDT1-LDT4) based on combination of standard and numerical values. Examples illustrating this process are shown in Table 20.

After compling lists of engine families by standard, model year and vehicle class, we obtained estimates of final sales from the EPA VERIFY database for MY 2001-2007[29]. We merged the certification records with the sales estimates, by model year and engine family.

Then to estimate the default "Federal" phase-in, we summed the sales by model year, standard level and vehicle class, for a subset of sales areas in which Federal or California standards applied, excluding those sales areas in which only California standards applied. Estimates of numbers of engine families certified for various sales areas are listed in Table 21. Sales-weighted phase-in scenarios for each vehicle class are shown in Figure 28 through Figure 31. As noted, the results in the Figures reflect the certifications in the "Fed" or "Both" groups shown in Table 21.

Proportions of each standard represent actual phase-in history for MY 2001-2007. We projected phase-in assumptions through MY2010, after which we held assumptions constant, under assumption that the Tier-2 phase-in would be complete.

The National LEV (NLEV) standards apply only to LDV, LDT1 and LDT2 vehicle classes, for which Tier 1 certification ended in MY 2000. Certification to NLEV standards began in 2001 and ended in 2006, however, NLEV vehicles dominate the (Federal) fleet between 2001 and 2003. Tier 2 vehicles enter the fleet in 2003 and completely comprise new sales by 2010.
The phase-in for LDV, LDT1 and LDT2 are broadly similar in that LEV and Bin 5 vehicles dominate certifications and sales. There are relatively small differences in that LDV-T1 contains higher fractions of ULEV and Bin 8.

The phase-in for heavy light-duty trucks is simpler in that Tier-1 certifications continue through 2004, after which Tier-2 standards are introduced. After 2003, certifications are dominated by Bin 8, Bin 5 and Bin 4.

Table 20. Examples of Information obtained from Certification Test Records, with Vehicle Class inferred from combinations of Standard, and FTP Certification values.

Standard	Engine Family	Sales Area	FTP Standard			Vehicle-Class
			50,000-mi	100,000-mi	120,000-mi	
LEV	2HNXV02.0VBP	NLEV all states	0.075	0.09		LDV, LDT1
LEV	2MTXT02.4GPG	NLEV all-states	0.100	0.13		LDT2
Tier 1	2CRXT05.95B2	Federal all-altitude	0.32		0.46	LDT3
Tier 1	2CRXT05.96B0	Federal all-altitude	0.39		0.56	LDT4

Table 21. Approximate Numbers of Engine Families Certified, by Model Year and Age Group, Model Years 2001-2007.

Sales Area	Code	Group[1]	Model Year							Total
			2001	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	
California	CA	CA	114	116	118	240	251	275	255	1,369
Clean Fuel Vehicle	CF	Fed	38	46	81	76	69	61	55	426
California + NLEV (all states)	CL	Both	149	140	129					418
Federal All Altitude	FA	Fed	79	75	86	209	219	271	274	1,213
Federal + CA Tier 2	FC	Both			16	81	41	33	16	187
Clean Fuel Veh + NLEV(ASTR)[2] + CA	NF	Both	57	56	45					158
NLEV (All States)	NL	Fed	31	47	74					152
TOTAL			468	480	549	606	580	640	600	3,923

[1] "Fed" denotes areas for which vehicles were certified to Federal Tier 1, NLEV or Tier 2 standards, "CA" denotes vehicles certified to California LEV-I or LEV-II standards, including the "section 177" states, "Both" denotes vehicles certified for Federal or California Sales Areas.
[2]. "ASTR" = "All-state trading Region."

Figure 28. Phase-in Assumptions for Tier 1, NLEV, and Tier 2 standards, for LDVand LDT1

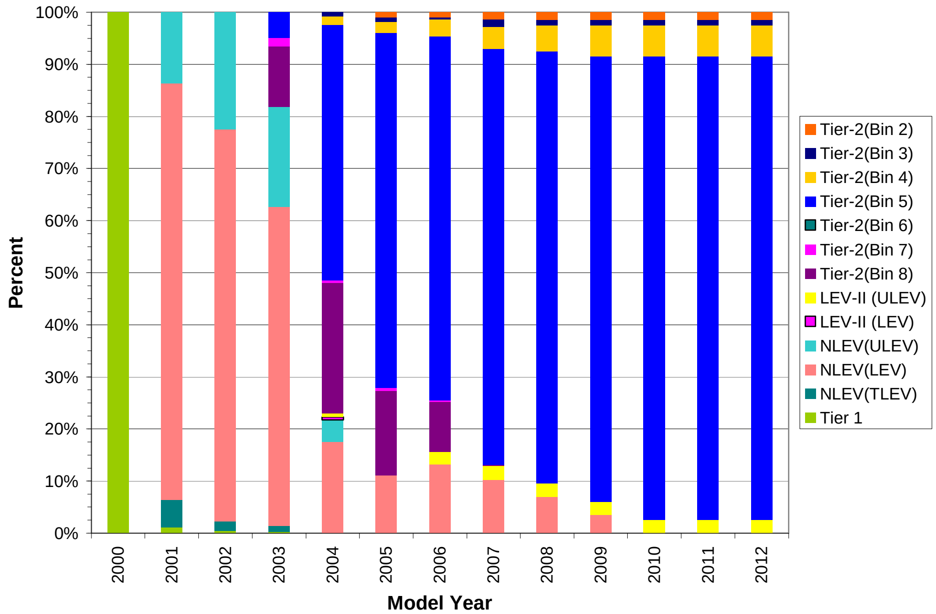


Figure 29. Phase-in Assumptions for Tier 1, NLEV and Tier 2 standards, for LDT2.

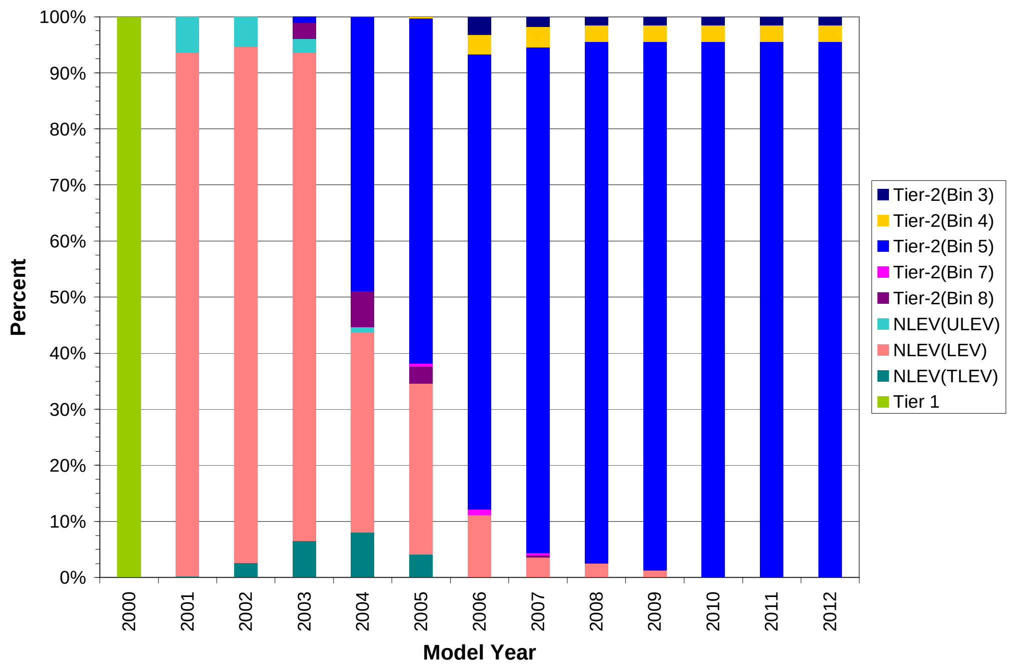


Figure 30. Phase-in Assumptions for Tier 1 and Tier 2 standards, for LDT3

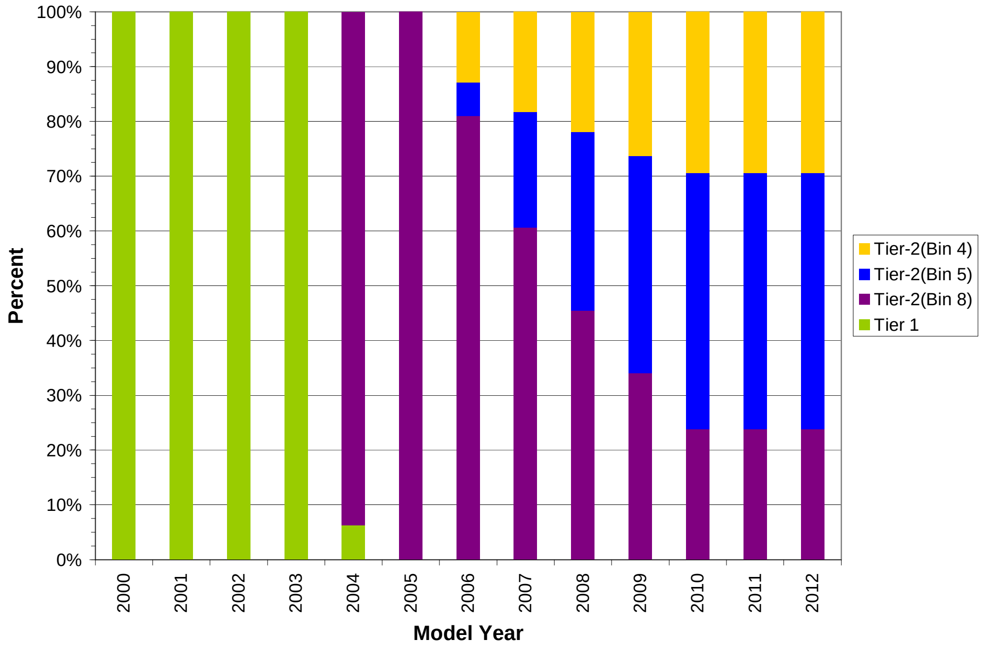
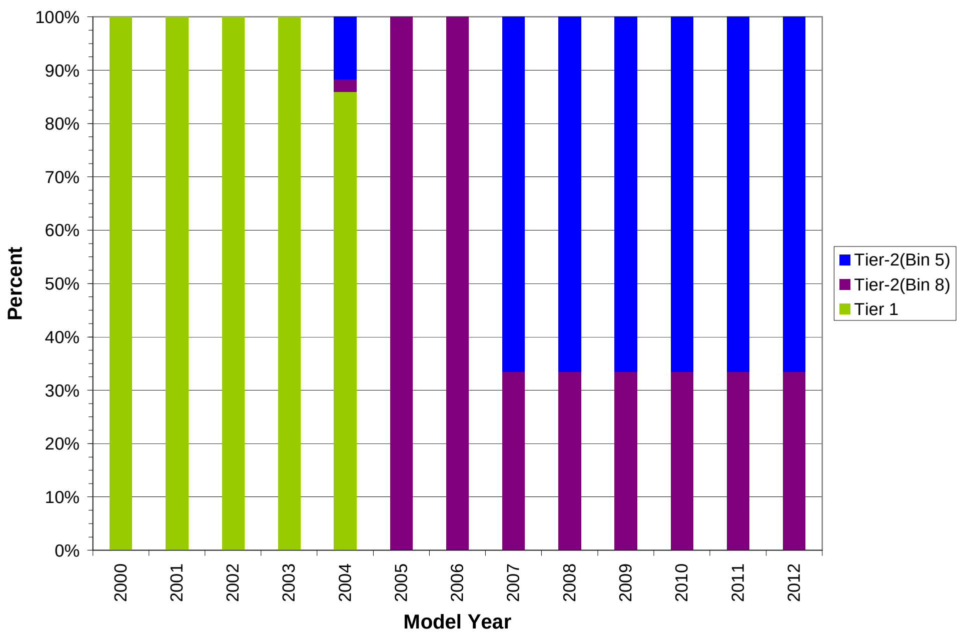


Figure 31. Phase-in Assumptions for Tier 1 and Tier 2 standards, for LDT4.



1.3.4.2.3 Merge FTP results and phase-in Assumptions

The goal of this step is to calculate weighted averages of the FTP cold-start and running results for all standards in each model year, with the emissions results weighted by applicable phase-in fractions. We do this step for each vehicle class separately, then we weight the four truck classes together using a set of fractions also derived from the weighted sales estimates. Through MY 2007, where we had actual history, these fractions vary by model year, but are held stable after 2008. See Figure 32.

Figure 33 shows an example of the Phase-in calculation for NOx from cars between model years 2000 and 2010. The figure shows cold start and running FTP values for Tier 1, NLEV and Tier 2 standards, as well as the phase-in fractions for each standard in each model year. Start and running emissions in each model year are simply calculated as weighted averages of the emissions estimates and the phase-in fractions. The resulting weighted start estimates are used directly to represent cold-start emissions for young vehicles in each model year (ages 0-3). For running emissions, however, the averages are not used directly; rather, each is expressed as a ratio to the corresponding Tier-1 value.

Table 22 shows weighted average values for model-years 2001-2010 for simulated FTP composites, cold-start and hot-running emissions. The start values, expressed as the cold-start mass increment (g), are used directly in the MOVES emission rate table to represent cold-start emissions (operating mode 108). The composites and running emissions, expressed as rates (g/mi), are presented for comparison. For running emissions, however, the averages shown in the table are not used directly; rather, each is expressed as a ratio to the corresponding Tier-1 value, as shown in, Figure 34 to Figure 36 below.

Figure 32. Relative Fractions of Truck Classes, by Model Year.

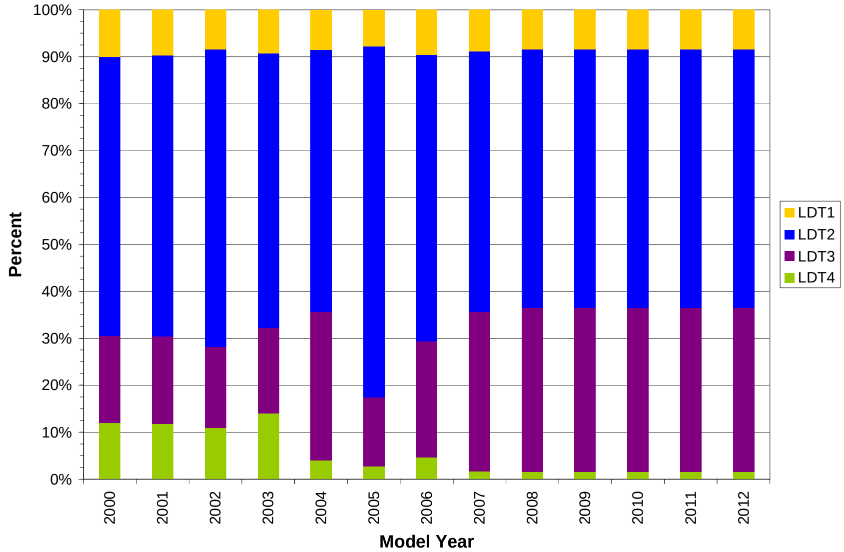


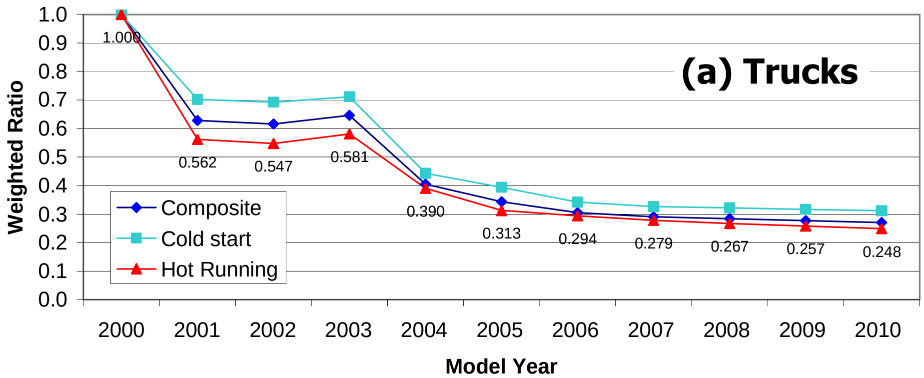
Figure 33. Example of Phase-In Calculation, for NOx from Cars, for MY 2000-2010.

Standard		Cold start (g)	Hot Running (g/mi)	Phase-in by Model Year 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Tier 1	Tier 1	0.888	0.127	1	0.011	0.004	0.002	0	0	0	0	0	0	0
	TLEV	0.888	0.127	0	0.052	0.018	0.011	0	0	0	0	0	0	0
NLEV	LEV	0.566	0.040	0	0.801	0.752	0.613	0.175	0.110	0.132	0.103	0.070	0.035	0
	ULEV	0.566	0.040	0	0.136	0.226	0.192	0.042	0	0	0	0	0	0
	bin8	0.418	0.035	0	0	0	0.115	0.251	0.163	0.095	0.002	0	0	0
	bin7	0.364	0.052	0	0	0	0.017	0.004	0.005	0.004	0	0	0	0
Tier 2	bin5	0.165	0.008	0	0	0	0.049	0.491	0.682	0.698	0.799	0.830	0.855	0.890
	bin4	0.090	0.005	0	0	0	0	0.016	0.021	0.033	0.042	0.050	0.060	0.060
	bin3	0.071	0.004	0	0	0	0	0.008	0.009	0.003	0.013	0.010	0.010	0.010
	bin2	0.067	0.000	0	0	0	0	0	0.010	0.011	0.014	0.015	0.015	0.015
LEV-II	LEV	0.165	0.008	0	0	0	0	0.0052645	0.000	0.000	0.000	0.000	0.000	0.000
	ULEV	0.071	0.004	0	0	0	0	0.0074988	0.000	0.024	0.026	0.025	0.025	0.025
			Start (g)	0.888	0.586	0.573	0.530	0.314	0.248	0.237	0.199	0.185	0.170	0.156
			Running (g/mile)	0.127	0.046	0.042	0.039	0.022	0.016	0.015	0.011	0.010	0.009	0.008
			RATIO to Tier 1	***1.00***	***0.36***	***0.33***	***0.31***	***0.17***	***0.13***	***0.12***	***0.087***	***0.079***	***0.070***	***0.061***

Table 22. Weighted Average FTP Values Projected for Trucks and Cars for MY 2001-2010.

regClass	MY	CO			HC			NOx		
		Composite (g/mi)	Start (g)	Running (g/mi)	Composite (g/mi)	Start (g)	Running (g/mi)	Composite (g/mi)	Start (g)	Running (g/mi)
Trucks	2000	2.28	17.90	1.01	0.175	1.87	0.104	0.304	1.12	0.174
	2001	1.43	12.56	0.566	0.0965	1.23	0.0400	0.171	0.843	0.0876
	2002	1.41	12.40	0.552	0.0941	1.21	0.376	0.169	0.836	0.0865
	2003	1.47	12.73	0.586	0.100	1.25	0.0424	0.181	0.863	0.0934
	2004	0.92	7.92	0.393	0.0535	0.786	0.0123	0.0849	0.473	0.0434
	2005	0.78	7.05	0.315	0.0440	0.703	0.00574	0.0596	0.367	0.0291
	2006	0.70	6.12	0.296	0.0378	0.612	0.00511	0.0381	0.264	0.0183
	2007	0.66	5.85	0.281	0.0361	0.587	0.00490	0.0315	0.226	0.0148
	2008	0.65	5.75	0.270	0.0356	0.580	0.00479	0.0285	0.208	0.0130
	2009	0.63	5.67	0.260	0.0350	0.571	0.00470	0.0258	0.192	0.0115
	2010	0.62	5.58	0.251	0.0345	0.564	0.00462	0.0233	0.177	0.0101
Cars	2000	1.62	11.40	0.805	0.126	1.53	0.0571	0.209	0.888	0.127
	2001	0.856	7.68	0.287	0.0361	0.954	0.00509	0.0948	0.586	0.0457
	2002	0.821	7.27	0.284	0.0333	0.893	0.00451	0.0898	0.573	0.0421
	2003	0.808	7.05	0.299	0.0340	0.839	0.00462	0.0824	0.530	0.0394
	2004	0.714	6.16	0.298	0.0356	0.664	0.00488	0.0461	0.315	0.0220
	2005	0.672	5.91	0.274	0.0358	0.634	0.00477	0.0351	0.248	0.0161
	2006	0.657	5.85	0.257	0.0350	0.633	0.00462	0.0335	0.239	0.0150
	2007	0.621	5.63	0.234	0.0341	0.608	0.00443	0.0271	0.201	0.0112
	2008	0.611	5.55	0.232	0.0341	0.592	0.00443	0.0248	0.187	0.0101
	2009	0.601	5.47	0.231	0.0339	0.574	0.00442	0.0224	0.172	0.00896
	2010	0.591	5.38	0.229	0.0339	0.557	0.00442	0.0201	0.158	0.00784

Figure 34. Weighted Ratios for Composite, Start and Running CO Emissions, for (a) Trucks and (b) Cars.



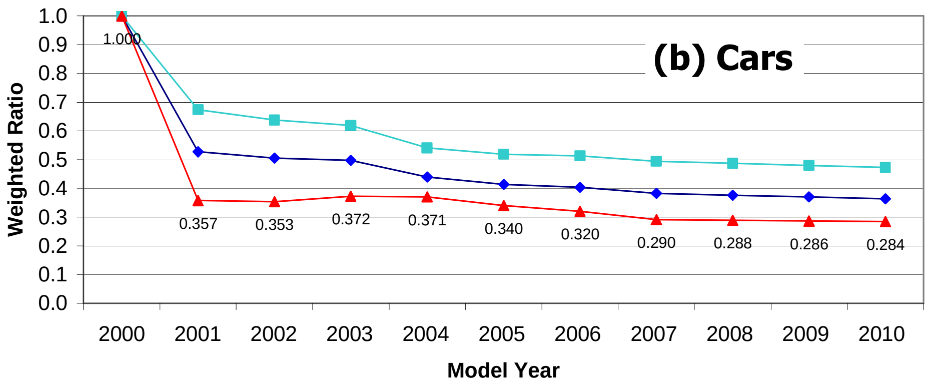
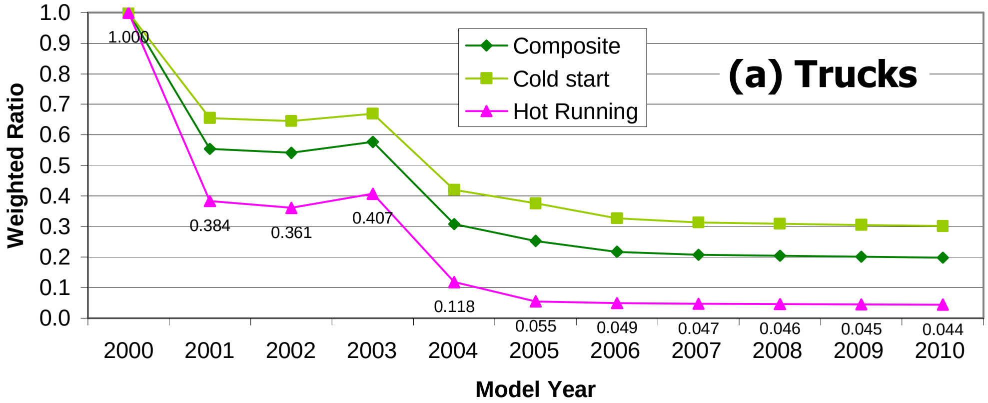


Figure 35. Weighted Ratios for Composite, Start and Running THC Emissions, for (a) Trucks and (b) Cars.



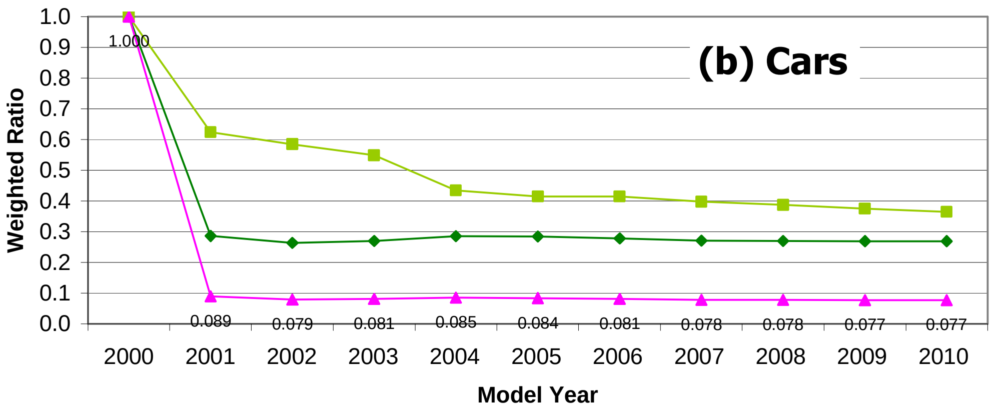
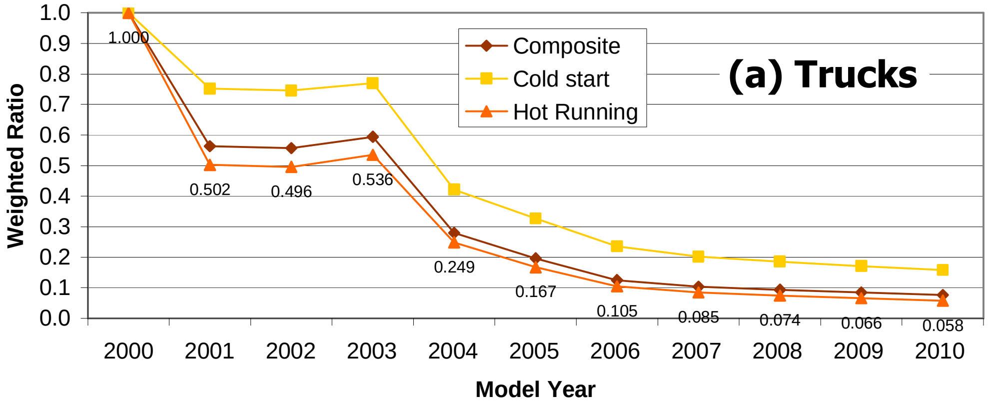
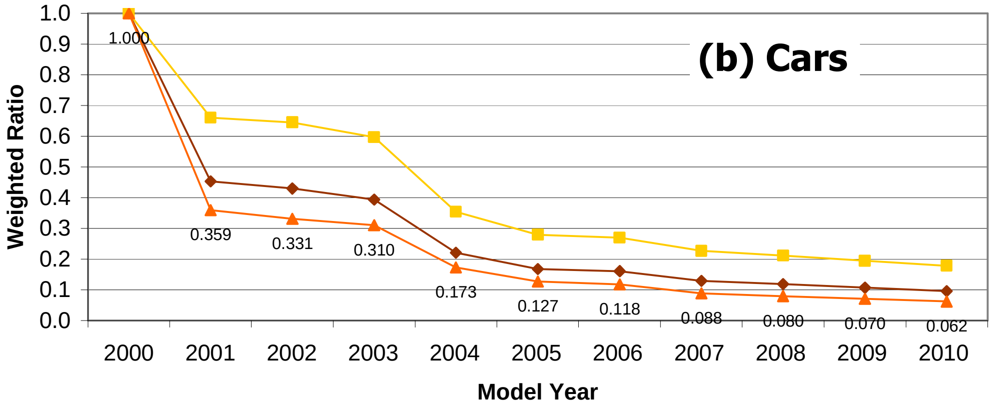


Figure 36. Weighted Ratios for Composite, Start and Running NOx Emissions, for (a) Trucks and (b) Cars.





1.3.3.2.4 Estimating Emissions by Operating Mode

With the introduction of the NLEV standards, new emissions requirements were imposed, in addition to standards defined in terms of the Federal Test Procedure. The new requirements, under the "Supplemental Federal Test Procedure" (SFTP), imposed more stringent emissions control under conditions of high speed and power (through the US06 cycle), and with air-conditioning running (through the SC03 cycle). To project emissions for NLEV and Tier-2 vehicles, we divided the operating modes for running exhaust into two groups. These groups represent the ranges of speed and power covered by the FTP standards (< ~18 kW/metric ton), and the ranges covered by the US06 cycle. For convenience, we refer to these two regions as "the hot-running FTP region" and "US06 region," respectively (See Figure 37). Data measured on the SC03 cycle did not play a role in emission rate development.

To estimate emissions by operating mode, the approach was to multiply the emission rates for MY 2000, representing Tier 1, by a specific ratio for each model year from 2001 to 2010, to represent emissions for that year. For the FTP operating modes, we applied the ratios shown in Figure 34 to Figure 36 above.

1.3.4.2.4.1 Running Emissions

For the "US06" operating modes, we followed a different approach from that described above in 1.3.4.2.3. At the outset, we noted that the degree of control in the FTP standards increases dramatically between MY 2000 through MY 2010, following phase-in of the Tier-2 standards, giving pronounced declines in emissions on the FTP. For our purposes, we are referring specifically to declines in running emissions, as shown by changes in Bag-2 emissions. However, it was not obvious that the degree of control would increase as dramatically for the SFTP standards, as shown by the US06. Thus, in preparation of the draft rates, we adopted a conservative assumption that emissions in the "US06" region would not drop as sharply as those in the "hot-running FTP" region.

It was therefore necessary to estimate different sets of ratios. Two alternative approaches were developed.

The first involved returning to the Phoenix I/M data. To create pre- and post-SFTP estimates, we pooled tests for two model-year groups, 1998-2000, representing Tier 1 vehicles not subject to SFTP requirements, and 2001-2003, representing NLEV vehicles subject to the SFTP. For each group, we calculated means for each pollutant for the US06 operating modes (as a group), and calculated ratios between the two groups.

$$R_{\text{SFTP}} = \frac{\overline{E}_{\text{poll,SFTP},01-03}}{\overline{E}_{\text{poll,SFTP},98-00}} \qquad \textbf{Equation 39}$$

The resulting ratios were used for CO and HC, as shown in Figure 38.

The second approach involved compilation of results on the US06 cycle and calculation of ratios in a manner similar to that used for FTP data as described in 1.3.4.2.3 above. It was possible to obtain data representing US06 tests representing vehicles in MY 1996-97 from the Mobile-Source Observation Database (MSOD), developed and maintained by EPA/OTAQ.[30] For NLEV and Tier-2 vehicles manufactured after MY2000, US06 results were available from the IUVP program. Emissions results on the US06 by standard were weighted by the phase-in assumptions for MY 2001-2007 as with the FTP results. Resulting ratios were used for NOx, as shown in Figure 38.

Figure 39 and Figure 40 show application of the ratios to the hot-running FTP and US06 operating modes in model years 2000 (the reference year), 2005, and 2010, both calculated with respect to 2000. The sets of ratios shown in Figure 38 are used for both sets of modes. Note that the values for the SFTP modes are equal in 2005 and 2010 for HC and CO, because the SFTP ratios are constant by model year. In these figures, the results are presented on both linear and logarithmic scales. The linear plots display the differences in the high-power modes, but obscure those in the low-power modes. The logarithmic plots supplement the linear plots by making visible the relatively small differences between MY 2005 and 2010 in the lower power modes.

Figure 37. Operating modes for running Exhaust Emissions, divided broadly into "hot-running FTP" and "US06" regions.

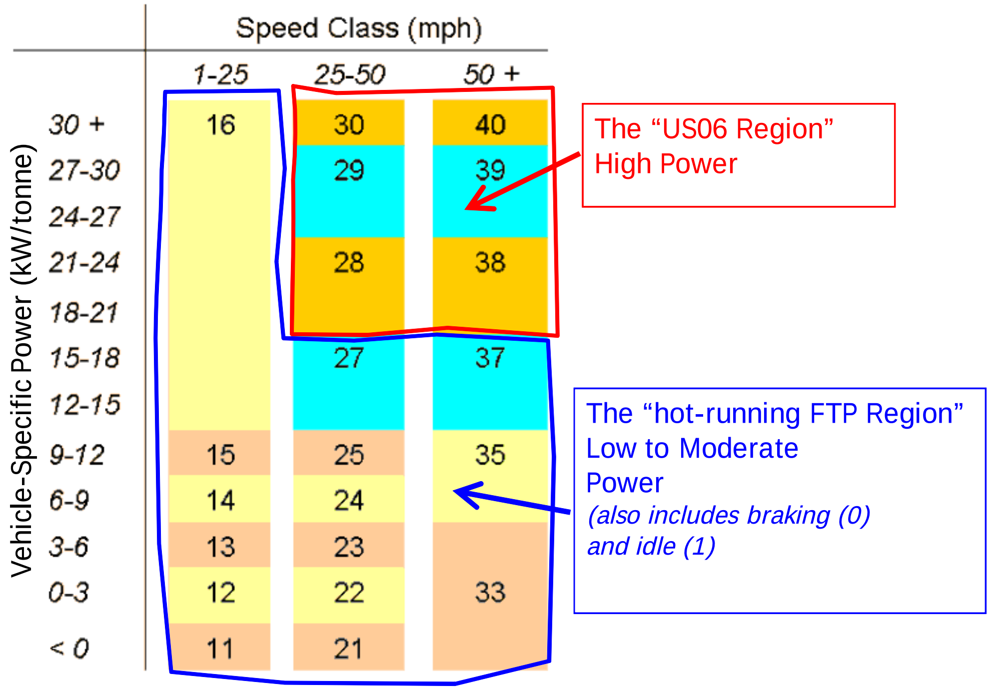


Figure 38. Weighted Ratios for Cars, for hot-running emissions, representing the "hot-running FTP Region" (FTP) and the "US06 Region" (US06), for (a) CO, (b) THC and (c) NOx.

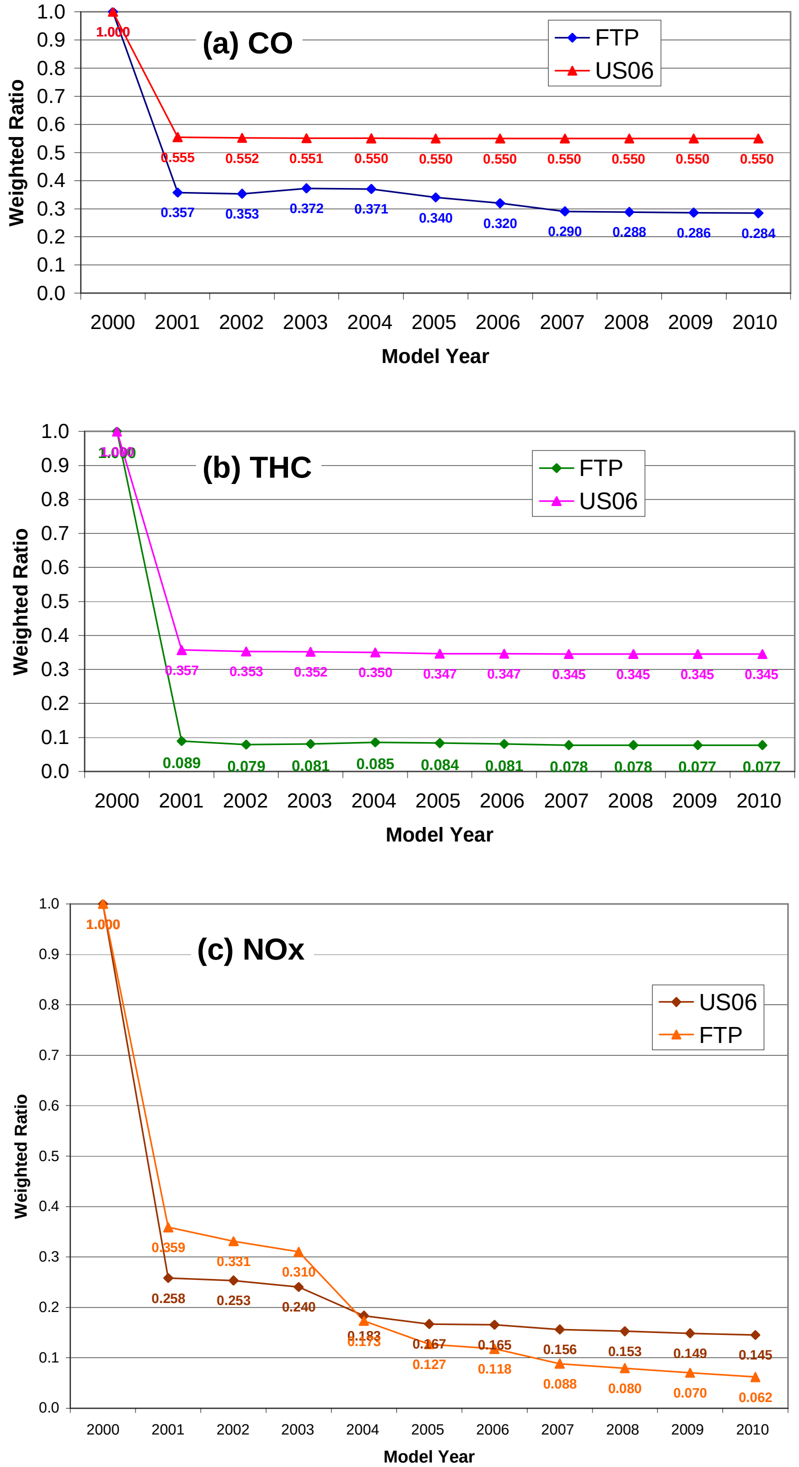


Figure 39. Projected Emission Rates for Cars, by Operating mode for ageGroup 0-3 years, for three model years (LINEAR SCALE).

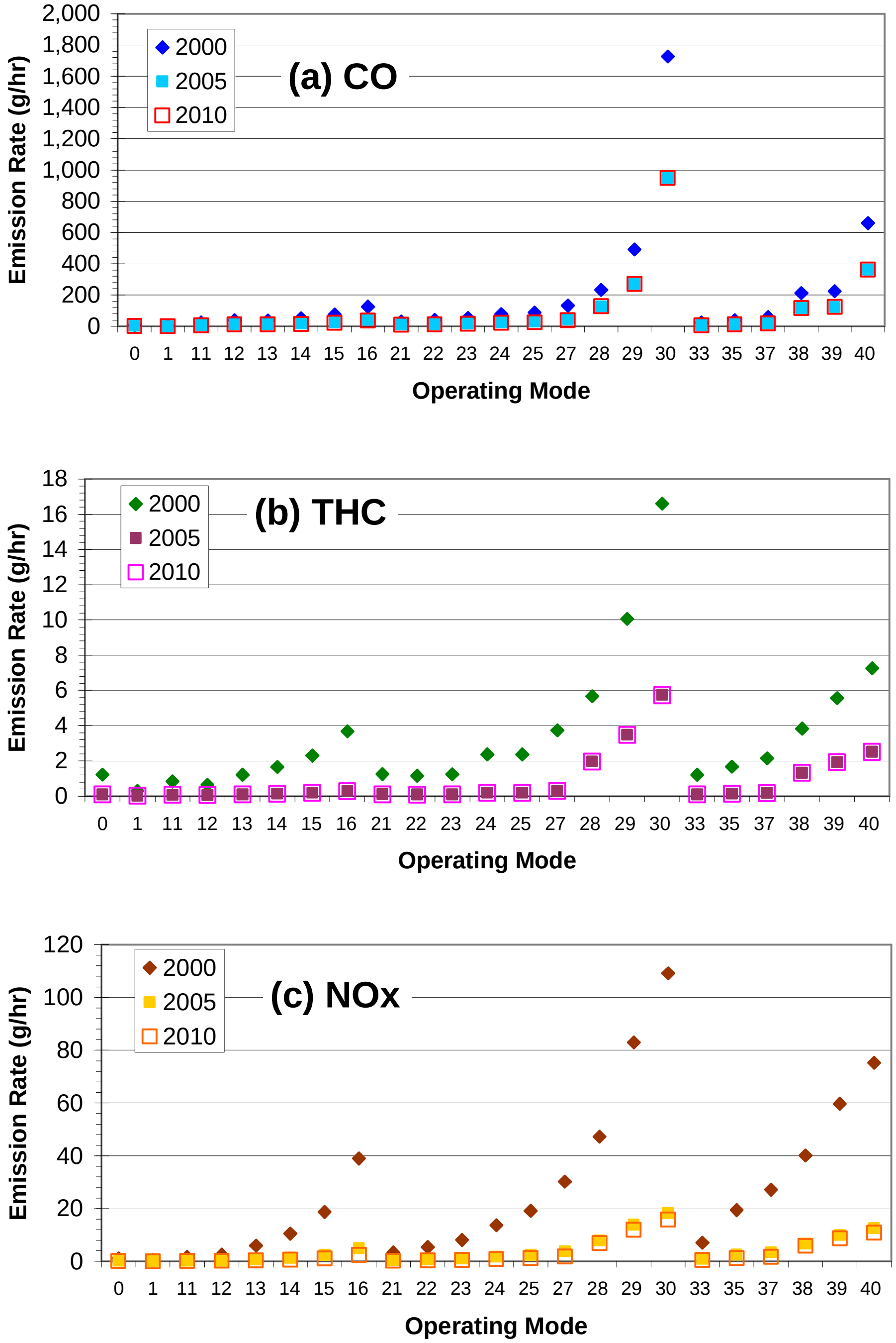
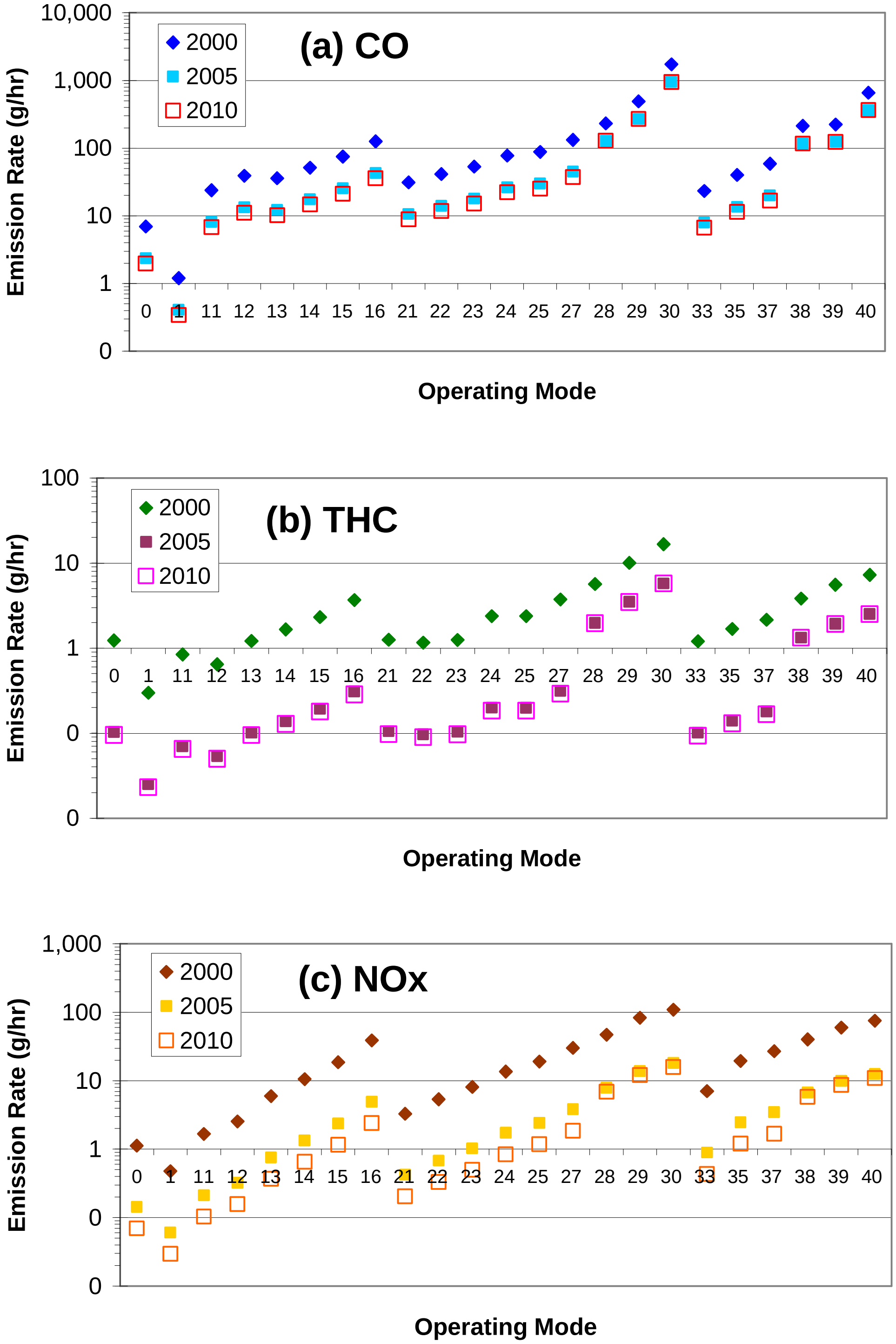


Figure 40. Projected Emission Rates for Cars, by Operating mode for ageGroup 0-3 years, for three model years (LOGARITHMIC SCALE).



1.3.4.2.5 Apply Deterioration

Based on review and analysis of the Phoenix I/M data, we assume that deterioration for different technologies is best represented by a multiplicative model, in which different technologies, represented by successive model-year groups, show similar deterioration in relative terms but markedly different deterioration in absolute terms. We implemented this approach by translating emissions for the 0-3 age Group, as calculated above, into natural logarithms and applying uniform logarithmic age trends to all model-year groups. We derived logarithmic deterioration slopes for Tier-1 vehicles (MY 1996-98) and applied them to NLEV and Tier-2 vehicles. In this process we applied the same logarithmic slope to each operating mode, which is an extension of the multiplicative deterioration assumption.

1.3.4.2.5.1 Recalculate the logarithmic mean

Starting with the values of the arithmetic mean (x_a) calculated above, we calculate a logarithmic mean (x_l), as shown in Equation 40. Note that this equation is simply a rearrangement of Equation 30.

$$\bar{x}_l = \ln \bar{x}_a - \frac{\sigma_l^2}{2}$$ **Equation 40**

The values of the logarithmic variance are intended to represent values for young vehicles, as the estimates for x_a represent the 0-3 year age Group. The values of σ_l^2used for this step were 1.30, 0.95 and 1.60 for CO, THC and NOx, respectively.

1.3.4.2.5.2 Apply a logarithmic Age slope

After estimating logarithmic means for the 0-3 age class ($x_{l,0\text{-}3}$), we estimate additional logarithmic means for successive age classes ($x_{l,\text{age}}$), by applying a linear slope in ln-space (m_l).

$$\bar{x}_{l,\text{age}} = \bar{x}_{l,0-3} + m_l(\text{age -1.5})$$ **Equation 41**

The values of the logarithmic slope are adapted from values developed for the 1996-98 model – year group. The values applied are shown in Table 23 . When calculating the age inputs for this equation, we subtracted 1.5 years to shift the intercept to the midpoint of the 0-3 year age Group, as shown in Equation 41.

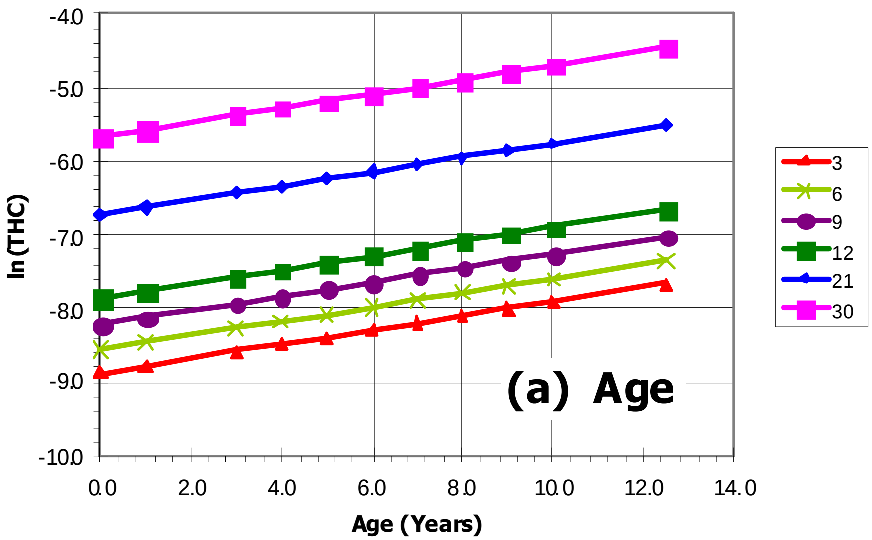
Figure 41 shows an example of the approach, as applied to THC from LDV in the 1996-98 model-year group. The upper plot (a) shows lnTHC vs Age, by VSP, where the VSP acts as a surrogate for operating mode. The defining characteristics of the plot are a series of parallel lines, with the gaps between the lines reflecting the magnitude of the VSP differences between them. Similarly, the lower plot shows lnTHC vs. VSP, by Age, where age acts as a surrogate for deterioration. In this view, deterioration appears as the magnitude of the gaps between a family of similar trends against power.

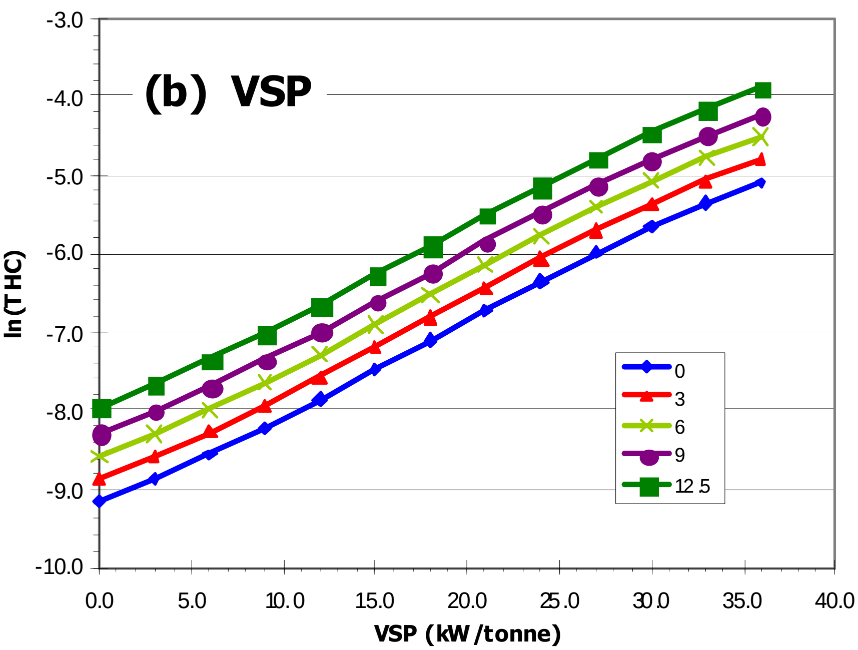
Table 23. Values of the logarithmic deterioration slope applied to running-exhaust emission rates for MY following 2000.

pollutant	opMode Group	Logarithmic slope (m_l)
CO	"hot-running FTP"[1]	0.13
	"US06"[2]	0.06
THC	"hot-running FTP"	0.09
	"US06"	0.09
NOx	"hot-running FTP"	0.15
	"US06"	0.15

[1] Includes opModeID = 0,1, 11-16, 21-25, 27, 33,35,37.
2 Includes opModeID = 28,29,30, 38,39,40.

Figure 41. Example of Logarithmic Deterioration Model for THC (Cars, MYG 96-98): (a) lnTHC vs age, by VSP level (kW/metric ton), and (b) lnTHC vs. VSP, by Age (yr).





1.3.4.2.5.3 Apply the reverse transformation

After the previous step, the values of $x_{l,\mathrm{age}}$ were reverse-transformed, as in Equation 30. The values of the logarithmic variance used for this step were adapted from the Phoenix I/M results and are intended to represent emissions distributions for "real-world" vehicle populations, meaning that the values are higher than the value used in step 1.3.4.2.5.1 and may vary with age. Values of logarithmic variances for all three pollutants are shown in Table 24.

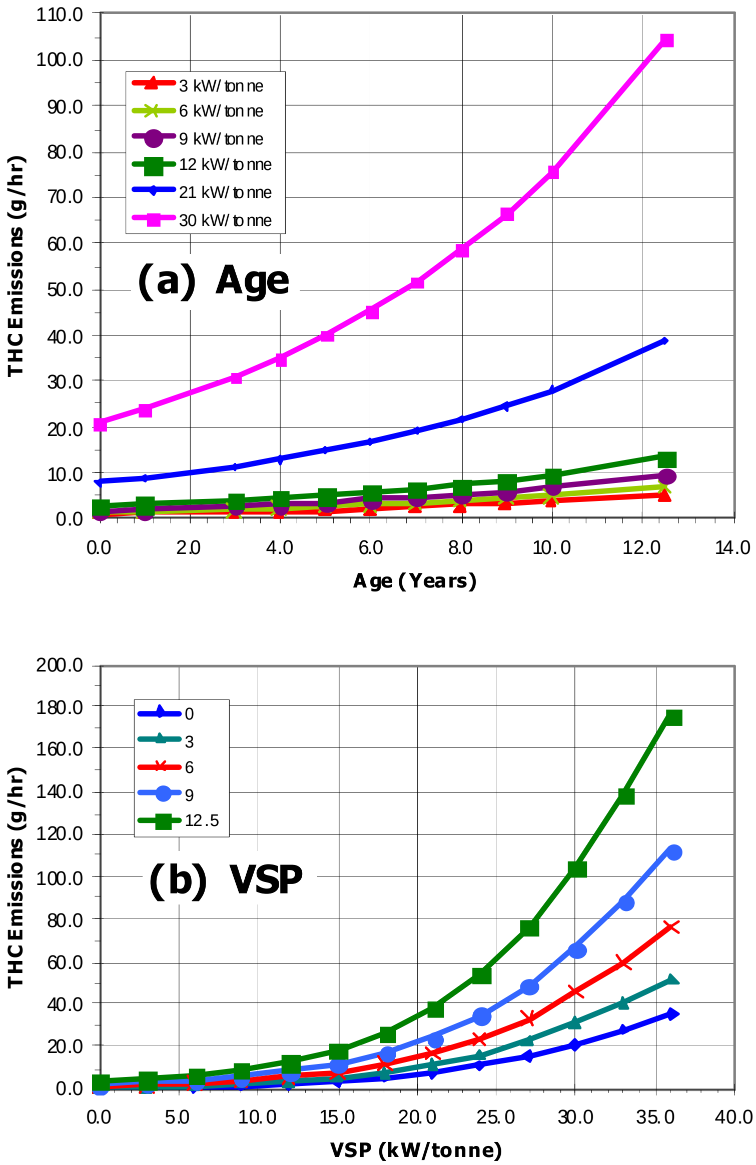
Table 24. Values of Logarithmic Variance Used to Calculate Emissions Deterioration by Reverse Transformation of Logarithmic Means.

Age Group	**Pollutant**		
	CO	**THC**	**NOx**
0-3 years	1.30	0.95	1.60
4-5	2.05	1.50	1.60
6-7	2.00	1.70	1.40
8-9	1.80	1.90	1.40

No values are presented in the table for the 10-14, 15-19 and 20+ year age Groups. This omission is intentional, in that we did not want to extrapolate the deterioration trend beyond the 8-9 year age Group. Extrapolation beyond this point is incorrect, as we know that emissions tend to stabilize beyond this age, while the ln-linear emissions model would project an increasingly steep and unrealistic exponential emissions trend. For the 10-14, 15-19 and 20+ age Groups, the "stabilization of emissions with age" was estimated as described in section 1.3.3.7.

Figure 42 shows the same results as Figure 41, following reverse transformation. The families of parallel logarithmic trends are replaced by corresponding "fans" of diverging exponential trends. An implication of this model is that as deterioration occurs, it is expressed more (in absolute terms) at high power. Similarly, the relationship between emissions and VSP becomes more pronounced, in absolute terms, with increasing age.

Figure 42. Example of Reverse Transformation for THC (LDV, MYG 96-98): (a) THC vs. Age, by VSP level (kW/metric ton), (b) THC vs. VSP, by Age (yr).



1.3.4.2.6 Estimate non-I/M References

Completion of steps 1.3.4.2.1 – 1.3.4.2.6 provided a set of rates representing I/M reference rates for MY 2001-2021. As a final step, we estimated non-I/M reference rates by applying the same ratios applied to the I/M references for MY 2000 and previous, as described above.

1.4 Exhaust Emissions for Start Operation

1.4.1 Subgroup 1: Vehicles manufactured in model year 1995 and earlier

In EPA's previous emissions model (MOBILE6), start emissions for passenger cars and light-duty trucks, were dependent upon three factors:

1. the (base) emissions of that vehicle at 75 degrees Fahrenheit[31] ,
2. an adjustment factor based on the length of soak time[32], and
3. an adjustment factor based on the ambient temperature[33]

Within the MOVES modal structure, operating modes for start emissions are defined in terms of soak time (preceding an engine start). The following sections will discuss the development of base rates for "cold starts" (operating mode 108), as well as those for "warm" or "hot" starts following seven soak times of varying length (operating modes 101-107).

Note that the development and application of temperature adjustments is discussed in a separate report. [34]

1.4.1.1 Methods

1.4.1.1.1 Data Sources

Data used in these analyses come from the following four sources:

1. EPA's Mobile Source Observation Database (MSOD) as of April 27, 2005. Over the past decades, EPA has performed emission tests (usually the Federal Test Procedure) on tens of thousands of vehicles under various conditions. EPA has stored those test results in its Mobile Source Observation Database (MSOD).

   We identified (in the MSOD) 549 gasoline-fueled vehicles (494 cars and 55 trucks) that had FTPs performed at temperatures both within the normal FTP range (68º to 86º Fahrenheit) as well as outside that range (i.e., either below 68º or above 86º). Aside from the differences in ambient temperature, the test parameters for the paired FTPs on each vehicle were identical. The FTPs were performed at temperatures from 16 through 111º F.

2. EPA's Office of Research and Development (ORD) contracted (through the Clean Air Vehicle Technology Center, Inc.) the testing of five cars (model years 1987 through 2001). Those vehicles were tested using both the UDDS and the IM240 cycle at temperatures of: 75, 40, 20, 0 and –20 ºF[35].

3. Under a contract with EPA, Southwest Research Institute (SwRI) tested four Tier-2 vehicles (2005 model year car and light-duty trucks) over the UDDS at temperatures of: 75, 20, and 0 ºF [citation?]

4. During 2004-05, USEPA OTAQ and ORD, in conjunction with the Departments of Energy and Transportation, conducted a program in the Kansas-City Metropolitan Area. During this study, designed to measure particulate emissions, gaseous emissions were also measured on the LA92 cycle[36].

1.4.1.1.2 Defining Start Emissions

Using the FTP data described above, we estimated cold-start emissions as the difference in mass between Bag-1 and Bag-3 (g). However, because Bag 1 follows a 12-hour (720 minute) soak and Bag 3 follows a 10-minute soak, it is possible to use soak/time relationships to modify the Bag1-Bag3 difference so as to account for the respective soak periods. The start/soak relationships we applied were adapted from a study performed by the California Air Resources Board[37] Based on these data, we derived a correction factor "A" as shown in Equation 42 and Table 25.

$$\text{Cold-start Emissions} = \frac{(\text{Bag 1 - Bag 3})}{1 - A} \quad \textbf{Equation 42}$$

Table 25. Correction Factor *A* for application in Equation 39.

Vehicle Type	**HC**	**CO**	**NOx**
No Catalyst	0.37101	0.34524	1.57562
Catalyst Equipped	0.12090	0.11474	0.39366
Heated Catalyst	0.05559	0.06937	1.05017

1.4.1.1.3 Relationship between Soak Time and Start Emissions

In the MOVES input database, "operating modes" for start emissions are defined in terms of soak time preceding an engine start. The "cold-start," as defined and calculated above, is represented as opModeID=108. An additional seven modes are defined in terms of soak times ranging from 3 min up to 540 min (opModeID = 101-107). To estimate start rates for the additional seven modes, we applied the soak-time/start relationships mentioned above. The specific values used are adapted from the MOBILE6 soak-effect curves for catalyst and non-catalyst equipped vehicles[15]. To adapt these relationships to the MOVES operating modes, the soak time was divided into eight intervals, each of which was assigned a "nominal" soak time, as shown in Table 26.

Table 26. Operating-Mode Definitions for Start Emissions, Defined in terms of Soak Time.

Nominal Soak Period (min)	OpModeID	OpModeName
3	101	Soak Time < 6 minutes
18	102	6 minutes <= Soak Time < 30 minutes
45	103	30 minutes <= Soak Time < 60 minutes
75	104	60 minutes <= Soak Time < 90 minutes
105	105	90 minutes <= Soak Time < 120 minutes
240	106	120 minutes <= Soak Time < 360 minutes
540	107	360 minutes <= Soak Time < 720 minutes
720	108	720 minutes <= Soak Time

We have adapted and applied soak time adjustments used in MOBILE6.2 for gasoline-fueled vehicles, as shown in Table 27. Additionally, all pre-1981 model year passenger cars and trucks use the catalyst equipped soak curve adjustments, although some of these vehicles are not catalyst equipped.

Table 27. Calculated soak-time adjustments, derived from MOBILE6 soak-time coefficients for catalyst-equipped vehicles.

opModeID	Soak period (min)	Adjustment		
		HC	CO	NOx
101	3	0.051	0.034	0.093
102	18	0.269	0.194	0.347
103	45	0.525	0.433	0.872
104	75	0.634	0.622	1.130
105	105	0.645	0.728	1.129
106	240	0.734	0.791	1.118
107	540	0.909	0.914	1.053
108	720	1.000	1.000	1.000

Model-year groups used to calculate start rates for vehicles in model year 1995 and earlier are shown in Table 28. In some cases, model-year groups were adjusted to compensate for sparsity of data in narrower groups. For example, the average NOx emissions for MY 1983-1985 trucks are slightly negative. This result is possible, but is likely due to erratically behaving means from small samples. Thus, these model years were grouped with the 1981-1982 model years, which for trucks had similar emission standards. In addition, the MY1994-1999 gasoline truck sample includes a very high-emitting vehicle, which strongly influences the results for CO. To compensate, these vehicles were grouped with the 1990-1993 model years. The values in the table represent the difference of Bag-1 minus Bag-3, adjusted, as described above, to estimate cold-start emissions.

Table 28. Cold-start emissions (Bag 1 – Bag 3,) for gasoline-powered cars and trucks

Model-year Group Years	*n*	Mean (g)			Standard deviation (g)			CV-of-the-Mean (RSE)		
		THC	***CO***	***NOx***	***THC***	***CO***	***NOx***	***THC***	***CO***	***NOx***
Cars										
1960-1980	1,488	5.172	75.832	0.608	6.948	83.812	2.088	0.035	0.029	0.089
1981-1982	2,735	3.584	52.217	1.118	7.830	60.707	1.682	0.042	0.022	0.029
1983-1985	2,958	2.912	34.286	0.922	5.216	44.785	1.321	0.033	0.024	0.026
1986-1989	6,837	2.306	21.451	1.082	2.740	32.382	1.034	0.014	0.018	0.012
1990-1993	3,778	1.910	17.550	1.149	1.728	13.953	1.034	0.015	0.013	0.015
1994-1995	333	1.788	16.233	1.027	1.203	31.648	0.742	0.037	0.107	0.040
Trucks										
1960-1980	111	9.008	115.849	0.155	9.179	113.269	2.682	0.097	0.093	1.641
1981-1985	910	4.864	94.608	0.0412	4.992	67.871	1.797	0.034	0.024	1.445
1986-1989	1192	3.804	45.918	2.107	2.298	36.356	2.152	0.017	0.023	0.030
1990-1995	1755	3.288	40.927	2.192	4.211	42.478	2.158	0.031	0.025	0.024

1.4.2 Subgroup 2: Vehicles manufactured in MY1996 and later

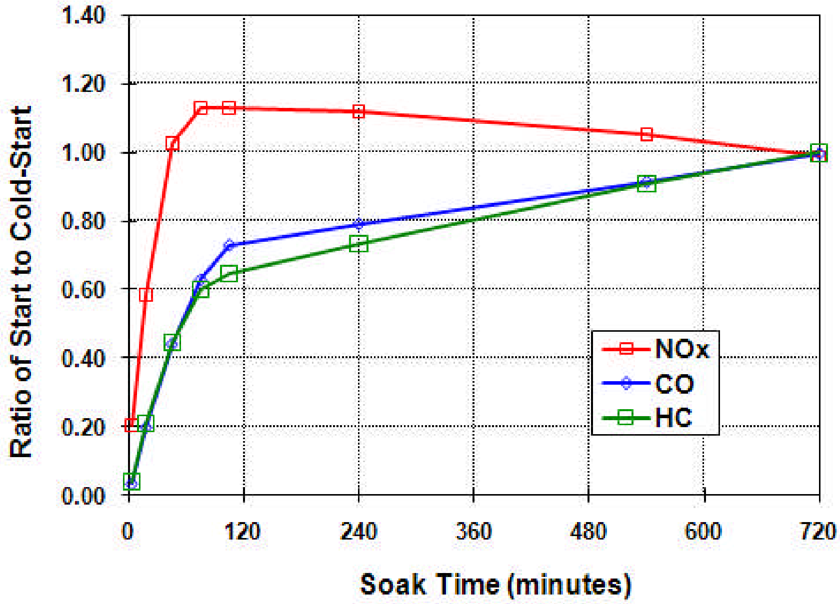
Start rates for vehicles manufactured in model year 1996 and later were estimated using data from the EPA In-use Verification Program (IUVP), as with running rates for MY 2001 and later (see 1.3.4 above).

For model years 1996-2000, rates for vehicles at 0-3 years of age (ageGroup=0003), are shown above in Table 22, in the row for MY2000.

For MY 2001 and later, cold-start rates (opModeID=108) were estimated as described in 1.3.4 above, using the data and approaches described in steps 1-4 and step 6 (as described on page 60). We applied the FTP averages as shown in Figure 26 and Figure 27, and the phase-in assumptions shown in Figure 28, Figure 29, Figure 30, Figure 31 and Figure 32. As with running emissions, Figure 33 illustrates the calculation of weighted average FTP results by model year.

To estimate start emissions for the remaining seven operating modes, we applied "soak fractions" to the "cold-start" emissions, as described above. The soak fractions were adapted from the approach applied in the MOBILE model[20]. Specifically, the part-wise regression equations used in MOBILE6 for "conventional catalyst" engines were evaluated at the midpoint of the soak period for each operating mode. For each mode, the start rate is the product of the cold-start rate and the corresponding soak fraction. Figure 43 shows the soak fractions for HC, CO and NOx, with each value plotted at the midpoint of the respective soak period.

Figure 43. Soak Fractions Applied to Cold-Start Emissions (opModeID = 108) to Estimate Emissions for shorter Soak Periods (operating modes 101-107).



1.4.3 Applying Deterioration to Starts

1.4.3.1 Assessing Start Deterioration in relation to Running Deterioration

The large datasets used to develop rates for running emissions provided much information about deterioration for hot-running emissions, but no information on deterioration for start emissions. After some consideration, it occurred to us that the data from the IUVP program, used to develop running rates for NLEV and Tier-2 vehicles, could also be useful to evaluate the relationship between deterioration trends for start and running emissions. A valuable aspect of these data is that they provide FTP results with the measurement phases separated. As before, we focused on cold-start emissions, calculated as Bag1 - Bag3 (g), and hot-running emissions, represented by Bag2 (g/mi). For this purpose, these data are also valuable because they provide emissions measured over a wide range of mileage, up to 100,000 mi, although the corresponding range of vehicle age is relatively narrow (0-5 years). Thus, we elected to evaluate trends in emissions vs. mileage.

At the outset, we plotted the data for NMOG and NOx vs. odometer reading, on linear and natural log scales. Scatterplots of start and running NMOG emissions are shown in Figure 44 and Figure 45; corresponding plots for lnNMOG are shown in Figure 46 and Figure 47. Similarly, scatterplots of start and running NOx emissions are shown in Figure 48 and Figure 49; corresponding plots for lnNOx are shown in Figure 49 and Figure 50.

In viewing the data, some observations are apparent. The data are grouped, with one group representing vehicles measured at less than 50,000 miles, centered around 10,000-20,000 miles, and a second group representing vehicles measured at 50,000 to 100,000 miles. Given the purpose of the IUVP program, the two groups are designed to assess compliance with certification (< 50,000 mi) and useful-life (>50,000 mi) standards, respectively. As expected, distributions of emissions are skewed, but with running emissions more skewed than start emissions. In the log plots, the degree of skew is shown by the variability of the transformed data, with the ln(start) spanning 3-3.5 factors of e, and the ln(running) spanning 6-7 factors of e. Finally, and of most relevance to this analysis, deterioration trends are visible in the ln plots, with the masses of points at >50,000 miles centered higher than those for < 50,000 miles.

To assess the presence of trends in emissions and mileage more rigorously, we ran linear statistical models on the ln-transformed data. To illustrate, we will focus on models run on vehicles certified to LEV standards, as shown in Table 31 and Table 32. The model structure includes a uniform intercept for all vehicle classes (LDV, LDT1-4), with separate intercepts for each vehicle class. All parameters are highly significant, both for lnNMOG and lnNOx. A more complex model structure was attempted, which included individual mileage slopes for different vehicle classes. However, this model was not retained, as it did not improve the fit, nor were the interaction terms themselves significant. The covariance structure applied was simple, in that a single residual error variance was fit for all vehicle classes.

Models were fit to vehicles certified to other standards, such as ULEV and Tier-2/Bin-5, the results for which are not shown here. The models for ULEV show very similar patterns to those for LEV, whereas the models fit to Bin5 data were not considered useful as the range of mileage covered for these more recent vehicles was not wide enough to demonstrate deterioration trends (i.e., < 25,000 mi).

The models confirm the visual impression given by the plots of lnNMOG and lnNOx. Positive trends in emissions do appear evident in these data, but the increase in emissions with mileage is very gradual. The trends in lnNOx are steeper than those for lnNMOG, and the trends for running emissions are steeper than those for start emissions. For lnNOx, the running slope is 1.65 times that for starts, and for lnNMOG, the running slope is 1.25 times that for starts.

Figure 44. Cold-start FTP emissions for NMOG (g) vs. Odometer (mi), for LEV vehicles, from the IUVP program

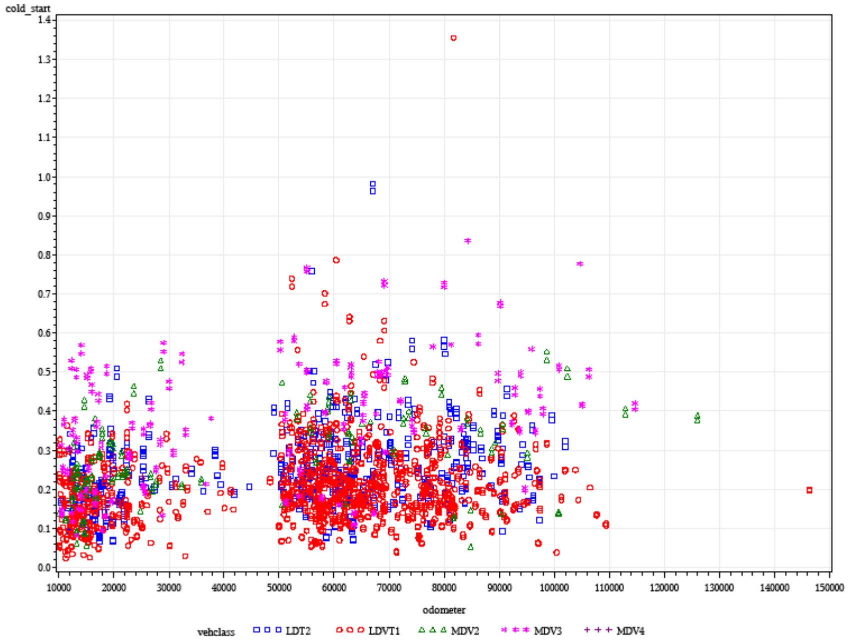


Figure 45. Hot-running (Bag 2) FTP emissions for NMOG (g/mi) vs. Odometer (mi), for LEV vehicles, from the IUVP program

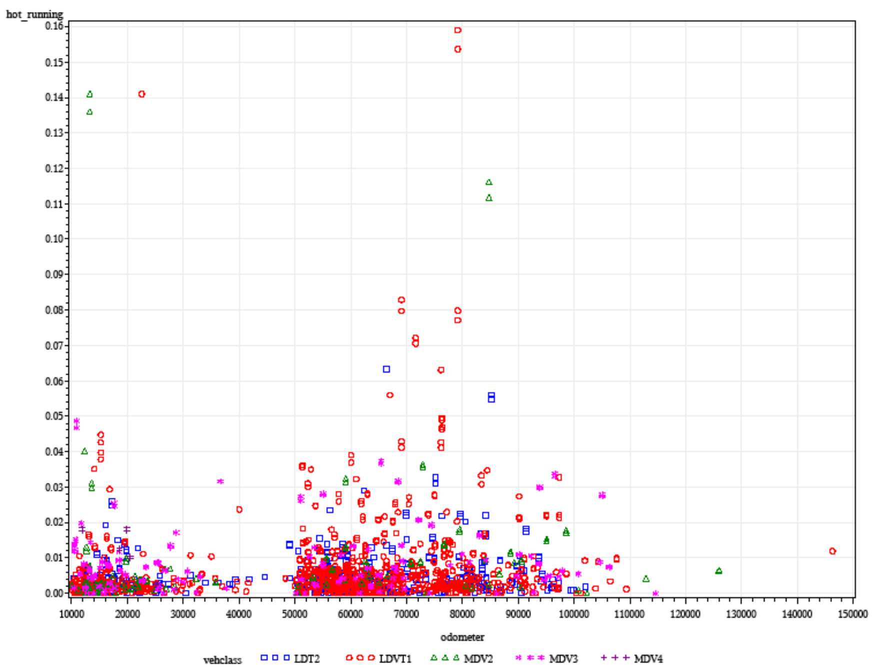


Figure 46. Cold-start FTP emissions for ln(NMOG) vs. Odometer (mi), for LEV vehicles, from the IUVP program

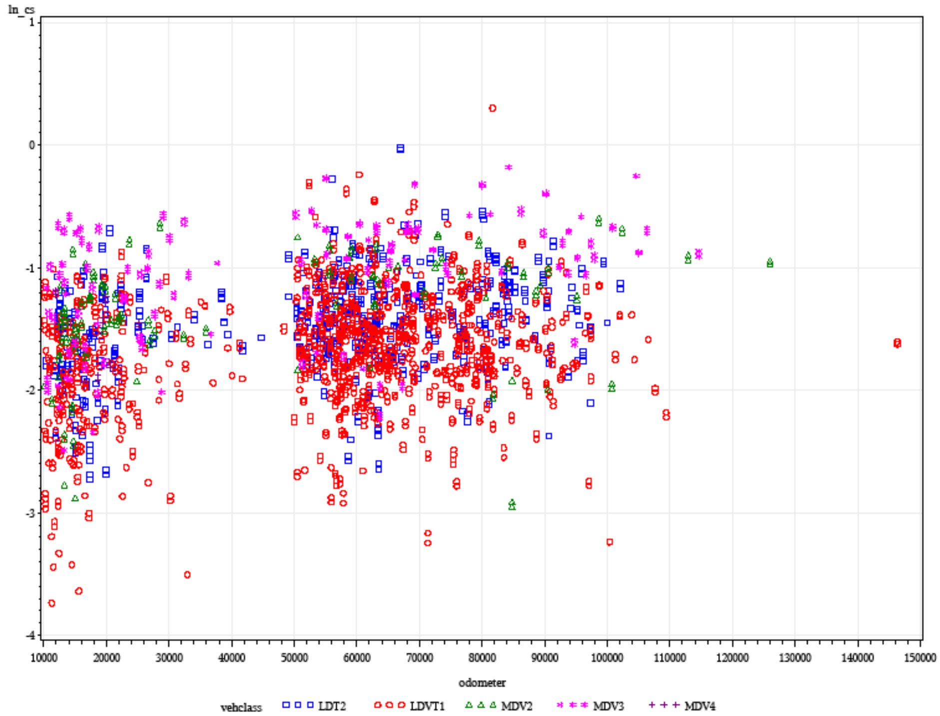


Figure 47. Hot-running (Bag 2) FTP emissions for ln(NMOG) vs. Odometer (mi), for LEV vehicles, from the IUVP program

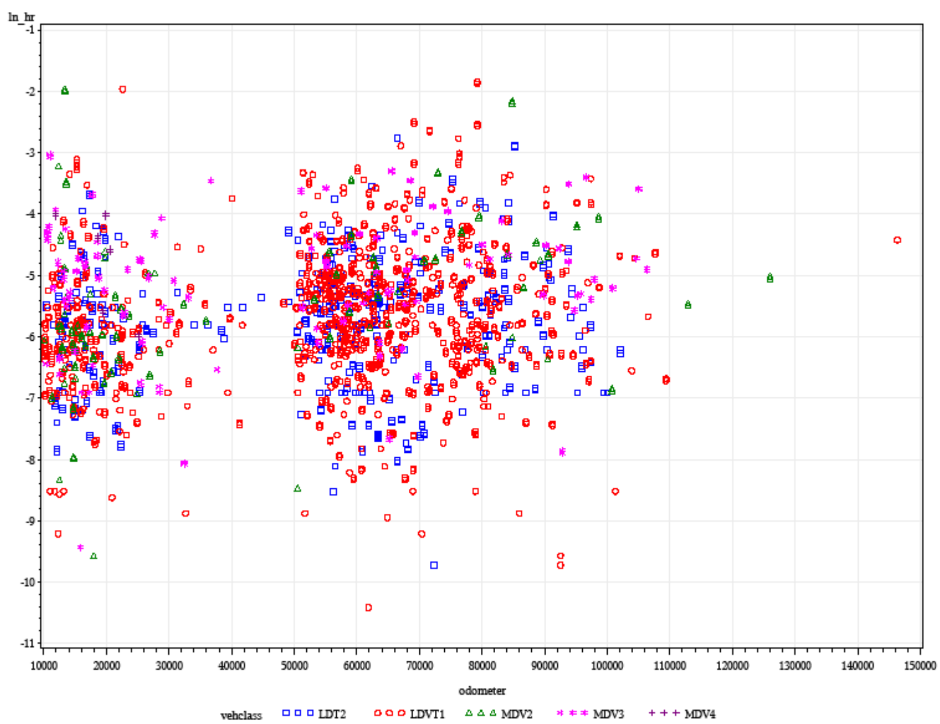


Figure 48. Cold-start FTP emissions for NOx (g) vs. Odometer (mi), for LEV and ULEV vehicles, from the IUVP program

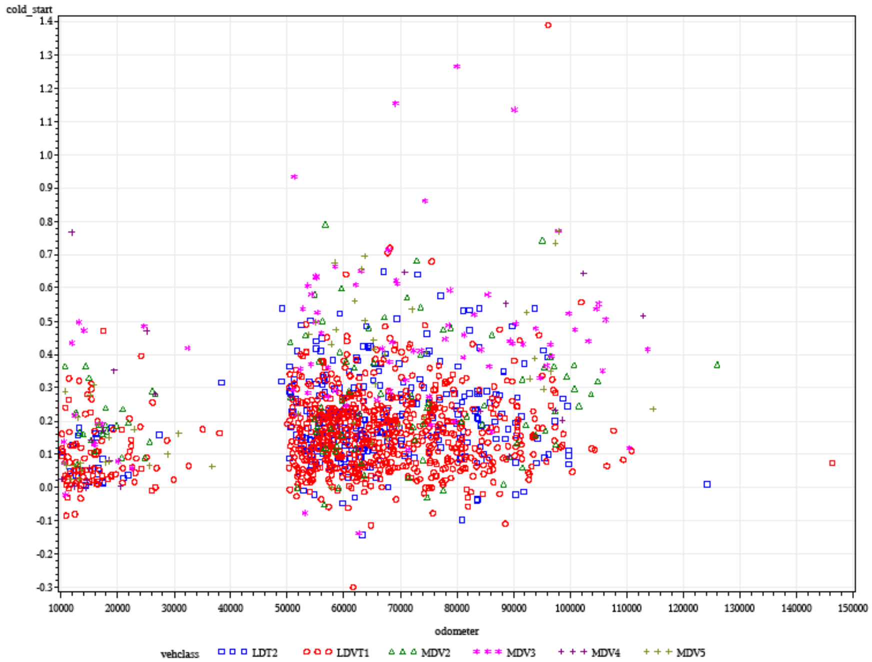


Figure 49. Hot-running (Bag 2) FTP emissions for NOx (g/mi) vs. Odometer (mi), for LEV and ULEV vehicles, from the IUVP program

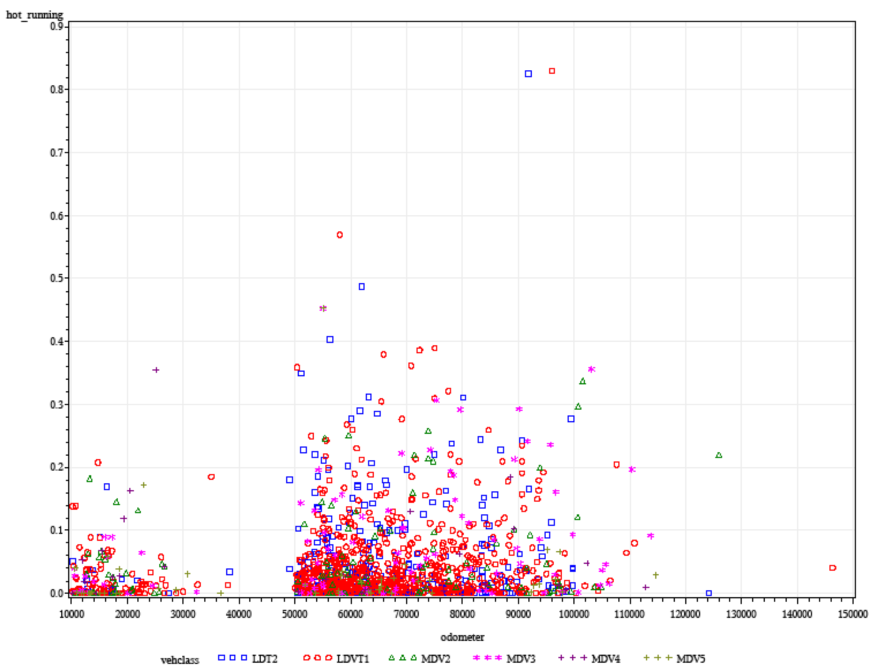


Figure 50. Cold-start FTP emissions for ln(NOx) vs. Odometer (mi), for LEV vehicles (Source: IUVP program).

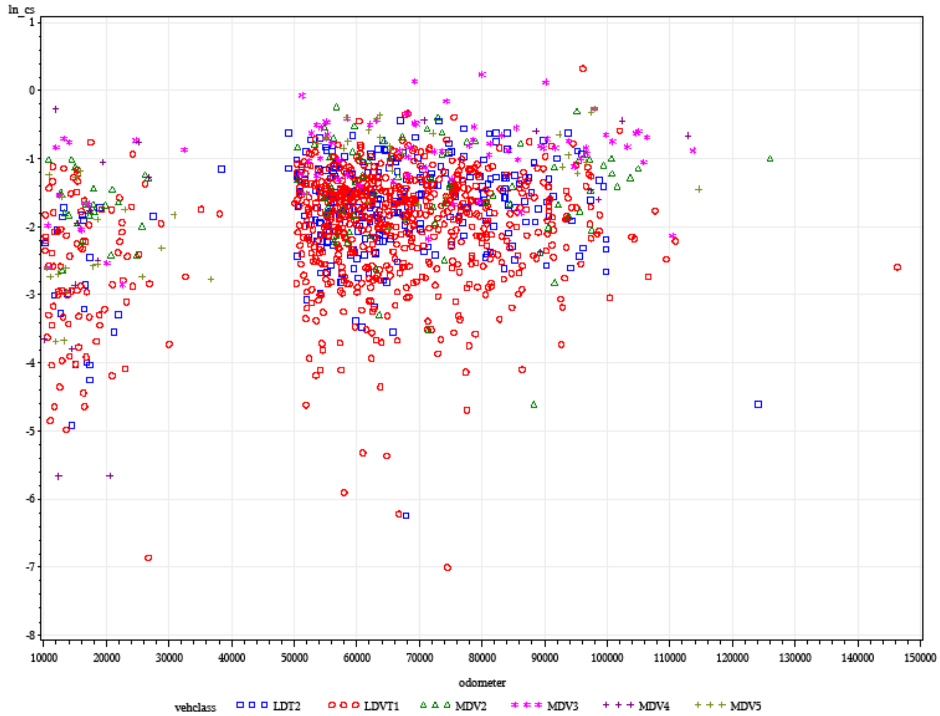


Figure 51. Hot-running (Bag 2) FTP emissions for ln(NOx) vs. Odometer (mi), for LEV vehicles (source: IUVP program).

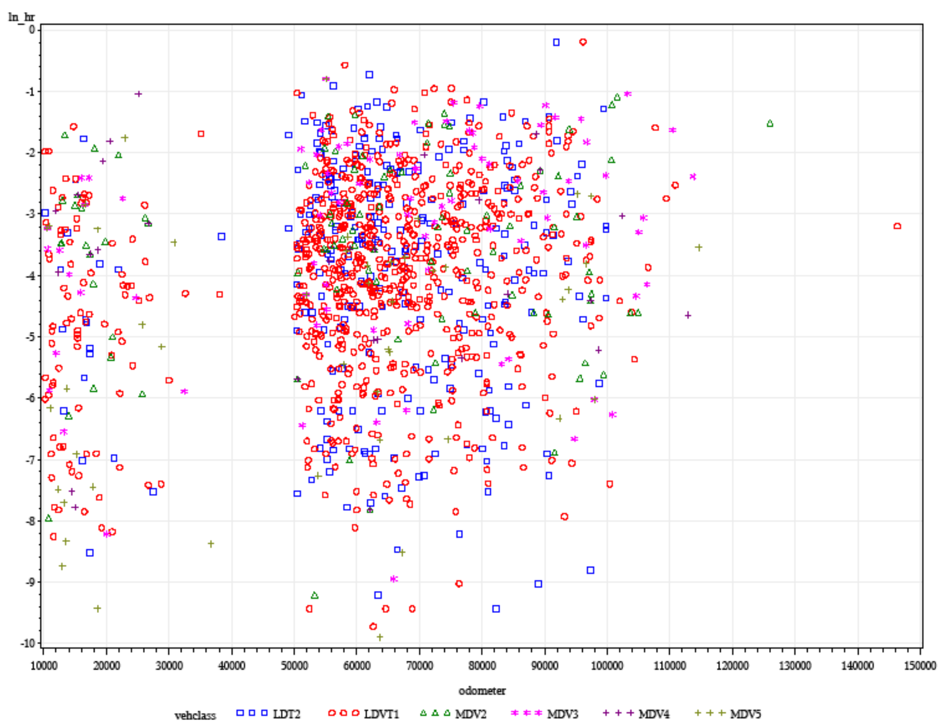


Table 29. Model fit parameters for lnNMOG, for LEV vehicles

Parameter	Predictor	Estimate	Standard error	Denom. D.F.	*t*-value	Pr > *t*
Cold-Start (Bag 1 – Bag 3) (residual error = 0.1942)						
Slope	Odometer (mi)	0.000004982	0.0	2,404	∞	<0.0001
intercept	LDV-T1	-1.9603	0.02224	2,404	-88.14	<0.0001
intercept	LDT2	-1.7353	0.02429	2,404	-71.43	<0.0001
intercept	LDT3 (MDV2)	-1.5735	0.03520	2,404	-44.70	<0.0001
intercept	LDT4 (MDV3)	-1.2937	0.03233	2,404	-40.01	<0.0001
Hot-Running (Bag 2) (residual error = 1.3018)						
Slope	Odometer (mi)	0.000008237	0.0	2,225	∞	<0.0001
intercept	LDV-T1	-6.1604	0.05961	2,225	-103.34	<0.0001
intercept	LDT2	-6.2554	0.06577	2,225	-95.11	<0.0001
intercept	LDT3 (MDV2)	-5.9018	0.09239	2,225	-63.88	<0.0001
intercept	LDT4 (MDV3)	-5.5949	0.08766	2,225	-63.83	<0.0001

Table 30. Model fit parameters for lnNOx, LEV+ULEV vehicles ,

Parameter	Predictor	Estimate	Standard error	Denom. D.F.	*t*-value	Pr > *t*
Cold-Start (Bag 1 – Bag 3) (residual error = 0.68)						
Slope	Odometer (mi)	0.000009541	0.0	1,657	∞	<0.0001
intercept	LDV-T1	-2.6039	0.05231	1,657	-50.74	<0.0001
intercept	LDT2	-2.4538	0.06056	1,657	-40.52	<0.0001
intercept	LDT3 (MDV2)	-2.0769	0.08173	1,657	-25.41	<0.0001
intercept	LDT4 (MDV3)	-1.645	0.08882	1,657	-18.52	<0.0001
Hot-Running (Bag 2) (residual error = 2.9643)						
Slope	Odometer (mi)	0.000012	0.00000165	1,622	7.13	<0.0001
intercept	LDV-T1	-4.7396	0.1092	1,622	-43.40	<0.0001
intercept	LDT2	-4.9527	0.1304	1,622	-37.98	<0.0001
intercept	LDT3 (MDV2)	-4.3144	0.1740	1,622	-24.80	<0.0001
intercept	LDT4 (MDV3)	-4.1214	0.1835	1,622	-22.47	<0.0001

Having drawn these conclusions, we developed an approach to apply them to emission rate development. To begin, we applied the statistical models by calculating predicted values of lnNMOG and lnNOx at mileages from 0 (the intercept) to 155,000 miles. We reverse-transformed the models using Equation 30 (page 32) to obtain predicted geometric and arithmetic means with increasing mileage, as shown in Table 31for NMOG and Table 32 for NOx.

We normalized the predicted means at each mileage to the value at 0 miles to obtain a "deterioration ratio" R_{det}, by dividing each predicted value at a given mileage by the predicted value at 0 miles (i.e., the intercept); R_{det} for the intercept = 1.0 (Equation 43).

$$R_{\text{det}} = \frac{\bar{x}_{a,\text{miles}}}{\bar{x}_{a,0}} \qquad \textbf{Equation 43}$$

We took this step to express start and running trends on a comparable relative multiplicative basis, as trends in absolute running and start emissions are clearly not comparable.

Finally, to relate start and running trends, we calculated the ratio in R_{det} for start to that for running, designated as R_{rel}

$$R_{\text{rel}} = \frac{R_{\text{det,start}}}{R_{\text{det,running}}} \qquad \textbf{Equation 44}$$

Values or R_{det} and R_{rel} for NMOG and NOx are shown in Table 31 and Table 32, respectively, with corresponding results shown graphically in Figure 52 and Figure 53, respectively.

Table 31. Application of Models for NMOG, representing emissions trends for LDV-T1 vehicles certified to LEV standards.

Parameter	Odometer (mi, ×10,000)								
	0	*1.5*	*2.5*	*3.5*	*4.5*	*5.5*	*6.5*	*7.5*	*8.5*
Cold Start									
lnNMOG	-1.960	-1.886	-1.836	-1.786	-1.736	-1.686	-1.636	-1.587	-1.537
Geometric mean	0.141	0.152	0.159	0.168	0.176	0.185	0.195	0.205	0.215
Arithmetic mean	0.156	0.168	0.176	0.185	0.195	0.205	0.215	0.226	0.238
Deterioration ratio (R_{det})	1.000	1.078	1.133	1.190	1.251	1.315	1.382	1.453	1.527
Hot Running									
lnNMOG	-6.160	-6.037	-5.954	-5.872	-5.790	-5.707	-5.625	-5.543	-5.460
Geometric mean	0.00211	0.00239	0.00259	0.00282	0.00306	0.00332	0.00361	0.00392	0.00425
Arithmetic mean	0.00404	0.00458	0.00497	0.00540	0.00586	0.00636	0.00691	0.00750	0.00815
Deterioration ratio (R_{det})	1.000	1.132	1.229	1.334	1.449	1.573	1.708	1.855	2.014
Relative Ratio (R_{rel})	1.000	0.9952	0.922	0.892	0.864	0.836	0.809	0.783	0.758

Table 32. Application of Models for NOx, representing emissions trends for LDV-T1 vehicles certified to LEV standards

Parameter	Odometer (mi, ×10,000)								
	0	*1.5*	*2.5*	*3.5*	*4.5*	*5.5*	*6.5*	*7.5*	*8.5*
Cold Start									
lnNOx	-2.604	-2.461	-2.365	-2.270	-2.175	-2.079	-1.984	-1.888	-1.793
Geometric mean	0.0740	0.0854	0.0939	0.1033	0.1137	0.1250	0.1376	0.1513	0.1665
Arithmetic mean	0.1039	0.1199	0.1319	0.1452	0.1597	0.1757	0.1933	0.2126	0.2339
Deterioration ratio (R_{det})	1.000	1.154	1.269	1.396	1.536	1.690	1.859	2.045	2.250
Hot Running									
lnNOx	-4.740	-4.560	-4.440	-4.320	-4.200	-4.080	-3.960	-3.840	-3.720
Geometric mean	0.0087	0.0105	0.0118	0.0133	0.0150	0.0169	0.0191	0.0215	0.0242
Arithmetic mean	0.0385	0.0461	0.0520	0.0586	0.0660	0.0745	0.0840	0.0947	0.1067
Deterioration ratio (R_{det})	1.000	1.097	1.350	1.522	1.716	1.935	2.181	2.460	2.773
Relative Ratio (R_{rel})	1.000	0.964	0.940	0.918	0.895	0.874	0.852	0.832	0.811

Figure 52. Deterioration Ratios for Cold-Start and Hot-Running NMOG Emissions.

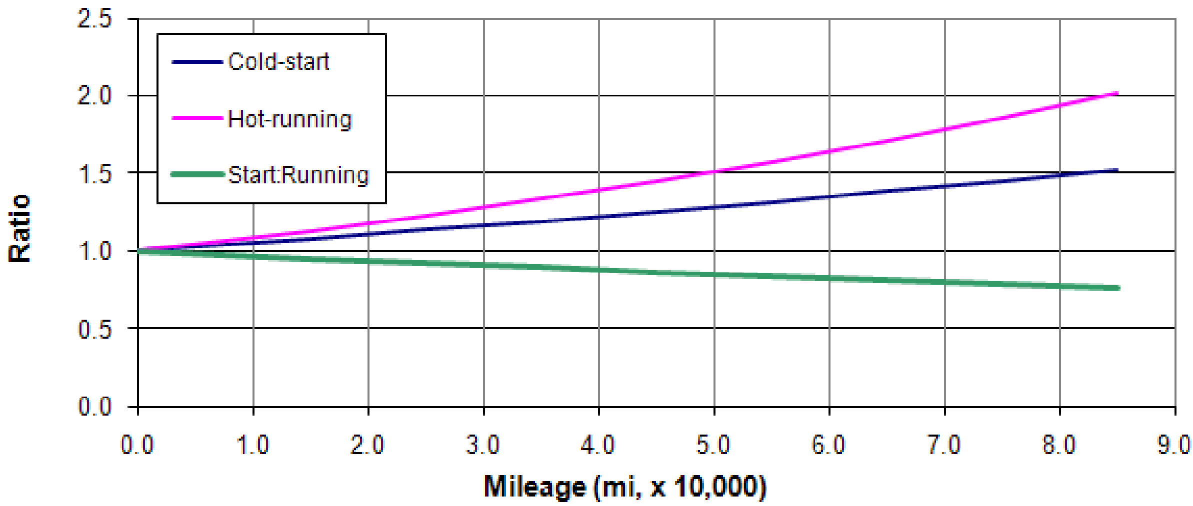
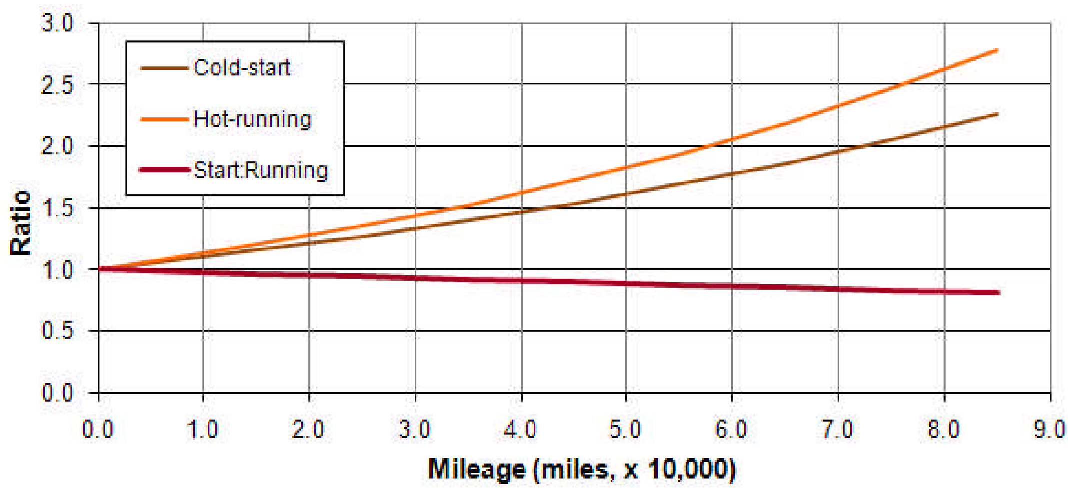


Figure 53. Deterioration Ratios for Cold-Start and Hot-Running NOx Emissions.



For NOx (Figure 53) we decided to assign start NOx the same multiplicative relative deterioration as running NOx. However, for HC, the difference between running and start deterioration was greater, large enough that we reduce to reduce start deterioration relative to running deterioration.

1.4.3.2 Translation from Mileage to Age Basis

The question remained, as to how the results derived from the IUVP data and presented above could be applied during the generation of emission rates. At the outset, a question arises from the fact that the results shown above were generated on the basis of mileage, whereas MOVES

assigns deterioration on the basis of age. It was therefore necessary to translate the R_{rel} from a mileage basis to an age basis. We achieved the translation through a series of steps.
First, we assumed a rate of mileage accumulation of about 10,000 miles per year, from which it follows that the R_{rel} at 125,000 miles would occur at about 12.5 years of age, or would be represented by the 10-14 year ageGroup. Accordingly, we assigned midpoints to the 0-3 and 10-14 year ageGroups of 2 and 12.5 years, respectively, and assume that R_{rel} declines linearly with age. These assumptions allow calculation of a declining trend in the ratio with respect to age. The slope of the trend is the change in ratio (ΔR_{rel}) over the corresponding change in time (Δtime).

$$m_{R\text{rel}} = \frac{\Delta R_{\text{rel}}}{\Delta \text{time}} = \frac{0.675 - 1.0}{12.5 - 2} = \frac{-0.325}{10.5} = -0.30952 \qquad \textbf{Equation 45}$$

The calculation of the slope lets us estimate a value of R_{rel} for each ageGroup.

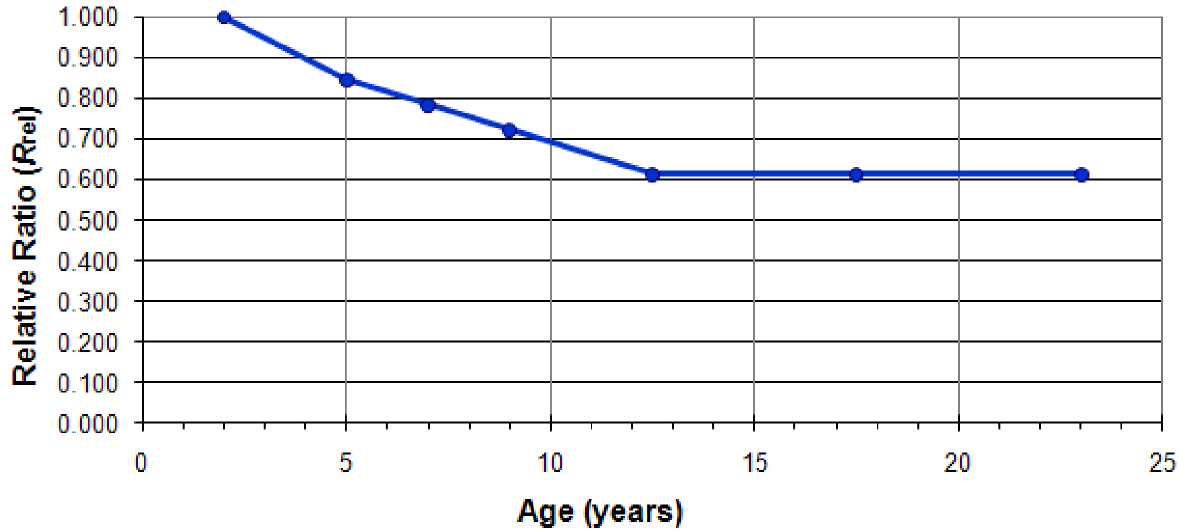
$$R_{\text{rel,age}} = 1.000 - m_{R\text{rel}}\text{age} \qquad \textbf{Equation 46}$$

The results, as applied for hydrocarbons and CO, are shown in Table 33 and Figure 54. The net result is a 15-40% reduction in multiplicative start deterioration, relative to running deterioration.

Table 33. Relative deterioration ratios (Rrel), for NMOG (and CO), assigned to each ageGroup.

AgeGroup	Age (years)	Relative Ratio (R_{rel})
0-3	2	1.000
4-5	5	0.845
6-7	7	0.783
8-9	9	0.721
10-14	12.5	0.613
15-19	17.5	0.613
20 +	23	0.613

Figure 54. Relative Deterioration Ratios (Rrel), for NMOG (and CO), assigned to each ageGroup.



1.4.3.3 Application of Relative Multiplicative Deterioration

An advantage of the modal approach is that any driving cycle can be represented as a weighted average of the MOVES emission rates and the “operating-mode distribution” for the cycle. In this case, we applied an operating-mode distribution for the “hot-running” phase of the FTP. This phase is 860 seconds long that represents urban driving over a 3.86 mile route after the engine has stabilized at its normal operating temperature. We estimated an operating-mode distribution using the “*Physical Emission Rate Simulator*” (PERE)[16]. This distribution, shown in Table 34, represents a “typical” car, with engine displacement and test weight of 2.73 L and 3,350 lb. A corresponding “typical” truck was represented with displacement and test weight of 4.14 L and 4,364 lb, respectively.

Combining emission rates for hot-running emissions with the operating-mode distributions, we calculated aggregate cycle emissions for the second hot-running phase of the FTP (g/mi), for all model-year and age groups. Figure 55 and Figure 56 show resulting cycle aggregates for THC and NOx. Note that the underlying rates for model years 1995 (representing Tier 0) and 2000 (representing Tier 1) were derived using data and methods described above in Section 1.3.3 (starting on page 15), and those for model years 2005 and 2010 were derived using data and methods described above in Section 1.3.4 (starting on page 60).

It is important to note that this step is performed both for vehicles in inspection-and-maintenance areas (I/M, using the meanBaseRateIM) and for vehicles outside I/M areas (using meanBaseRate). Because deterioration is represented differently for the non-I/M and I/M reference rates (see 1.3.3.7.2, page 58), and this difference is carried into deterioration for the start rates, the result is that the MOVES rates represent that I/M programs have effects on start as well as running emissions.

$$R_{\mathrm{det,MYG,Age}} = \frac{\overline{E}_{\mathrm{FTP2,MYG,Age}}}{\overline{E}_{\mathrm{FTP2,MYG,0-3}}}$$ **Equation 47**

Table 34. Operating-mode distributions for running emissions, representing a "typical" car and truck on the hot-stabilized phase of the FTP (Bag 2).

opModeID	Cars (LDV)		Trucks (LDT)	
	Time in mode (sec)	*Time in mode* (%)	*Time in mode* (sec)	*Time in mode* (%)
0	97	11.27	97	11.27
1	155	18.00	155	18.00
11	77	8.94	74	8.59
12	121	14.05	112	13.01
13	83	9.64	88	10.22
14	59	6.85	66	7.67
15	22	2.56	19	2.21
16	4	0.46	7	0.81
21	42	4.88	41	4.76
22	111	12.89	102	11.85
23	62	7.20	69	8.01
24	18	2.09	21	2.44
25	7	0.81	7	0.81
27	2	0.23	2	0.23
28	0	0.00	0	0.00
29	0	0.00	0	0.00
30	1	0.12	1	0.12
33	0	0.00	0	0.00
35	0	0.00	0	0.00
37	0	0.00	0	0.00
38	0	0.00	0	0.00
39	0	0.00	0	0.00
40	0	0.00	0	0.00

Figure 55. Cycle-aggregate THC emission rates by age, projected from MOVES running-exhaust emission rates, for the hot-stabilized phase of the FTP, representing vehicles in I/M areas.

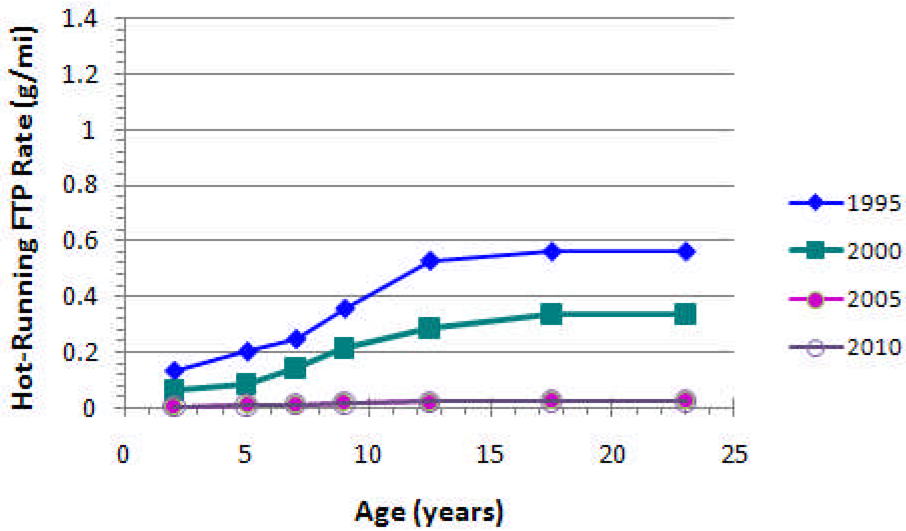
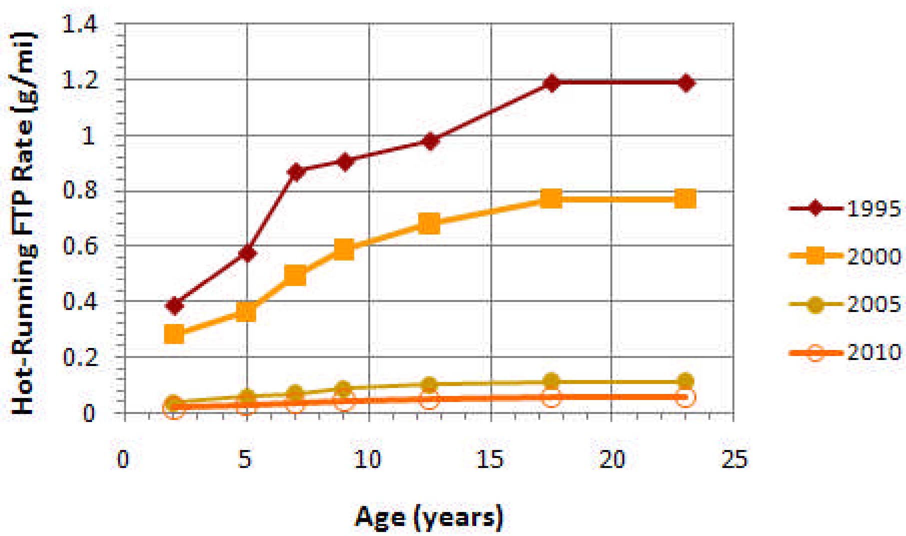


Figure 56. Cycle-aggregate NOx emission rates by age, projected from MOVES running-exhaust emission rates, for the hot-stabilized phase of the FTP, representing vehicles in I/M areas.



For each model-year group, we divided cycle aggregate for each ageGroup ($E_{\mathrm{FTP2,MYG,Age}}$) by the estimate for the 0-3 year ageGroup ($E_{\mathrm{FTP2,MYG,0\text{-}3}}$), to obtain a deterioration ratio ($R_{\mathrm{det,MYG,Age}}$) as shown in Equation 47. As examples, ratios for cars are shown for THC in Figure 57(I/M) and Figure 59 (non-I/M). Corresponding ratios for NOx are shown in Figure 59 (I/M) and Figure 60 (non-I/M). The ratios show that, in relative multiplicative terms, the MOVES rates represent greater deterioration for running exhaust THC than for NOx.

Figure 57. Deterioration Ratios for THC, representing the hot-stabilized phase of the FTP (Bag 2), Representing vehicles in I/M areas.

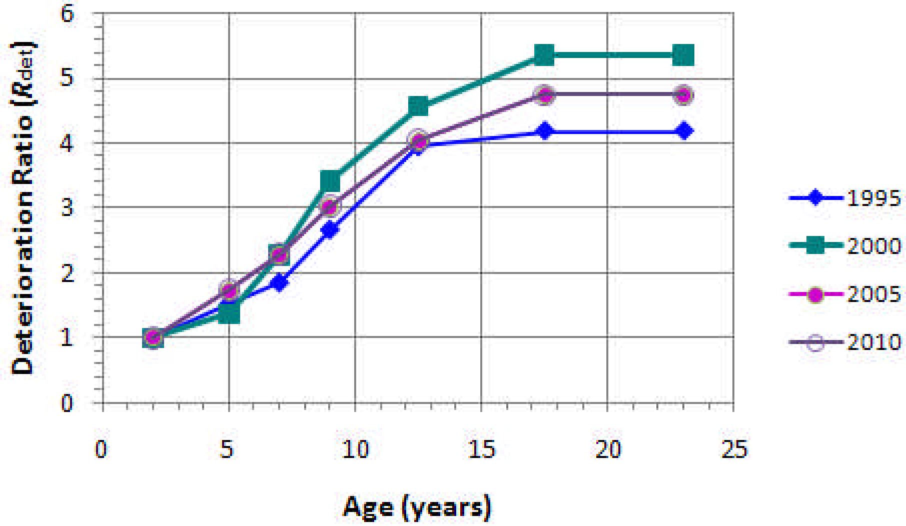


Figure 58. Deterioration Ratios for THC, representing the hot-stabilized phase of the FTP (Bag 2), Representing vehicles in non-I/M areas.

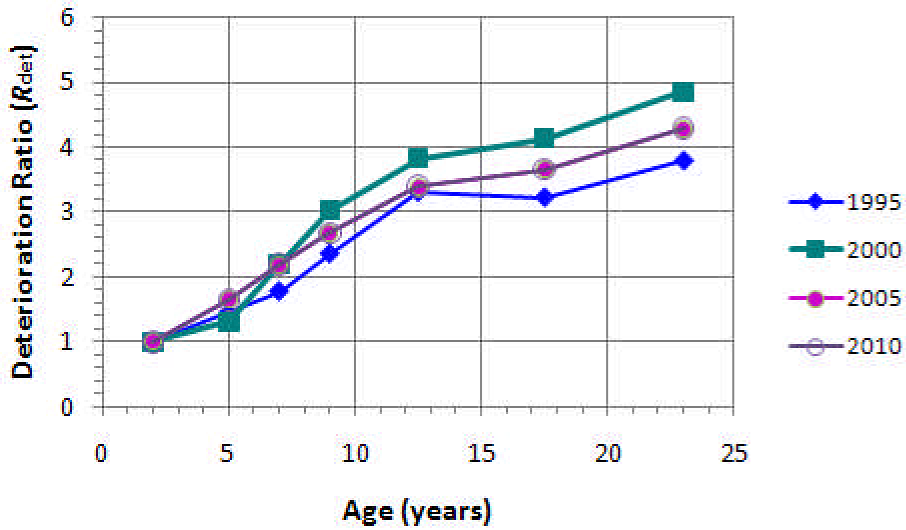


Figure 59. Deterioration Ratios for NOx, representing the hot-stabilized phase of the FTP (Bag 2), representing vehicles in I/M areas.

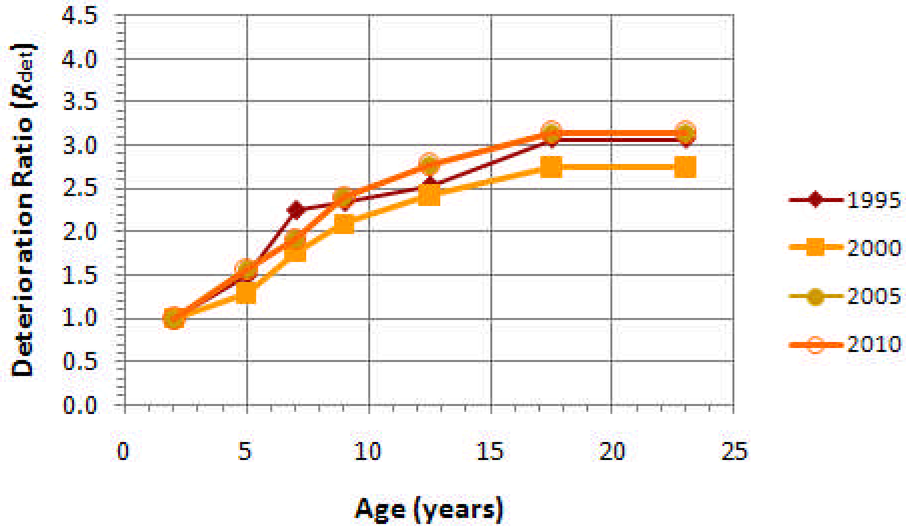
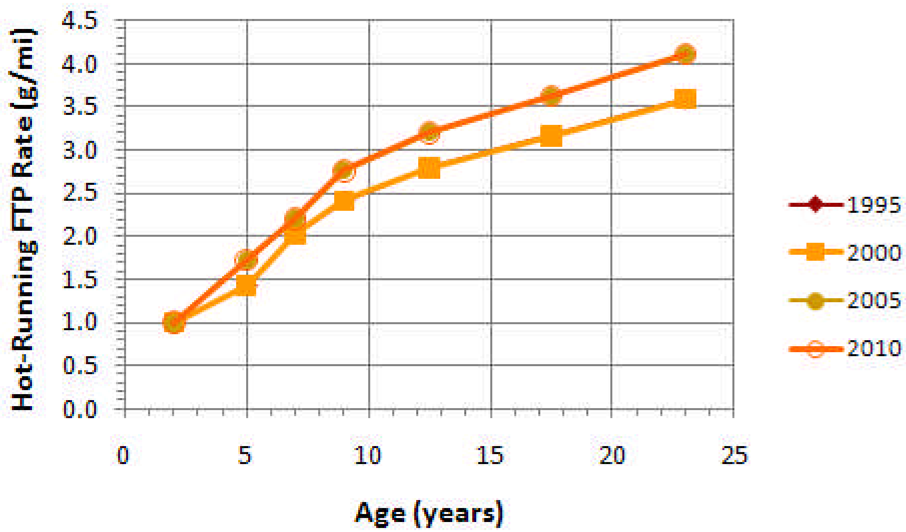


Figure 60. Deterioration Ratios for NOx, representing the hot-stabilized phase of the FTP (Bag 2), representing vehicles in non-I/M areas.



At this point, projecting deterioration for start emissions is a simple matter of multiplying the start rate for the 0-3 year ageGroup in each relevant operating mode (opModeID =101-108) by the deterioration ratio (R_{det}) and the relative deterioration ratio (R_{rel}) for each ageGroup. The projected start rate in each agegroup ($E_{\text{start,age}}$) is

$$E_{\text{start,age}} = E_{\text{start},0-3} R_{\text{det,age}} R_{\text{rel,age}}$$ **Equation 48**

Note that for NOx the values of R_{rel} are 1.0 for all agegroups, i.e., relative multiplicative deterioration for start emissions is the same as for running emissions. For THC and CO, however, R_{rel} takes the values shown in Table 33, which reduces reduced relative start emissions in comparison to relative running emissions. To illustrate the results, Figure 61 and Figure 62 show deterioration for cold-start emissions (opModeID=108) for THC and NOx, respectively.

Figure 61. Projected Deterioration for Cold-start THC Emissions (opModeID=108), in four Model years, representing vehicles in I/M areas.

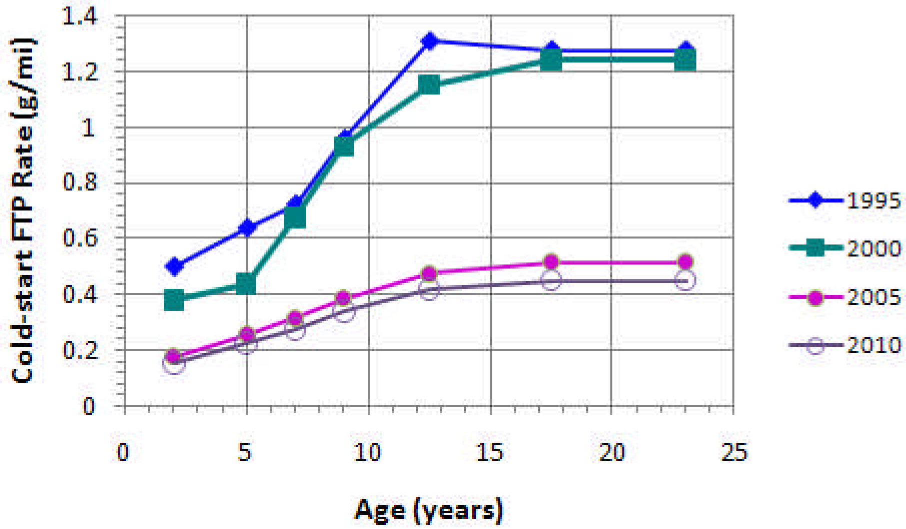
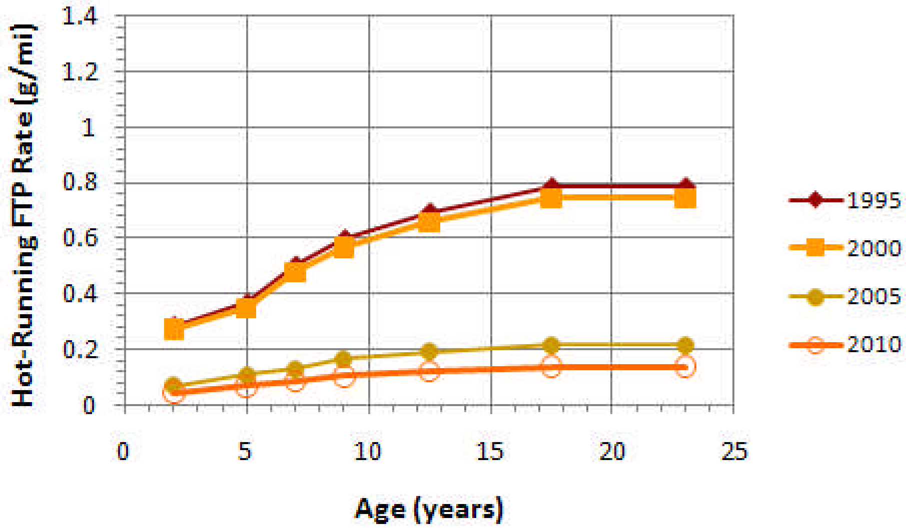


Figure 62. Figure 63. Projected Deterioration for Cold-start NOx Emissions (opModeID=108), in four Model years, representing vehicles in I/M areas.



1.7 Replication and Data-Source Identification

The rates developed as described in Section 1 represent gasoline-fueled conventional-technology engines. For purposes of the draft version of the emissionRateByAge table, we replicated these rates to represent other fuels and technologies.

At the outset, we replicated the entire set of gasoline rates for ethanol blends. However, for ethanol blends, the effect of ethanol (and other effects related to blending) is represented through fuel adjustments, rather than through the base rates, as described in this document. The development and application of fuel adjustments is described in a separate document[34].

Table 35. Fuel types and Engine technologies represented for gaseous-pollutant emissions from light-duty vehicles.

Attribute	sourceBin attribute	Value	Description
Fuel type	fuelTypeID	01	Gasoline
		02	Diesel
		05	Ethanol
Engine Technology	engTechID	01	Conventional internal combustion (CIC)
		30	Electric

Throughout the process, we assigned dataSourceIDs to subgroups of rates, which identify the data and methods used to develop particular subsets of rates. The dataSourceIDs developed for these analyses are listed and described in Table 36. Note that the table also lists the numbers of records in each dataSourceID and relevant report section describing rate development for each dataSourceID.

Finally, Table 37 shows the accounting for all rates developed for light-duty gaseous-pollutant emissions and included in the emissionRateByAge table. The leftmost four columns delineate subsets of rates by the pollutant processes included (Running, Start), and the respective fuel types (fuelTypeID), engine technologies (engTechID) and dataSourceIDs. The next seven "accounting" columns show the construction of subtotals corresponding to combinations of fueltype, engtech, and dataSource. The values in these columns represent numbers of groups or categories covered, as follows. Fueltype and engtech always represent single categories, as only one of each is represented in a single row. Two regClasses in each row always refer to two categories, cars (LDV) and trucks (LDT). The numbers of model-year groups (MYG), age groups and operating modes (opModes) covered varies with combinations of process and dataSource. Each row always represents the three gasous pollutants (CO, THC and NOx).

The rates for datasourceID = 4400 – 4601 were summed as a single category, as these groups represent the outcome of a set of interrelated processes, as described in "Section 1.3.3 Emission-Rate development: Subgroup 1 (Model years through 2000)." The count of 15 modelyeargroups includes MY 2000 and earlier. The dataSourceIDs 4800 and 4801 represent running emissions for MY 2001+, as described in "Section 1.3.4 Emission-Rate Development:

Subgroup 2 (MY 2001 and later)." For these rows, a count of one agegroup refers to the 0-3 year ageGroup, whereas a count of three refers to the 4-5, 6-7, and 8-9 year ageGroups.
For these rates, the total of 21modelyeargroups represent groups 2001 – 2021-2050.

DataSourceIDs 4805 – 4807 represent start emissions for MY2001 – 2031-2050. For these groups, counts of 26 or 36 modelyeargroups denote MY 1996-2031 and 1980 and earlier - 20212050, respectively. Counts of one or six ageGroups refer to the 0-3 ageGroup and the remaining six ageGroups, respectively. Counts of one or seven opModes refer to the cold-start emissions (opmode 108) or the remaining seven start modes, respectively.

The dataSourceID 4900 refer to the replication of the gasoline/conventional rates to provide base rates for ethanol blends. The Count of 36 modelyeargroups includes all groups from 1980 & earlier through 2021-2050. The count of 31 opModes includes all modes for both the start and running processes; 8 modes for start emissions and 23 modes for running emissions.

The count for dataSourceID 4910 is similar, except that the 12 modelyeargroups include only 2010 – 2021-2050, as mentioned previously.

Table 36. Description of data sources and methods used in development of gaseous-pollutant emission rates for light-duty vehicles.

DataSourceID	Description	No. Records	Report Section
4400	Data driven rates: averaged from continuous (second-by-second) IM240/IM147 data from Phoenix random evaluation sample, CY1995-99 and CY2002-05, on temperature range of 68-86 °F.	6,968	
4027	For opModeID = 29,39 only; use meanBaseRateIM calculated by ratio relative to value in opMode 27; neither data mean or model prediction eligible	118	
4037	For opModeID = 30,40 only; use meanBaseRateIM calculated by ratio relative to value in opMode 27; neither data mean or model prediction eligible.	252	
4427	For opModeID = 29,30,39,40 only; use meanbaseRatIM calculated by ratio realative to value in opMode 27; either data mean or model prediction, or both is eligible	138	
4500	imputed using statistical hole-filling models.	3,572	
4527	For opModeID = 29,30,39,40 only; use meanbaseRateIM calculated by ratio relative to value in opMode 27; model prediction eligible, data mean not eligible.	268	
4601	calculated by ratio relative to ageGroup 8-9, ***modelyeargroups 2000 and earlier***, ageGroupID 10-14, 15-19 and 20+ only)	3,174	
SUBTOTAL		**14,490**	
4601	calculated by ratio relative to ageGroup 8-9, ***modelyeargroups 2001 and later***, ageGroupID 10-14, 15-19 and 20+ only)	8,694	
4800	calculated by ratio from MY2000 rates, with ratios calculated from IUVP FTP Bag-2 data, (modelyeargroups 2001 and later only, ageGroup 0-3 only).	2,898	
4801	calculated by applying deterioration to 4800 values, (modelyeargroups 2001 and later only, ageGroups 4-5 through 8-9)	8,694	
4805	calculated from IUVP FTP results, as Bag 1 - Bag 3 mass (cold start, opMode 108 only, ageGroup 0-3 only).	156	
4806	calculated by applying deterioration ratios to 4805 values (cold start, opMode 108 only, ageGroup 4-5 and older).	1,296	
4807	calculated by applying soak fractions and deterioration ratios to 4805 values (opModes 101-107 only, all ageGroups).	10,584	
4900	replicated from gasoline rates (fueltypeid = 1) to represent ethanol blends (fueltypeid = 5).	46,872	
4910	replicated from gasoline rates for all engine technologies to represent rates for tier-2 light-duty diesel engines (MY 2010 and later only).	15,624	

Table 37. Accounting for the segment of the emissionRateByAge table contributed by rates for gaseous-pollutant emissions for light-duty vehicles.

Process(es)	fuelTypeID	engTechID	dataSourceID	Accounting (No. classes or groups)							No. records
				fueltypes	engTechs	regClasses	MYG	ageGroups	opModes	pollutants	
Start	01	01	101	1	1	2	10	1	1	3	60
Running	01	01	4400	1	1	2	15	7	23	3	14,490
Running	01	01	4027								
Running	01	01	4037								
Running	01	01	4500								
Running	01	01	4527								
Running	01	01	4601								
			4601	1	1	2	21	3	23	3	8,694
Running	01	01	4800	1	1	2	21	1	23	3	2,898
Running	01	01	4801	1	1	2	21	3	23	3	8,694
Start	01	01	4805	1	1	2	26	1	1	3	156
Start	01	01	4806	1	1	2	36	6	1	3	1,296
Start	01	01	4807	1	1	2	36	7	7	3	10,584
SUBTOTAL											46,872
Running & start	05	01	4900	1	1	2	36	7	31	3	46,872
Running & start	02	01	4910	1	1	2	12	7	31	3	15,624
TOTAL											109,368

2. Particulate-Matter Emissions from Light-Duty Vehicles

2.1 Introduction and Background

A large body of research is available on the formation and measurement of particulate matter (PM) emissions from combustion engines. This chapter describes the process by which emissions measured in a subset of the PM research programs on light-duty gasoline vehicles was employed to generate emission rates for MOVES. The emission rates developed by this approach embody a strictly "bottom-up" method whereby emission rates are developed from actual vehicle measurements following intensive data analysis, and are then structured as inputs to the emissions inventory model. This is in contrast to a "top-down" approach which uses measurements of ambient PM concentrations from local regions and may apportion these emissions to vehicles (and other sources), which are then input into inventory models.

The primary study that this chapter relies on is the "Kansas City Characterization Study" conducted in 2004-2005[38]. The Environmental Protection Agency and several research partners conducted this study to quantify tailpipe particulate-matter emissions from gasoline-fueled light duty vehicles in the Kansas City Metropolitan Area. This study is the most comprehensive and representative study of its kind. In the context of a rigorous recruitment plan, strenuous efforts were made to procure a representative sampling of the fleet. During the summer and winter phases, 261 and 278 vehicles were measured, respectively, with some overlap between the phases. The measurements were conducted on a portable dynamometer using the LA92 driving cycle under ambient temperature conditions.

Analyses of some of the data from this program are presented in the report: "*Analysis of Particulate Matter Emissions from Light-Duty Gasoline Vehicles in Kansas City*"[39] This "analysis report" (which is the partner to this chapter) presented preliminary emission rates for PM, elemental carbon fraction (EC), organic carbon fraction (OC), as well as temperature adjustment factors for start and hot-running emissions processes. These preliminary results form the basis for the emission rates developed in this chapter. The rates in the analysis report are based on aggregate or "bag" emissions measured on the filters, and are thus presented as grams/start for start emissions and grams/mile for hot running operation.

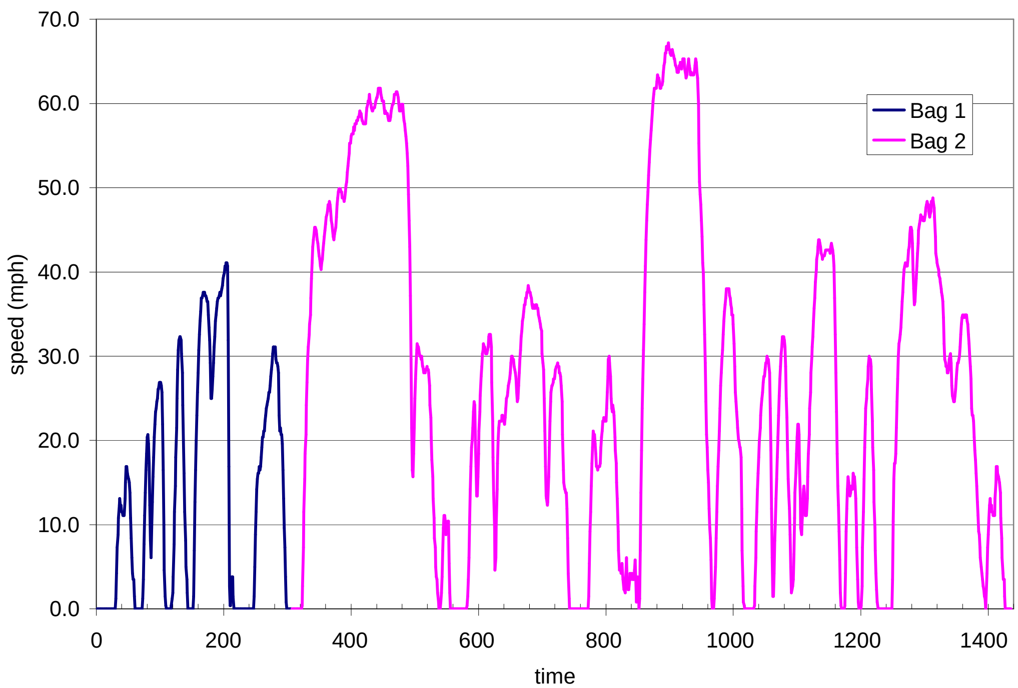
The dataset included vehicles manufactured over several decades, measured at various ages during CY2004-05. Thus, the program taken alone did not enable us to forecast emissions for current vehicles as they age, or to hindcast emissions of older vehicles when they were young. This chapter describes the development of a deterioration model based on a comparison of former PM studies with the 2005 Kansas City study. The rates from this deterioration model allow both forecasting and hindcasting as required by MOVES.

In addition, the previous analyses did not attempt to translate results measured on the LA92 cycle (used in Kansas City) into terms of other cycles (such as the FTP) or to "real-world" driving. As with the gaseous pollutants, MOVES has the capability to represent hot running "modal" emission rates so that emissions vary depending on the driving pattern represented. The operating modes defined for PM are the same as for the gaseous emissions (see Table 5, page 10). This chapter describes how the continuous PM measurements collected in the study were used to populate the modal rates for MOVES. Because of the reliance on continuous PM measurement, it is worth describing the measurement procedures used in Kansas City.

2.1.1 Particulate Measurement in the Kansas City Study

For measurements conducted on the dynamometer, vehicles were operated over the LA92 Unified Driving Cycle (see Figure 64). The LA92 cycle consists of three phases or "bags". Phase 1 ("bag 1") is a "cold start" that lasts the first 310 seconds (1.18 miles). "Cold start" is technically defined as an engine start after the vehicle has been "soaking" in a temperature controlled facility (typically ~72°F) with the engine off. In the Kansas City study, the vehicles were soaked overnight under ambient conditions. Phase 1 is followed by a stabilized Phase 2 or "hot running" (311 – 1427 seconds or 8.63 miles). At the end of Phase 2, the engine is turned off and the vehicle is allowed to "soak" in the test facility for ten minutes. At the end of the soak period, the vehicle is started again, and is driven on the same driving schedule as Phase 1. This Phase 3 is called a "hot start" because the vehicle is started when the engine and after-treatment systems are still hot. Criteria pollutants were measured both in continuous and aggregate modes. Particulate was collected during each of the three phases on 47 mm Teflon filters at 47°C ± 2°C.

Figure 64. Phases 1 and 2 of the LA92 Cycle, representing "cold-start" and "hot-running" operation, respectively.



In addition to the gaseous pollutants measured via the constant-volume sampler (CVS), continuous measurements of total PM mass were taken using two instruments. The first was an Booker Systems Model RPM-101 Quartz-crystal microbalance (QCM) manufactured by Sensors, Inc.; the second was a Thermo-MIE Inc. DataRam 4000 Nephelometer. In addition to total mass, estimated black carbon was measured continuously with a DRI photoacoustic instrument. In addition, integrated samples were collected and analyzed by DRI for PM gravimetric mass, elements, elemental and organic carbon, ions, particulate and semi-volatile organic compounds, and volatile organic air toxics. All sampling lines were heated and maintained at 47°C ± 2°C. The samples were extracted from the dilution tunnel through a low particulate loss 2.5 µm cutpoint pre-classifier. Further details and a schematic of the sampling instrumentation are shown in Figure 65 and Figure 66.

Figure 65. Schematic of the constant-volume sampling system used in the Kansas-City Study.

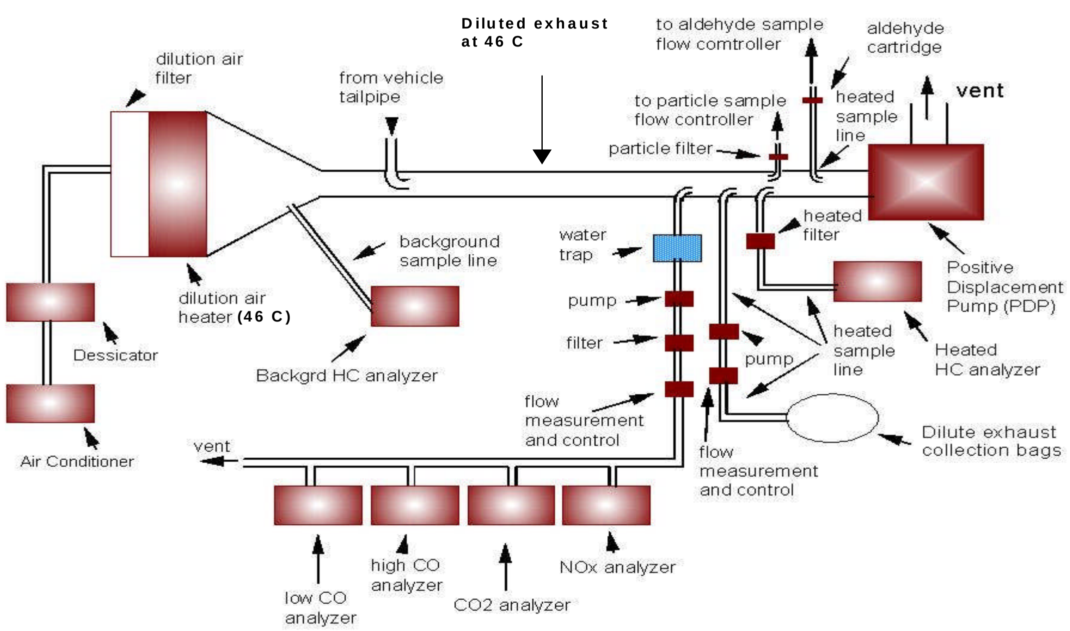
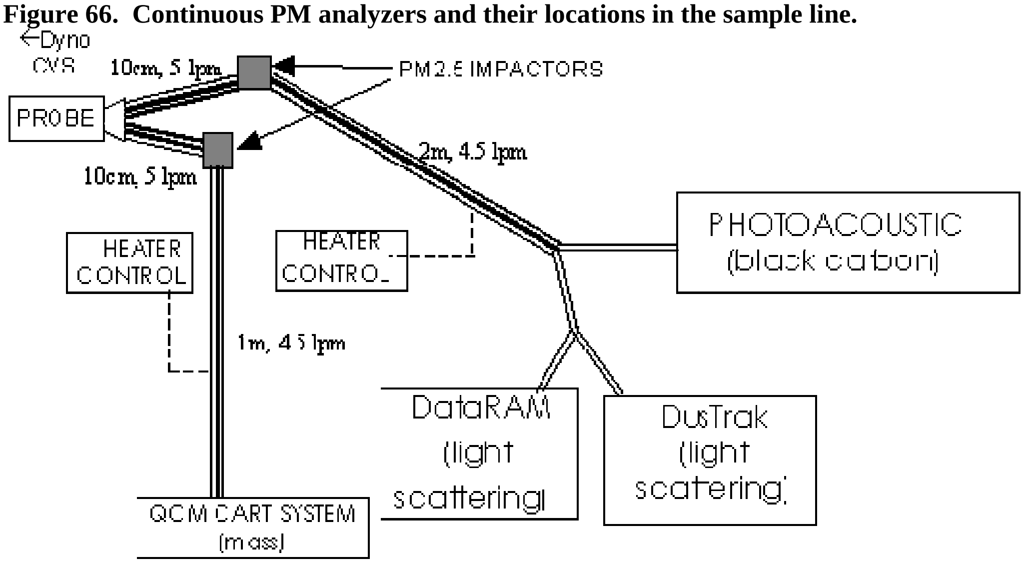


Figure 66. Continuous PM analyzers and their locations in the sample line.



It is worth briefly describing the apparatus used to measure PM on a continuous basis. A more thorough description may be found in the contractor's report[40]. As of the date of this program, measuring continuous particulate was a daunting technical challenge. Each technique has specific advantages and disadvantages. For this study, the cumulative mass as measured on the Teflon filters was treated as a benchmark. Thus, prior to using the continuous measurements to estimate modal emissions, the sums of the time series for the continuous measurements were normalized to their corresponding filter masses to compensate for systematic instrument errors.

The Quartz Crystal Microbalance measures the cumulative mass of the PM deposited on a crystal face by measuring the change in its oscillating frequency. It is highly sensitive to many artifacts such as water vapor and desorption of lighter organic constituents. Due to the high degree of noise in the continuous time series, the measurements were averaged over 10 seconds, thus damping the temporal effects of transients. The QCM can accurately capture cumulative PM over time, however, measurement uncertainties increase for successive points in time because the values depend on a calculated difference between two sequential, and similar, measurements. Due to the resulting high variability, including large and rapid fluctuations from positive to negative emissions at any given instant, and vice versa, use of the QCM measurements was not viewed as a practical option for use in emission rate development MOVES at this time, except as a check on the other instruments.

The Dustrak and Dataram both work on light-scattering principles. As such, they have very rapid response times and can measure larger PM volumes with reasonable accuracy. However, their accuracy degrades when measuring low PM volumes. Since most PM mass lies within the larger particles, the instruments should be able to capture most of the continuous mass concentrations though it may miss a substantial portion of the smaller (nano) particles. To provide a qualitative check on this supposition, the time-series for the QCM and optical instruments were aligned and checked to ensure that significant mass was not missed. Based on this analysis, the Dustrak instrument was observed to be the more reliable of the 3 instruments, and mass correction at low loads was not judged to be worth the effort given the uncertainties involved. This time-consuming analysis was done by eye for each test and the results are not presented in this chapter.

The photoacoustic analyzer (PA) is unique among the continuous instruments in its ability to capture only the soot or elemental carbon components of PM. The fast analyzer detects the resonances coming off the carbon-carbon bonds in soot. Unfortunately, there were insufficient Thermal Optical Reflectance (TOR) elemental carbon (EC) measurements from quartz filters to normalize the PA data, but some comparisons are shown in the contractor's report[40]. In this study, the PA data were compared qualitatively with the Dustrak and Dataram and found to be consistent with expected ratios of elemental to total carbon during transient events, leading to the conclusion that these instruments were largely consistent with one another. These results are also not presented in this chapter as every single trace was compared by eye. The data is used to determine the modal relationship of elemental to total PM.

Due to the uncertainty of experimental measurement techniques for real-time PM at the time of the Kansas City study, these instruments are employed only as a semi-qualitative/quantitative means of determining modal emission rates, and the use of such data does not qualify them as EPA recommended or approved devices or processes.

2.1.2 Causes of Gasoline PM Emissions

In gasoline-powered spark-ignition engines, particulate matters is formed during incomplete fuel and oil combustion (although the amount of oil consumed in combustion and its contribution to PM varies greatly from vehicle to vehicle). During operation, numerous distinct technologies used in vehicles are in various states of repair or disrepair which also affect PM emissions. Even brand new vehicles emit PM from combustion but at very low levels. A complete description of the causes of PM emissions and associated mechanisms is beyond the scope of this report, as many aspects of the science that are still not well understood. We will briefly summarize factors that contribute to gasoline PM in the vehicle fleet in this section. Where appropriate, we will make comparisons to the mechanisms of hydrocarbon (HC) formation, since parallels are often drawn in the literature.

Simply put, particulate matter forms primarily during combustion when carbon-containing molecules condense or otherwise agglomerate. This form of PM is generally composed of higher molecular weight hydrocarbon compounds, some of which originate in the fuel/oil and some of which are formed during combustion. Unlike diesel engines, elemental (molecular) carbon or soot is not very prevalent with gasoline engines but does form in larger quantities under relatively rich conditions, e.g., low air:fuel ratios. The amount of elemental carbon in PM varies from vehicle to vehicle (and, even for a given vehicle, varies depending on operating conditions and state of repair). For gasoline-fueled vehicles, a typical fraction is about 20% of PM mass compared to about 70% for a diesel engine.

Other compounds in the fuel or engine oil, such as trace levels of sulfur and phosphorus, form form sulfates and phosphates during combustion, both of which form particulate. The sulfur level in gasoline is now very low, almost eliminating sulfate formation from gasoline sulfur content but motor oil contains higher fractions of sulfur (and phosphorus) compounds. Also, trace metal constituents in gasoline and oil form PM in the combustion process as metallic oxides, sulfates, nitrates, or other compounds. Catalyst attrition products from the substrate and trace amounts of noble metals also form PM but not in the combustion process. The catalyst attrition products are mechanically generated and are usually in larger size ranges compared to exhaust PM. Exhaust PM as formed in the engine is generally very small in size (possibly much of it is nuclei mode PM in the range of 0.05 microns or smaller). In the exhaust system, including the muffler, some of the PM agglomerates and increases in size.

The wide assortment of technologies used in vehicles can affect PM formation. These technologies were mainly developed to control HC, CO and NOx emissions, but most have the side benefit of reducing PM, since reducing exhaust HC generally also reduces exhaust PM although not to the same extent. Older engines from the 1980s and earlier that deliver fuel through a carburetor typically have poorer fuel droplet quality, as well as looser control of fuel air stoichiometry. These older vehicles are expected to produce more PM (on average) then their fuel injected counterparts that followed generally in the late 1980s and early 1990s.

Among fuel injected engines, throttle body fuel injection (TBI) used in earlier engines with fuel injection typically has poorer fuel atomization quality and air:fuel ratio control than the port fuel injection (PFI) technology that replaced; thus, one might expect older model-year fuel-injected vehicles to have higher PM emissions (on average) than newer ones. Somewhat before the widespread adoption of fuel injection, closed-loop control systems were developed in tandem with oxygen sensors to improve the stoichiometric chemistry of combustion. These closed-loop controls improved combustion as well as the effectiveness of the after-treatment system.

The after-treatment system on most vehicles consists of a 3-way catalyst. The 3-way catalyst was designed for simultaneous control of hydrocarbons, carbon monoxide, and nitrogen oxides. Vehicles with 3-way catalysts would meet more stringent hydrocarbon and carbon monoxide emission standards while also meeting the first stringent nitrogen oxide standard. In oxidizing hydrocarbons, these systems are resulted in additional PM control. These systems were utilized on almost all gasoline-fueled vehicles beginning in the 1981 model year. On some model-year vehicles in the 1980s and a few more recently, a secondary air injection system was added between the engine and oxidation portion of the catalyst in order to add supplementary air to the oxidation reactions on the catalyst. These systems also helped oxidize PM (though probably not to the extent that it oxidizes CO or HC). The deterioration of these technologies may affect PM and HC quite differently. Throughout this chapter, there are parallels drawn between HC and PM formation as well as control, however it should be noted that the correlation between these emissions is far from perfect. Many examples of this relation are shown in the 2008 analysis report[39].

Amounts of PM emitted are very sensitive to the amount of fuel in combustion as well as the stoichiometry of the reaction. As mentioned above, over-fueled mixtures result in higher PM formation and in some cases, also excess soot formation. Over-fueling can occur under several different conditions. During cold start, engines are often run rich in order to provide sufficient burnable fuel (i.e. light ends that vaporize at colder temperatures) to start combustion when the cylinder walls are still cold (which results in increased flame quench). Additionally, under cold conditions (e.g., below 20ºF), additional enrichment of the fuel-air mixture is needed to start the engine and lasts longer while the engine warms up.

When high acceleration rates or loads are encountered (such as a wide-open throttle event), an extra amount of fuel is often injected for greater power or for catalyst and component temperature protection. Emission control systems in the late 1990s are better designed to control this enrichment. Finally, engines can run rich when a control sensor (e.g. oxygen, MAF, MAP, or coolant sensors) or the fuel system fails.

In addition to fuel, lubricating oil can get into the combustion chamber via several pathways. Some engines may have poor tolerances for pistons and piston rings, thus the negative pressures (engine intake vacuum) can pull oil through these larger gaps during the intake stroke. Furthermore, engine components, such as valves, valve seals, piston rings, and turbochargers can wear and deteriorate resulting in increasing emissions over time. In all gasoline automotive engines, the crankcase (where the oil bathes the engine components) is vented back into the combustion chamber through the intake manifold. This is known as Positive Crankcase Ventilation (PCV), and is required in order to remove and burn the excess hydrocarbons in the hot crankcase. Unfortunately, it can also introduce PM precursors and oil into the engine combustion chamber. Because of the relatively small amount of oil consumption compared to the volume of gasoline burned in a vehicle, the amount of HC from oil is typically small. However, organic PM from oil consumption can be quite significant because oil is a high molecular weight hydrocarbon, and more likely to persist as unburned droplets. Therefore, as vehicles age, those that consume more oil will probably have very different emissions behavior for HC than for PM, compared to when they were new. However, oil consumption can "poison" the catalyst substrate, reducing the effectiveness of the catalyst at oxidizing HC.

The fuel itself may have properties that exacerbate PM formation, which may be affected by concentrations of sulfur, lead, aromatics, and impurities. With the lower levels of lead and sulfur in fuels, the first two are presumably less of a factor in the Kansas City program than aromatics. In the calendar years that MOVES models, lead is not a significant portion of the inventory, thus is largely ignored.

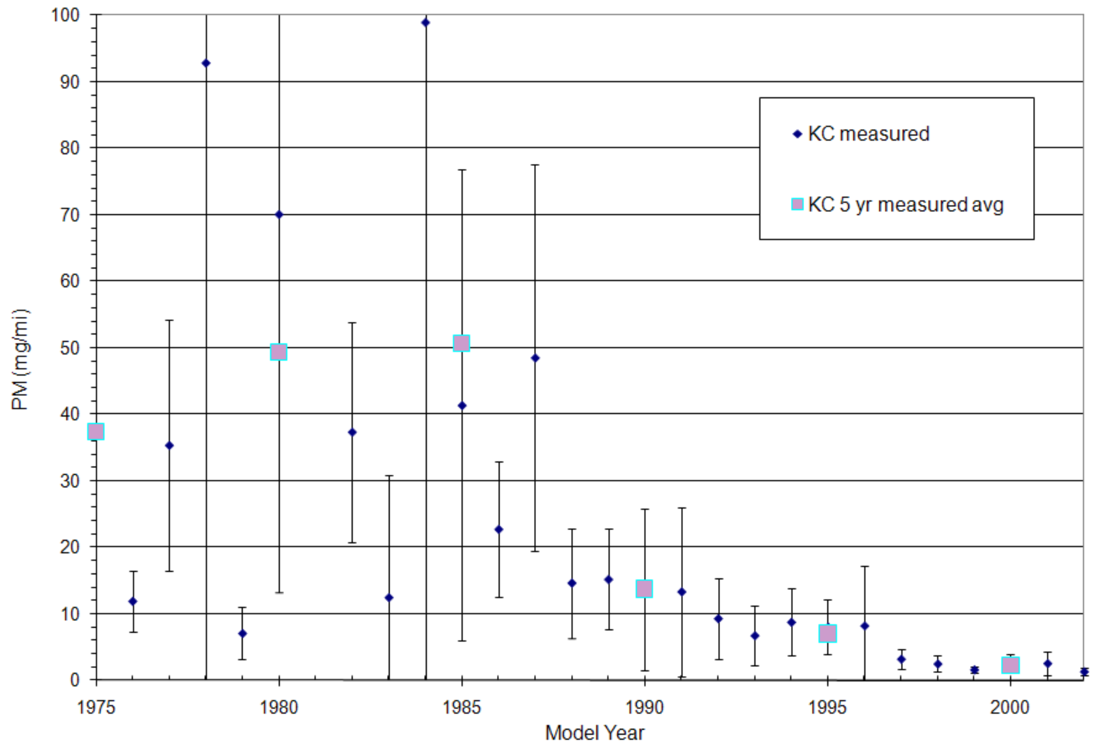
Some of these PM forming mechanisms clearly affect HC emissions. A control technology or a deterioration path for HC may or may not similarly affect PM depending on the source. It is also likely that the processes that cause high PM may not be the same processes that cause organic PM. Some of the mechanisms also form visible smoke. Smoke takes on a variety of characteristics depending on the source, and can be due to oil consumption or overfueling. The smoke is visible because of the relative size of the particles compared to the light wavelengths that are scattered. However, visible smoke is not necessarily a reliable indicator of high PM emissions.

2.2 New Vehicle or Zero Mile Level (ZML) Emission Rates

In this section, we develop an approach to extend the PM results from the Kansas City Study to estimate average emissions across the fleet. The section also compares the new vehicle results from many different studies in order to estimate zero mile level (ZML) emission rates for all model years. Before modeling deterioration, it is first necessary to capture ZML emission rates.

In constructing a model of emissions from the Kansas City data (Figure 67), the most significant challenge is distinguishing model year and age effects. As with most datasets, this issue arises because the program was conducted over a two-year period, thus ensuring a direct correspondence between model year and age. As a result, it is very difficult to distinguish the reduction in emissions with model year from the increase in emission with age. Emissions tend to decrease as technologies are introduced on vehicles (with later model years) in order to comply with more stringent emissions standards. However, these technologies and vehicles tend to deteriorate over time, thus for the same model year vehicle, older vehicles (greater age) will have higher emissions (on average) than newer vehicles.

Figure 67. Average Particulate Emission Rates from the Kansas City Study, by Model year, shown as cycle aggregates on the LA92.



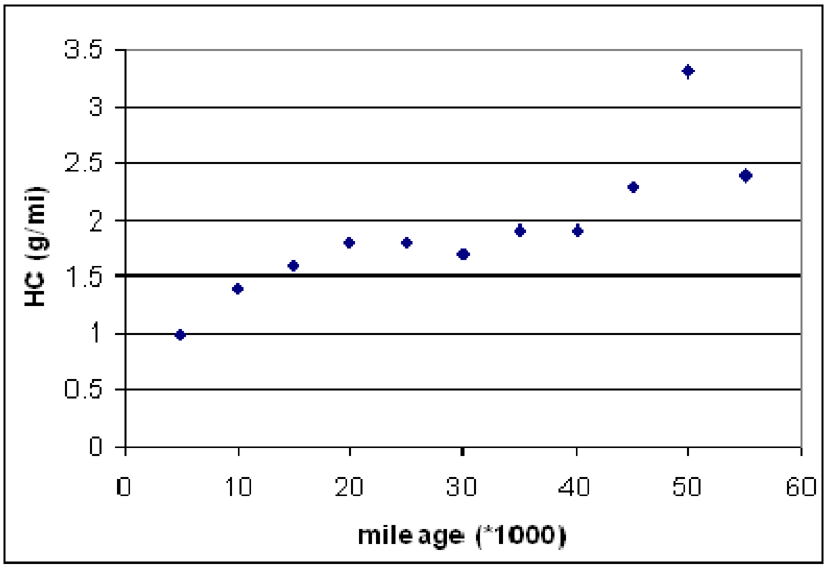
In concept, the most accurate means of quantifying emissions from vehicles over time is to conduct a longitudinal study, where emissions are measured for the same vehicles over several (or many) years. However, implementing such a study would be costly. Moreover, it is impossible to obtain recent model year vehicles that have been significantly aged. In the following sections, we will describe some limited longitudinal studies conducted in the past. Then we will present our modeling methodology to isolate model year (technology) in this chapter from age (deterioration) in the next.

2.2.1 Longitudinal Studies

There have been a few longitudinal studies conducted in the past that are relevant for PM emissions. Unfortunately, they are all limited in their ability to conclusively discern model from age effects.

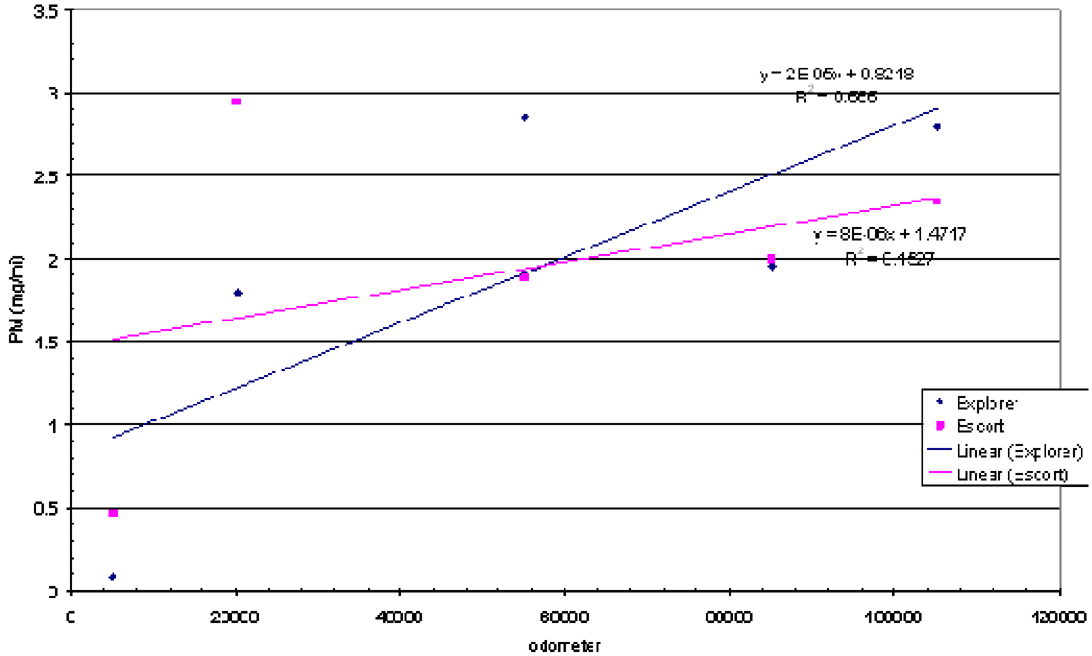
Gibbs et al. (1979) measured emissions from 56 vehicles with mileage ranging from 0 to 55,000 miles (odometer) on 3 different cycles[41]. Hydrocarbon emissions were analyzed, but unfortunately, PM results were not reported as a function of mileage. The authors' state that "emission rates of measured pollutants were not found to be a consistent function of vehicle mileage," however, the following figure shows that some increasing trend seems to exist for HC (Figure 68).

Figure 68. Hydrocarbon emissions a function of mileage (Gibbs et al., 1979)



Hammerle et al. (1992) measured PM from two vehicles over 100,000 miles.[42] However, their results for PM deterioration are somewhat inconclusive, as the following figure shows, since the deterioration seems to occur mainly in the beginning of life, with very little occurring after 20,000 miles. Also, the study is limited to two specific vehicle models.

Figure 69. Particulate emissions as a function of odometer for two Ford vehicles (Hammerle et al., 1992)



Both of these studies assume that odometer is a surrogate for age. While there are some deterioration mechanisms that worsen with mileage accumulation, there are others that deteriorate with effects that occur over time, such as number of starts, corrosion due to the elements, deposits and impurities collecting in the gas tank and fuel system, etc. Therefore, we believe that any study that describes deterioration as a function of odometer (alone) may not account for all causes of deterioration.

Whitney (2000) re-recruited 5 vehicles that had been measured in previous study 2 years prior (CRC-E24)[43]. There are two significant limitations of this follow-up study: (1) the interval between studies was only 2 years, though the odometers had increased 22,200 miles (on average) and (2) these vehicles were tested on a different drive cycle, the LA92 compared to the previous study, which used the FTP. We will explore the potential cycle differences on PM later, but assuming the cycles give similar PM results, the PM emissions were only 8% higher (on average). This increase is due to a single vehicle, which had significantly increased PM emissions (the rest were the same or slightly lower). Unfortunately, this is not a large enough sample and time period on which to resolve age effects, but it may be sufficient to conclude that the differences between PM from the FTP and LA92 drive cycles are minimal for PM.

The three longitudinal studies described above are inconclusive, though they do hint that deterioration does occur.

2.2.2 New Vehicle, or ZML Emission Rates and Cycle Effects

In order to isolate the effect of model year (technology) from age (deterioration), it is useful to look at the model-year effect independently. This can be done by analyzing emissions from new vehicles from historical studies. New vehicle emission rates tend to have lower variability than older vehicles (in absolute terms) since they have lower emissions that comply with more stringent HC standards. These standards, which decrease over time, tend to affect PM emissions as well since many of the mechanisms for HC formation also form PM.

Several independent studies have measured PM emissions from nearly new vehicles. For our purposes, we will define "new" as a vehicle less than 3 years old, i.e., vehicles within the 0-3 year age Group. Table 38 lists the 15 studies employed for this analysis.

Table 38. Historical gasoline PM studies including new vehicles at time of study.

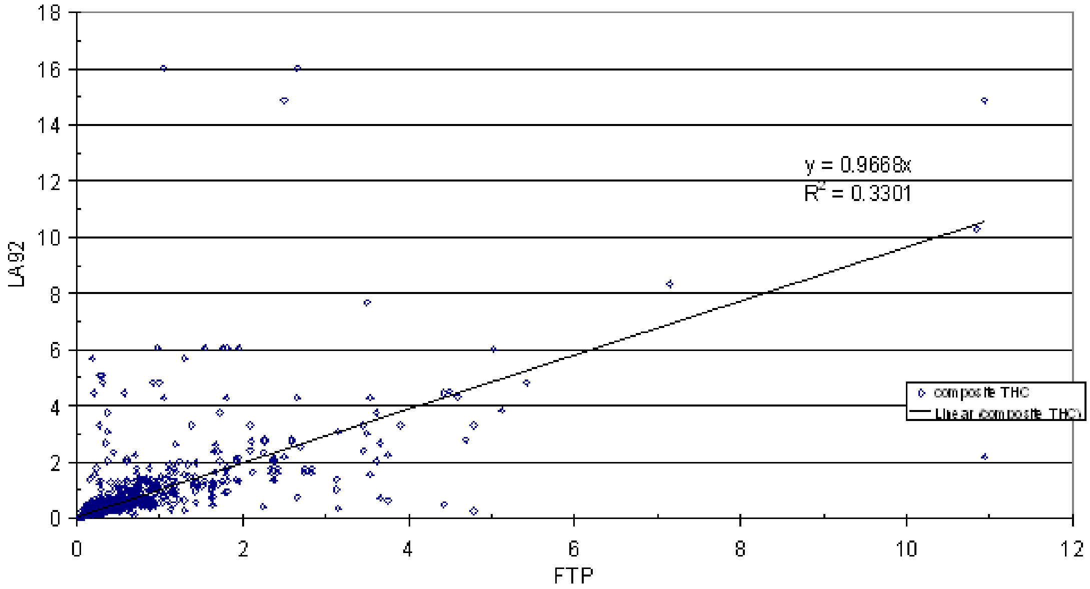
Program	Year of Study	No. vehicles	Drive cycle
Gibbs *et al.*[41]	1979	27	FTP
Cadle *et al.*[44]	1979	3	FTP
Urban & Garbe[45,46]	1979, 1980	8	FTP
Lang et al.[47]	1981	8	FTP
Volkswagen[48]	1991	7	FTP
CARB[49]	1986	5	FTP
Hammerle et al., 1992[42]	1992	2	FTP
CRC E24-1 (Denver)[50]	1996	11	FTP
CRC E24-2 (Riverside)[51]	1997	20	FTP
CRC E24-3 (San Antonio)[52]	1998	12	FTP
Chase et al.[53]	2000	19	FTP
Whitney (SwRI)[43]	1999		LA92
KC (summer)[39,40]	2004	13	LA92
EPA (MSAT)[54]	2006	4	FTP

Before we examine these emissions, we should convince ourselves that the LA92 driving cycle will not give significantly different PM emissions than the FTP so that we can compare these test programs directly. As described above, the results from Whitney (2000) seem to indicate little difference between the two cycles. Even though the tests were conducted 2 years apart, one would expect that the aging effects in combination with the slightly more aggressive LA92 cycle (used later) would have given higher PM emissions. However, this was not the case, and only one of the 5 vehicles showed significantly increased emissions.

Li *et al.*, (2006) measured three vehicles on both cycles at the University of California, Riverside[55]. The PM emissions from the LA92 were 3.5 time larger (on average) than the FTP results. However, the HC emissions were only 1.2 times higher. These results seem rather contradictory and inconclusive. The 3.5 factor also seems excessive.

Finally, the California Air Resources Board conducted an extensive measurement program over several years comparing many different drive cycles. Unfortunately, PM was not measured in this program. However Figure 70 shows the HC emissions compared for the two cycles. The trends indicate that there is little cycle effect for HC.

Figure 70. Hydrocarbon emissions on the LA92 versus corresponding results on the FTP

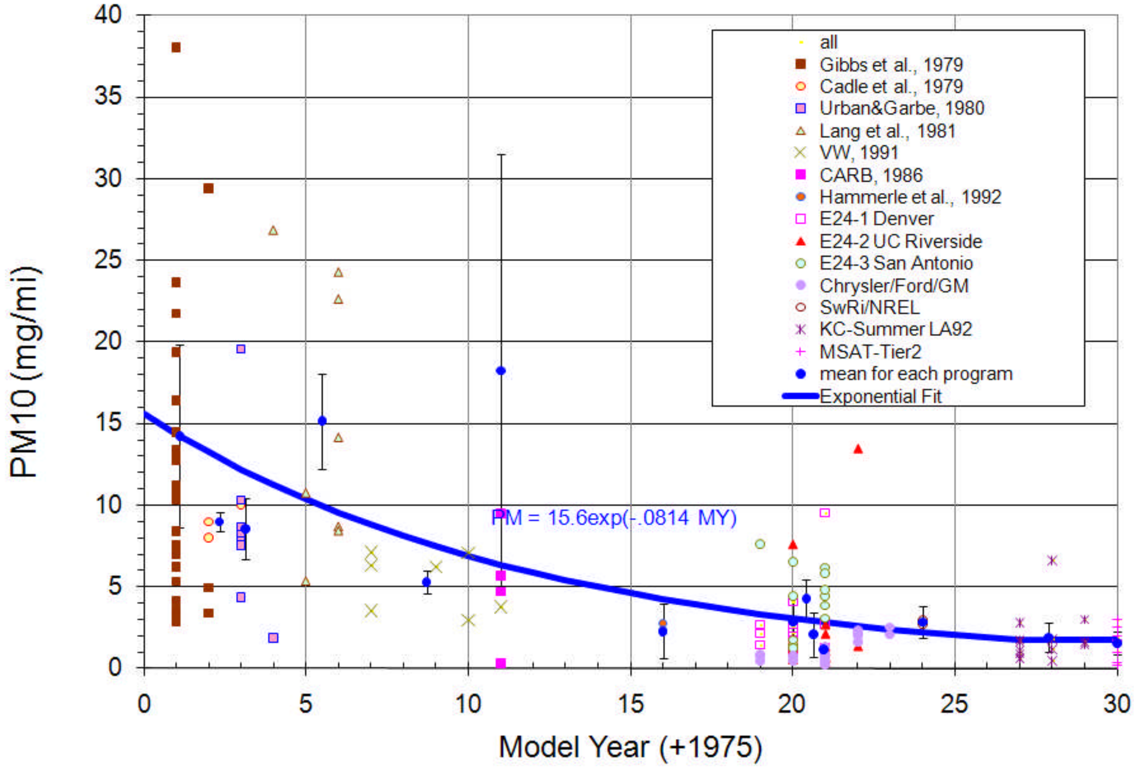


Based on these studies, we conclude that there is little difference in PM emissions between the LA92 and FTP cycles on an aggregate basis (though their bag by bag emissions may differ). We shall demonstrate that, for the purposes of ZML analysis, the results will be nearly identical even if we omit the LA92 data, thus minimizing the significance of this issue.

Figure 71 shows the new-vehicle emission rates from the 11 studies listed in Table 38. The data points represent each individual test, and the points with error bars represent the average for each source. The plot presents evidence of an exponential trend (fit included) of decreasing emissions with increasing model year. The fit is also nearly identical if we omit the two programs that employed the LA92 cycle. We will use this exponential ZML relationship as the baseline on which to build a deterioration model. However, the measurements from the older programs primarily measured total particulate matter. These have been converted to PM10 (for the plot), which is nearly identical (about 97% of total PM is PM10). We also assume that 90% of PM10 is PM2.5 (EPA, 1981)[56]. For the older studies, we accounted for sulfur and lead directly if they were reported in the documentation. In those cases where sulfur was not reported, the levels were approximated using MOBILE6 sulfur emission factors and subtracted as an adjustment.

Unfortunately, many of the older studies used a variety of methods for measuring particulate matter. There were many differences in filter media, sampling temperature, sample length, dilution, dynamometer load/settings etc. It is beyond the scope of this project to normalize all of the studies to a common PM metric. It is likely that documentation is not sufficient to even attempt it. Therefore no attempts at adjustment or normalization were made except for size fraction, lead and sulfur, as described above.

Figure 71. Particulate emission rates for new vehicles compiled from 11 independent studies.



To determine the ZML emission rates from these data, the next step was to separate results for cars and trucks, and to separate cold-start from hot-running emissions. Unfortunately, the historical data does not present PM results by cycle phase. Therefore, the 2005 hot-running ZMLs for cars vs. trucks were determined from the KC dataset, and the model year exponential trend from the aggregate trendline (-0.08136) is used to extend the ZMLs back to model year 1975. The base hot running ZML emission rate for cars (LDV) ($E_{HR,y}$) is:

$$E_{HR,y} = E_{HR,2005} e^{-0.814\,y}$$ **Equation 49**

where

y = model year – 1975, and

$E_{HR,2005}$ = hot running ZML rate for MY 2005.

To estimate equivalent rates for trucks, we multiplied this expression by a factor of 1.43. This value is based on an average of all the studies with new vehicles from 1992 onward (before this model year, there were no trucks measured). It is also multiplied by 0.898 to give hot running bag 2 rates and 1.972 to give the cold start emission rate (here defined as bag 1-bag 3 in units of g/mi). These values were estimated by running a general linear model of bag 2 and bag1-3 with respect to composite PM, respectively, using the SPSS statistical software tool. The averages of these ratios by model year are shown in Figure 72, in which no clear trend is discernable. The parameters of the model are summarized in Table 39.

Figure 72. Ratios of hot-running/composite and cold-start/composite, Bag2 and Bag1-Bag3, respectively, averaged by model year.

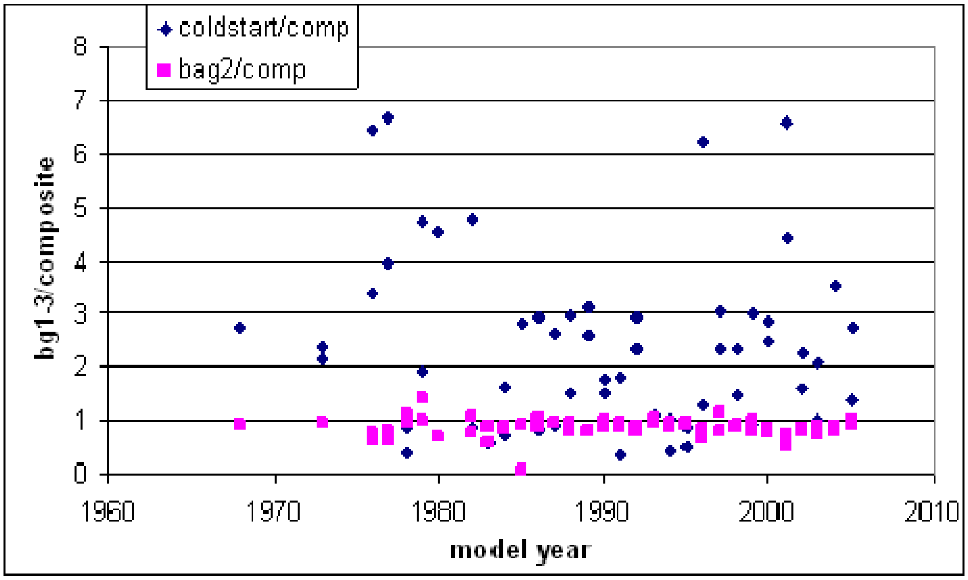
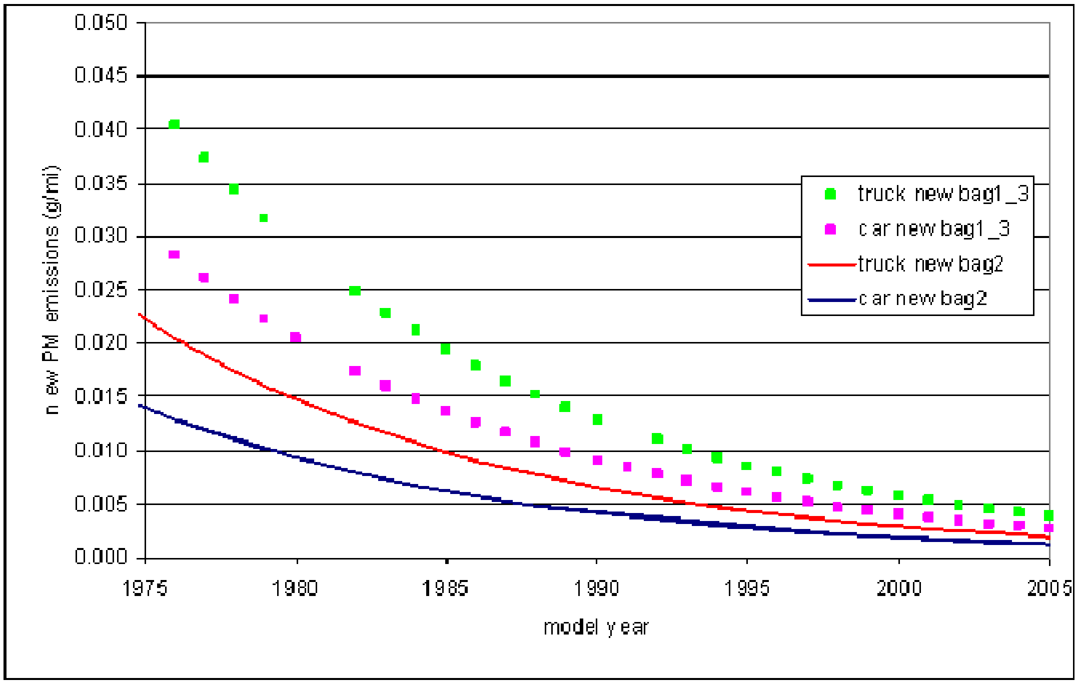


Table 39. Best-fit parameters for cold-start and hot-running ZML emission rates.

Parameter	Value
LDV hot-running ZML (g/mi)	0.01558
Exponential slope	0.08136
Truck/car ratio	1.42600
Bag-2 coefficient	0.89761
Cold-start coefficient	1.97218

Figure 73 shows the ZML emission rates. The rates are assumed to level off for model years before 1975 and again after 2005. Elemental and organic carbon fractions are another modification to the ZML rates. These fractions are already reported in the analysis report.

Figure 73. Particulate ZML emission rates (g/mi) for cold-start and hot-running emissions, for LDV and LDT.



2.2.3 Aging or Deterioration in Emission Rates

In this section, a deterioration model is introduced that captures how new vehicles in all model years deteriorate over time so that gasoline PM from any given calendar year can be modeled in MOVES. The purpose of this model is to characterize the PM emissions from the fleet and to hindcast the past as well as forecast the future, as required in inventory models.

2.2.2.4 Age Effects or Deterioration Rates

The ZMLs determined in the previous section represent baseline emissions for new vehicles in each model–year group. By comparing the emissions from the "aged" Kansas City vehicles in calendar year 2005, to the new rates determined earlier, we can deduce the "age effect" for each corresponding age. However, simple an approach as this seems, there are many ways to connect two points. This section describes the procedure and the assumptions made to determine the rate at which vehicle PM emissions age.

We first break the data into age Groups. We use the MOVES age groups which correspond to the following age intervals: 0-3 (new), 4-5, 6-7, 8-9, 10-14, 15-19, 20+. Having a single age category for 20 years and older implies that emission rates have stabilized by 20 years of age. The bag measurements from all of the vehicles measured in Kansas City were first adjusted for temperature using the equation derived in the analysis report[39]. The equation used is:

$$E_{\mathrm{PM},72} = E_{\mathrm{PM},T}\mathrm{e}^{-0.03344(72-T)}$$ **Equation 50**

where $E_{\mathrm{PM},72}$, is the adjusted rate at 72ºF for cold-start or hot-running emissions, $E_{\mathrm{PM},T}$ is the corresponding measured emissions for cold-start or hot-running, respectively, at temperature T, respectively.

The temperature-adjusted measurements are the "aged" rates, i.e., the rates in each model-year group represent emissions for that group at the age of measurement in 2004-05, at 72ºF rather than at the actual ambient temperature.

The method adopted is to ratio the aged rates with the new rates so that the changes with deterioration rates are all proportional. This approach will be referred to as the "multiplicative deterioration model", and is analogous to the approach used with the gaseous emissions (Chapter 1).

It is likely that some of the same mechanisms that cause HC and CO to increase over time would also result in PM increases. These factors include deterioration in the catalyst, fuel control, air:fuel-ratio control, failed oxygen sensors, worn engine parts, oil leaks, etc. Figure 74 shows trends in the natural logarithm of THC rates over approximately 10 years, based on random-evaluation samples in the Phoenix I/M program. On a ln-linear scale, the deterioration rates appear approximately linear over this time period, suggesting that the deterioration rates are exponential over this time interval. This observation, combined with the approximate parallelism of the trends for successive model years, implies that emissions follow a multiplicative pattern across model-year or technology groups, calling for a multiplicative deterioration model. In such a model, the aged rates and the new rates are converted to a logarithmic scale, after which the slopes are estimated by fitting a general linear model. The average slope is estimated, with the ZMLs determined earlier defining the y-axis offsets. The result is a series of ladder-like linear trends in log scale as shown in Figure 75. The lines fan out exponentially on a linear scale as shown in Figure 76. The dotted lines and the points with uncertainty bars represent the Kansas City data overlaid onto the model and indicate that the model is consistent with the data.

Figure 74. The natural logarithm of THC emissions vs. Age for LDV in the Phoenix (AZ) Inspection and Maintenance program over a ten-year period (1995-2005).

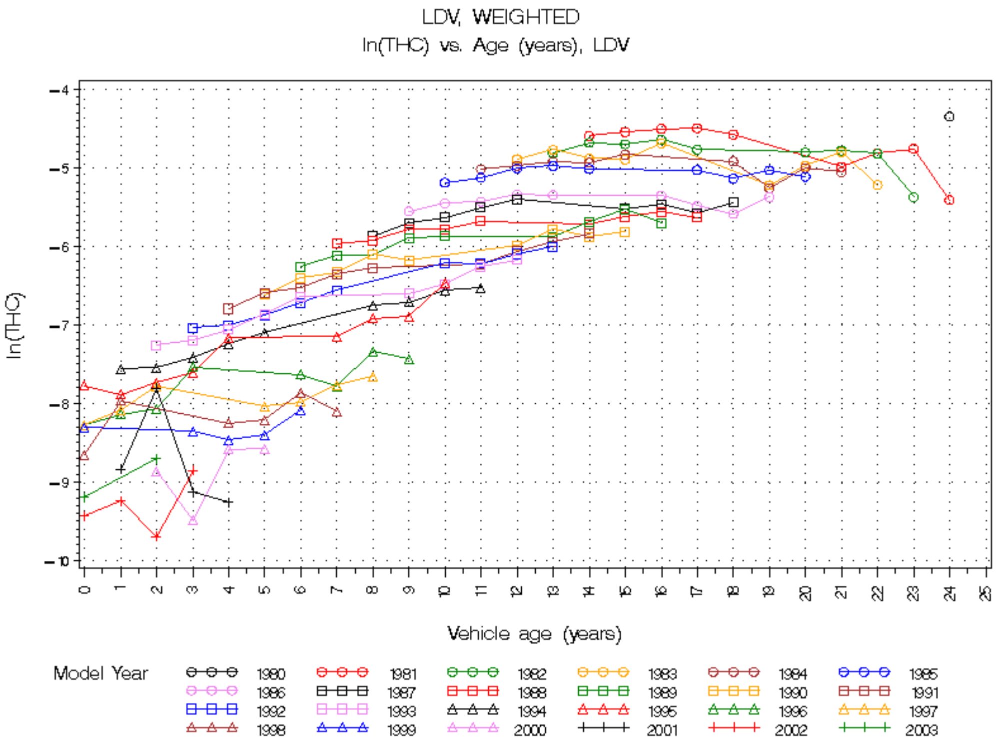


Figure 75. The Multiplicative deterioration model applied to PM results from Kansas City. The y-axis offsets represent ZML rates. The dotted line represents the Kansas-City Data.

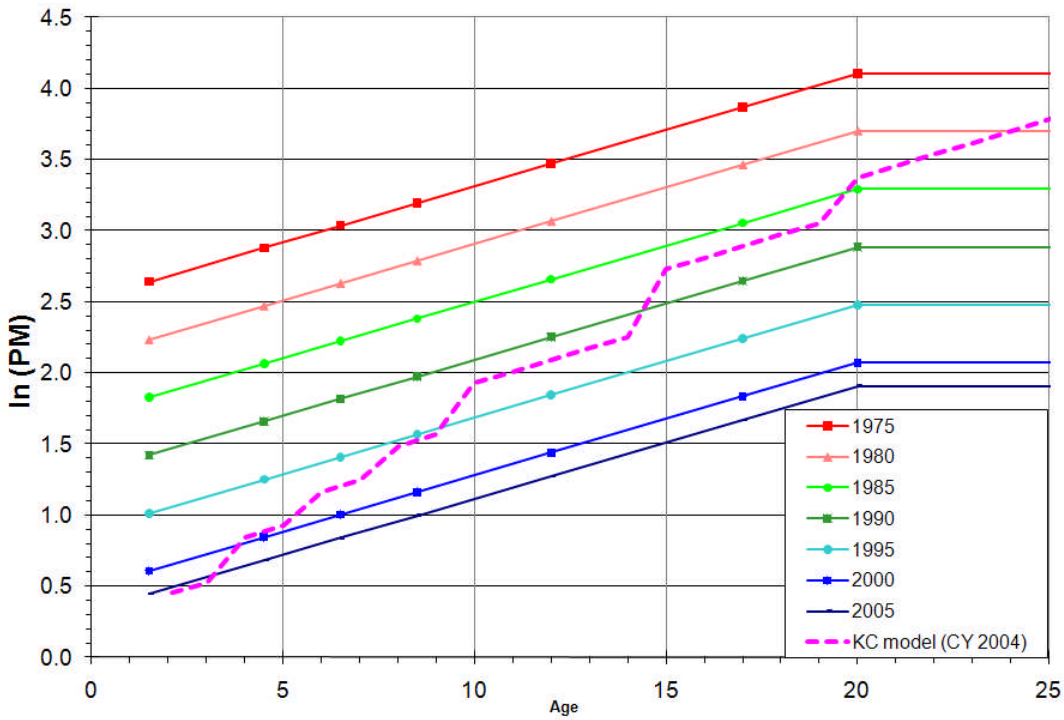
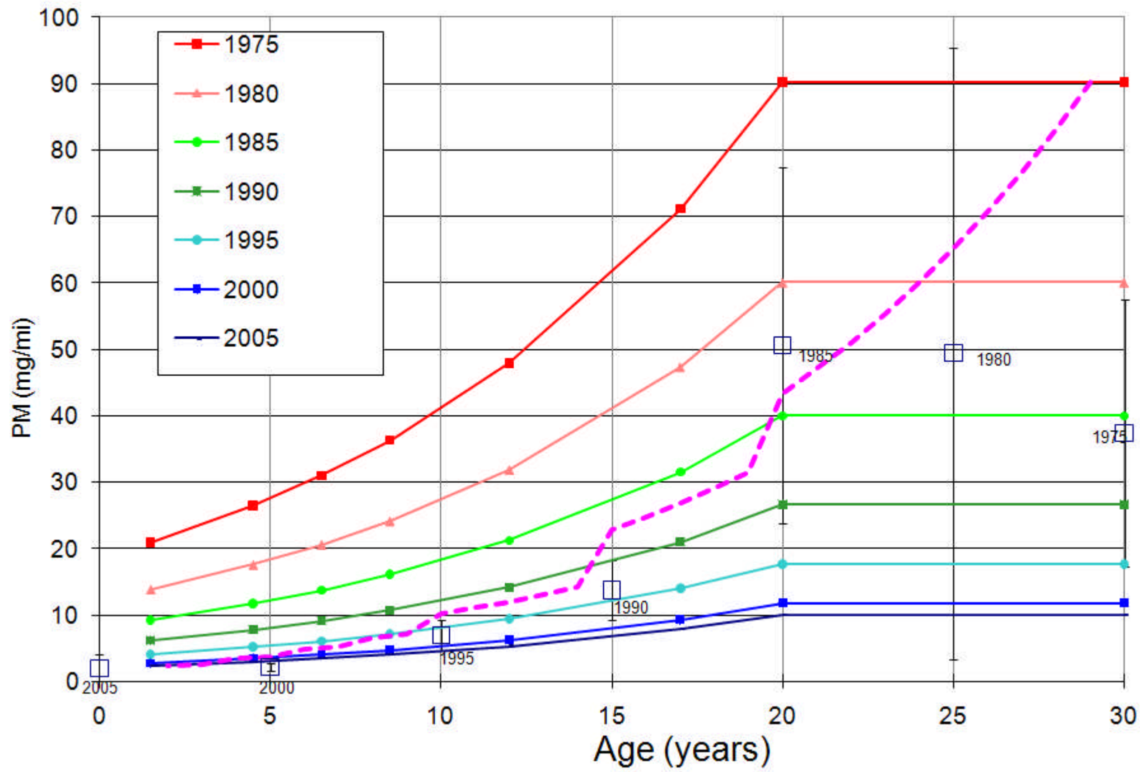


Figure 76. The multiplicative deterioration model shown on a linear scale. The y-axis offsets capture the new-vehicle ZML rates. The dotted lines and points with error bars represents the Kansas-City results (with 95% confidence intervals).



Because the model is multiplicative, the deterioration factors can be applied directly to trucks, cold start, hot-running, EC, and OC, since the order of operations does not matter. The start process requires only a soak time model to estimate remaining rates for starts other than the cold start (opmodeID=101-107). Because no data is available describing how particulate start emissions vary by soak time, we have used the HC soak curves shown previously (see p. 87).

Substantial analysis is yet required to fill modal particulate emission rates for emissionRateByAge table in the MOVES input database. Because the simple multiplicative model can be applied across the range of VSP, deteriorated rates by operating mode can be directly generated, as described in the next section.

2.3 Estimating Elemental and Organic Carbon Fractions

After performing the analyses described above to estimate total particulate (PM2.5), we partitioned the total into components representing elemental and organic carbon, EC and OC, respectively. Following this step, the values for EC and OC were loaded into the emissionRateByAge table, using the pollutant and process codes shown in Table 1.

Table 40. Combinations of pollutants and processes for particulate emissions.

pollutantName[1]	pollutantID[1]	processName[2]	processID[2]	polProcessID[3]
Primary $PM_{2.5}$ - Organic Carbon	111	Running exhaust	1	11101
		Start exhaust	2	11102
Primary $PM_{2.5}$ - Elemental Carbon	112	Running exhaust	1	11201
		Start exhaust	2	11202

[1] as shown in the database table “pollutant.” Note that MOVES will reaggregate the particulate components to construct “Primary Exhaust PM_{10}” (pollutantID 100) and “Primary Exhaust $PM_{2.5}$” (pollutantID 110).
[2] as shown in the database table “emissionProcess.”
[3] as shown in the database table “emissionRateByAge.”

This discussion in this section is reproduced and adapted from the Kansas-City analysis report[39].

Vehicle exhaust particulate matter consists of many different chemical species, including elemental carbon (EC), organic carbon (OC), sulfates, nitrates, trace metals and elements. The vast majority of the PM emissions is in the form of EC or OC. Elemental carbon, also known as soot or black carbon, is produced during combustion when fuel or fuel droplets are pyrolyzed (or carbonized) under low oxygen levels. In this process hydrogen is stripped from the carbon atoms in the hydrocarbon, and carbon soot residue remains. Elemental carbon is formed in gasoline engines primarily when the fuel air mixture is rich (even in localized portions of the air/fuel mixture of the engine). The hot oxygen-starved and fuel rich environment favors pyrolysis reactions.

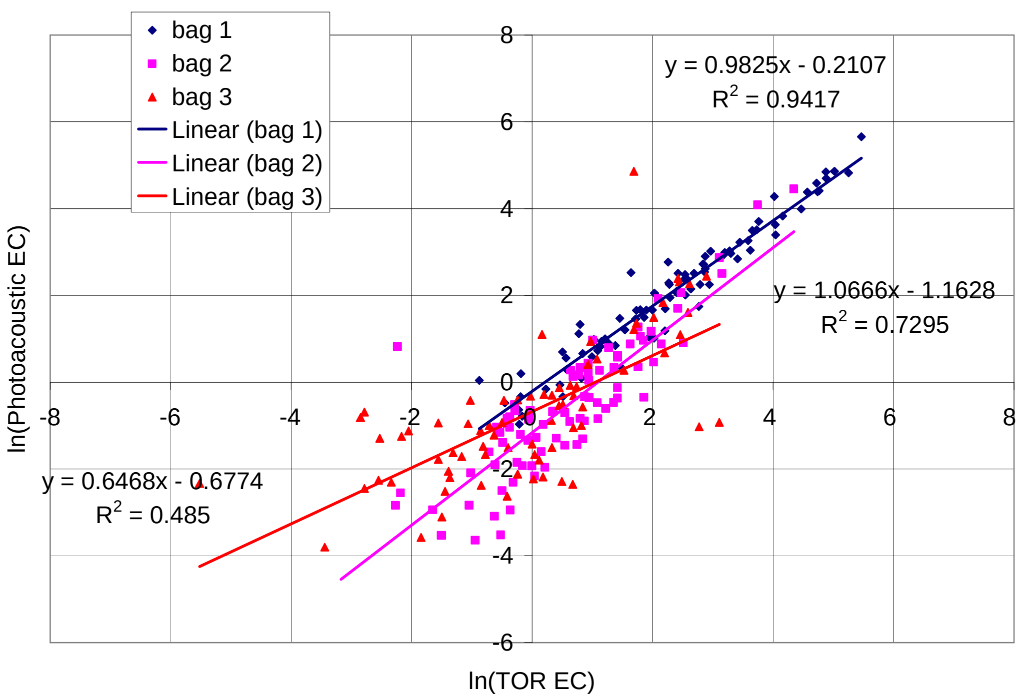
We might expect to see higher EC fractions in gasoline engines following engine starts, or when during enrichment mode such as under heavy engine load. These fine soot particles are generally non reactive in the atmosphere, though they may act as agglomerization centers for particle growth both in the exhaust stream and in the atmosphere. In other words, other compounds including organic carbon adsorb onto the surface of the elemental carbon. In turn, these adsorbed organic carbon compounds can react in the atmosphere, generally in oxidation reactions.

Organic carbon forms clusters of organic molecules that agglomerate and grow throughout combustion, as the exhaust cools, and finally as it disperses into the atmosphere. In gasoline engines OC can be formed normally during combustion from the fuel or the lubricating oil. Sulfate emissions have largely been controlled through fuel sulfur controls, and, previously, by the closer control of air:fuel ratio necessary for the three-way catalyst to effectively function. We expect the sulfate emissions to be much lower than past studies. Likewise, we also assume that nitrates and trace metals and elements are small on a mass basis by comparison. Therefore, we spend the remainder of this section discussing EC and OC only.

It is important to separate EC and OC in inventory estimation since photochemical models treat these fractions of particulate separately. Also, the ratios are helpful for comparing emissions (and air quality) models to source apportionment studies. Finally, EC is easier to measure and more stable in the atmosphere than OC, therefore it is useful to track for a variety of purposes.

In the Kansas City study, EC was measured using two different methods. The first was the technique of thermal optical reflectance (TOR). This procedure also measured OC and total PM, but unfortunately, not all the vehicles in the study were measured using this technique. Elemental carbon was also measured uing the photoacoustic analyzer, which measures EC on a continuous basis. More information can be found on these techniques and their calibration and comparison results in the contractor's report[40] and Fujita et al. (2006)[57]. The former reference indicates that the photacoustic analyzer has good correlation with TOR EC measurement especially at higher PM levels, however, at lower levels (in bag 3 for example), the correlation is poorer. This is not surprising since all instruments have limited ability to measure small signals. To accentuate the full range of operation, Figure 77 shows a plot of a comparison of the two instruments on a natural-log scale. The plot reinforces the excellent agreement between the two instruments in bag 1 of the test, when emissions levels are at their highest. The correlation (and slope) is also good for the high values in bag 2, however, as the measurements get smaller, the photoacoustic analyzer seems to be shifted by about 2.4 mg/mi (near the origin of the plot). An adjustment equation may be appropriate if the TOR is the accepted standard, but since this offset mainly affects small measurements only, it will probably have little impact on emissions inventory models.

Figure 77. Comparison of Photoacoustic to TOR EC measurements on a logarithmic scale.



We present trends of the ratio of EC to total PM (EC/PM) only. Since in most cases the sum of EC+OC = PM, generalizations can be extended to OC/PM as well, accounting, of course, for the inverse relationship between EC and OC. There may be a small amount of non-carbon emission in the PM, but we assume that it is negligible.

We explore the EC/PM ratio for the four measurement techniques employed in this study: photoacoustic analyzer (PM, continuous EC), Dustrak analyzer (DT, continuous optical PM), gravimetric filter (PM), and thermal optical reflectance (TOR, which measured both EC and total carbon, TC). Table 41 shows the comparison of the 3 different ratio methods using these instruments. The values were determined from ratios of average values in the numerator and denominator. The TOR ratios have two major limitations: the ratios are unexpectedly high and, after eliminating bad data points, there are only 75 valid measurements. Due to the latter condition (primarily), the TOR ratios will not be used in subsequent analysis. The photoacoustic to dustrak ratios present a reasonable approach, however, since the Dustrak and PM are not perfectly correlated[40], we elected to use the photacoustic to gravimetric filter ratios for EC/OC rate estimation.

Table 41. Elemental to total PM ratio for 4 different measurement techniques.

	all	start	running
PA/DT	0.128	0.188	0.105
PA/PM	0.197	0.340	0.164
EC/TC TOR	0.382	0.540	0.339

In the next 3 plots, we look for other factors that may affect the EC/PM variability. Temperature, model year and vehicle weight are all examined. Figure 78 shows the relationship between EC/PM to test temperature. These values were averaged for all test values within a 10ºF bin and then ratios were calculated between corresponding means. We conclude from this plot that there is very little temperature dependence to this ratio (though there may be a very small effect for hot running bag 2). Any temperature dependence is miniscule compared to the temperature effects presented earlier for total PM. One might have expected cold start EC ratios to be higher in colder temperatures due to the potential for extended rich starts, however the data does not seem to support this hypothesis.

Figure 78. Elemental Carbon to Total PM ratio as a function of test temperature.

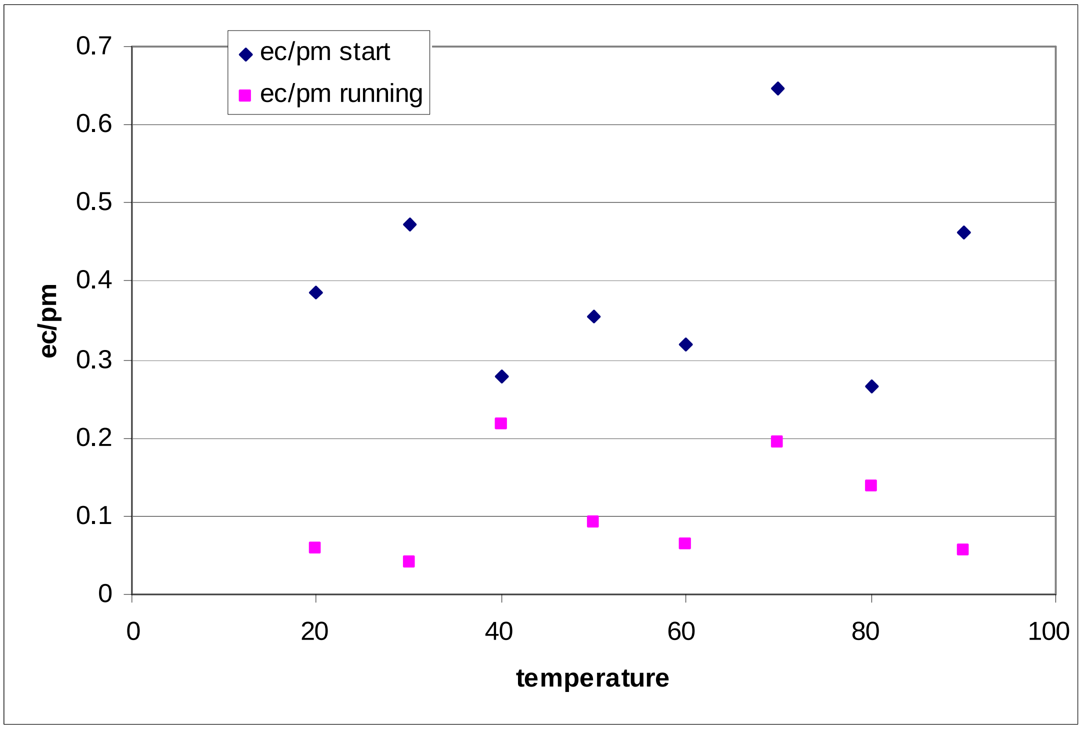


Figure 79 shows the EC/PM ratio within model year groups. We conclude from this plot that there seems to be very little model year or age dependence on the EC/PM ratio.

Figure 79. Elemental Carbon to Total PM ratio as a function of vehicle model year.

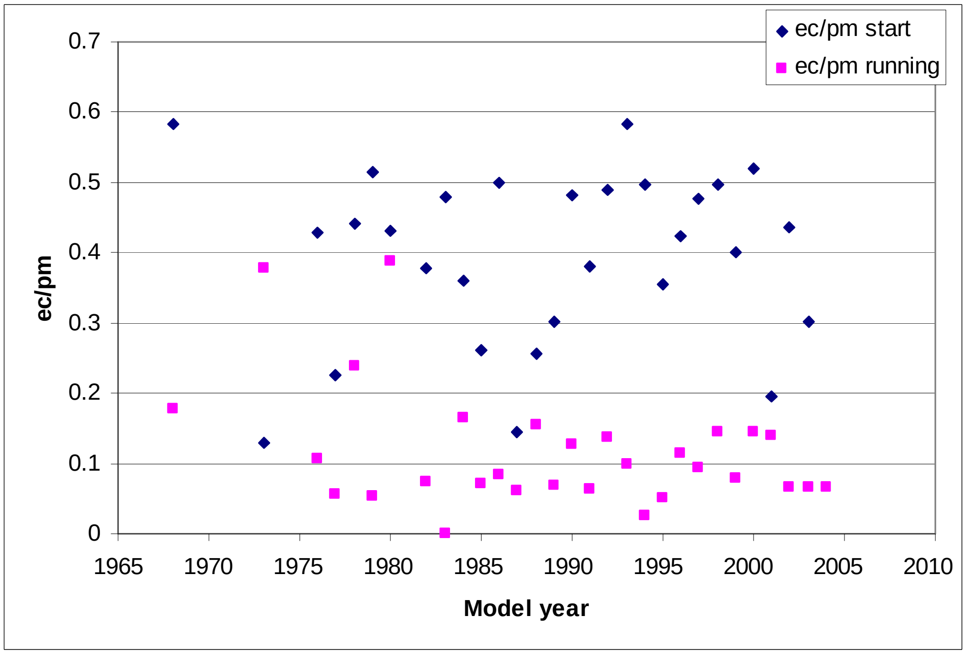
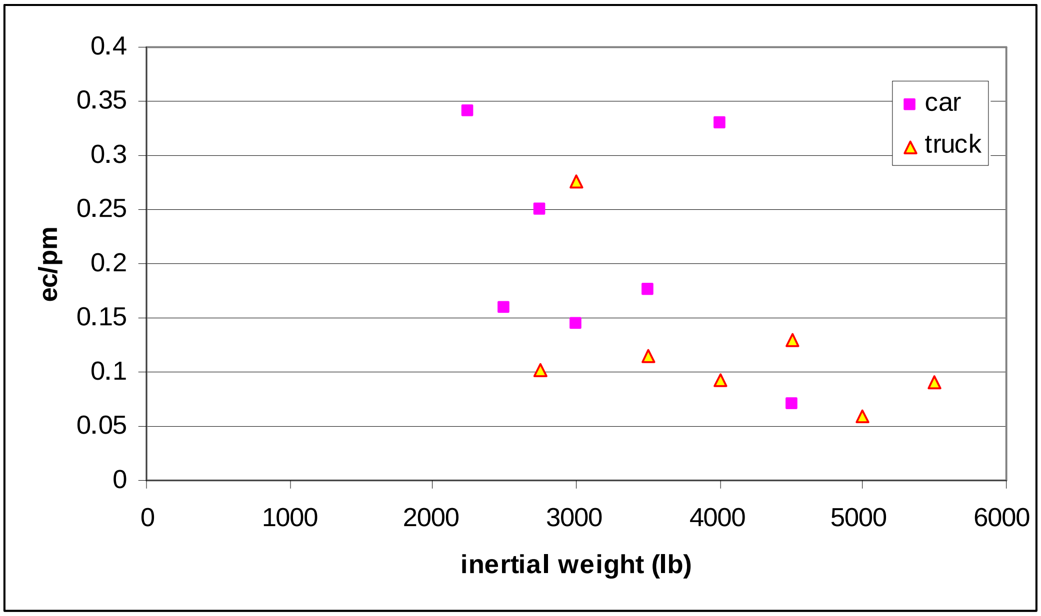


Figure 80 shows the EC/PM ratio as function of vehicle weight. This plot shows a clear trend of decreasing EC/PM ratio as weight increases. This could be a function of engine displacement (and peak power) as much as vehicle weight (the two tend to be correlated with each other). The trend may also be a function of the drive schedule since lighter (and possibly underpowered vehicles) may be more likely to go into enrichment than more powerful vehicles if driven on identical drive cycles. In subsequent modeling (in MOVES), cars and light trucks are modeled as separate vehicle types, which will capture some of this weight effect.

Figure 80. EC/PM ratio as a function of vehicle inertial weight.



An analysis shows the following statistics, with the breakdown of car vs truck in Table 42:

- avg Start EC/PM = 0.337
- avg Running EC/PM = 0.132
- Composite EC/PM ratio = 0.173
- The respective OC ratios can be calculated from the above by subtracting the fraction from 1.0.

The markedly higher level of EC during starts is not surprising given the rich fuel conditions that exist during this mode of operation.

These results are roughly consistent with past studies, which found the OC:PM fraction in Denver to range from 61-89%[50], in the South Coast of California to range from 37-80%[51], and in San Antonio to range from 53-93%[52]. For emission rate development, we use the values derived from the Kansas-City study, summarized in Table 42. Non-carbon PM are included with OC and is assumed to be small.

Table 42. Elemental and Organic Carbon PM fractions in from vehicles in the KC study.

Process	EC/PM car	EC/PM Truck	OC/PM car	OC/PM truck
Start	0.345	0.325	0.655	0.675
Running	0.179	0.068	0.821	0.932

2.4 Modal PM Emission Rates

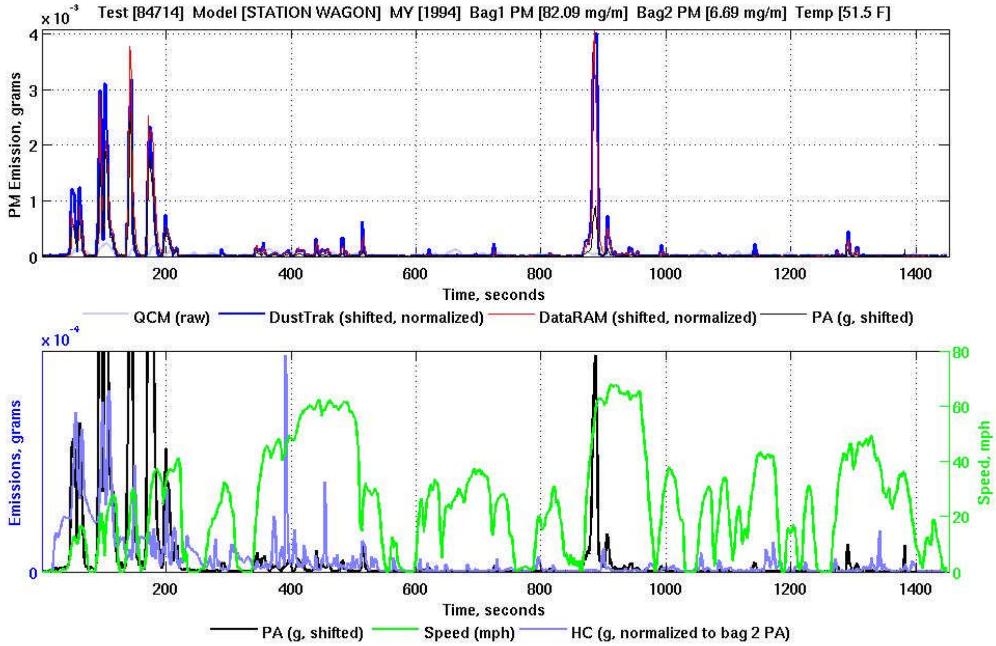
As mentioned earlier, the continuous emissions measurements from the Kansas City study were examined at great length, after which we determined that the Dustrak gave the most reliable second-by-second PM time-series data when compared to the quartz-crystal microbalance (QCM) and the Nephelometer. In the following sections, we describe some of the trends in continuous PM for “typical” normal-emitting and high-emitting vehicles. We conclude by describing the procedure by which results from the Dustrak were used to develop emission rates by operating mode.

2.4.1 Typical behavior in particulate emissions as measured by the Dustrak and Photoacoustic Analyzer

After looking at over 500 second-by-second traces, it became apparent that most of the vehicles fell into certain general patterns. The most common behavior involved a highly non-linear PM emissions increase as engine load increased. This pattern led to a monolithic “spike” in emissions during the most aggressive acceleration event in the LA92 drive cycle during the 2^{nd} (hot-running) bag, at around 850 seconds. This peak is captured in Figure 81, which includes two plots. The higher emissions prior to 300 seconds can be attributed to cold start, during which the engine is still cold and the fuel:air mixture tends to be on the rich side. The plot on the bottom confirms this supposition since it indicates that elemental carbon is relatively high during the start. The hydrocarbons are overlaid on the bottom plot merely for comparison, and provide a loose and qualitative comparison to organic PM emissions. Some vehicles had variations on this spike where it was much larger than even the cold start emissions, but this pattern is more typical of the newer vehicles tested on the warmer days.

On the following series of plots the dustrak (most prominent), nephelometer and QCM are overlaid on the top chart, while the photoacoustic analyzer, hydrocarbon and speed are overlaid on the bottom chart.   Ordinate values are all relative and not absolute. “Shifted” means time-aligned, “Temp” means ambient temperature and the filter measurements as well as vehicle type and model year are written above the figures.

Figure 81. A typical time-series plot of continous particulate emissions as measured by several instruments.



The next series of two figures shows how in some cases, the cold-start emissions appear to be persist into the "hot-running" phase of the cycle (bag 2). Figure 82 shows an older MY1976 vehicle tested at 54°F, for which one might expect the cold start emissions to have a longer duration than a newer vehicle. In this case, the cold start emissions seem to end at around 550 seconds (based on the HC trace). However, such cases where large portions of the cold start emissions leak occur during bag 2 were rare in the dataset, and thus they were not "corrected". This step can be considered for future study.

Figure 82. Continous particulate emissions from a 1976 Nova measured at 54°F.

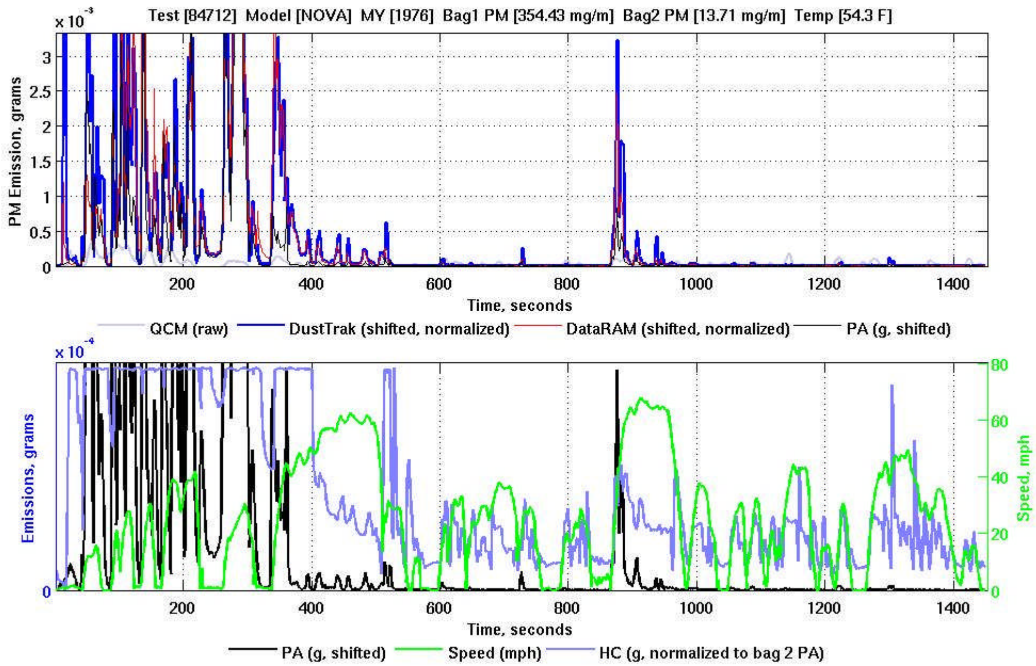
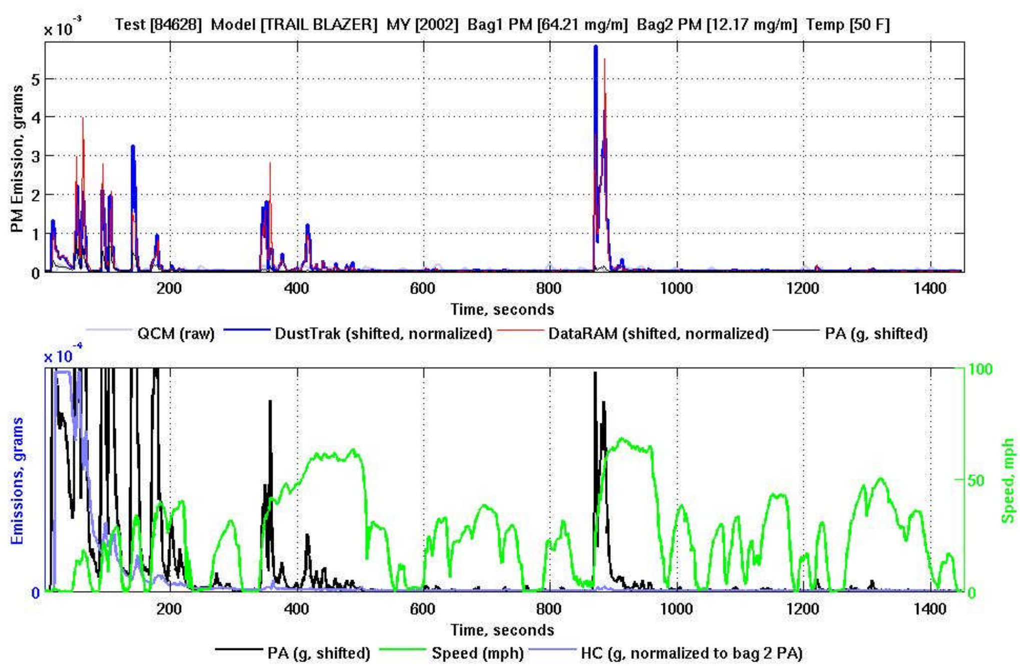


Figure 83 shows a similar but slightly more commonly seen effect for a newer vehicle. The difference is that the cold start seems to end at around 250 seconds in bag 1, but then is high again when bag 2 starts at around 350 seconds. Here the HC is low, but the EC (as indicated by the PA) is relatively high hinting at a slightly fuel rich mixture. It is uncertain at this time, why these vehicles need to go into enrichment during this relatively mild acceleration.

Figure 83. Measured Particulate time series for a recent model year vehicle.



The traces shown so far have been "normal emitters" during hot running operation, i.e. they did not have unusually high emissions during bag 2. These vehicles represent the bulk of the data. However, some vehicles do exhibit higher or otherwise unusual hot-running PM emissions. Examples are shown in the following series of figures.

Figure 84 shows a large "hump" of PM emissions starting at the beginning of bag 2 that lasts for nearly 600 seconds. The dustrak, nephelometer and the QCM all register this hump to varying degrees, so it's unlikely that it is a mere instrument artifact. The bulk of the bag 2 PM emissions lies in this "hump," which does not coincide with a high load event. It is interesting that the PA is not detecting a broad EC portion, so this hump is most likely organic carbon (OC), which leads us to deduce that this hump probably represents OC particulate due to oil consumption. Because these humps are not load based events, they don't suit themselves well to characterization by VSP as correlation to power should not be high during the event. Moreover, it is interesting to note that the broad hump does not repeat. Some vehicles have the hump at different locations in the cycle (or throughout the whole cycle in rare cases), thus making this effect impossible to model physically using only a power-based approach. Therefore, the effect can only be captured on an aggregate level by simply averaging with the normal emitters described earlier. It follows logically that if the recruitment of these "high emitters" was representative in Kansas City, and these high emissions humps are not load dependent, then this effect on the inventory should be captured by normalizing the modal rates to the filter measurements; i.e. they are captured in the base emission rates.

Figure 84. Particulate time-series for a 1988 Dynasty.

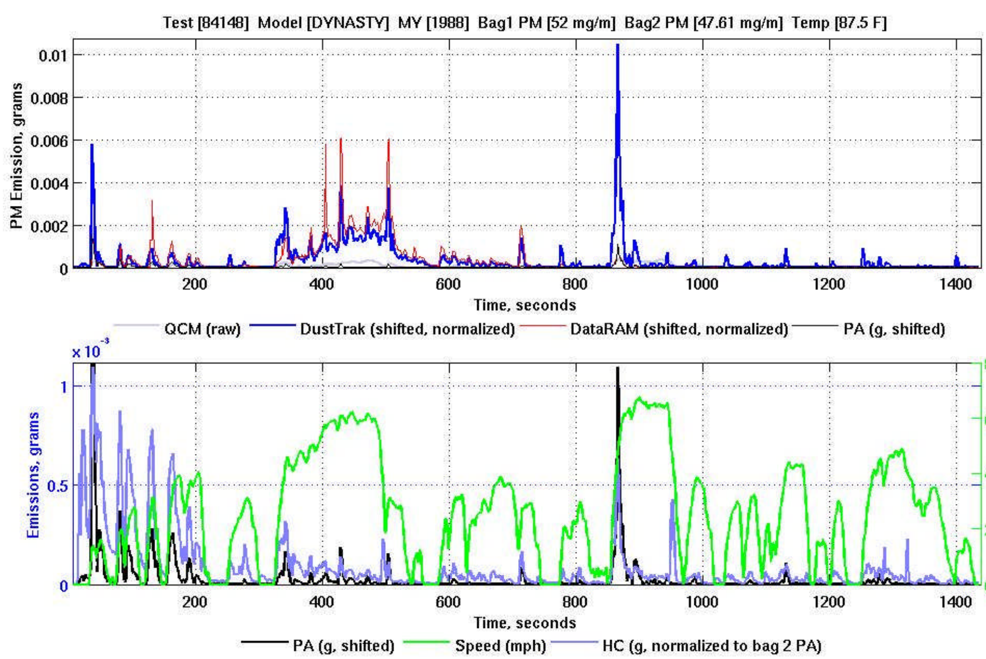
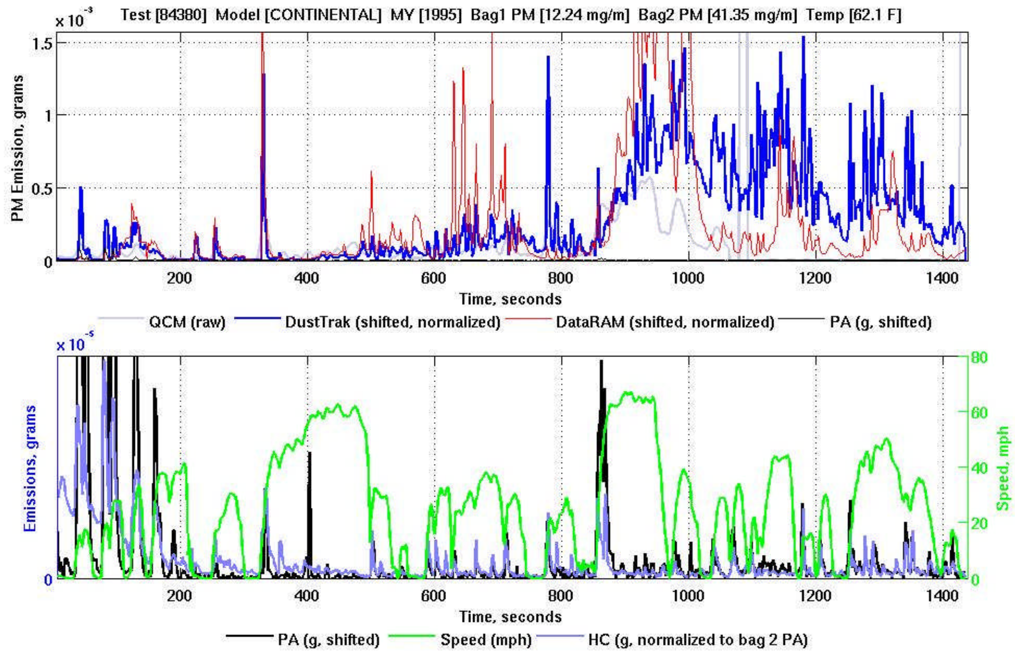


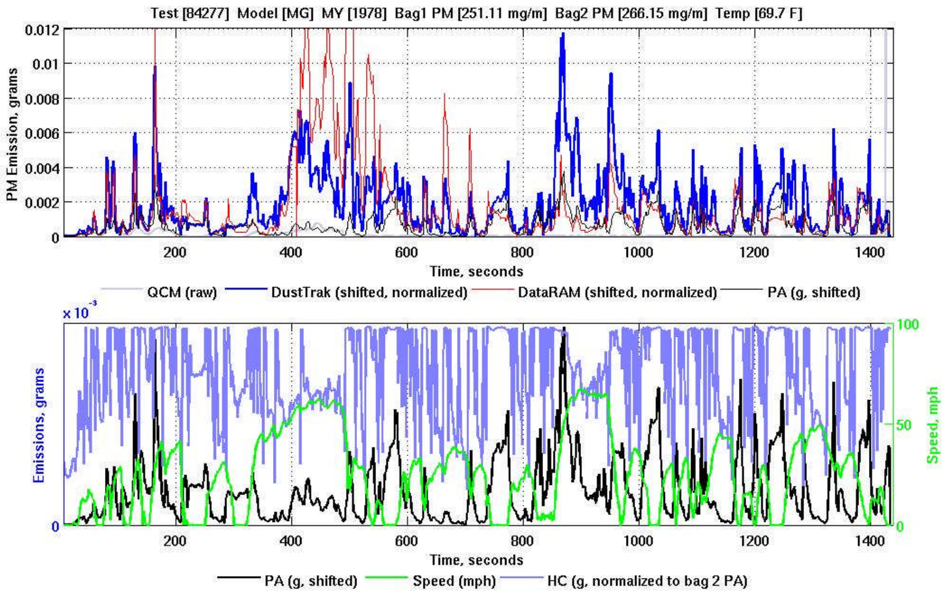
Figure 85 shows another likely candidate for designation as an oil burner. The emissions humps are much broader, though the absolute emissions are similar to the Dynasty. Note again that the dustrak, nepholometer, and the QCM all register the hump, while the PA shows very little EC, one of the “fingerprints” of oil-based particulate. In one of the repeat test vehicles in the study, one test exhibited a hump in emissions and the repeat test did not. The inconsistency and non-repeatability of some of these humps arising from oil consumption explains how some vehicles can flip from “high” to “normal” emissions or vice-versa in replicate measurements. These observations have ramifications for future PM research, in that sample sizes should be large and fleets properly representative.

Figure 85. Continuous particulate time series for a 1995 Lincoln Continental.



The next figure (Figure 86) shows a more typical high PM emitter, where the bag 2 emission rate is 266 g/mi. Here the EC does mirror the high emissions seen in the other instruments. Even the HC measurements are saturated. This trace, representing a 1978 MG, is an indicator of poor fuel control, as might be expected with an older (1978) carbureted engine.

Figure 86. Continuous particulate (and HC) time series for a 1978 MG.



We are now ready to classify the emission rates into operating modes based on speed, acceleration and vehicle-specific power (VSP) (Table 5). The following two figures show Dustrak PM emissions binned by VSP and classified by model year Groups. Figure 87 shows this relationship on a linear scale and Figure 88 shows the relationship on a logarithmic scale. It is clear from the latter plot that VSP trends for PM tend to be exponential with VSP load, i.e. they are approximately linear on a log scale, showing similar patterns to the gaseous emissions, particularly CO. Thus we assume smooth log-linear relations when calibrating our VSP based emission rates.

Figure 87. Particulate emissions, as measured by the Dustrak, averaged by VSP and model-year Group (LINEAR SCALE).

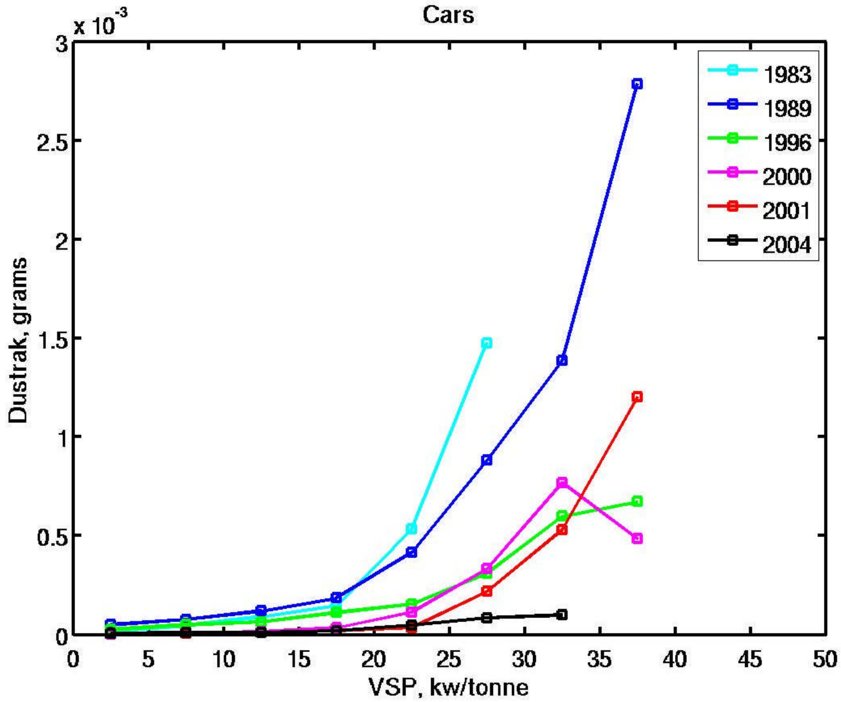
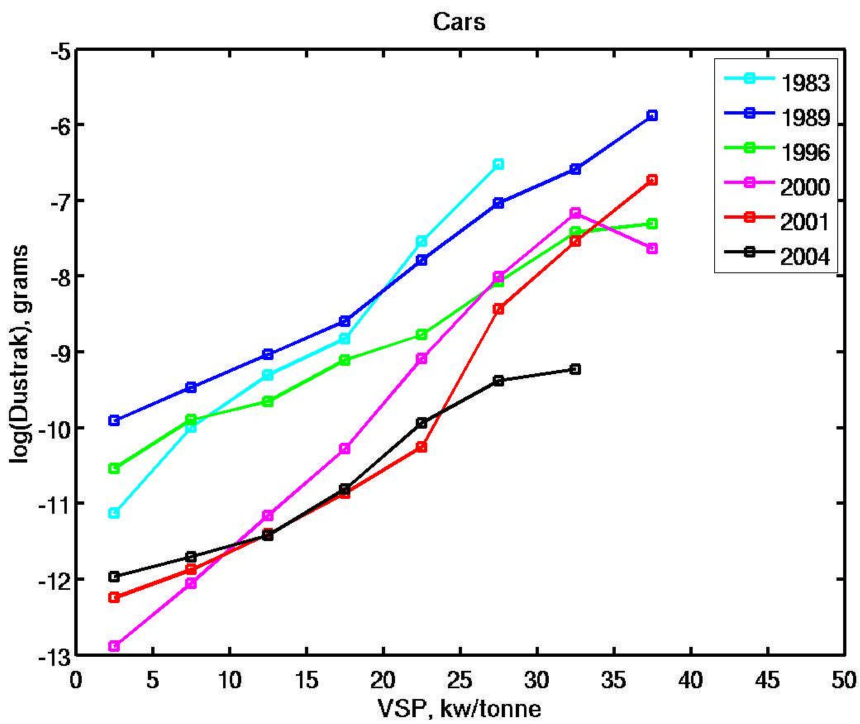


Figure 88. Particulate emissions, as measured by the Dustrak, averaged by VSP and model-year Group (LOGARITHMIC SCALE).

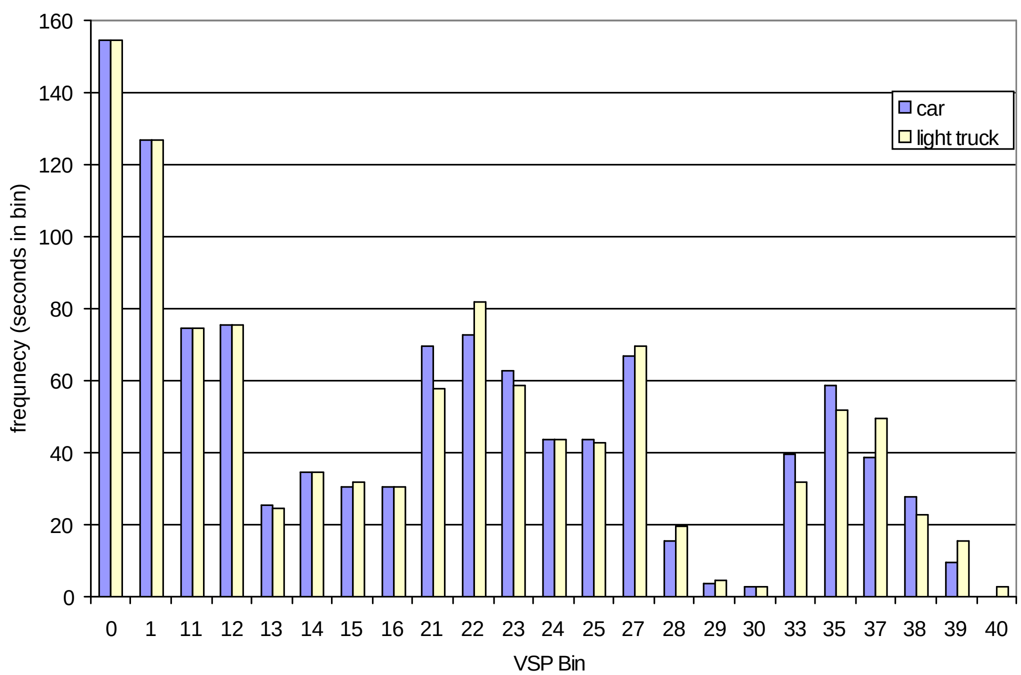


In order to determine the actual MOVES VSP based rates, followed seven steps:

1. The LA92 equivalent hot-running emission rate (g/mi) is determined for every model year and age group from the model described in section 2.2.
2. The gram per second (g/s) emission rate is determined from the dustrak for cars and trucks based on the KC data. These trends are then extrapolated to the higher VSP bin levels where data is missing.
3. The VSP operating-mode distribution is calculated for bag 2 of the LA92 drive cycle for cars and trucks separately – this step is equivalent to determining the number of seconds in each mode.
4. The modal rates (Step 2) are then combined with the operating-mode distribution and summed to give a total bag 2 emission factor that must match the aggregate LA92 emission rates in step 1 (as calculated from the filter measurements).
5. The emission rates are normalized to match the filter values through a normalization factor that is applied to every combination of model year and age group.
6. The rates from step 5 are then multiplied by the corresponding EC and OC factors to give rates for the hot-running process.
7. Steps above are repeated for all ages and model years.

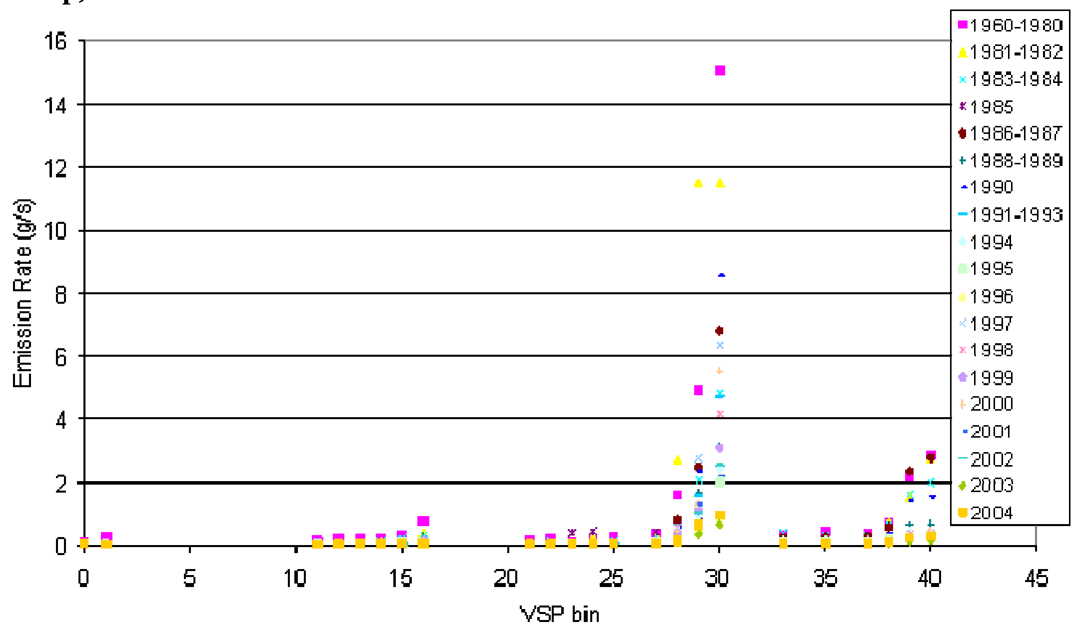
The output from step 3 (operating-mode distribution) for cars and light trucks is shown in Figure 89. For operating-mode definitions, see Table 5.

Figure 89. Operating-Mode distribution for cars and light trucks representing the hot-running phase (Bag 2) of the LA92 cycle.



The output of step 5 for each model year ZML (0-3 year age Group) is shown in Figure 90.

Figure 90. Particulate emissions for passenger cars (LDV) from Kansas City results, by model year Group, normalized to filter mass measurements.



After the rates were calculated, a quality check was performed to ensure that the aged rates in any particular bin were not too high. A multiplicative model with exponential factors risks excessively high emission rates under extreme conditions. For example any rate over 100 g/sec was considered too high, this would be an extremely high-smoking vehicle. This behavior was corrected in only two cases bins in operating mode 30, representing values for cars and trucks in the 1975 model-year Group. In these cases, the value from operating mode 29 was copied into mode 30.

2.5 Conclusions

The previous discussion describes analyses of particulate-matter emissions designed to develop operating-mode based emission rates for use in the MOVES emissionRateByAge table, incorporating the effects of temperature, model year and age. These rates include organic and elemental carbon for cold-start and hot-running emissions from cars and light trucks (e.g., LDV and LDT). This analysis is crucial for understanding how PM emissions have changed over the years and how new vehicle PM rates are projected to deteriorate over time. The new vehicle (zero mile level) PM emissions are estimated by analyzing the new-vehicle emissions rates from historical PM studies. The trends indicate that emissions have been decreasing exponentially with model year as the engine and fuel controls have improved and after-treatment devices have been installed. The new truck rates are found to be larger than the car rates. The deterioration effect of age is determined by comparing the new vehicle rates to the Kansas City data. Based on patterns observed for the gaseous emissions, we have assumed that emissions deteriorate exponentially with the age of the vehicle, but remain constant after about 20 years. We also found that PM emission increase exponentially with VSP (or road or engine load).

There is still much analysis that can be conducted with these data. In the future, it would be important to examine trends in the speciated hydrocarbons and organic PM from the standpoint of toxic emissions and also quantifying the PM emissions due to oil consumption. These analyses are likely to expand the scientific understanding of PM formation and why certain gasoline fueled vehicles emit more PM than others under certain conditions. It would also be useful to explicitly capture the non carbon portion of particulate emissions.

3. Gaseous and Particulate Emissions from Light-Duty Diesel Vehicles (THC, CO, NOx, PM)

In MOVES, emission rates for running emissions are calculated for each operating mode. However, for the diesel-fueled passenger cars (LDV) and light-duty trucks (LDT), we lack the necessary continuous or “second-by-second” measurements to directly calculate emission rates in relation to vehicle specific power. Therefore, we used aggregate results (in grams per mile) from the Federal Test Procedure (FTP) to estimate aggregate rates, which we then translated into corresponding modal rates (in grams per hour).

3.1 Gaseous Emissions: MY2009 and earlier, Particulate Emissions: MY2003 and earlier.

The analyses in this section pertain to development of rates representing vehicles manufactured prior to introduction of Tier-2 standards. For gaseous emissions, this grouping is represented by MY 2009 and earlier. For particulate emissions, the grouping represents MY 2003 and earlier.3.1.1 Estimating Zero-Mile FTP Emissions:

We identified FTP results on the Annual Certification Test Results & Data website (http://www.epa.gov/otaq/crttst.htm) and on the Test Car List Report Files Website (http://www.epa.gov/otaq/tclrep.htm) for 513 diesel-powered LDV and 187 LDT from the 1978 through 2008 model years. These vehicles had been measured for purposes of engine certification or generation of fuel economy estimates. These vehicles were new (age = zero years), with each vehicle having accumulated about 4,000 miles. These data were used to calculate mean (composite) FTP emissions (grams per mile of HC, CO, NOx, and PM10) for each model year group. (We examined, but did not include data on European diesels since those vehicles might not be representative of those sold in the U.S.) The sample sizes (by model year group) and the mean composite FTP emissions are given in Table 43 for cars and Table 44 for trucks:

Table 43. Mean Composite FTP Emissions (g/mile) for diesel-fueled Cars (LDV).

Model Year Group	Sample Size	HC	CO	NOx	PM[1]
Pre-1981	104	0.4883	1.3425	1.4126	---
1981-82	114	0.2508	1.0861	1.1859	0.2999
1983-84	116	0.2006	0.9809	1.0517	0.2881
1985	73	0.2178	1.1386	0.8436	0.2751
1986-90	79	0.2075	1.3581	0.5952	0.5668
1991-93	13	0.2123	1.6854	0.5685	0.4990
1994	3	0.2273	1.2233	0.8567	0.1747
1995-2005	5	0.1364	0.4140	0.8180	0.0848
2006-2008	6	0.0196	0.5367	0.3925	---

[1] Measurements of PM emissions were not performed for the Pre-1981 model year cars (or trucks). For this analysis, we applied the (later) 1982 standard of 0.6 grams per mile to those earlier model years.

Table 44. Mean Composite FTP Emissions (g/mile) for diesel-fueled light-duty trucks (LDT).

Model Year Group	Sample size	HC	CO	NOx	PM[1]
Pre-1981	13	0.6900	1.7923	1.6577	---
1981-82	45	0.3478	1.3277	1.3748	0.3296
1983-84	56	0.2578	1.0302	1.3052	0.2700
1985	11	0.2297	1.1200	0.9473	0.2673
1986-90	20	0.2364	0.9985	1.4435	0.2790
1991-93	5	0.3020	1.7000	1.2600	0.1280
1994	17	0.2213	1.6256	1.3814	0.1114
1995-2005	14	0.1526	1.6179	1.4629	0.0960
2006-2008	6	0.0181	0.2767	0.4583	---

[1] Because measurements of PM emissions were not performed for the Pre-1981 model year cars (or trucks), we applied the (later) 1982 standard of 0.6 grams per mile to those earlier model years. Due to questionable PM results for the 2006-2008 LDT, we used the LDV average PM value (0.0312 grams/mile).

3.1.1.2 Estimating Bag Emissions:

The 700 certification (car and truck) test results were composite FTP results (HC, CO, NOx, and PM), not differentiated by test phase (bag). Therefore, the first task was to estimate the individual bag results based on the composite results.

A smaller sample (151 tests) of FTPs from other data sets had emission results by bag. These FTPs of in-use vehicles (of various ages from various model years) were used only to develop correlations between the composite FTP emissions and the corresponding emissions of each of the three bags/modes. The sources of these data are summarized in Table 45.

We regressed the Bag-2 emissions (in grams per hour) against the corresponding composite FTP emissions (in grams per mile) to obtain an estimate of running emissions. For these regressions, we used a piecewise linear approach rather than a polynomial regression to account for slight curvature in the relationships. Similar analyses were performed regressing Bag-1 emissions and Bag-3 emissions (in total grams) each against the corresponding composite FTP emissions (in grams per mile). Each of the 14 regressions produces an equation, such as the following example, which correlates the Bag-1 "cold-start" HC emissions ($E_{HC,Bag1}$, g) to the corresponding composite FTP HC emission rate ($E_{HC,composite}$,g/mile):

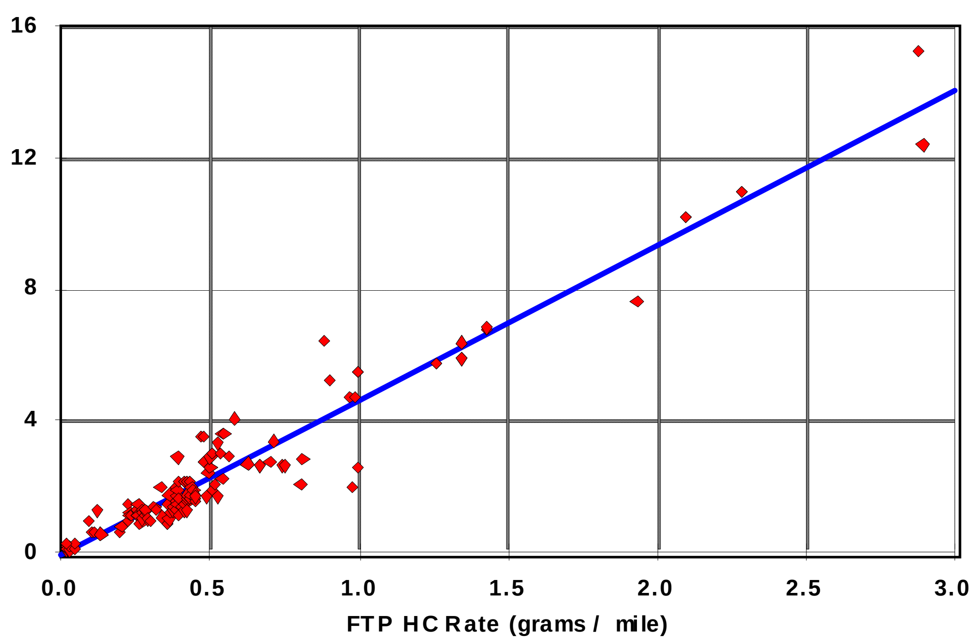
$$E_{HC,Bag1} = -0.6433 + 4.702885\, E_{HC,composite} \qquad \textbf{Equation 51}$$

Graphing this equation along with the 146 FTP test results, as shown in Figure 91 below, illustrates the relationship between the individual bag HC emission and the composite HC emission.

Table 45. Data Sources used to distinguish emissions by phase (bag) on the FTP for light-duty diesels.

Source	No. Tests
Norbeck et al., (1998a)[51]	19
Norbeck et al., (1998b)[58]	15
USEPA In-Use Verification Program	12
Mobile-Source Observation Database (MSOD)[30]	105
Total	151

Figure 91. Example: Bag-1 HC (g) versus Composite FTP HC (g/mile)



We then applied those 14 equations (derived from the regression analyses) to the corresponding composite FTP emissions shown in Table 43 and Table 44. This step yielded (for each model year group in Tables 1 and 2) estimates of the emissions rate (in grams per hour) for Bag-2 as well as the total emissions (in grams) for each of Bag-1 and Bag-3.

We then assumed that the running emission rates (in grams per hour) on Bag-2 were comparable to the rates on the running portion of the Bag-1 (and Bag-3). Subtracting the total emissions associated with those running rates from the estimated total emissions of Bag-1 (based on the regressions of Bag-1 versus composite FTP) yielded estimates of the cold-start emissions (by model year). Similarly, subtracting the estimated running emissions from the estimated total Bag-3 emissions produced estimates of hot-start emissions. Those estimated emission rates (running, cold-start, and hot-start) are summarized in the four following tables (Table 46 to Table 49), one table for each of the four pollutants.

Table 46. Estimated Aggregate HC Emission Rates.

Model Year Group	**Diesel-Fueled Passenger Cars**			**Diesel-Fueled Light-Trucks**		
	Running (g/hr)	**Cold-Start (g)**	**Hot-Start (g)**	**Running (g/hr)**	**Cold-Start (g)**	**Hot-Start (g)**
Pre-1981	8.0991	1.0961	0.1688	11.2131	1.6077	0.3280
1981-82	4.0262	0.5505	0.1626	5.6533	0.7784	0.2161
1983-84	3.1838	0.4325	0.1349	4.1427	0.5668	0.1664
1985	3.4727	0.4729	0.1444	3.6724	0.5009	0.1510
1986-90	3.2992	0.4486	0.1387	3.7835	0.5165	0.1546
1991-93	3.3802	0.4600	0.1414	4.8847	0.6707	0.1908
1994	3.6322	0.4953	0.1496	3.5308	0.4811	0.1463
1995-2005	2.1069	0.2816	0.0995	2.3782	0.3196	0.1084
2006-2008	0.1477	0.0071	0.0351	0.1226	0.0036	0.0342

Table 47. Estimated Aggregate CO Emission Rates.

Model Year Group	**Diesel-Fueled Passenger Cars**			**Diesel-Fueled Light-Trucks**		
	Running (g/hr)	**Cold-Start (g)rt**	**Hot-Start (g)**	**Running (g/hr)**	**Cold-Start (g)rt**	**Hot-Start (g)**
Pre-1981	21.3626	3.0900	1.0957	28.8186	4.0993	1.5010
1981-82	17.1121	2.5146	0.8647	21.1168	3.0567	1.0824
1983-84	15.3696	2.2787	0.7700	16.1856	2.3892	0.8144
1985	17.9833	2.6326	0.9121	17.6745	2.5908	0.8953
1986-90	21.6212	3.1250	1.1098	15.6605	2.3181	0.7858
1991-93	27.0463	3.8594	1.4046	27.2886	3.8922	1.4178
1994	19.3873	2.8226	0.9884	26.0552	3.7252	1.3508
1995-2005	5.9718	1.0066	0.2592	25.9270	3.7079	1.3438
2006-2008	8.0052	1.2818	0.3698	3.6954	0.6984	0.1355

Table 48. Estimated Aggregate NOx Emission Rates.

Model Year Group	Diesel-Fueled Passenger Cars			Diesel-Fueled Light-Trucks		
	Running (g/hr)	Cold-Start (g)rt	Hot-Start (g)	Running (g/hr)	Cold-Start (g)rt	Hot-Start (g)
Pre-1981	23.4257	1.6481	1.5561	27.6186	1.8543	1.7824
1981-82	19.5462	1.4573	1.3466	22.7786	1.6162	1.5211
1983-84	17.2503	1.3444	1.2227	21.5870	1.5576	1.4568
1985	13.6886	1.1692	1.0304	15.4631	1.2565	1.1262
1986-90	9.4389	0.9602	0.8009	23.9537	1.6740	1.5846
1991-93	8.9815	0.9377	0.7762	20.8139	1.5196	1.4151
1994	13.9128	1.1802	1.0425	22.8916	1.6218	1.5272
1995-2005	13.2512	1.1477	1.0067	24.2849	1.6903	1.6025
2006-2008	5.5883	0.8433	0.6673	6.4738	0.9325	0.7619

Table 49. Estimated Aggregate PM Emission Rates.

Model Year Group	Diesel-Fueled Passenger Cars			Diesel-Fueled Light-Trucks		
	Running (g/hr)	Cold-Start (g)rt	Hot-Start (g)	Running (g/hr)	Cold-Start (g)rt	Hot-Start (g)
Pre-1981	7.0131	2.4362	1.2789	7.0131	2.4362	1.2789
1981-82	3.3778	1.2427	0.6436	3.7378	1.3609	0.7065
1983-84	3.2356	1.1960	0.6188	3.0160	1.1239	0.5804
1985	3.0774	1.1441	0.5911	2.9830	1.1131	0.5746
1986-90	6.6108	2.3041	1.2086	3.1250	1.1597	0.5995
1991-93	5.7897	2.0346	1.0651	1.7460	0.4961	0.2167
1994	2.4073	0.6682	0.3020	1.5101	0.4347	0.1863
1995-2005	1.1338	0.3368	0.1378	1.2931	0.3782	0.1583

The PM rates in the preceding table represent the PM10 rates for all particulate matter on the collection filter (i.e., elemental carbon (EC), organic carbon (OC), sulfates, etc.). Disaggregating the PM estimates to obtain rates separately for EC and for OC, will be described in 3.3 below.

3.1.1.3 Assigning Operating Modes for Starts (Adjustment for Soak Time)

MOVES has start emission rates for eight operating modes (opModes), each based on the length of the soak time prior to engine start. One mode corresponds to the 12 hour cold-soak (opmodeID = 108). The remaining seven modes have soak times ranging from three minutes up to nine hours (opModeID = 101-107).

Assuming that the start emissions change as functions of the temperature of the engine, and assuming that the engine temperature decreases (cools) exponentially with the soak period (i.e., length of time the engine is shut off), then we should be able to approximate the start emissions (following a soak E_{opModeID}) by exponential functions of the form:

$$E_{\text{opModeID}} = E_{108}\left(1.001 - \alpha\, e^{-\beta t}\right) \quad \textbf{Equation 52}$$

where E_{108} = cold-start emissions (g) and t = soak time (min), in minutes.

(Note that the factor of 1.001 (rather than 1.0) in the preceding equation allows the exponential curve to pass through the cold-start value at 720 minutes rather than simply approaching it.)

Using the estimated cold-start (CS) emissions i.e., emissions following a soak of at least 720 minutes (E_{108}) and the hot-start emissions i.e., the emissions following a soak of only 10 minutes (E_{101}) from the preceding four tables, we solved algebraically for both the α and β coefficients, specifically:

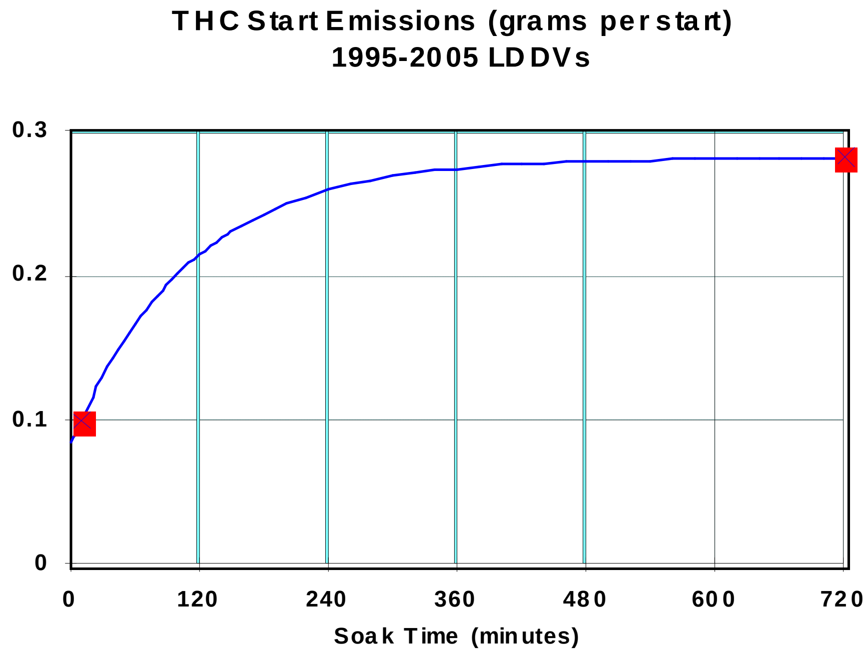
$$\alpha = e^{720\beta + \ln 0.001}$$

$$\beta = \frac{\ln\left(1 - \frac{E_{101}}{E_{108}}\right) - \ln 0.001}{710} \qquad \textbf{Equation 53}$$

This approach yielded a unique start emission curve (as a function of soak time) for each pollutant and for each model year group.

The effect of this exponential approach is illustrated in the following example (Figure 92) which was created using the estimated cold-start THC emissions of 0.281593 grams for the 1995-2005 model year diesel-fueled passenger cars and the estimated hot-start THC emissions of 0.099486 grams from the preceding table.

Figure 92. Estimated THC Start Emissions (g) in terms of Soak Time (1995-2005 LDV).



This continuous concave curve is broadly comparable to the piecewise approach that the California Air Resources Board used in its analysis of the effect of soak time on the start emissions of gasoline-fueled vehicles and that EPA used in MOBILE6[32].

3.1.2 Running Emissions by Operating Mode

In MOVES, running emission rates are estimated for a set of operating modes defined in terms of vehicle-specific power, speed and acceleration (see Table 5, page 14). However, we lacked the requisite second-by-second data for the diesel-fueled cars and light-trucks to perform those calculations. Therefore, we developed modal rates for LDT from corresponding rates for light heavy-duty diesel-fueled trucks (LHD<=14K) (i.e., from trucks with gross vehicle weight ratings between 8,500 and 14,000 pounds).

To adapt the LHDDT operating modes for application to LDDs, we developed operating mode frequencies in each mode for the 1,372-second LA-4 drive cycle (the first two phases of the FTP run sequentially). Due to differences in vehicle weight, we obtained separate (slightly different) distributions for passenger cars and and light-trucks, as shown in Table 50.

Table 50. Operating-Mode Distribution for the LA-4 Drive Cycle.

opModeID	LDV	LDT
0	164	164
1	255	255
11	93	96
12	142	139
13	99	103
14	69	66
15	34	33
16	20	20
21	68	70
22	149	164
23	123	110
24	35	33
25	21	19
27	14	15
28	8	7
29	2	2
30	0	0
33	25	29
35	35	33
37	13	11
38	3	3
39	0	0
40	0	0

Applying the appropriate distribution to the modal emission rates for the LHDDVs, we obtained estimates of the emission rates (in grams per hour) over a simulated LA-4 driving cycle. Dividing those rates into the hour running rates for the light-duty diesels (Table 46 through Table 49), by model-year group, yielded ratios of the light-duty emission rates to the light heavy-duty rates. The resulting ratios are then used as adjustment factors to scale the modal LHD rates to give estimated modal LDD rates. For example, applying the LA-4 operating-mode distribution to the NOx modal rates for the 1999-2002 model year LHDDVs produces an estimated NOx rate of 143.66993 grams per hour compared to the actual passenger car average rate of 13.2512 grams per hour. Dividing yields a ratio of 0.092234. Therefore, we used that ratio (0.092234) as a scaling factor to multiply all of the modal LHDDV rates for that model-year group to produce the corresponding VSP bins for the 1999-2002 model year diesel-fueled passenger cars. Thus, summing all of the LA-4 modal rates will exactly match the total estimate LA-4 (running) emissions.

Not all of the operating modes are represented by the LA-4 driving cycle. Specifically, modes 30, 39, and 40 do not occur during the LA-4. For this analysis, we applied the same adjustment factor to all operating modes.

This approach is illustrated by the following plots (Figure 93 to Figure 96) of the estimated modal emission rates for 1995-1998 model year diesel-fueled passenger cars and trucks.

Figure 93. Modal Emission Rates for THC, for MY1995-98 diesel-fueled Cars and Trucks.

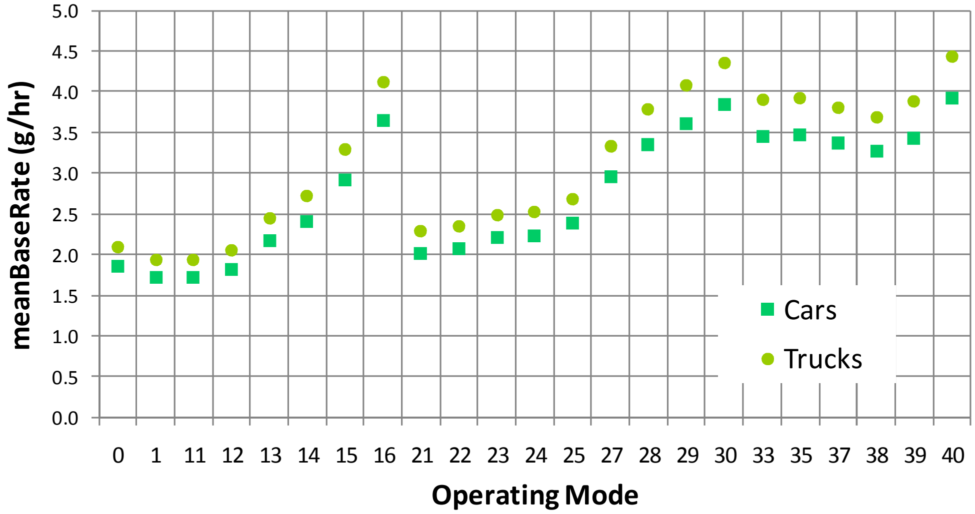


Figure 94. Modal Emission Rates for CO, for MY1995-98 diesel-fueled Cars and Trucks.

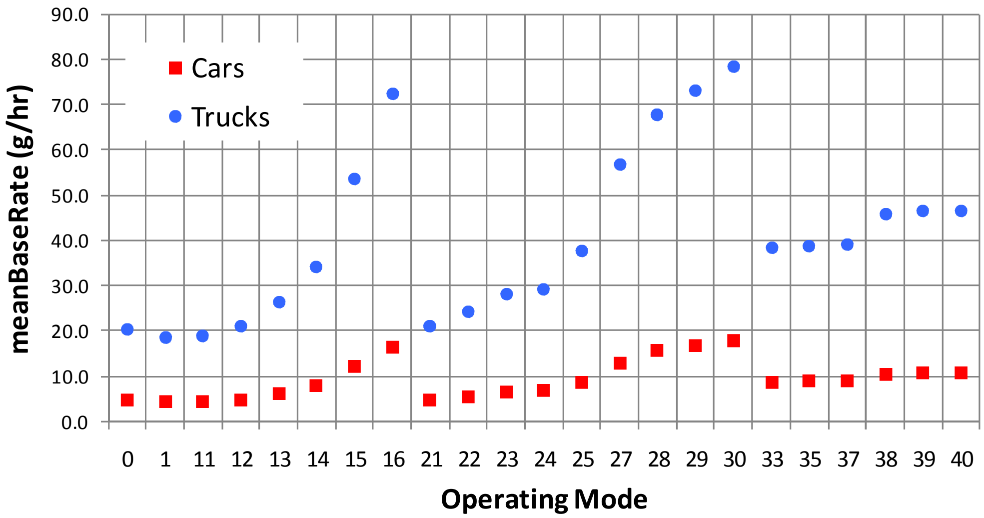


Figure 95. Modal Emission Rates for NOx, for MY1995-98 diesel-fueled Cars and Trucks.

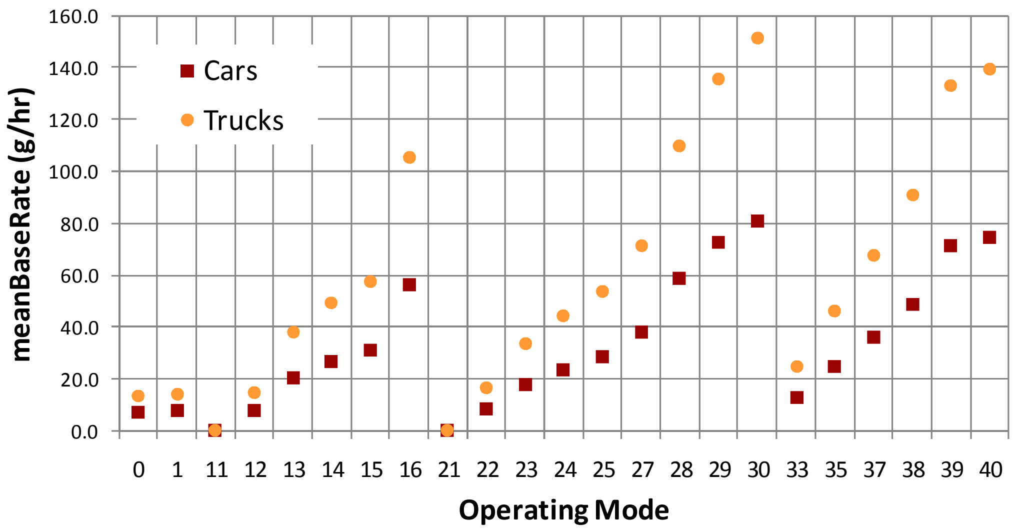
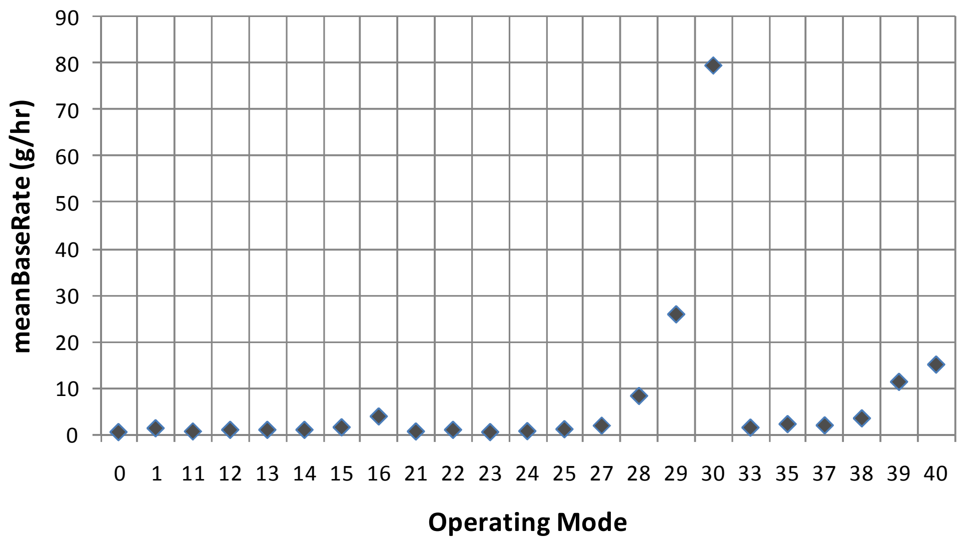


Figure 96. Modal Emission Rates for PM, for MY1998 diesel-fueled Cars.



3.2 Gaseous Emissions: MY2010 and Later, Particulate Emissions: MY2004 and Later.

3.2.1 Gaseous Emissions

For model years 2010 and later, we did not apply the analyses described above in 3.1. Start and running rates for light-duty diesels in model years 2010 and later were assumed to equal those for light-duty gasoline vehicles, as vehicles running on both fuels would be certified to the same standards. See Table 36 and Table 37 (dataSourceID 4910).

3.2.2 Particulate Emissions

To achieve substantially lower PM emissions, manufacturers are now equipping their diesel-fueled vehicles (cars and trucks) with particulate traps.

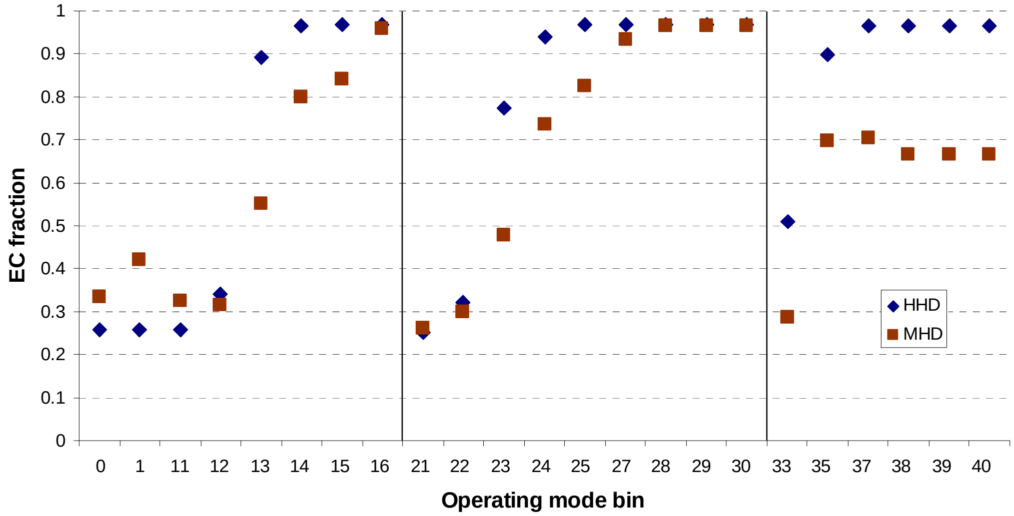
Similarly to the gaseous emissions, for MY 2004 and later, particulate emissions for light-duty diesels were assumed to equal those for light-duty gasoline vehicles. Thus, for these model years, corresponding gasoline rates, as described in Chapter 2.0 above, were replicated to represent diesel vehicles.

3.3 Particulate Emissions: Estimating Elemental and Organic Carbon Components (EC, OC)

3.3.1 Group 1: MY 2003 and earlier

For these model years, total PM was partitioned into EC and OC components using ratios developed for application to heavy-duty diesels. Figure 97 below, which is reproduced from the Heavy-Duty Emissions Report[59], shows the ratios.

Figure 97. Elemental Carbon (EC) fractions running-exhaust particulate emissions, for Heavy-heavy-duty and medium-heavy-duty diesel vehicles, by operating mode.



3.3.2 Group 2: MY 2004 and later

For these model years, total PM was partitioned into EC and OC components using ratios developed for application to light-duty gasoline rates. See 2.3 And Table 42 above.

4.0 Crankcase Emissions

In an internal combustion engine, the crankcase is the housing for the crankshaft. The enclosure forms the largest cavity in the engine and is located below the cylinder block. During normal operation, a small amount of unburned fuel and exhaust gases escape around the piston rings and enter the crankcase, and are referred to as "blow-by." These unburned gases are a potential source of vehicle emissions.

To alleviate this source of emissions, the Positive Crankcase Ventilation (PCV) system was designed as a calibrated air leak, whereby the engine contains its crankcase combustion gases. Instead of the gases venting to the atmosphere, they are fed back into the intake manifold where they reenter the combustion chamber as part of a fresh charge of air and fuel. A working PCV valve should prevent virtually all crankcase emissions from escaping to the atmosphere.

PCV valve systems have been mandated in all gasoline vehicles, both light-duty and heavy-duty, since model year 1969. Diesel vehicles with turbocharged engines , both light- and heavy-duty have only been required to have PCV valves since model year 2008. Thus, MOVES emission inputs assume that all 1968 and earlier gasoline vehicles, and 2007 and earlier diesel vehicles do not have PCV valves.

The MOBILE series of models included crankcase emission factors solely for gasoline hydrocarbons. For purposes of MOVES, we have developed additional emission factors, as explained below.

Crankcase emissions are calculated in MOVES by chaining the emission calculators which calculate start, running, or extended idling emissions to a crankcase emission ratio. Crankcase emissions are calculated as a fraction of tailpipe exhaust emissions, which are equivalent to engine-out emissions for pre-1969 vehicles. Crankcase emissions are calculated for selected pollutants, including THC, CO, and NO_x, and the particulate fractions organic carbon $PM_{2.5}$, elemental carbon $PM_{2.5}$, sulfate $PM_{2.5}$, and sulfate PM_{10}. For each of these pollutants, the crankcase emissions are calculated from the start, running exhaust, or extended idling emissions of the same pollutant and then multiplying by the appropriate ratio in the CrankcaseEmissionRatio table.

For vehicles with working PCV valves, we assume that emissions are zero. Based on EPA tampering surveys, MOVES assumes a 4% PCV valve failure rate.[60] Consequently, for fuelType/model-year combinations equipped with PCV valves, we assume a crankcase ratio of 0.04; i.e., emission fractions for the crankcase process are estimated as 4% of the emission fractions assumed for uncontrolled emissions. While this 4% estimate may be pessimistic for new vehicles, and optimistic for old vehicles, available data does not support a more detailed estimate. As older vehicles have higher overall emissions due to deterioration effects, use of the aggregate rates may understate the impacts of crankcase emissions.

Very little information is available on crankcase emissions, especially those for gasoline vehicles. A literature review was conducted in order to identify available data sources for emission fractions (Table 51).

Table 51. Selected Sources of published data on crankcase emissions from gasoline and diesel vehicles (light- and heavy-duty).

Authors	**Year**	**Type**	**# Vehicles**	**HC**	**PM(all species)**	**CO**	**NOX**	**Units**
Hare and Baines[61]	1973	Diesel	1	0.2-4.1	0.9-2.9	0.005-0.43	0.005-0.43	% of exhaust
Heinen and Bennett[62]	1960	Gasoline	5	33	X	x	x	% of exhaust
Bowditch[63]	1968	Gasoline	x	70	X	x	x	% of exhaust
Montalvo and Hare[64]	1985	Gasoline	9	*1.21-1.92*	*X*	*x*	*x*	g/mi
Williamson[65]	1995	Diesel	1	50	35	x	x	% of exhaust
Kittelson[66]	1998	Diesel	1	*x*	*0.038*	*x*	*0.005*	g/hp-hr
Hill[67]	2005	Diesel	9	x	100	x	x	% of exhaust
Ireson[68]	2005	Diesel	12	x	25-28	*x*	*x*	% of exhaust
Zielinska[69]	2008	Diesel	2	x	20-70	*x*	*x*	% of exhaust
	x = no data							

Based on these sources, we estimated emission fractions for model years without mandated PCV valves (Table 52). In absence of better information, gasoline emission fractions are a reflection of diesel research, with the exception of the gasoline HC ratio. Given that the diesel vehicles studied here are largely heavy duty, and most gasoline vehicles are light duty, there is a potential mismatch between the data sources, which is necessitated by a paucity of data. As noted previously, model years with PCV valves were assigned emission fractions calculated as 4% of the fractions shown in the table.

Table 52. Emission Fractions for Vehicles without PCV systems (percent of exhaust emissions)

Emission Type	Gasoline	Diesel
HC	33%[1]	2%
NO_x	0.03%	0.03%
CO	0.005%	0.005%
PM (all species)	20%	20%

[1] The gasoline HC fraction is substantially larger than the diesel ratio. This result may be driven by differences between the Otto and diesel cycles, wherein the Otto cycle potentially allows a significantly greater proportion of combustion gases to escape to the crankcase.

The crankcase emission fractions for HC, CO and NO_x may underestimate emissions. These percentages of exhaust emissions are generally based on [engine- out] uncontrolled exhaust, which is not calculated by MOVES. MOVES produces exhaust estimates based on a number of control technologies (such as catalytic converters). Uncontrolled exhaust in the 1970s was considerably higher than current tailpipe exhaust.

A 1995 study by Williamson[65] estimated a significantly higher proportion of HC, CO, and NO_x exhaust due to crankcase than earlier works. However, Williamson tested only a single engine. In absence of more consistent or compelling evidence, the emission fractions in MOVES rely on the older set of data and maintain consistency with those emission factors used in the NONROAD model. However, we note the wide range in the data sources.

Emission fractions for other fuels (LPG, methanol, etc) were set equivalent to diesel emission factors. Emission factors for electric vehicles were set to zero.

Generally, the contributions of crankcase emissions to the overall emission inventory are expected to decrease as additional diesel vehicles acquire PCV systems.

Appendix A: Peer-Review Comments and Response: Reviewer 1

Reviewer 1: John M. German, International Council on Clean Transportation, Washington, D.C.

Mr. German is a Senior Fellow and Program Director with the International Council on Clean Transportation. He is a highly qualified expert in the areas of automotive engineering and emissions control, whose career includes experience with both the industry and the USEPA. His experience with the EPA includes managing the development of the US06 and SC03 test cycles used to implement the Supplemental Federal Test Procedure, oversight of the development of the Comprehensive Modal Emissions Model, a project conducted by engineers at the University of California at Riverside, management of the cold-temperature CO Rule, and development of facility cycles used in the MOBILE6 model. His industry experience includes power-train engineering at both Chrysler and Honda over a period of 19 years.

This document contains comments received from Mr. German following conclusion of his review of the draft report. Following each comment, I have included our specific response, describing whether we have accepted the comment and made corresponding revisions in the final report, or whether we have offered a rebuttal or otherwise declined to make revisions.

Note that page and paragraph numbers listed in the comments refer to the draft document: *Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator (MOVES2009): Draft Report.* A copy of this document is included in the peer-review records, and is also available at http://www.epa.gov/otaq/models/moves/techdocs/420p09002.pdf.

Comment Summary

In general, the MOVES draft did an excellent job of assessing emissions. This is a very difficult task, especially considering the lack of data in many areas. Of course, given the lack of data and the multitude of assumptions that have to be made, there were a number of places where different approaches may yield better results, as discussed in my comments.

My detailed comments were written as annotations on the draft report itself. I did not have the time or facilities to print out all 124 pages of the draft report with my annotated comments. Thus, the detailed comments are submitted only in electronic form. It is perfectly OK if EPA wants to print out these detailed comments.

PEER REVIEW CHARGE QUESTIONS:

1. For the most part, the report provides adequate description of selected data sources to allow the reader to form a general view of the quantity and representativeness of data used in development of emission rates. In some cases information about the sources of data used in the report were lacking. My detailed comments note these places and asks for additional description of the data.
2. The description of the analytic methods and procedures was generally excellent and allowed the reader to understand the steps taken and assumptions made. There were a few cases where additional explanation would be helpful, as noted in my detailed comments. The examples chosen for tables and figures were also generally excellent.
3. Most of the methods and procedures employed were technically appropriate and reasonable. However, there were some areas where alternative approaches might better achieve the goal of developing accurate and representative model inputs. These are listed in my detailed comments. The major areas of concern are as follows (these duplicate the summary at the beginning of my detailed comments):
    a. I did not see anything on ambient temperature adjustments. This is a very large factor.
    b. The use of IM data for pre 2000 vehicles needs to be validated. If I recall correctly, there are offsets between IM data and the FTP and the correlation is not all that good. While the IM data is needed to determine deterioration rates over time, it may not be a good idea to use it directly for baseline emissions.
    c. Diesels used yet another source of data - FTP data instead of IUVP or IM data. Should establish a correlation between FTP and IUVP data and apply this as an offset to the FTP data.
    d. The use of bag 2 for running emissions is not appropriate. Running emissions plus start emissions should equal the FTP. Using only bag 2 completely ignores the running emissions from the 505 (bag 1/3). Running emissions should be determined by subtracting start emissions from total FTP emissions and dividing by 7.5 miles.
4. In most cases, EPA's assumptions when applicable data is meager or unavailable were reasonable. My detailed comments note areas where different assumptions might be better. The major area of concern is that the modeling of PM deterioration implicitly assumed that PM correlated with HC (this is also in the summary at the beginning of my detailed

comments). However, CO is a much better predictor of air/fuel ratio than HC (reasons explained in my detailed comments on page 88). I would investigate how well your individual PM test results correlate with CO, or with a combination of HC and CO, instead of just assuming they correlate with HC. If a reasonable correlation can be established, this would be a much better way to establish PM cold start and running emissions and to assess PM deterioration.

5. In general, the model inputs were appropriate and are reasonably consistent with physical and chemical processes involved in exhaust emissions formation and control. Cases where better inputs could be used are listed in my detailed comments.

My most important recommendation is outside the scope of reviewing the draft report. EPA desperately needs to have better data upon which to base the MOVES model. Collection of consistent data across the variety of vehicles and operation conditions would allow creation of a much better model and help avoid all the assumptions needed in the current version.

Overall comments.

1. I did not see anything on ambient temperature adjustments. This is a very large factor.

RESPONSE:

The base rates described in this report represent the temperature range of 68-86 °F, i.e., the "FTP temperature range". They are not designed to represent the effect of temperature. The revised report mentions this fact and refers readers to the appropriate report describing adjustments for temperature (and other factors).

2. The use of IM data needs to be validated. If I recall correctly, there are offsets between IM data and FTP and the correlation is not all that good. While the IM data is needed to determine deterioration rates over time, it may not be a good idea to use it directly for baseline emissions.

RESPONSE:

The I/M data used were not used as cycle aggregates. Rather, second-by-second data were used, after being classified into operating modes on basis of vehicle-specific power and speed, as described in 1.3. Breaking down the cycle in this way neutralizes the differences that would be expected had we used cycle aggregate values, as in MOBILE6.

The potential offset is made worse by the use of FTP data for diesels. Need to establish a correlation between FTP and IUVP data and apply this as an offset to the FTP data.

RESPONSE:

As with the data for gasoline vehicles, the FTP data for diesels was not used directly, as in MOBILE, but rather to develop scaling factors that were applied to modal emission rates for light-heavy-duty diesels so as to represent light-duty-diesels.

3. The use of bag 2 for running emissions is not appropriate. Running emissions plus start emissions should equal the FTP. Using only bag 2 completely ignores the running emissions from the 505 (bag 1/3). Running emissions should be set by subtracting start emissions from total FTP emissions and dividing by 7.5 miles.

RESPONSE:

Again, we did not use FTP bag 2 emissions directly to assign emission rates for running operation. Rather, we used them to derive relative changes in hot-running emissions for vehicles in different standard levels relative to Tier 1. These relative changes, or ratios, were used to scale down Tier 1 modal emissions appropriately to represent vehicles certified to NLEV and Tier 2 standards. We used Bag-2 emissions for this purpose because we are confident that the engine is conditioned before Bag 2 commences, and because we lack a way to readily separate start and running emissions in Bags 1 and 3, i.e., none of the data available to use included Bag 1 run under hot stabilized conditions ("hot-running505"). In the revised report, this process is described in 1.3.4.2.

We explicitly avoided the use of FTP composites, which include both start as well as running emissions. While the FTP standard represents the effects of control of both start and running emissions, the relative levels of control for start and running differ both from each other and from that for the composite. Generally, start emissions decline less than the standard would suggest, and running emissions decline more. We elected to treat start and running separately to account for these differences in levels of control. Thus, to represent start emissions, we followed the common practice of estimating the cold start as the difference between Bags1 and 3. We selected Bag 2 to represent hot-running emissions because unlike Bags 1 and 3, it does not contain a "start increment". We did not use Bags 1 or 3 to represent running because it is not possible to isolate the "running component" from the "start increment" in these bags, except for the cold start, as described.

4. Modeling of PM deterioration implicitly assumed that PM correlated with HC. However, CO is a much better predictor of air/fuel ratio than HC (reasons explained in my comments on page 88). I would investigate how well your individual PM test results correlate with CO, or with a combination of HC and CO, instead of just assuming they correlate with HC. If a reasonable correlation can be established, this would be a much better way to establish PM cold start and running emissions and to assess PM deterioration.

RESPONSE:

We agree that PM, as well as CO, respond to enrichment. More generally, though, a major component of PM is HC consisting of higher molecular weight compounds (about C10-12) including semi-volatiles and non-volatile compounds, both of which are emitted in the particulate phase, with particulate being formed from unburned and partially burned fuel components. In the cylinder, processes such as wall quenching, particularly during cold starts, tends to create both HC and particulate. In addition, since the introduction of NLEV or LEV-I standards, targeted reductions in HC have yielded associated reductions in PM, but have not driven compliance for CO, which the manufacturers have easily achieved. Taking these factors in combination, we suggest that while a relationship between CO and PM exists, the corresponding relationship between HC and PM is primary.

Chapter 1. Light-Duty Gasoline Criteria Exhaust Emissions (HC/CO/NOx)

1. Page 8, 1.5.1 :
   Are you considering only IM data? If so, you should state so. If not, should state what the data sources are and why FTP data was not included.

RESPONSE:

We did not restrict consideration to I/M data as such, although we did require that data was measured on vehicles subject to I/M requirements. For example, data from the New York Instrumentation Protocol Assessment (NYIPA) received serious attention. These data are not I/M program data, but were measured on vehicles subject to the I/M program in New York City between 1998 and 2002. Nor did we exclude the FTP as such. Had datasets measured on the FTP been available and met all requirements, we would have considered using them.

2. Page 9, 1.5.1.1.1, Re: Eq 1-2:
How were these equations derived? Should describe or include a reference. Also, are A, B, and C derived directly from these equations? As A is proportional to v, B to v sq., and C to v cubed, it seems like these equations are missing a step.

RESPONSE:

We have cited a reference for these equations in the final report. They are taken from the "IM240 and Evap Technical Guidance", April, 2000, EPA420-R-00-007. Note that the squared and cubic exponents in the denominators of the equations for B and C lead to correct proportionality in the resulting units.

3. Page 10, 1.5.1.3, 2nd para:
Table 1-6 only lists about 80,000 vehicles. If the large majority of these "several million" are RSD or poor data, this statement probably should be revised.

RESPONSE:

The data sources listed in Table 1-5 in the draft report represent data determined to be available and potentially suitable, before we began examination to verify suitability and quality. Table 1-6 lists datasets that did received detailed scrutiny, and with the exception of the St. Louis I/M data, were also confirmed to be suitable. The corresponding Tables in the final report are Tables 8 and 9.

4. Page 11, 1.5.1.3, Table 1-6:
What about British Columbia, Denver, Indiana, Ohio, and Wisconsin listed in Table 1-5? Why were they not discussed and/or excluded?

RESPONSE:

These data were not considered or discussed due to a combination of quality issues or lack of time and people needed to process them. In the final report, we have removed references to these datasets in Table 8 (formerly Table 1-5).

5. Page 18, 1.5.4.2.2, first para:
To help the reader, might want to mention here that extrapolation to high VSP bins was modified based on actual high VSP data in section 1.5.5.

RESPONSE:

We have added a sentence in this paragraph to refer the reader to the description of the adjustments in 1.3.3.5. (formerly 1.5.5).

6. Page 26, Table 1-11:
   Emission rates for 81-82 are very different than for 1980 and previous. Probably not appropriate to use 81-82 to represent older vehicles.

RESPONSE:

While acknowledging the differences between the two groups of vehicles, our difficulty with the 1980 and older vehicles is that we lacked sufficient data to backcast their emissions to young ages. Given this difficulty, and the negligible influence of the 1980 and older model-year group on inventory, we considered the substitution reasonable.

7. Page 26, 1.5.5, 2nd para:
   Should provide a reference for this program [NCHRP].

RESPONSE:

In the final report, we have cited a reference for this program: "Development of a Comprehensive Modal Emissions Model: Final Report", NCHRP Project 25-11, April, 2000.

8. Page 26, 1.5.5, 2nd para:
   Should say something about why it [MEC cycle] was developed and by whom.

RESPONSE:

In the final report, we have added a brief description of the context and purposes for development of the MEC cycles.

9. Page 27, 1st para, bottom of page:
   Typo here [incomplete sentence].

RESPONSE:

We have corrected the incomplete sentence.

10. 1.5.6, Page 35, 1st para:
    Were the vehicle compositions the same for the migrating and local I/M vehicles? Need to demonstrate that the comparison did not include effects of different mix of vehicle types (car, light trucks) and sizes within vehicle type. If there are effects, this should be corrected. This is especially important, considering that the migrating vehicles had lower HC and NOx than the local vehicles.

RESPONSE:

At the time lacked a means to verify standard levels or vehicle class, without information on engine family for measured vehicles. Since release of the draft, we have made progress in this area. It may be possible to revisit the analysis in terms of truck classes for revisions to be considered during the next 24 months.

11. Section 1.5.6, Page 35, 2nd para:
Can this data be sorted by the same age groups as the new data? This would help the comparisons.

RESPONSE:

Unfortunately, we are unable to distinguish age groups in these data, which we acquired from a published source.

12. Section 1.5.6, Page 35, 3rd para:
Were the locations controlled so that they produced similar vehicle speeds and accelerations at the point of [remote] sensing? Some discussion of why these data are compatible should be included. Also, were the fleet mixes similar?

RESPONSE:

For the data collected in the Atlanta area, the researchers attempted to select multiple sites with similar driving characteristics, as described in the 2004 Biennial Evaluation Report. " RSD sampling sites are selected to ensure physically consistent but demographically diverse characteristics. Single straight lines of traffic with an average 35 mile-per-hour velocity are sought to facilitate single vehicle measurements and speeds that maximize measurement opportunities. Driver behavior and driving maneuvers are also observed at each site to ensure that remote sensing measurements would not be biased high by acceleration or low by coasting." (Reference 10 in the Final Report). In the 2004 comparisons, the areas used were geographically continguous, to account for the existence of a new low-sulfur fuel requirement in the 25-county Atlanta area (13 I/M and 12 non-I/M counties), which suggests broad similarity in the composition and age of the two fleets. In addition, before generating aggregate fleet-level results, we compared the I/M and non-I/M remote-sensing data on a model-year basis, to control for potential differences in fleet age.

13. Page 37, Figure 1-13:
It is troubling that the migratory vehicles had lower emissions than the local vehicles in Phoenix for the 0-4 age group. Need to explore possible biases in the data, such as vehicle composition, and correct if possible.

RESPONSE:

It is possible that fleet composition could contribute bias. As mentioned above, we lacked a way of assigning vehicle class and standard level while performing these analyses. Recent developments in this area may allow to reevaluation of this question in the future. In any case, the differences shown in the figure are not statistically significant for HC or CO, and perhaps marginally so for NOx.

14. Page 38, 1st para:

Does this mean that you ignored the data from the 0-4 year age group? If so, should explain why and if not, should explain how the 0-4 year age data was used.

Also, how were the three data sets combined to determine the value at 7.5 years?

Also, why is the midpoint of the 4-5 MOVES age group 5 years instead of 4.5?

RESPONSE:

We did not combine the three datasets, but rather assigned the ratios on the basis of our analysis of the Phoenix data. Accordingly, we used the other two datasets for verification. We did tend to discount the 0-4 yr age group in the case of Phoenix. Because this program had a four-yr exemption period, it did not make sense to assume that the program was achieving benefits for vehicles that were exempt from testing. For Phoenix we assumed a ratio of 1.0 during the exemption period. However, the development of the non-I/M reference rates must allow for the fact that many programs have exemption periods shorter than those in Phoenix. For this reason we did not think it reasonable to assign no I/M difference in the MOVES 0-3 year ageGroup, and performed the interpolation to estimate a difference for this group. In the interpolation, the value at 7.5 years was taken as the value for the 5-9 year group from the Phoenix analysis.

When the midpoint of the 4-5 year ageGroup was set at 5 rather than 4.5 years is because this age group spans two full years. Vehicles enter this group when they turn 4, and leave it when they turn 6. When they turn 5 they have been in the group for one year, and will remain in it for another year. When they turn 4.5, they have been in the group only 0.5 year, but will remain in the group for another 1.5 years. On this basis, we concluded that 5, rather than 4.5, is the actual midpoint of the ageGroup.

15. Page 38, 2nd para:

This implies that the 10+ data was also ignored.

RESPONSE:

No. The statement reflects the fact that the ratios in Figure 1-13 show that the ratios in the 10+ age class are very similar to those in the 5-9 year age class, suggesting that the ratio has stabilized by 10 years of age.

You need to add explanations of how the three data sets were combined and how the data was translated into the lines in Figure 1-14 and the bars in 1-15.

RESPONSE:

As mentioned above, the datasets were not combined; the ratios were assigned based on the Phoenix data, as modified by the interpolation, with the remote-sensing data used for verification.

It is potentially troubling that the non-I/M ratios stabilized at only 6 years of age. I would expect that emissions from vehicles in I/M areas would stabilize after a certain age due to being required to be fixed, but I would NOT expect emissions from vehicles in non-I/M areas to stabilize with age. So, the ratios should continue to increase beyond 6 years.

RESPONSE:

Note that the fact that the ratio stabilizes does not mean that the absolute emissions in the non-I/M area stabilize at six years, because the absolute emissions in the I/M area continue to increase until after 10 years. Therefore, the absolute emissions in the non-I/M areas also continue to increase.

16. Page 40, 3rd para:
I don't understand this statement. The non-I/M % increases appear to be the same for both modes. Mode 27 simply has much higher emissions whether the vehicle is from an I/M or non-I/M area. The I/M factor has the same effect on both.

RESPONSE:

In percentage terms the effect is the same, but in absolute terms the effect is greater in opMode 27 than in 11, simply because the emission rate is correspondingly higher.

17. Page 43, 1st para:
Again, this seems to be reasonable for vehicles in I/M areas, due to requirement to maintain emissions. But is it also true in non-I/M areas? Do you have data supporting this?

RESPONSE:

We revised assumptions for non-I/M areas between the draft and final releases. The revised assumptions are described in the final report and in the response to comment #20 below.

18. Page 46, 1st para:
For NOx, the average emissions for the 15-19 age group were lower than for the 10-14 age group for your 1986-89 model year control group. Is it appropriate to lower NOx emissions for higher age vehicles for model years after 1990? Probably better to assume that they don't change after 10-14 years.

RESPONSE:

The apparent decline with increasing age can be seen in various datasets. It is uncertain whether it is a real effect, or due to erratic behavior in sub-samples of decreasing size. We have thus assumed that rates do not decline after stabilizing.

19. Page 46, Table 1-14:
These ratios don't match the data in graphs 1-15, which shows that the NOx for 15-19 year old vehicles was lower than 10-14. However, the ratios in Table 1-14 are the reverse.

RESPONSE:

Table 1-14 has been obviated by revisions since release of the draft. Its counterpart in the final report is Table 17. The approach used to stabilize emissions has been modified, as described in 1.3.3.7 of the final report.

20. Page 48, 2nd para:
In section 1.5.6, you presented extensive analyses for non-I/M areas based upon Phoenix I/M data. You need to explain what that data doesn't work for this section.

RESPONSE:

The migrating vehicle sample used to develop the non-I/M reference rates was not sufficient in itself to allow assessment of age trends in non-I/M areas past about 10 years. For this reason, it was not useful to inform modeling of emissions stabilization in non-I/M areas.

I think this is a poor assumption. Catalyst problems identified by HC and CO monitors will also lower NOx emissions. On the other hand, fixing air/fuel ratio problems may well increase NOx emissions. Many malfunctions are being identified and repaired – and these repairs have impacts on NOx emissions. This is not similar to a non-I/M area. For I/M areas, the emission increase was not the same for all pollutants. Why would it be the same for non-I/M areas?

RESPONSE:

After some consideration, we have come to agree with this comment. We have accordingly revised the assumptions used to represent trends in emissions for vehicles over 15 years of age in the non-I/M reference rates. In the final report, the revised assumptions are described in 1.3.3.7.2. In the revisions, we assume that the relative trend observed between the 10-14 and 15-19 year ageGroups will persist from the 15-19 year ageGroup to the 20+ ageGroups. Thus, in non-I/M areas, rates continue to rise after ten years, but at lower rates than before ten years.

21. Page 49, 1.5.9, 1st para:
How are start emissions calculated? I don't see any discussion or reference.

RESPONSE:

Discussion of start emissions, especially for vehicles manufactured prior to 1996, was inadequate in the draft report. In the final document material has been added; the expanded discussion has been inserted in the new section 1.4.

22. Page 49, 2nd para:
Where? [is the definition of start rates?].

RESPONSE:

In the final report, start emissions are defined in 1.3.4, and in 1.4.1.1.2.

23. page 50, para 1:
What simulated FTPs? All you have talked about is bag 2. Also, what relationship does bag 2 have to start emissions? This doesn't make sense.

RESPONSE:

In this paragraph, the "simulated FTPs" would have been more accurately referred to as "simulated FTP Bag 2." The Bag 2s were simulated to describe the relative deterioration rate for running emissions, as described in [draft] Table 1-16. The relative deterioration trend for starts was then assessed in relation to the relative deterioration trend for running emissions, as described in the following paragraphs.

24. page 50, para 2:
Are your "rates" multiplicative or additive?

RESPONSE:

The rates are multiplicative. For light-duty gaseous emissions, deterioration is applied multiplicatively, and any adjustments or modifications are also multiplicative.

25. page 52, 1.6, 1st para:

How does the FTP data from the IUVP program correlate with the IM data used for pre-2000 vehicles? If there is an offset between the IM and FTP data, this will lead to discontinuities in your assessment.

Not to mention the simple correlation between IM data and real world data. You need to validate that IM second-by-second data correlates with FTP data, or apply an offset factor to the IM data.

RESPONSE:

We address this question in our responses to overall comments 2 and 3 above.

26. Page 53, 5th para (step 4):

This may be true for vehicles certified before SFTP phase-in. But for vehicles certified to the SFTP, it may not be a valid assumption.

RESPONSE:

Based on supplementary analyses performed since release of the draft, we believe that the assumption holds, although uncertainty remains in estimating differing degrees of control.

27. Page 53, 1.6.2.1, 1st para:

This means that you are throwing away running emissions on bags 1 and 3. Would be more appropriate to subtract cold start emissions from total FTP emissions, then calculated the running emissions over the entire drive cycle, not just bag 2.

RESPONSE:

While it would be a desirable step, we are unaware of away to distinguish running from start emissions in Bags 1 and 3, to allow calculation of running emissions over the total FTP as you suggest. See our response to overall comment 3 above.

28. Page 53, 1.6.2.1, 2nd para:
It's not HC control, its NOx control. Manufacturers have found that catalysts are most efficient when the air/fuel control is precisely at stoich, instead of cycling from slightly rich to slightly lean. The elimination of the slightly rich events has reduced CO, as well as fast catalyst lightoff.

RESPONSE:

While we don't disagree that prevention of rich events and promotion of fast lightoff would reduce CO, as well as NOx, we would suggest that as CO and exhaust hydrocarbons are both products of incomplete hydrocarbon combustion, and that the overall control strategy is to drive oxidation towards completion, CO control is more fundamentally linked to HC control than to NOx control.

29. Page 56, 1st para:
Or there are running emissions in bags 1 and 3, which were not evaluated.

RESPONSE:

There are running emissions in Bags 1 and 3, of course. Incorporating them would not fundamentally change the relationships shown in the figure 1-23, as most of the mass of Bag 1 is attributable to the start increment, with the imputed running component making a relatively small contribution.

30. Page 56, 1.6.2.2, 3rd para:
This is not correct. LDT3/4 had interim standards that had the same phase-in as LDV/LDT1/LDV2. However, the phase in to the final Tier 2 standards for LDT3 and 4 was 50% in 2008 and 100% in 2009.

RESPONSE:

Since release of the draft model, we have fundamentally revised the phase-in assumptions based on certification records and sales figures, as described in 1.3.4.2.2 in the final report.

31. Page 58, 1.6.2.3, 1st para:
LDT1s are rapidly disappearing; although it probably doesn't matter, as they are becoming LDT2s which have the same standards.

RESPONSE:

Revised phase-in assumptions project low fractions of LDT1 , on basis of certification records and sales.

32. Page 64, 1st para:
Your "FTP region" INCLUDES bag1/3 driving, but your running emissions don't. This mismatch needs to be fixed.

RESPONSE:

We agree that the text at this point is unclear, and not reflective of what the rates represent. In the final report we redesignate the "FTP region" as the "hot-running-FTP" region, and the "SFTP region" as the "US06 region." Under this designation, the "hot-running-FTP" region includes the speed and power ranges covered by the FTP Bag 2 (or the IM240/IM147). It is not intended to include the somewhat more aggressive driving represented in Bags 1/3. The revised discussion is in 1.3.3.2.4 in the final report.

33. Page 64, 3rd para:

You can justify this – you don't have to just assume it. The SFTP standards were calibrated to the Tier 1 and NLEV FTP standards. When the FTP standards were increased in stringency with Tier 2, the SFTP standards were NOT increased correspondingly. Instead, the SFTP standards are still calibrated to NLEV levels. Thus, the SFTP standards are not as stringent and the expected reductions are less.

RESPONSE:

We agree on this point.

34. Page 64, 5th para:

You have SFTP data for 2001-2003? If so, you should discuss the data, similar to how you discussed the data for vehicles prior to 2000 in section 1.5.5 and Table 1-12. Is the vehicle composition for 2001-3 similar to 1998-2000?

RESPONSE:

In revisions to the rates for MOVES2010, SFTP results from the IUVP program were applied for the NOx rates, but not for the HC or CO rates. For each pollutant, we adopted the approach that appeared to most improve verification against external data.

35. Page 65, 2nd para:

If I follow this correctly, this means that SFTP emissions are the same for 2010 vehicles as for 2005 vehicles. If this is accurate, should state this explicitly.

RESPONSE:

This is correct. In the final report, this point is made clear in Figure 34.

While I agree that the reduction in SFTP emissions should not track FTP reductions, as SFTP standards were not reduced in conjunction with Tier 2 FTP reductions, it may not be reasonable to assume that there is no reduction in SFTP emissions for Tier 2 vehicles.

In the rates released with MOVES2010, we assume some reduction in Tier 2 vehicles for NOx, but not for HC or CO. Revisions made to the draft rates are described in 1.3.4.2.4.1.

36. Page 69, Table 1-19:

You have a minor problem here. You define cold start emissions as > 720 min soak period minus a 10 minute soak period. But you then apply start emissions for a 10 minute soak. This implies that your cold start emissions are understated and should be corrected by adding the 10 minute soak start emissions to the emissions from bag 1 minus bag 3.

We have neglected the component associated with the 10-min soak in the cold start rates. We have assumed this was reasonable in that for Tier-1 and later vehicles, we lacked data to estimate the start for a "0-min" soak. We preferred not to apply the soak curve relationships (Figure 39) for this purpose as to use the relationships to estimate the cold start and then to reuse them to estimate warm starts would introduce circular reasoning into the process.

37. Page 69, 2nd para:

Some information on the vehicles used to derive these soak fractions would be very useful. The NOx start fractions suggests that these are from older vehicles – I would not expect to see higher NOx for an intermediate start on an NLEV or Tier 2 vehicle.

It is true that these relationships were derived for older vehicles, manufactured before 1995. In the final report we cite the study, released by CARB, from which they were derived: "Methodology for Calculating and redefining Cold and Hot Start Emissions", California Air Resources Board, El Monte, CA, March, 1996 (Reference 22).

38. Page 69, 3rd para:

How do you handle ambient temperatures other than 75 degrees? Colder temperatures will dramatically change the soak fractions as a function of soak time. For example, at 20 F a soak time of 240 to 360 minutes should result in a complete cold start and even a 30 minute soak will have a completely cold catalyst.

Emissions for temperatures outside the "FTP range" of 68-86 F are estimated through the application of temperature adjustments. Adjustments are described in a separate report: "MOVES2010 Highway Vehicle Temperature, Humidity, Air Conditioning, and Inspection and Maintenance Adjustments" EPA-420-R-10-027. (http://www.epa.gov/otaq/models/moves/420r10027.pdf). At present, the model does not have the sophistication to apply interactions of soak time and temperature. Soak relationships and temperature relationships are assumed to be independent.

39. Page 74, 1.7, 2nd para:

Replicating gasoline data for ethanol and advanced gasoline technologies, including hybrids, is reasonable. However, it is NOT reasonable to replicate the gasoline data for diesels. Diesels are inherently lean-burn, which changes both the emissions from new vehicles and how they deteriorate.

Lacking better data on light-duty diesel vehicles under Tier 2, we have retained this assumption at the present.

Chapter 2 Light-Duty Gasoline Particulate Exhaust Emissions

1. Page 84, para 3:
Should note that at colder temperatures, additional enrichment is needed and the enrichment lasts longer.

We have added a sentence to this effect.

2. Page 88, 2nd para:
Not a good assumption. LA92 is a higher load cycle which induces more enrichment. The additional enrichment should be expected to cause additional PM emissions, so there might not be any deterioration effects.

The effects of enrichment can be analyzed using CO emissions. There is a direct relationship between enrichment and CO from the engine – virtually all of the excess fuel is emitted as CO, not HC. In fact, air/fuel ratio can be calculated from engine-out CO emissions. Of course, the catalyst interferes with this relationship, but during rich operation CO conversion efficiency drops faster than HC conversion efficiency. Thus, tailpipe CO is still a reasonable predictor of the amount of enrichment.

So, for example, you could see if the single vehicle with significantly increased PM also had large increases in CO emissions. If there were large increases in CO, then it could have been an enrichment effect caused by the additional load on the LA92 – especially if the vehicle had a lower power to weight ratio. If the CO did not increase dramatically, then you can be more confident that this is actually deterioration of PM.

Notwithstanding the aggressiveness of the LA92 with respect to the FTP, the data we reviewed showed reasonably good and direct correlation between the two, when working with cycle composites, that would probably not be expected if comparing individual bags. Perhaps the inclusion of the longer start bag in the FTP compensates for the aggressiveness of the hot-running bag of the LA92.

3. Page 89, para 2:
Not necessarily. Again, if the LA92 caused additional enrichment, the higher PM could be from the enrichment. Comparing the CO emission rates, not the HC emission rates, will give you a better handle on this.

See our response to overall comment #4 above.

4. Page 89, para 3:
Again, you shouldn't compare just HC. Enrichment is reflected in CO emissions, not HC emissions. The CO comparison is more important.

See our response to overall comment #4 above.

5. Page 90, para 1:
You can't conclude this just looking at HC. It is more important to compare CO.

See our response to overall comment #4 above.

6. Page 91, para 2:
Instead of this general PM methodology, you should evaluate how well your PM test results correlate with CO and/or HC emissions, after adjusting for fuel effects. If you can establish a reasonable correlation, then you can adjust PM rates based on HC and CO emissions. This would be especially useful in estimating PM deterioration.

At the outset, it is not clear to us how attempting to analyze PM through correlations with HC and CO, and introducing associated uncertainty, would improve the resulting model inputs when PM measurements are available. In addition, adjustment for fuel effects simply not possible with the older data, as the needed fuel parameter information is not available.

7. Page 91, para 2:
Again, bag 2 is not representative of hot running emissions, which should be the average of bag 2 and bag 3.

Bag 3 in the LA92 includes a hot-start component. As with the gaseous emissions, we lack a way to separate the start and running components in Bag 3. For this reason, we have focused on Bag 2, rather than Bag 3, to represent hot-running emissions.

8. Page 94, 2nd para:
You discuss this later, but it would help the reader if you would state here that the "aged" data are affected both by vehicle age and model year.

We have added text to clarify this point: "the rates in each model-year group represent emissions for that group at the age of measurement …"

9. Page 96, 3rd para:
Again, CO correlates better with air/fuel ratio than HC and air/fuel ratio has a strong impact on PM.

See our response to overall comment #4 above.

10. Page 98, Figure 2-15:
How does a multiplicative model based on CO instead of HC look? One based on both HC and CO?

Multiplicative patterns for CO look very similar to those for HC. For reference, see Figures 1-18, 1-19 in the draft report (Figures 18 and 19 in the final report).

11. Page , 2.3.1, 1st para:
What about CO (the air/fuel surrogate)? How does this compare with PM emissions?

See our response to overall comment #4 above.

12. Page 100, 1st para:
Again, HC is not the proper metric to determine when the cold start ends. CO is directly proportional to the air/fuel ratio and is a better predictor of closed-loop air/fuel control.

See our response to overall comment #4 above.

13. Page 101, 1st para:
Again, CO will tell you exactly when the vehicle runs rich and by how much.

See our response to overall comment #4 above.

14. Page 106, Figure 2-23:
Note that the PM emissions by VSP look a lot more like the CO emissions by VSP on page 28 than the HC emissions by VSP on page 29. An indication that PM may correlate more strongly with air/fuel ratio (CO) than with HC.

See our response to overall comment #4 above.

15. Page 109, 1st para:
This wasn't "determined" for PM. It was determined for other pollutants and assumed to be the same for PM.

The comment is well taken. We have revised the text to reflect the assumption that deterioration trends for PM would show patterns similar to those for the gaseous emissions.

Chapter 3 Light-Duty Diesel Criteria Exhaust Emissions (HC, CO, NOx)

1. Page 110, 1st para:

How do the FTP test results compare to the IUVP tests used for 2000+ gasoline vehicles and IM data used for pre 2000 gasoline vehicles? If the use of the FTP for in-use emissions is OK, then why wasn't it used for gasoline vehicles?

It would not be relevant to compare the IUV P or I/M data, used to develop rates for gasoline vehicles, to the FTP data used to develop rates for diesel vehicles. For gasoline vehicles, we did make use of FTP results (by bag) when second-by-second data was not available (for MY 2001+), as described above. Had second-by-second data for light-duty diesels been available, we would have applied it, had it been measured on the FTP or another cycle.

You need to establish a correlation between FTP and IUVP data and adjust the FTP data for the offset.

Given the way we used the data, correlating FTP and other datasets is unnecessary, as previously described.

2. Page 111, bottom of page:

Where were these other data from? Why aren't they suitable for determining baseline data? A short explanation (even if in a footnote) would be appreciated.

We have added a Table in the final report (Table 44) summarizing the sources of these data.

3. Page 112, 1st para:

Again, should subtract start emissions from total emissions to determine running emissions. Then regress start emissions and running emissions against total emissions. More accurate and much simpler than the method in this section.

It is unclear why the suggested approach would be either more accurate or simpler. Without a matched HR505, we cannot cleanly separate the hot-start and running components, as you suggest.

4. Page 112, bottom of page:

Bad assumption –and unnecessary.

We agree that this assumption is not appropriate, and leads to error in the resulting start emissions. The errors are relatively small due to the great difference between start and running components, particularly in Bag 1. Nonetheless, this assumption requires reexamination when the rates are evaluated for revision.

5. Page 115, 1st para:

Why is this procedure different than the soak adjustments for gasoline vehicles? Also note that my comment on gasoline vehicle soak time also applies here – determination of start emissions is bag 3 – bag 1, which implicitly assumes zero soak emissions at 10 minutes.

The soak/start relationships for diesel engines was assessed independently from those for gasoline engines, given that we lacked corresponding soak/start data for diesel engines .

6. Page 117, last para:
What about CO, NOx, and PM?
It would also be helpful to have graphs of HC, CO, NOx, and PM emissions versus VSP. This will help the reader compare the impacts of high load on diesel emissions to those on gasoline emissions on pages 28-29.

We have added similar plots for CO, NOx and PM (Figures 90 – 92 in the final report).

Chapter 4 Crankcase Emissions

1. Page 119, 5th para:
Should note that the emissions are actually a percentage of engine-out emissions, but that vehicles before 1969 did not have catalysts, so the tailpipe correlation works.

We have added text to clarify this point.

2. Page 119, 6th para:
Is it appropriate to assume the rate is 4% for all vehicles? Should be virtually zero for newer vehicles, especially those still under warranty, and be higher than 4% for old vehicles, with some function in between.

Text has been added to clarify this point. While this 4% estimate may be pessimistic for new vehicles, and optimistic for old vehicles, current data does not support a more detailed estimate. As older vehicles have higher overall emissions due to deterioration effects, this may understate the impacts of crankcase emissions. Should additional data become available, this may be a candidate for future updates.

3. Page 121, 1st para:
Probably not a good assumption. Diesels have much higher compression ratios and are likely to have higher blow-by rates.

Text has been added to clarify this point. Diesel engines have both higher compression ratios and require a tighter seal in order to operate. Otto cycle engines potentially allow a greater proportion of combustion gases to escape to the crankcase. As a result, it is difficult to predict whether diesel engines have higher or lower crankcase emissions.

That being said, we agree with the commenter that it would be preferable to have data on gasoline engines.

4. Page 121, Table 4-2:
Why is HC crankcase emissions 16.5 times larger for gasoline than diesel? Deserves explanation.

Text has been added to clarify this point. See previous response.

Appendix B: Peer-Review Comments and Response: Reviewer 2

Reviewer 2: Robert A. Harley, PhD., University of California at Berkeley.

Dr. Harley is a professor in the Department of Civil and Environmental Engineering. He has conducted research and published extensively in the field of automotive emissions measurement and control.

This appendix contains comments received from Dr. Harley following conclusion of his review of the draft report. Following each comment, we have included our specific response, describing whether we have accepted the comment and made corresponding revisions in the final report, or whether we have offered a rebuttal or otherwise declined to make revisions.

Note that page and paragraph numbers listed in the comments refer to the draft document: *Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator (MOVES2009): Draft Report.* A copy of this document is available at http://www.epa.gov/otaq/models/moves/techdocs/420p09002.pdf

Review of Draft Report

Development of Emission Rates for Light-Duty Vehicles in the
Motor Vehicle Emissions Simulator (MOVES2009)
June 2009 version

Reviewed by

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Prepared for

U.S. EPA Office of Transportation and Air Quality

September 2009

1. The draft report is missing introductory and concluding text.

Add Introduction. An introduction should be included, briefly describing motivation for developing MOVES. It may not be obvious or known to all readers that MOVES is intended to estimate emissions from both on-road and some off-road mobile sources, replacing the existing MOBILE and OFFROAD modeling tools. A discussion of why a new modeling approach is needed should be added (this might be simply a reference to other documents where more details are available). Where should one look for other MOVES-related documents and information? Clearly the present report is part of a larger effort, but that context is missing here.

RESPONSE:

> *We have added material to orient a reader to the broader context of MOVES and its development, and to refer them to available sources of more detailed information.*

The importance of light-duty (LD) vehicles as a source of air pollution should be summarized. Readers may not be aware of an earlier related report on development of MOVES2004 for estimating greenhouse gas emissions from LD vehicles. Some relevant background and findings on mobile source emission trends from recent studies are that:

(a) LD vehicle emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) have declined substantially in recent years [Harley et al., 2006; Bishop and Stedman, 2008; Ban-Weiss et al., 2008]

(b) in-use deterioration rates have declined for newer vehicles [Bishop & Stedman 2008]

(c) the effect of variations in engine load/driving conditions on emissions is not as large as in the past. For example, Bishop and Stedman [2008] show that plots of exhaust emission factors versus vehicle specific power (VSP) are flatter (i.e., there is less variation in emissions with changes in engine load) for newer vehicles.

(d) the relative importance of other mobile sources of air pollution has increased as LD vehicle emission control efforts have progressed. For example for NOx, diesel trucks now dominate total on-road emissions, and there are also significant contributions to NOx from off-road diesel-powered equipment [Harley et al., 2005; Ban-Weiss et al., 2008].

RESPONSE:

> *We have added a brief summary of light-duty exhaust emissions and their control. Given the length of the document, we did not attempt a lengthy or comprehensive discussion, but cite several sources in the peer-review literature.*

Provide Methodology Overview Key features of the modeling approach for LD vehicles emissions that should be summarized at the outset include use of g/hr (rather than g/km or g/kg) emission factors, binning of emission factors with vehicle specific power (VSP) serving as a master variable, changes in how I/M vs. non-I/M areas are modeled, and reliance on emissions data from Phoenix for pre-2000 vehicles, and manufacturer-conducted in-use vehicle emissions testing for post-2000 vehicles.

RESPONSE:

We have added an overview describing the content of sections and subsections in Chapter 1, and briefly discussing important differences between MOVES and MOBILE, including changes with respect to time-based rather than distance-based emission rates, and changes in the approach to modeling I/M.

Add Recommendations/Conclusions What are the data needs, and how will new data be incorporated into the MOVES model to update it? What are key areas of uncertainty that would benefit from additional study?
Most importantly, how will MOVES be verified against independent data that were not used in model development? In addition to doing overall comparisons of MOVES against older MOBILE/OFFROAD models, I recommend efforts to evaluate/verify each component of MOVES as part of the model development process. Documenting the modeling approach and input data can serve as a starting point for this, but the evaluation itself (or at least plans for such an evaluation) is missing from the present LD vehicle emissions report. If this were a manuscript being reviewed for publication in a scientific journal, verification of the model predictions using independent observations would be an essential component. Given the potential future importance of MOVES predictions to national air pollution control policy, I believe that similarly high standards should apply with respect to including model evaluation/verification in this report.

RESPONSE:

Since the release of the draft model and database, we have made substantial efforts to verify several aspects of MOVES with respect to independent data. Of course, it is very difficult and labor intensive to verify evaporative and start emissions, which is unfortunate, given their importance. Nonetheless, we have verified running emissions for light-duty (and heavy-duty) emissions and have identified several areas that merit attention and improvement. The results of these analyses will be made available in a separate report, within which data and research needs will be discussed.

2. There is unnecessary/imprecise use of acronyms and jargon where plain language would be clearer and more accurate.

Light-duty vehicles (LDV) include cars as well as light trucks. The report often uses the LDV acronym in text, figures, and tables when referring only to cars. In those situations, I recommend using the term "cars". Use of LDV when you mean cars is confusing: for me LDV includes light trucks as well. The report title uses the phrase "Light-Duty Vehicles" which emphasizes the point that both cars and LD trucks are included under the heading LDV.

RESPONSE:

We have added a paragraph describing the technical designations for "LDV" and "LDT." Throughout the rest of the document, we have simplified the discussion by substituting "car" *and "truck" for "LDV" and "LDT."*

I recommend changing the first chapter title to be "Gaseous" rather than "Criteria" pollutant emissions. *Criteria pollutant* is confusing jargon. Isn't PM also a criteria pollutant? Also I suggest merging the discussion of gaseous emissions from LD diesel vehicles (currently section 3) together with section 1. This would provide a more consistent parallel report structure between gaseous and PM emissions, and between gasoline and diesel engines.

RESPONSE:

The comment is well taken, given that particulate matter is also a criteria pollutant. Accordingly, we have revised the document to refer to HC, CO and NOx as the "gaseous exhaust pollutants."

3. Discussion of evaporative emissions and weather effects on all emissions is missing.

I did not find any discussion of evaporative emissions. If a separate report is planned to discuss methods for representing evaporative emissions, that should be mentioned. Also climate variables such as temperature and humidity affect vehicle emissions through increases in cold start emissions as ambient temperature decreases, increased evaporative emissions with increasing diurnal temperature range, and increased use of vehicle air conditioning on hot days. I did not find any discussion of how changes in weather affect vehicle emissions, or how such effects are modeled in MOVES. Ambient temperature affects gaseous as well as PM emissions, including cold start effects and gas/particle partitioning of semi-volatile organics present in the exhaust.

RESPONSE:

Both evaporative emissions and adjustments to exhaust emissions are discussed in separate reports. The revised report refers readers to these additional documents.

A potential problem with using emissions data from Phoenix to represent all pre-2000 model year vehicles nationwide is that mild winters in Phoenix may extend vehicle lifetimes and reduce in-use emission deterioration rates relative to other parts of the country that experience more severe weather.

RESPONSE:

This issue was raised and considered in the FACA MOVES Review workgroup. It is difficult to address because datasets broad and deep enough to assess deterioration are difficult to locate, and where they do exist (such as remote-sensing), observed differences potentially attributable to "climate" are likely to be confounded by several other factors. Prominent confounders can include measurement differences related to instrumentation and calibration, differences in fuel composition, differences in I/M requirements, differences in the degree of representativeness, and random error. Nonetheless, we attempted to evaluate *the issue by comparing the Phoenix data to evaluation data from the Chicago I/M program, as well as data collected during the New York Instrumentation Protocol Assessment (NYIPA). Both the Chicago and New York data represent fleets operating in colder climates with harsher winters than in Phoenix. Aside from differences ostensibly attributable to I/M requirements, e.g., the lack of a NOx requirement in Chicago, the three programs appeared comparable enough to suggest that "climate" per se was not a major issue.*

4. Reliance on IUVP Data Raises Concerns

Going forward, the pre-2000 vehicle model year data from Phoenix will play a minor role in determining LD vehicle emissions, as those vehicles are 10+ years old already, and they will constitute a declining fraction of the in-use vehicle fleet in assessments of future year emissions.

For emissions from 2000 model year and newer vehicles, the MOVES model relies on data from the In-Use Verification Program (IUVP), a program that started in 2003 which is administered by EPA and run by the vehicle manufacturers. Relying on IUVP data to model vehicle emissions is a questionable approach. The IUVP appears to have been instituted as a regulatory compliance program, and as such may not be well-suited to capturing the full range of vehicles, operating conditions, and emissions that are relevant to the MOVES model and developing emission inventory estimates. For example, will the vehicle sample in IUVP be large and random enough to ensure that major emission contributions from malfunctioning/ high-emitting vehicles will be captured? How will high-emitting vehicles be represented in MOVES? As fleet-average emissions decline, the remaining emissions are increasingly dominated by contributions from high-emitting vehicles (Bishop and Stedman, 2008).

RESPONSE:

We agree that the IUVP is not necessarily designed to obtain representative data for the entire "real world" fleet. But it is important to remember that similar issues apply equally to most sources of emissions data, including high-quality laboratory studies reported in the peer-reviewed literature, which very frequently use relatively small vehicle samples. This situation is entirely understandable, given the difficulty and expense of measurement using dynamometers or portable instruments combined with the difficulty of acquiring representative samples. Despite these questions, we found the IUVP to be a very valuable source, in that it provided information allowing assignment of standard level to individual vehicles, which we found indispensable in projecting NLEV and Tier-2 emissions. However, we did not take the representativeness of IUVP entirely for granted, and the approaches we adopted compensated in three ways. (1) We used IUVP only to estimate rates for "young" vehicles, aged 0-3 years. (2) we used the IUVP to develop scaling factors that we applied to results from Phoenix I/M that represented Tier-1 rates. Thus the rates developed using the IUVP data incorporate a direct link to "real-world" results, that probably more effectively represent "high-emitting" or "mal-functioning" vehicles. (3) In projecting deterioration from NLEV and Tier-2 vehicles, we used logarithmic variances "borrowed" from the Phoenix I/M data, which are higher than those obtained directly from the IUVP. Because this parameter represents the degree of skew in the distribution, increasing it effectively represents an increase in the fraction of "high-emitting" vehicles, with associated increases in mean emission rates.

5. *PM Emissions*

MOVES relies on data from the 2005 Kansas City PM study which focused on LD gasoline vehicles. This was a comprehensive and well-conducted study and the resulting emissions data are relatively current. Cold start as well as running emissions were measured. A limitation of this study is the lack of information on how vehicle emissions for a given model year increase with vehicle age/odometer reading.

On pp. 91-92, following equation 2-1, there is excessive precision and no associated uncertainty reported for the multiplicative adjustment factors (0.898 and 1.972) used to give hot running and cold start emission rates for LD trucks. Excessive precision and lack of uncertainty estimates concern also applies to values presented in Table 2-2.

There is no discussion of PM emission rates from LD diesel vehicles; the Kansas City study was for LD gasoline vehicles only. Chapter 3 on LD diesel vehicle emissions covers only the gaseous pollutant emissions, not exhaust PM. Also non-exhaust PM emissions (e.g., tire wear, brake wear) from LD vehicles are not discussed in this report.

RESPONSE:

> *Chapter 3 does cover PM emissions for light-duty diesel vehicles, as it does for HC/CO/NOx. See tables 42-47 in the final report.*

As a model evaluation case study, EPA staff may wish to consider long-term LD vehicle PM emission trends reported by Ban-Weiss et al. (2008) at the Caldecott tunnel in California. LD vehicle fleet-average $PM_{2.5}$ mass emission rates were measured to have decreased by 36±17% over a 9-year time period between 1997 and 2006, due to model year effects on zero mile levels and/or deterioration rates. Both VSP and average vehicle age (i.e., calendar year–average model year) were similar between the two field campaigns. Cold start emissions were not measured by Ban-Weiss et al.

RESPONSE:

> *We thank the reviewer for pointing out the availability of this dataset as an opportunity to verify PM predictions. It could make a good candidate for a future verification effort.*

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