Exhaust Emission Rates for Light-Duty Onroad Vehicles in MOVES3

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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EPA-420-R-20-019
November 2020

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List of Acronyms

ALVW	Adjusted Loaded Vehicle Weight
CAA	Clean Air Act
CAFE	Continuous Atlanta Fleet Evaluation
CARB	California Air Resources Board
CA/S177	Clean Air Act Section 177 California LEV-II emissions standard
CD	Compliance Division
CIC	conventional internal combustion
CO	carbon monoxide
CO_2	carbon dioxide
CV	coefficients of variation
CVS	constant-volume sampler
DRI	Desert Research Institute
DT	DusTrak analyzer (measures mass and size fraction of PM)
EC	elemental carbon
ECPM	elemental carbon particulate matter
EGR	exhaust-gas recirculation
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act of 2005
°F	degrees Fahrenheit
FTP	Federal Test Procedure
FUL	full useful life
GDI	Gasoline Direct Injection engines
g/hr	Grams per hour
g/km	Grams per kilometer
g/mi	Grams per mile
g/sec	Grams per second
g/SHO	grams per source-hours operating
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbons
HLDT	Heavy Light-Duty Truck
HNO_2	nitrous acid (HONO)

HP	horsepower
I/M	Inspection and Maintenance program
IM147	Inspection and Maintenance transient loaded-mode emissions test
IM240	Inspection and Maintenance transient loaded-mode emissions test
IUVP	In-Use Verification Program
KCVES	Kansas City Light-Duty Vehicle Emissions Study
kW	kilowatt
LA92	Unified driving schedule
lb	pound
LDT	Light-Duty Truck
LDT1	Light-Duty Truck LVW = 3750 lbs.
LDT2	Light-Duty Truck LVW > 3750 lbs.
LDT3	Light-Duty Truck ALVW =5750 lbs.
LDT4	Light-Duty Truck ALVW > 5750 lbs.
LDV	Light-Duty Vehicle
LEV	Low Emission Vehicle
LEV-I	California PC, LDT and MDV exhaust emission standards of 1990
LEV-II	California PC, LDT and MDV exhaust emission standards of 1999
LEV-III	California PC, LDT and MDPV exhaust emission standards of 2012
LLDT	Light Light-Duty Truck
LVW	Loaded Vehicle Weight
MDPV	Medium-Duty Passenger Vehicle
Mg	mass weight
MOBILE6	EPA Highway Vehicle Emission Factor Model, Version 6
MOVES	Motor Vehicle Emission Simulator
mpg	miles per gallon
MY	model year
NAAQS	National Ambient Air-Quality Standards
NLEV	National Low Emission Vehicle
NMHC	Non-Methane Hydrocarbons
NMOG	non-methane organic gases
NO_x	oxides of nitrogen ($NO + NO_2 + HONO$)
NTR	Northeast Trading Region

NYIPA	New York Instrumentation/Protocol Assessment
OBD	On-Board Diagnostic (System)
OC	Organic Compounds/Organic Carbon
ORD	Office of Research and Development
OTAQ	Office of Transportation and Air Quality
PA	photoacoustic analyzer
PC	passenger cars
PCV	positive crankcase ventilation
PEMS	portable emissions measurement system
PFI	port fuel injection
PM	Particulate Matter
$PM_{2.5}$	particulate matter < 2.5 microns in diameter
PM_{10}	particulate matter < 10 microns in diameter
QCM	Quartz-crystal microbalance
RSD	Remote Sensing Device
RSE	relative standard error
SC03	SFTP chassis dynamometer test
SEMTECH-D	vehicle emissions measurement instrument produced by Sensors, Inc.
SFTP	Supplemental Federal Test Procedure
SHO	source-hours operating
SPSS	IBM Statistical Package for the Social Sciences software
SULEV	Super Ultra Low Emission Vehicle
SwRI	Southwest Research Institute
TC	Total Carbon
THC	Total Hydrocarbon (by flame ionization detector)
Tier 1	vehicle emissions certification standards phased in from 1994 – 1997
Tier 2	vehicle emissions certification standards phased in from 2004 – 2009
Tier 3	vehicle emissions certification standards phased in from 2017 - 2025
TLEV	Transitional Low Emission Vehicle
TOR	Thermal Optical Reflectance
TRLP	track road load power
UDDS	Urban Dynamometer Driving Schedule
ULEV	Ultra Low Emission Vehicle

US06	Test cycle comprising one component of the Supplemental Federal Test Procedure (SFTP)
VIN	Vehicle Identification Number
VSP	vehicle specific power
ZML	zero-mile emission level

1 Summary

This report is divided into seven chapters, including this summary.

At the outset, Chapter 2 gives some background and history for the Motor Vehicle Emissions Simulator (MOVES) model. It also introduces concepts and structures common to the various emissions estimated by the model. Specifically, it defines the concepts "emissions source," "regulatory class," "emissions process" and "operating mode."

Chapter 3 is by far the longest in the report. It describes the data and methods used to develop light-duty gasoline emission rates for the "gaseous emissions," defined to include total hydrocarbons (THC), carbon monoxide (CO) and oxides of nitrogen (NO_x).

Sections 3.2, 3.3, and 3.4 describe the development of emission rates for "hot-running" vehicle operation in MOVES2014. This MOVES2014 material has been retained because the MOVES3 rates were generated by applying adjustments to the MOVES2014 rates (which, in turn, were based on rates developed for MOVES2010). The content in these sections is largely unchanged from the corresponding sections in the MOVES2014 report. The exception to this rule concerns the revisions to emission rates in "high-power operating modes," the basis for which is described in 3.3.2.4.

Section 3.5 lays the foundation for how MOVES3 accounts for the effects of "Inspection and Maintenance" (I/M) programs. It describes the data and methods used to develop the proportional differences between default "I/M" and "non-I/M" base rates. This material is identical to that in the MOVES2014 report, although it has been reorganized to be more independent in relation to the sections that precede and follow it, as its applicability in the emission rates is broad.

The most prominent and far-reaching change in the updates to emission rates in MOVES3 is the reevaluation and modification of emissions deterioration. Sections 3.6 and 3.7 describe the underlying data and analyses for NO_x, THC and CO. New analysis of recently acquired large data sets from the Denver Metropolitan Area was used to develop broad models of deterioration covering 20 model years over 20+ years of age and to calculate adjustment ratios to apply to the MOVES2014 rates.

The next two sections cover the development of emission rates for start operation. The development of rates representing "cold-start" operation is covered in Section 3.8. The development of rates representing "warm" or "hot" engines is presented in Section 3.9. Important revisions in the estimation of these start emissions for "Tier-2" vehicles, i.e., vehicles in model years 2004 and later, are presented in 3.9.2.

Section 3.10 describes specific steps taken to derive revised rates for MOVES3 by applying adjustments to emission rates from MOVES2014. These revisions were applied to rates representing model years 1990 and later. This section also covers the steps followed in generating the full set of revised light-duty gasoline emission rates for MOVES3.

Section 3.11 presents selected results in which revised rates for MOVES3 are compared to each other and to their MOVES2014 counterparts. Trends in emissions in relation to important variables including power, age and time since key-off are included.

The rates presented in Sections 3.3 to 3.11 describe rates representing emissions from vehicles compliant with "Federal" standards, i.e., standards developed and promulgated at the Federal level by the US EPA. Section 3.12 describes development of a corresponding set of rates that represent emissions from vehicles compliant with standards developed and promulgated by the State of California and additional states that have adopted "California" emissions standards at some point in the past 25 years.

Chapter 4 covers the development of emission rates for particulate matter (PM). In the emission rates, Particulate matter is defined as particles < 2.5 microns in diameter (PM2.5). An important update since MOVES2014 is the development of rates accounting for the expected transition from "port fuel injection" to "gasoline direct injection" between 2005 and 2030. These analyses introduce recent data that supplements the "Kansas-City Vehicle Emissions Study" that provided the sole basis for PM emission rates in MOVES2014.

Chapter 5 briefly describes how light-duty emission rates are assigned to represent fuels other than gasoline, including diesel and "high-level" ethanol blends, i.e., E85. In addition, it discusses briefly how MOVES3 treats hybrid and electric vehicles.

Chapter 6 discusses how MOVES estimates crankcase emissions by relating them to tailpipe emissions for running and start operation. We assume that the majority of light-duty vehicles with properly functioning positive crankcase ventilation (PCV) have no crankcase emissions. However, crankcase emissions are estimated for small fractions of vehicles that either lack PCV or have malfunctioning PCV.

Chapter 7 discusses partition of nitrogen oxide species among several related species for several vehicle types, including motorcycles, as well as gasoline- and diesel-powered light-duty vehicles.

Note that energy consumption rates for light-duty cars, trucks and motorcycles are documented in a separate report.[1]

MOVES3 includes substantial updates from MOVES2014. These updates were peer-reviewed in two separate processes. In 2017, the updates to the light-duty gasoline $PM_{2.5}$ emission rates were reviewed.[2] In 2020, the updates to the light-duty gasoline THC, CO, and NO_x emission rates and deterioration effects were reviewed.[3] The draft reports, peer-review comments and EPA responses are available on the EPA Science Inventory Webpage.

2 Background

2.1 Development of the Motor Vehicle Emissions Simulator (MOVES)

The United States Environmental Protection Agency's Motor Vehicle Emission Simulator—commonly referred to as MOVES — is a set of modeling tools for estimating air pollution emissions produced by onroad (highway) and nonroad mobile sources. MOVES estimates the emissions of greenhouse gases (GHGs), criteria pollutants and selected air toxics. The MOVES model is currently the official model for use for state implementation plan (SIP) submissions to EPA and for transportation conformity analyses outside of California. The model is also the primary modeling tool for estimating the impact of mobile source regulations on emission inventories.

MOVES calculates emission inventories by multiplying emission rates by the appropriate emission-related activity, applying correction and adjustment factors as needed to simulate specific situations and then summing the emissions from all sources and regions.

Thus, 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 evaporative emissions, estimation of usage and activity patterns for vehicles, estimation of adjustments that account for fuel parameters, ambient temperature and humidity, air conditioning effects and the impact of various Inspection and Maintenance program designs, 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.[4]
- A subsequent "*Draft Design and Implementation Plan*" describes the MOVES design and introduces the reader to concepts and terminology developed for the new model.[5]
- Readers wishing to further understand the development of the modal design for running emissions can consult the "*Methodology for Developing Modal Emission Rates,"*[6] as well as the "*Shoot Out*"[7] conducted among several candidate approaches.

A large volume of additional documention and supporting materials can be obtained at https://www.epa.gov/moves/moves-onroad-technical-reports. In general, the most recent and relevant materials are at the top of the page, with older material 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.

2.1.1 Light-Duty Vehicles

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 "light-duty trucks" (LDT) which are further sub-classified 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 light-duty truck classes for purposes of inventory estimation, we will refer to "cars" and "trucks" throughout. The development of emission rates for motorcycles are covered in a separate report.[8]

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 fifty years. The Clean Air Act (CAA), passed in 1970 (and amended in 1977 and 1990), set "National Ambient Air-Quality Standards" (NAAQS) for carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3) particulate matter (PM), and sulfur dioxide (SO_2). The CAA provides authority to the EPA to set emission standards for CO to help achieve the CO NAAQS, and for THC and NO_x largely for their roles in production of ground-level ozone. 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, Tier 2 standards starting in 2004, and Tier 3 standards starting in 2017. Concurrently, the state of California and additional states electing to adopt "California" in lieu of "Federal" standards have implemented "LEV-I," "LEV-II" and "LEV-III" 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 an important 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, on-board diagnostic systems (OBD) and gasoline direct injection (GDI). Development of emission rates thus largely involves constructing a "quantitative" account of this history. 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 model. However, this history has been well described elsewhere, and we refer interested readers to the USEPA website[9] and to the peer-reviewed literature.[10,11,12,13,14,15,16,17,18]

2.2 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 gaseous criteria pollutants include: total hydrocarbons (THC), carbon monoxide (CO) and oxides of nitrogen (NO_x). Relevant particulate criteria pollutants include elemental and organic carbon.

MOVES estimates other organic gas aggregations by ratio relative to THC emissions, including methane (CH_4), non-methane hydrocarbons (NMHC), volatile organic compounds (VOC), total organic gases (TOG), and non-methane organic gases (NMOG). The definitions and methods for estimating these other organic gas aggregations are documented in the MOVES speciation report.[19] THC emissions are intended to include all hydrocarbon emissions and are operationally defined as measurements taken by flame ionization detector. In this report we also use the term hydrocarbons (HC) emissions to refer specifically to emissions of compounds of carbon and hydrogen (regardless of the measurement method), and more generally, to other measures of organic gases that are primarily composed of hydrocarbons, including NMHC and NMOG.

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 2-1. 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."

Table 2-1 Combinations of pollutants and processes for gaseous pollutant emissions

pollutantName	pollutantID	processName	processID	polProcessID
THC	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
Elemental Carbon (ECPM)	112	Running exhaust	1	11201
		Start exhaust	2	11202
Non-elemental Carbon (non-ECPM)	118	Running exhaust	1	11801
		Start exhaust	2	11802

Note that this document describes only emission rates for exhaust hydrocarbons. Modeling of emission rates for evaporative hydrocarbons is described in a separate report.[20]

Vehicle classes as "emissions sources" are described by a label known as the "sourceBinID". The identifier is a 19-digit numeric label, of the form "1*fftteeyyssssswwww*00," as described in Table 2-2. Note that the engine-size and weight-class attributes are not used to classify vehicles in MOVES3.

Table 2-2 Construction of sourceBins for exhaust emissions for light-duty vehicles

Parameter	MOVES Database Attribute[1]	Values
Fuel type	fuelTypeID	Gasoline = 01 Diesel = 02 E85 = 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."		

As an example, Table 2-3 shows the construction of sourceBin labels for light-duty gasoline vehicles, manufactured in model years 1998 and 2010.

Table 2-3 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 1998)	1 01 01 30 98 0000 0000 00
1	1	20 (Car)	98 (MY 2010)	1 01 01 20 30 0000 0000 00
1	1	30 (Truck)	30 (MY 2010)	1 01 01 30 30 0000 0000 00

2.2.1 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 2-4. 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, when present, 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.

2.2.1.1 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. The resolution of these groups is finest between 4 and 9 years of age, when the emission deterioration curves are steepest.

Table 2-4 Description of the EmissionRateByAge table

Field	Description
SourceBinID	Source Bin identifier. See Table 2-2 and Table 2-3.
PolProcessID	Combines pollutant and process. See Table 2-1.
opModeID	Operating mode: defined separately for running and start emissions. See Table 2-5.
ageGroupID	Indicates age range for specific emission rates.
meanBaseRate	Mean emission rates in areas not influenced by inspection and maintenance programs.
meanBaseRateCV	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 reference program.
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.

2.3 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.

2.3.1 Operating Modes (opModeID)

For running emissions, the key concept underlying the definition of operating modes is “vehicle-specific power” (VSP). This parameter represents the tractive power exerted by a vehicle to move itself and its cargo or passengers.[21] It is estimated in terms of a vehicle’s speed and mass, as shown in Equation 2-1.

$$VSP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t\left(a_t + g\sin(\theta_t)\right)}{m} \qquad \textbf{Equation 2-1}$$

In this form, VSP at time *t* (kW/Mg) is estimated in terms of vehicles’:

- speed at time *t* (v_t, m/sec),
- acceleration a_t, defined as $v_t - v_{t\text{-}1}$, (m/sec^2)
- road grade, where $sin(\theta_t)$ = fractional road grade at time *t*, and *g* is the acceleration due to gravity (9.8 m/se^{c2}), mass *m* (Mg) (usually referred to as “weight,”)
- track-road load coefficients *A*, *B* and *C*, 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.[3]

For purposes of the data used in this analysis, the grade is assumed to be zero because the vehicles were measured on chassis dynamometers. Note that during model operation, MOVES accounts for grade when characterizing vehicle activity only in project-scale mode.

On the basis of VSP, speed and acceleration, a total of 23 operating modes are defined for the running-exhaust process (Table 2-5). 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/Mg. For reference, each mode is identified by a numeric label, the “opModeID.” In cases where the deceleration/braking definition overlaps with other operating modes, the deceleration/braking categorization takes precedence over other definitions.

Table 2-5 Definition of MOVES operating modes for running-exhaust operation

opModeID	Description	Vehicle Speed (v_t, mi/hr)	Vehicle-Specific Power (VSP_t)	Vehicle Acceleration (a_t, mi/hr-sec)
0	Deceleration/ Braking			$a_t \leq -2.0$[d] OR ($a_t < -1.0$[e] & $a_{t-1} < -1.0$ & $a_{t-2} < -1.0$)
1	Idle	$-1.0 \leq v_t < 1.0$[a]		
11	Coast	$1 \leq v_t < 25$[b]	$VSP_t < 0$	
12	Cruise/Acceleration		$0 \leq VSP_t < 3$	
13			$3 \leq VSP_t < 6$	
14			$6 \leq VSP_t < 9$	
15			$9 \leq VSP_t < 12$	
16			$VSP_t < 12$	
21	Coast	$25 \leq v_t < 50$[c]	$VSP_t < 0$	
22	Cruise/Acceleration		$0 \leq VSP_t < 3$	
23			$3 \leq VSP_t < 6$	
24			$6 \leq VSP_t < 9$	
25			$9 \leq VSP_t < 12$	
27			$12 \leq VSP_t < 18$	
28			$18 \leq VSP_t < 24$	
29			$24 \leq VSP_t < 30$	
30			$30 \leq VSP_t$	
33	Coast/ Cruise/Acceleration	$50 \leq v_t$	$VSP_t < 6$	
35	Cruise/Acceleration		$6 \leq VSP_t < 12$	
37			$12 \leq VSP_t < 18$	
38			$18 \leq VSP_t < 24$	
39			$24 \leq VSP_t < 30$	
40			$30 \leq VSP_t$	

[a]Corresponds to 0.44704 m/sec.
[b]Corresponds to 11.176 m/sec.
[c]Corresponds to 22.352 m/sec.
[d]Corresponds to -0.89408 m/sec^2.
[e]Corresponds to -0.44704 m/sec^2.

2.4 Exhaust Emissions for Start Operation

Up to this point, the discussion has concerned emissions occurring after both the engine and the emissions control system (primarily the catalyst) have come to operating temperature. Under these conditions, the catalyst, if properly functioning, controls emissions.

In contrast, "start" emissions occur during a brief period (several minutes) immediately after the engine is turned on. If sufficient time has elapsed since the engine last operated ("keyoff"), both the engine and emissions control systems will be “cold,” i.e., near ambient temperature. Operationally, we define cold start as a start after the engine has been off (“soaked”) for 12 hours or more. The engine and catalyst heat up fairly quickly when the vehicle is driving, but if the catalyst is cool, it will not effectively control emissions. In addition, to start the engine, it is necessary to inject “excess” fuel into the cylinder to provide enough flammable vapor to ignite when the spark plug fires. Incomplete combustion of this fuel, in addition to emissions control systems being below operating temperature, yields a bolus of “excess” emissions during a brief “start period” following key-on events. These emissions are referred to as “start emissions,” in contrast to the “hot running” emissions discussed in section 2.3.

Emission rates for start emissions are expressed as mass emitted for a single start event following key on (mass/start).

In MOVES, start emissions for light-duty vehicles are defined in terms of the Federal Test Procedure (FTP). The cycle includes three phases, or “bags,” which are intended to represent, “cold-start”, “hot-running” and “hot-start” emissions, respectively. The first, or “cold-start” phase, is 505 seconds (8.42 min.) in duration. The second, or “hot-running” phase is 867 seconds long. Following the second phase, the engine is turned off, and allowed to “soak” for 10 min., after which the engine is restarted and the third “hot-start” phase is performed, repeating the first-phase driving cycle. To estimate true “cold-start” emissions, the mass emitted during the third phase is subtracted from that emitted during the first phase, as described in more detail below.

2.4.1 Operating Modes for Start Emissions

The “cold-start,” as defined 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), as shown in Table 2-6.

Table 2-6 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

2.4.2 Adjustments to Start Emissions

Note that all discussion in this section applies to start conditions under "warm ambient" conditions, i.e., for temperatures above 68°F. For start emissions at colder temperatures, MOVES applies a separate "temperature adjustment." Note that the development and application of temperature adjustments is discussed in a separate report.[22] Start emissions are also adjusted to account for fuel characteristics as explained in the Fuel Effects Report.[23]

3 Gaseous Exhaust Emissions from Light-Duty Gasoline Vehicles (THC, CO, NO_x)

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 (NO_x). The resulting model inputs are stored in the emissionRateByAge table included in the MOVES input database.

3.1 Approach

In estimation of the regulated gaseous pollutants, it is essential to know with 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.

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.

3.2 Emission-Rate development: (Model years 1989-and-earlier)

MOVES3 updates light-duty gaseous emission rates for model years 1990-and-later, but the rates for 1989-and-earlier are unchanged from MOVES2010 and MOVES2014.

3.2.1 Data Sources

For emissions data to be eligible for use in this analysis, 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, or higher, e.g., continuous or "second-by-second" measurements.
- To make allowance for application of temperature adjustments (developed separately), it was necessary to know the ambient temperature at the time of test.

Vehicles were subject to I/M program requirements at the time of measurement.

3.2.1.1 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 3-1.

Table 3-1 Required vehicle parameters

Parameter	Units	Purpose
VIN		Verify MY or other parameters
Fuel type		Distinguish gasoline vehicles
Make		Distinguish cars and light trucks
Model		Distinguish cars and light trucks
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*

3.2.1.1.1 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 3-1.[24]

$$A = PF_A \cdot \left(\frac{\text{TRLHP} \cdot c_1}{v_{50} \cdot c_2} \right)$$
$$B = PF_B \cdot \left(\frac{\text{TRLHP} \cdot c_1}{(v_{50} \cdot c_2)^2} \right) \quad \textbf{Equation 3-1}$$
$$C = PF_C \cdot \left(\frac{\text{TRLHP} \cdot c_1}{(v_{50} \cdot c_2)^3} \right)$$

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.[25]

3.2.1.1.2 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 3-2.

Table 3-2 Required test parameters

Parameter	**Units**	**Purpose**
Date		Determine vehicle age at test
Time of day		Establish sequence of replicate tests
Ambient temperature	°F	Identify tests in 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

3.2.1.1.3 Candidate Data Sources

In addition to the parameters listed in Table 3-1 and Table 3-2, 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.

When this analysis was conducted for MOVES2010 (2005-2008), a large volume of emissions data was available, representing over 500,000 vehicles when taken together (Table 3-3). 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 3-3 Datasets available for use in estimating running emissions from cars and trucks

Dynamometer	
I/M	non-I/M
AZ (Phoenix)	
IL (Chicago)	
MO (St. Louis)	
NY (New York)	

Remote-Sensing	
I/M	non-I/M
AZ (Phoenix)	
IL (Chicago)	
MO (St. Louis)	
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 MY 1989-and-earlier rates, for several reasons: (1) For the most part, at the time of the analysis, the remote-sensing 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 remote sensing 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 THC measurements by other methods.[26] (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,[27] mass rates cannot be calculated without an independently estimated CO_2 mass rate. It followed that remote-sensing would not provide rates for any MY×Age combinations where dynamometer data were not available. In these cases, remote-sensing 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, remote-sensing cannot provide measurements for coasting, deceleration/braking or idle modes. For these reasons we reserved the remote-sensing for additional roles, such as verification of results obtained from dynamometer data.

Table 3-4 Characteristics of candidate datasets

Criterion	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 3-4.

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 ($n \sim 9{,}000$ 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 presumably 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 percent 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 percent 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.

3.2.1.2 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 percent 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. For these two species, the trends with respect to VSP were not linear, nor were distributions of emissions close to normal at any VSP level. Consequently, we concluded that the Spearman coefficients, as measures of association, rather than linear correlation, performed as well or better than Pearson coefficients for CO and THC.

3.2.1.3 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 3-1. 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 3-2.

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

Equation 3-2

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 3-3.

$$w_{\mathrm{f,MY,CY}} = \frac{1}{f_{\mathrm{f,MY,CY}}} \qquad w_{\mathrm{p,MY,CY}} = \frac{1}{f_{\mathrm{p,MY,CY}}}$$

Equation 3-3

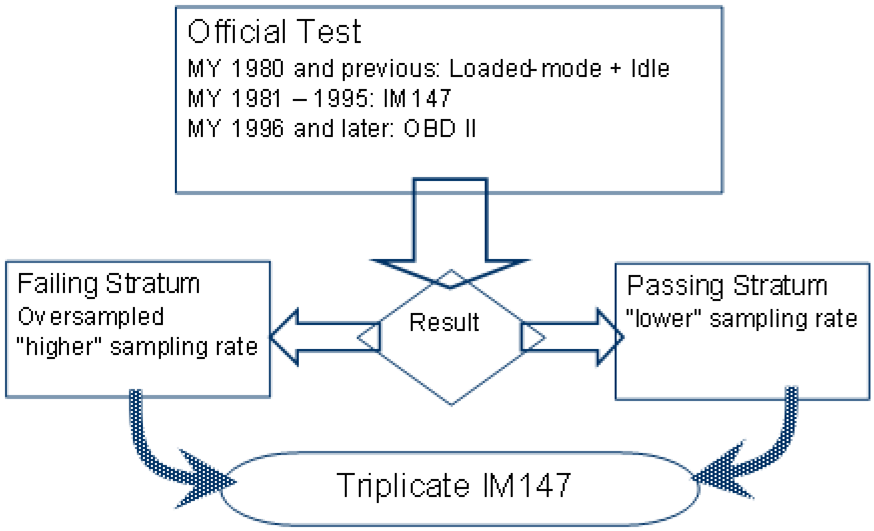


Figure 3-1 Stratified sampling as applied in selection of the random evaluation sample in the Phoenix I/M Program (CY 2002-05)

3.2.1.4 Data Source Selection

After excluding the St. Louis dataset, and comparing the Phoenix, Chicago and NY datasets, 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 3-4 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. [23]

3.2.2 Methods

3.2.2.1 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 2-5). The model-year groups used are shown in Table 3-5, along with corresponding samples of passing and failing tests. Note that the analysis for 1990-and-later model years was substantially updated as explained in Section 3.6 and Section 3.7 below.

Table 3-5 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, THC or NO_x, 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*'.

3.2.2.1.1 Rates: Calculation of Weighted Means

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

$$E_h = \frac{\sum_{i=1}^{n_{\text{test}}} w_i R_{i,t}}{\sum_{i=1}^{n_{\text{test}}} w_i}$$ **Equation 3-4**

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*.

3.2.2.1.2 Estimation of Uncertainties for Cell Means:

In the emissionRateByAge table, uncertainties for individual rates are stored in the "meanBaseRateCV" fields (Table 2-4). 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.[28] To enable estimation of variances under this approach, we calculated a set of summary statistics, as listed below:

Test mean ($\overline{E}_i$): 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

$$s_{\mathrm{b}}^2 = \frac{\sum_{i=1}^{n_i} w_i \left(\overline{E}_i - \overline{E}_h\right)^2}{\sum_{i=1}^{n_i} w_i - 1}$$ **Equation 3-5**

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:

$$s_{\mathrm{w}}^2 = \frac{\sum_{i=1}^{n_h} w_i \left(n_i - 1\right) s_i^2}{\left(\sum_{i=1}^{n_h} w_i\right)\left(n_{h,i} - n_h\right)}$$ **Equation 3-6**

Variance of the cell mean ($s_{\overline{E}}^2$): 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.

$$s_{E_h}^2 = \frac{s_{\mathrm{b}}^2}{n_h} + \frac{s_{\mathrm{w}}^2}{n_{h,i}}$$ **Equation 3-7**

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

$$\mathrm{CV}_{E_h} = \frac{\sqrt{s_{E_h}^2}}{E_h}$$ **Equation 3-8**

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

3.2.2.1.3 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.” With respect to vehicle age, empty cells occur for age Groups not covered by available data. As shown in Figure 3-2, “age holes” are represented by un-shaded areas. Filling in these un-shaded areas required “back-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/Mg.

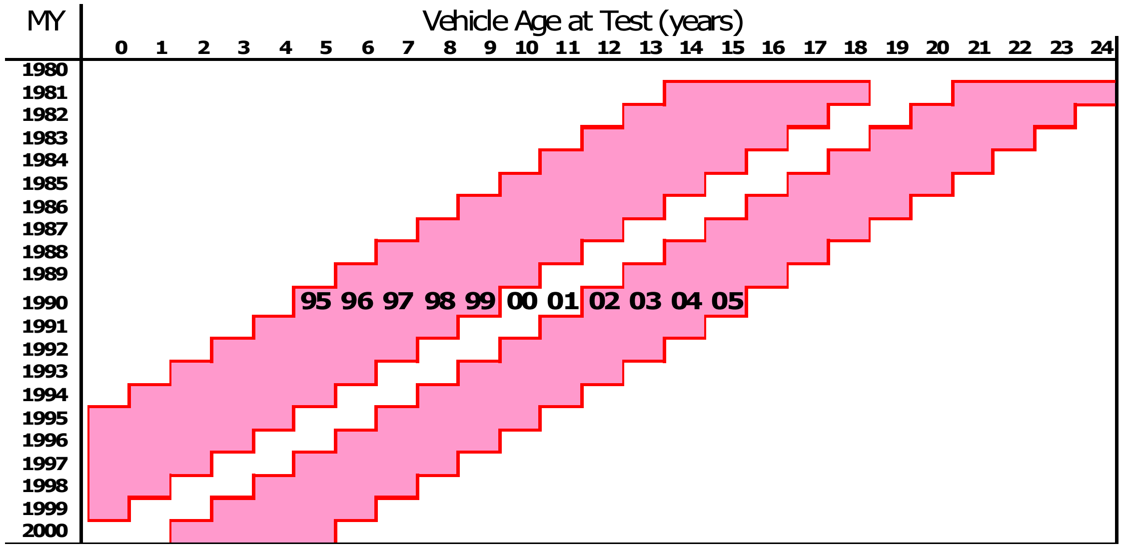


Figure 3-2 Model-year by age structure of the Phoenix I/M random evaluation sample

3.2.2.1.3.1 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 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/Mg (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 2-5.

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 2-5). Overall, we fit three models for each combination of cars and trucks, for the model-year groups shown in Table 3-5, 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 3-6). This sampling was performed to fit models on smaller volumes of data that a standard desktop computer could handle at the time. 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 3-9**

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 3-3.

$$w_{\text{final}} = w_{\text{result, MY, CY}} w_{\text{strat}}$$ **Equation 3-10**

Table 3-6 Sample sizes for statistical modeling, by regulatory class and test result[a]

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.

3.2.2.1.3.1.1 Coast/Cruise/Acceleration

Means model

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

$$\ln E_h = \beta_0 + \beta_1 P_{\text{V}} + \beta_2 P_{\text{V}}^2 + \beta_3 P_{\text{V}}^3 + \beta_4 a + \beta_5 s + \beta_6 P_{\text{V}} s + \gamma_7 t_i + \varepsilon$$ **Equation 3-11**

where :

[a] Note that model years 1990-and-later were subsequently updated as explained in later sections of this report.

- $\ln E_h$ = 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/Mg),
- 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 NO_x 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 $\ln E_h$, 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 3-6). 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

$$s_l^2 = \alpha_0 + \alpha_1 a + \alpha_2 P_V + \alpha_3 P_V a + \varepsilon \qquad \textbf{Equation 3-12}$$

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.

3.2.2.1.3.1.1.1 Model Application

Application of the model involved several steps. The first step was to construct a cell matrix including all emission rates to be calculated, as shown in Table 3-7.

Table 3-7 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 3-6
×	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 THC, CO, NO_x)	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 3-13**

Then, for each table cell, we constructed a vector of predictors ($\mathbf{X}_h$). Equation 3-14 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 3-8.

$$\mathbf{X}_h = \lfloor 1 \ \ P_V \ \ P_V^{\ 2} \ P_V^{\ 3} \ a \ 1 \ \ 0 \ \ 0 \ \ P_V \ \rfloor$$ **Equation 3-14**

Table 3-8 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*.

$$\ln E_h = \mathbf{X}_h^{'}\boldsymbol{\beta}$$ Equation 3-15

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

$$\boldsymbol{\alpha} = \left[\ \alpha_0\ \alpha_1\ \alpha_2\ \alpha_3\ \right]$$ Equation 3-16

$$\mathbf{X}_h = \left[1\ \ P_{\mathrm{V}}\ \ a\ \ P_{\mathrm{V}}a\ \right]$$ Equation 3-17

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

$$s_{l,h}^2 = \mathbf{X}_h\boldsymbol{\alpha}$$ Equation 3-18

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 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 3-11 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/Mg and the speed class is 25-50 mph.

$$\beta_0^* = \ln E_{a*} - 7.5\beta_1 - 7.5^2\beta_2 - 7.5^3\beta_3 - \beta_4^* a^* - \beta_{5(25-50)} - 7.5\beta_6 \qquad \textbf{Equation 3-19}$$

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.

3.2.2.1.3.1.2 Braking/Deceleration

3.2.2.1.3.1.2.1 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:

$$\ln E_h = \beta_0 + \beta_1 a + \gamma_7 t_i + \varepsilon \qquad \textbf{Equation 3-20}$$

3.2.2.1.3.1.2.2 Variances Model

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

$$s_l^2 = \alpha_0 + \alpha_1 a + \varepsilon \qquad \textbf{Equation 3-21}$$

3.2.2.1.3.1.2.3 Model_Application

In these operating modes, rates were to be modeled for a total of 840 cells. This total is calculated as in Table 3-7, 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

$$\boldsymbol{\beta} = \left[\ \beta_0\ \beta_1\ \right] \qquad \textbf{Equation 3-22}$$

and

$$\mathbf{X}_h = \left[\ 1 \quad a\ \right] \qquad \textbf{Equation 3-23}$$

respectively.

For the variances model the coefficients vector is

$$\boldsymbol{\alpha} = [\alpha_0 \ \alpha_1 \ ] \qquad \text{Equation 3-24}$$

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 backcast 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 3-25 is a rearrangement of Equation 3-20.

$$\beta_0^* = \ln E_{a*} - \beta_4 a* \qquad \text{Equation 3-25}$$

After these steps, the imputed values of $\ln E_h$ were calculated, as in Equation 3-17.

3.2.2.1.3.2 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 (s_β^2). This matrix contains covariances of each of the nine coefficients in relation to the others, with the diagonal containing variances for each coefficient.

$$\mathbf{s}_\beta^2 = \begin{bmatrix} \sigma_0^2 & . & . & . & \sigma_{0,4}^2 & . & . & . & \sigma_{0,6}^2 \\ . & \sigma_1^2 & . & . & . & . & . & . & . \\ . & . & \sigma_2^2 & . & . & . & . & . & . \\ . & . & . & \sigma_3^2 & . & . & . & . & . \\ \sigma_{4,0}^2 & . & . & . & \sigma_4^2 & . & . & . & \sigma_{0,4}^2 \\ . & . & . & . & . & \sigma_{5(0-25)}^2 & . & . & . \\ . & . & . & . & . & . & \sigma_{5(25-50)}^2 & . & . \\ . & . & . & . & . & . & . & \sigma_{5(50+)}^2 & . \\ \sigma_{6,0}^2 & . & . & . & \sigma_{6,4}^2 & . & . & . & \sigma_6^2 \end{bmatrix} . \qquad \text{Equation 3-26}$$

Using the parameter vectors $\mathbf{X}_h$ and the covariance matrix s_β^2, the standard of error of estimation for each cell was calculated as

$$s_{\ln E_h}^2 = \mathbf{X}_h^{'} \mathbf{s}_\beta^2 \mathbf{X}_h \qquad \text{Equation 3-27}$$

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.[29] 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.

3.2.2.1.3.3 Reverse Transformation

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

$$E_h = \mathrm{e}^{\ln E_h} \mathrm{e}^{0.5 s_{l,h}^2} \qquad \text{Equation 3-28}$$

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 3-28 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

$$s_l^2 = 2\ln\left(\frac{\bar{x}_a}{e^{x_l}}\right) \qquad \text{Equation 3-29}$$

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 3-28 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 3-7. Finally, we calculated the CV-of-the-mean (CV_{Eh}) for each modeled emission rate, as in Equation 3-8.

3.2.2.1.4 Table Construction

After compilation of the modeling results, the subset of results obtained directly from the data (Equation 3-4 to Equation 3-8), as shown in the shaded area in Figure 3-2 and the complete set generated through modeling (Equation 3-11 to Equation 3-29) 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 percent ($CV_{E_h} < 0.50$). 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 3-9.

Table 3-9 Mapping "analytic" model-year groups onto MOVES-database model-year groups[b]

"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

3.2.2.2 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/Mg for speed and VSP, respectively. Some data 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 in 3.2.2.1.3 above were used to extrapolate up to about 34 kW/Mg.

Based on initial review and comment on this aspect of the analysis, for MOVES2010, we gave 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

[b] Note that model years 1990-and-later were subsequently updated as explained in later sections of this report.

was collected in the course of the National Cooperative Highway Research Program (NCHRP)[30] 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 represent 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).[30] Driving traces for the US06 and MEC cycles are shown in Figure 3-3 and Figure 3-4. Both cycles range in speed up to over 70 mph and in VSP up to and exceeding 30 kW/Mg.

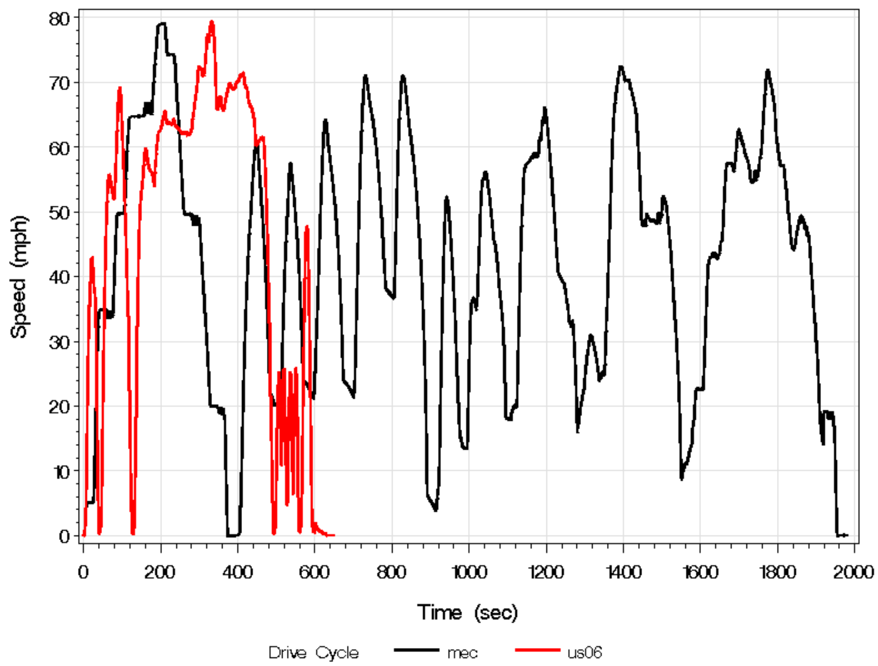


Figure 3-3 Example speed traces for the US06 and MEC cycles

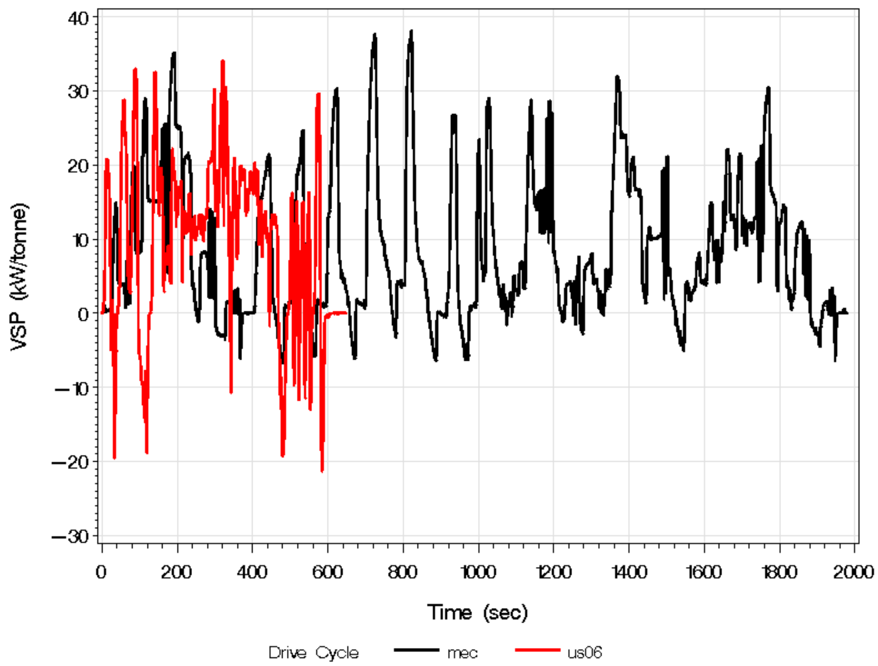


Figure 3-4 Example vehicle-specific-power (VSP) traces for the US06 and MEC cycles

Table 3-10 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 3-10 Sample sizes for US06 and MEC cycles (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 3-5, Figure 3-6 and Figure 3-7 show trends in emissions vs. VSP for CO, THC and NO_x for LDV and LDT by model year group. Both cycles were averaged and plotted as aggregates.

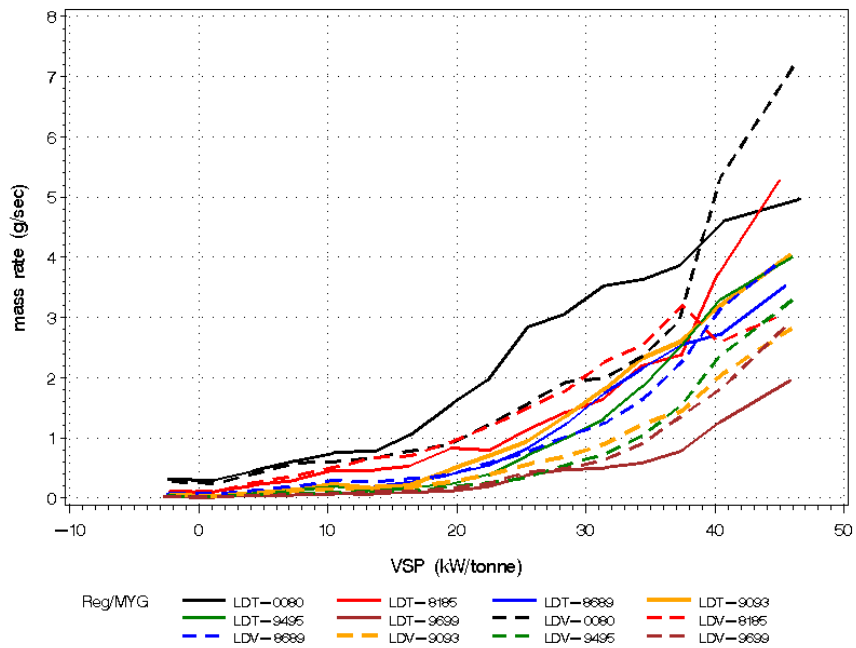


Figure 3-5 CO emissions (g/sec) on aggressive cycles, vs. VSP, by regulatory class and model-year group

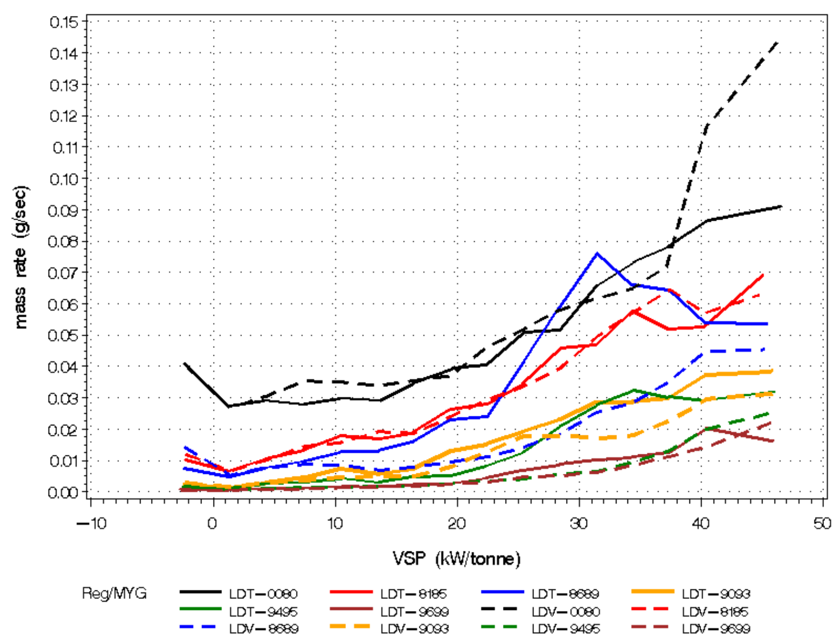


Figure 3-6 THC emissions (g/sec) on aggressive cycles, vs. VSP, by regulatory class and model-year group

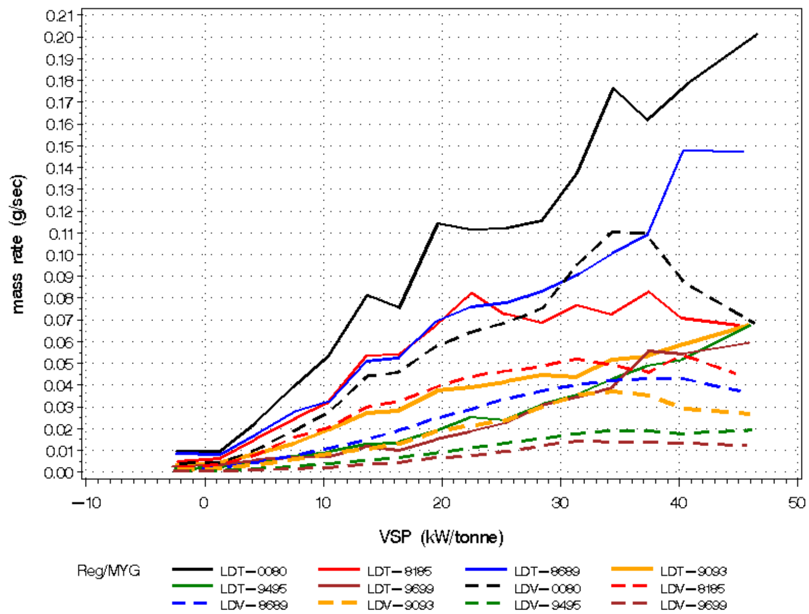


Figure 3-7 NO_x emissions (g/sec) on aggressive cycles, vs. VSP, by regulatory class and model-year group

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 3-10. 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/Mg. With mode 27 as a reference, we calculated ratios to modes 28, 29 and 30.

$$R_{i:27} = \frac{E_{h,i}}{E_{h,27}}, \text{ for } i = 28, 29, 30 \qquad \textbf{Equation 3-30}$$

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

$$R_{i:37} = \frac{E_{h,i}}{E_{h,37}}, \text{ for } i = 38, 39, 40 \qquad \textbf{Equation 3-31}$$

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

$$E^R_{h,i} = R_{i:27} E^{initial}_{h,27}, \text{ or } E^R_{h,i} = R_{i:37} E^{initial}_{h,37} \qquad \textbf{Equation 3-32}$$

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 changed substantially for the final rates used in MOVES2010 and later. 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) 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 emissions 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 3-8), 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 3-9). 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 THC. 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 NO_x example (Figure 3-10) 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 THC 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.

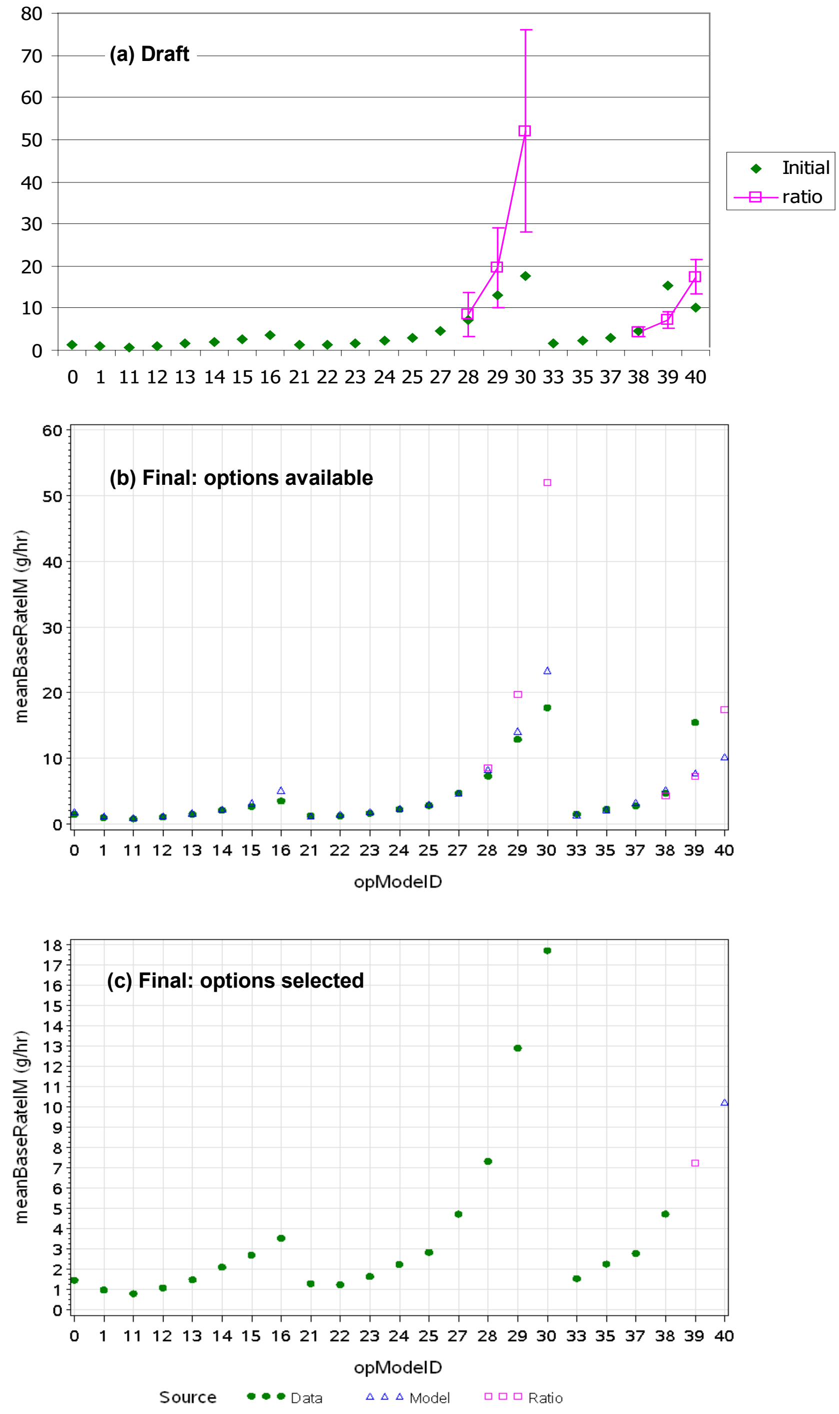


Figure 3-8 THC emission rates (g/hr), vs. VSP for MY 1998 cars at ages 4-5 years: (a) options for draft rates, (b) options for final model (data, model and ratio) and (c) options selected for final rates

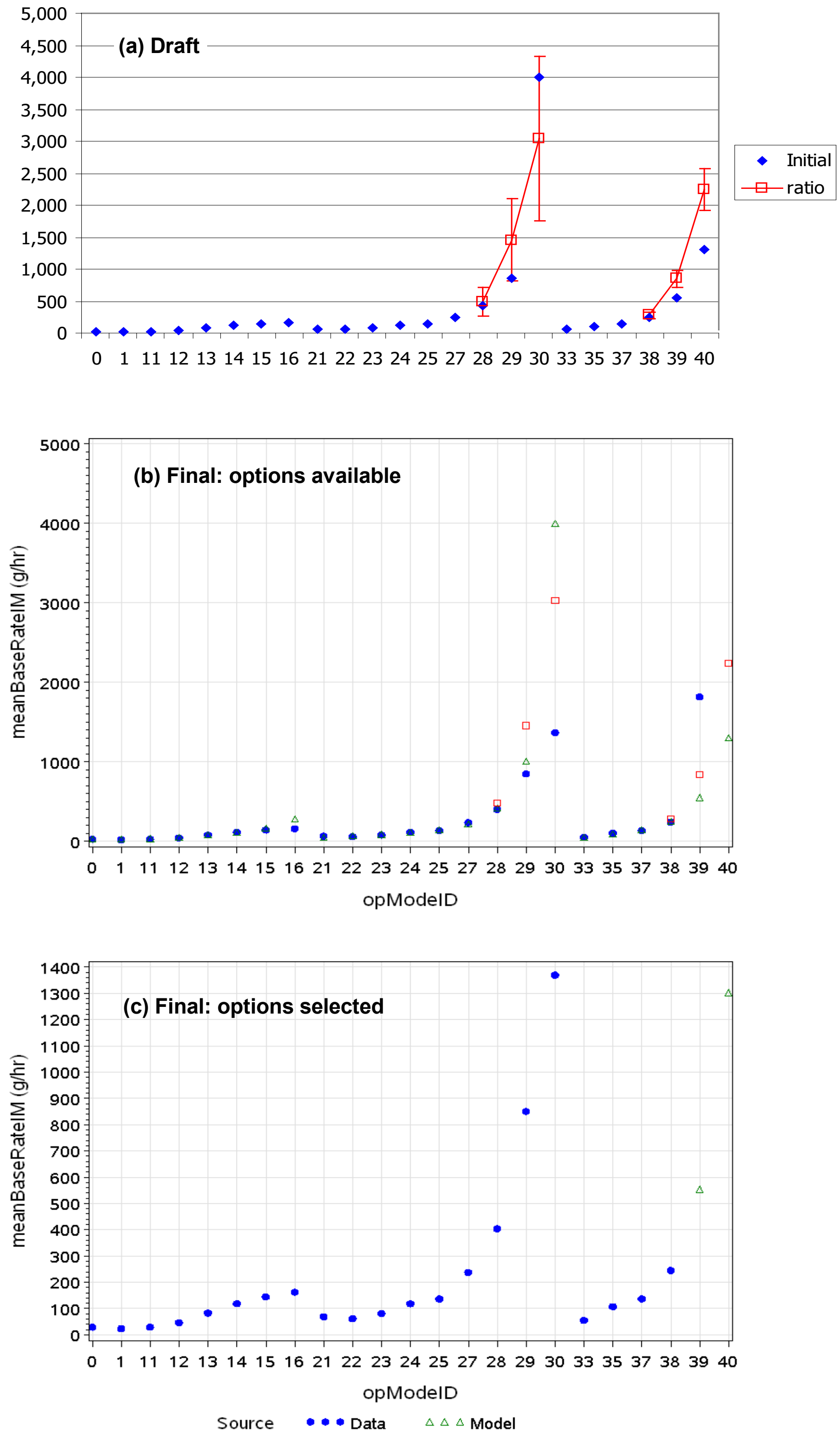


Figure 3-9 CO emission rates (g/hr), vs. operating mode for MY-1998 trucks at ages 6-7: (a) options for draft rates, (b) options for final model (data, model and ratio and (c) options selected for final rates

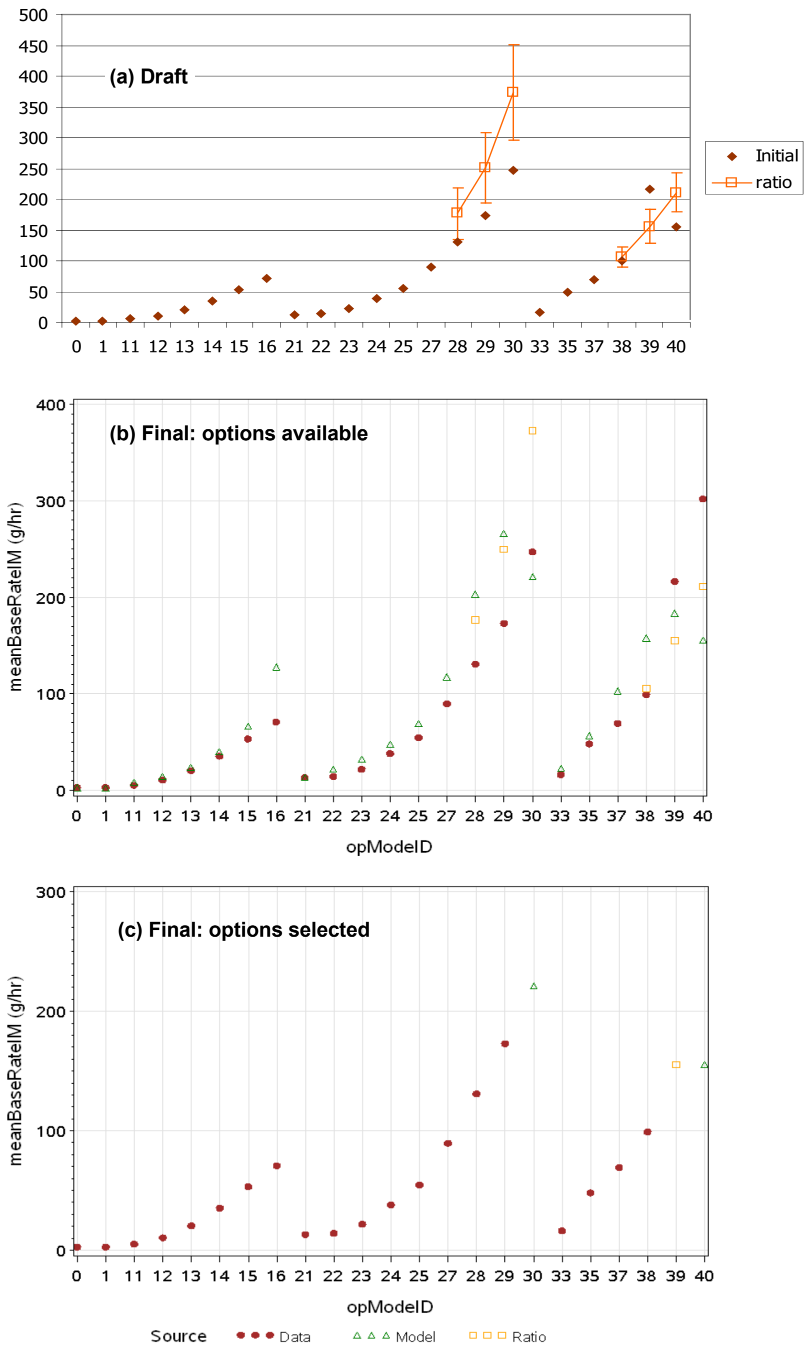


Figure 3-10 NO_x emission rates (g/hr) vs. operating mode for MY-1995 Cars at ages 8-9: (a) options for draft rates, (b) options for final model (data, model and ratio and (c) options selected for final rates

3.2.2.3 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.[14]

Figure 3-11 and Figure 3-12 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 NO_x.

At the time that emission trends with age were determined for the 1989-and-earlier vehicles, no data was available at ages older than 15 years for model years older than 1990. Thus it was necessary to project emissions.

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 the 15-19 year age groups, 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 3-13. 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.

$$R_{\text{age}} = \frac{\overline{E}_{10-14}}{\overline{E}_{8-9}}, \quad R_{\text{age}} = \frac{\overline{E}_{15-19}}{\overline{E}_{8-9}} \qquad \textbf{Equation 3-33}$$

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 3-37.

Table 3-11 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	NO_x	THC	CO	NO_x
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

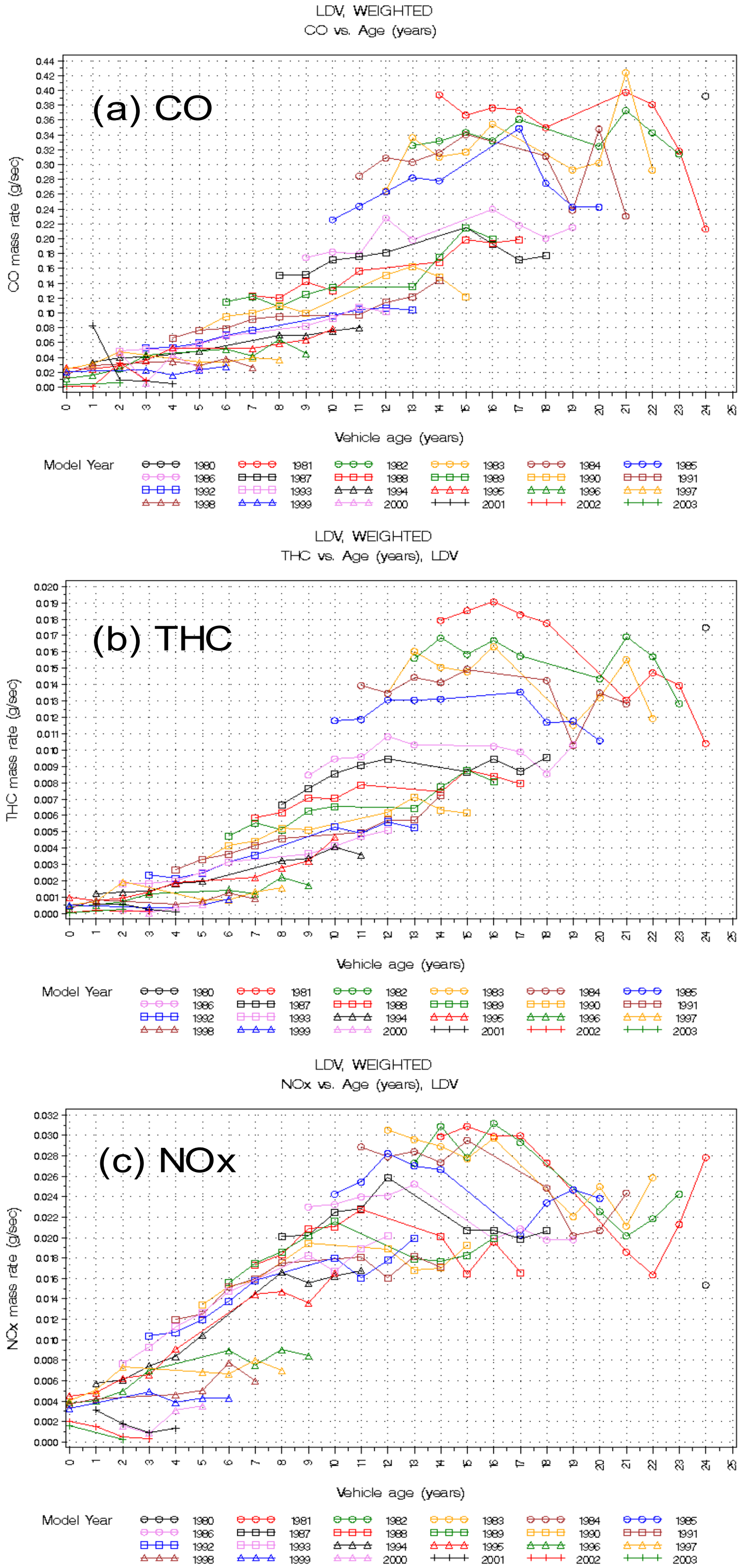


Figure 3-11 Aggregate IM147 emissions (g/sec) for cars, by model year and age, for the Phoenix random evaluation sample

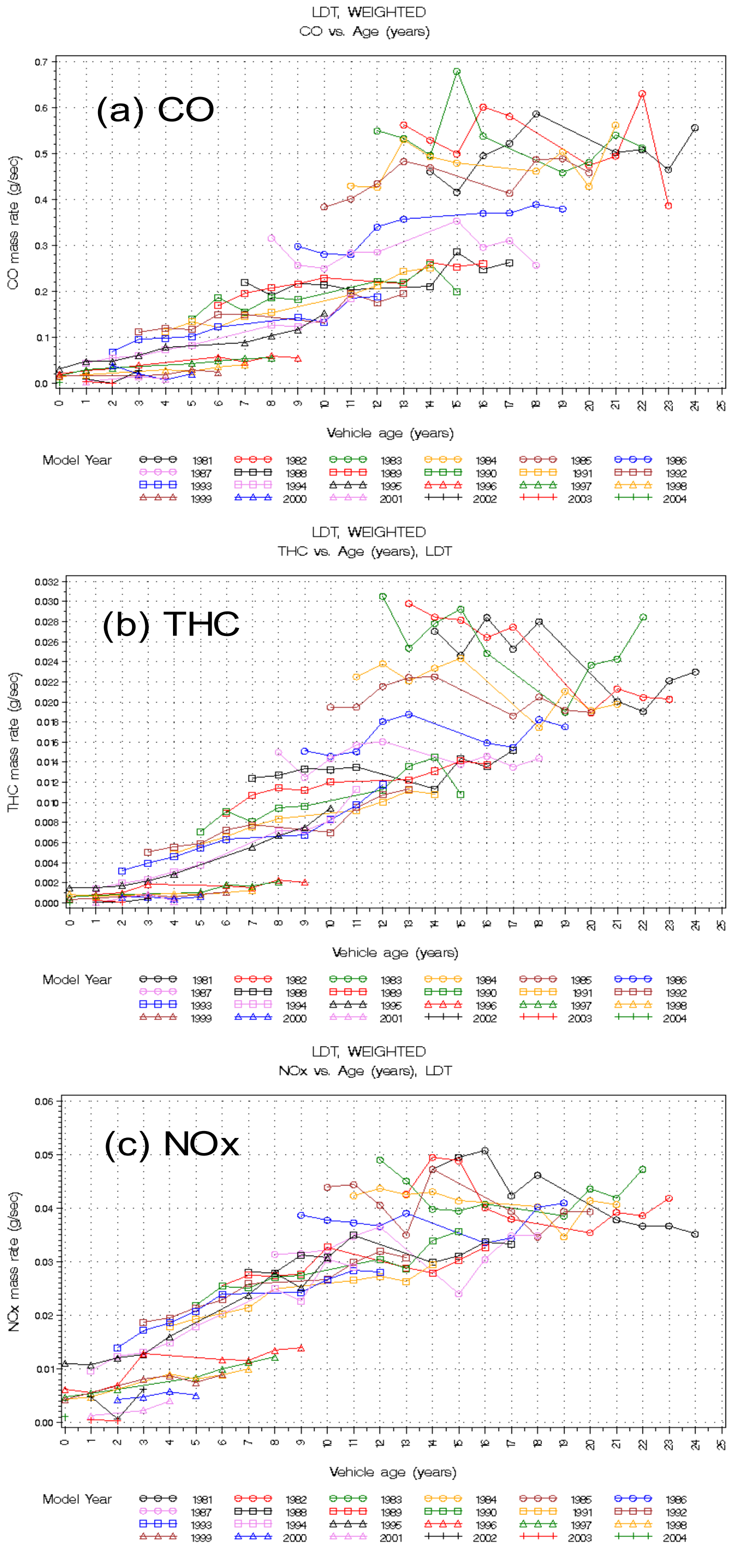


Figure 3-12 Aggregate IM147 Emissions (g/sec) for trucks, by model year and age, for the Phoenix random sample

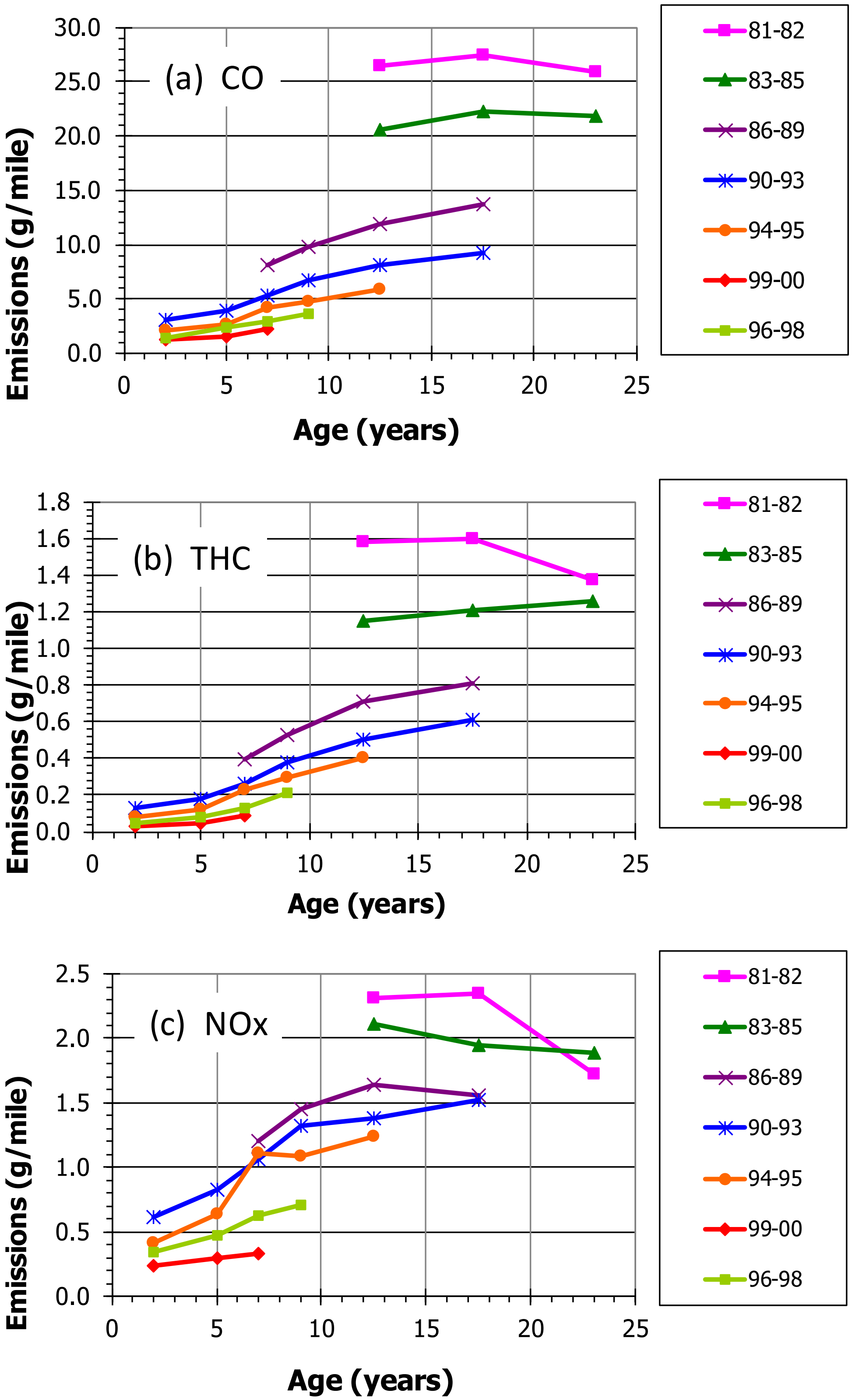


Figure 3-13 Aggregate IM147 emissions (g/mi) by model-year group and age group

3.2.2.3.1 Non-I/M Reference Rates

The ratios developed in 3.2.2.3 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. 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 3-12 shows the deterioration stabilization ratios for both the I/M and non-I/M reference rates. As mentioned above, the ratios are applied by multiplying them by the values for the 8-9 year age group in all operating modes. The ratios for I/M areas ($R_{\mathrm{age,I/M}}$) are identical to those in Table 3-11. The center column shows the ratio of values of $R_{\mathrm{age,I/M}}$ for the 15-19 to the 10-14 year ageGroups. Ratios for the non-I/M references ($R_{\mathrm{age,non\text{-}I/M}}$) 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 3-12 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)	$R_{age,non-I/M}$
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
NO_x	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 3-11.

[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.

3.3 MOVES2014 Emission-Rate Development (MY 2001-2016)

This section describes methods used in developing model rates for MOVES2010 and MOVES2014, representing emissions from vehicles certified to National LEV and Tier-2 standards, in model years 2001 and later. This material is retained because the MOVES2014 rates provide the basis for the updated MOVES3 rates, after being modified by adjustments as described in Sections 3.6, 3.7, and 3.10 below.

3.3.1 Data Sources

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

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.

3.3.1.1 Vehicle Descriptors

In addition to the parameters listed above in Table 3-2, the IUVP data provides test-group (formerly engine family) information. Using test group, 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 THC, CO or NO_x, where THC 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 3-13 Vehicle descriptors available in IUVP files and certification test records

Parameter	**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
Test group[1]	Y	Y	
Tier		Y	
Emissions Standard		Y	Assign Vehicle Class
[1]Formerly "engine family."			

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

3.3.2 Estimating Reference Rates

The goal of this process is to represent "with 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 Sections below.

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

2. *Develop phase-in assumptions* for MY 2001 – 2017, 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). 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).

4. *Estimate Emissions by Operating Mode*. Then calculate emissions by operating mode in each model year by multiplying the MY2000 emission rates by the weighted ratio for each model year.

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 51.

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 (see Section 3.5, page 95).

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

3.3.2.1 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 3-14 shows FTP composite results in relation to applicable certification and useful-life standards. For THC and NO_x, the data show expected compliance margins in the range of 40-60 percent in most cases. For CO, compliance margins are even larger, ostensibly reflecting the concomitant effects of HC or NO_x control on CO emissions.

Figure 3-15 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 3-16 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 NO_x, 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.

Figure 3-16 shows composite, start and running emissions each normalized to their Tier 1 levels. These ratios are applied in a subsequent step to estimate running emission rates.

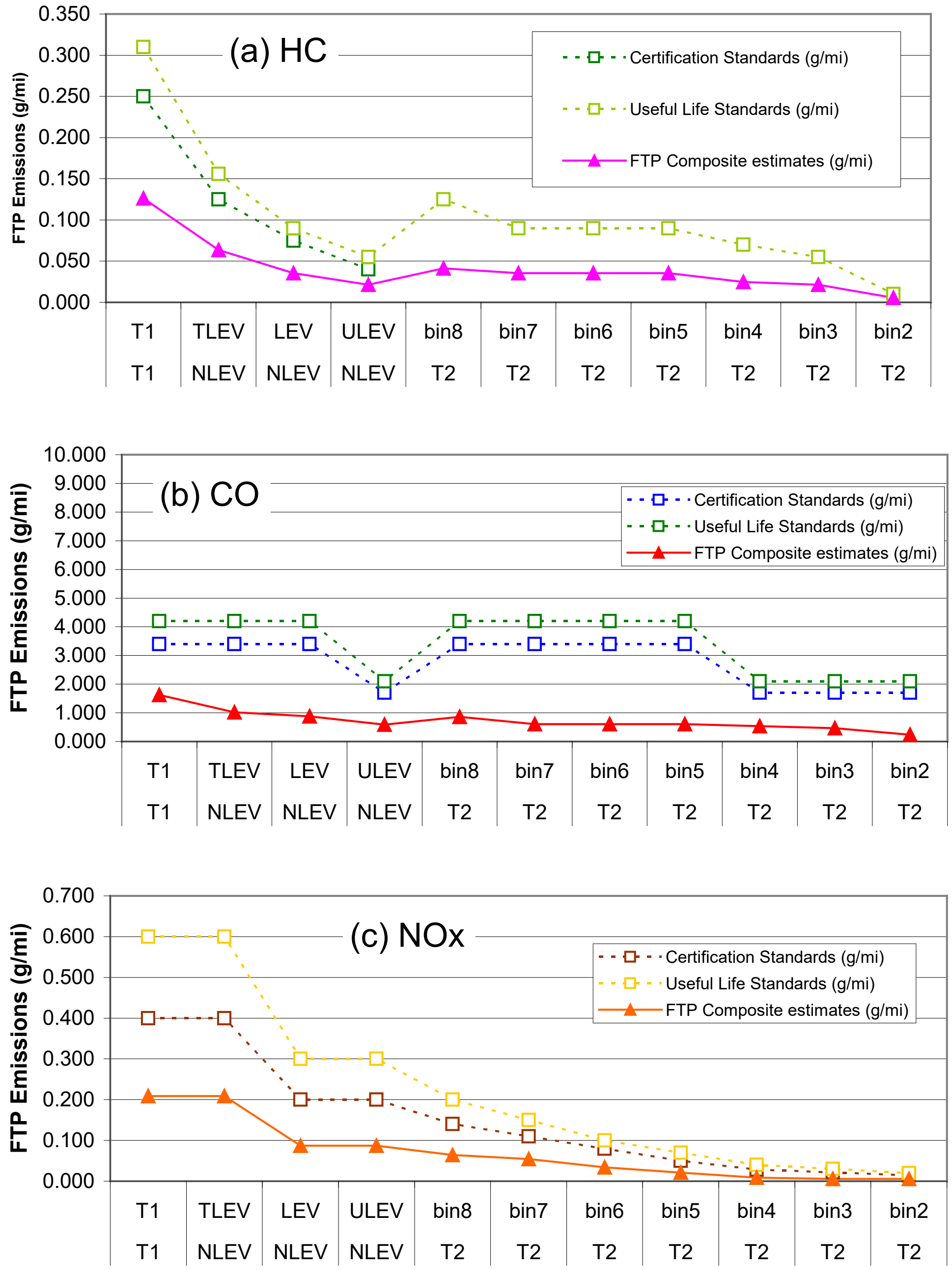


Figure 3-14 Composite FTP Results for Tier 1, NLEV and Tier 2 passenger cars (LDV), as measured by IUVP, in relation to corresponding certification and useful-life standards

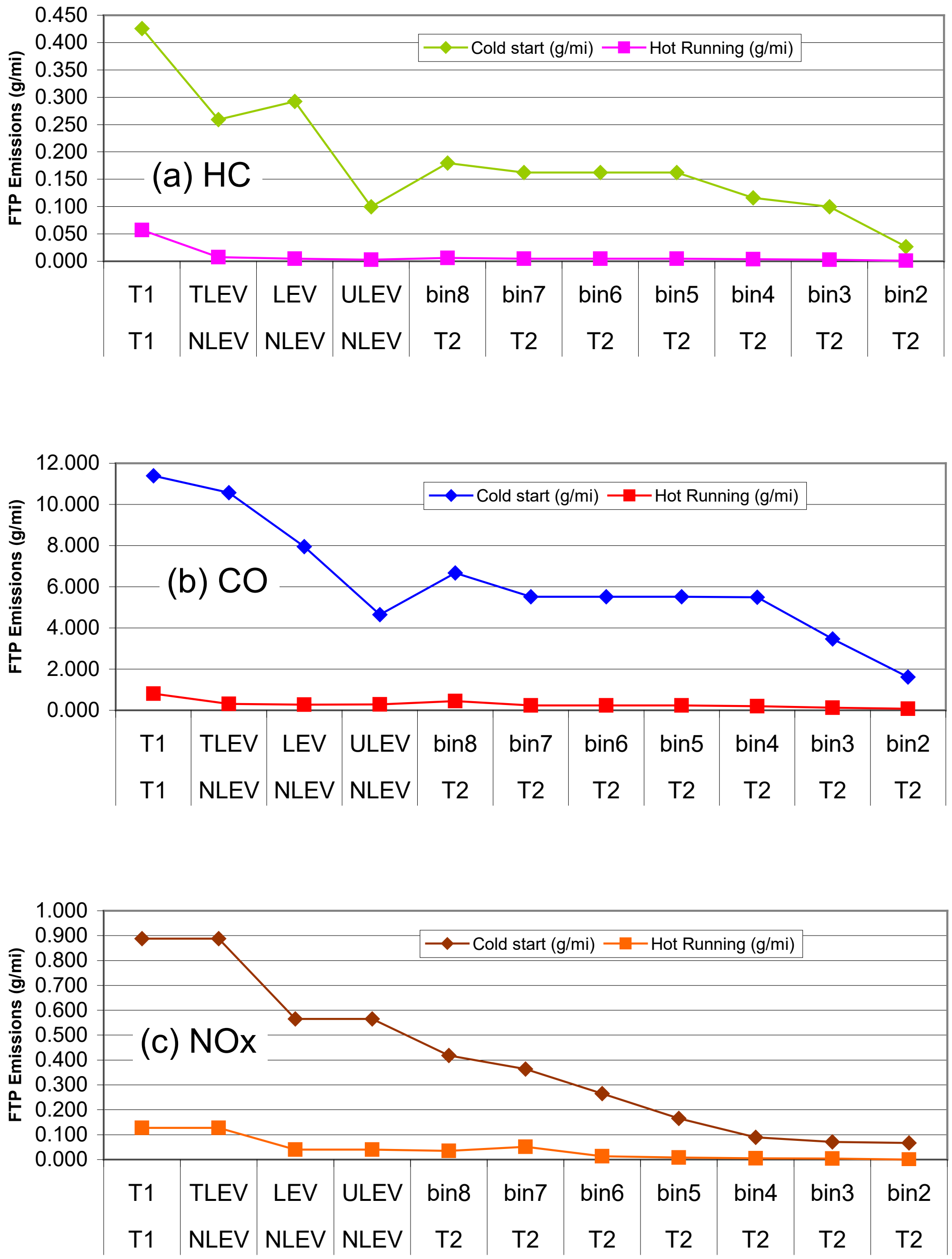


Figure 3-15 Cold-start (Bag 1 – Bag 3) and hot-running (Bag 2) FTP emissions for Tier 1, NLEV and Tier 2 passenger cars (LDV), as measured by IUVP (g/mi)

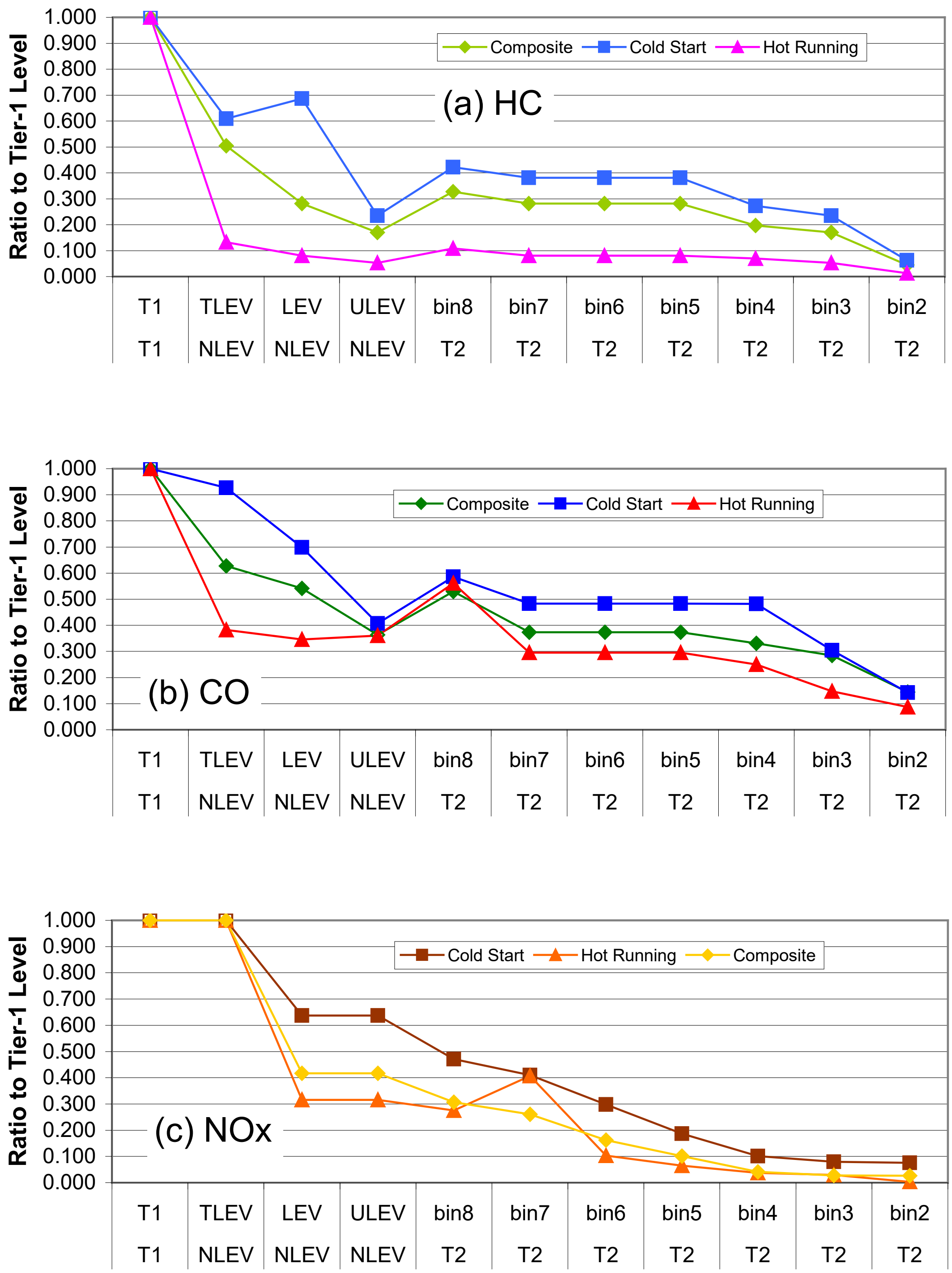


Figure 3-16 Composite, cold-start (Bag 1 – Bag 3) and hot-running (Bag 2) FTP emissions for Tier 1, NLEV and Tier 2 passenger cars (LDV), as measured by IUVP, normalized to respective Tier-1 levels

3.3.2.2 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.[31] These records contain information on certified vehicles, including model year, test group (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 3-14.

After compiling 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.[32,c] 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 3-15. Sales-weighted phase-in scenarios for each vehicle class are shown in Figure 3-17 through Figure 3-20. As noted, the results in the Figures reflect the certifications in the “Fed” or “Both” groups shown in Table 3-15.

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.

[c] Note that this database has been renamed as the “Engines and Vehicles Compliance Information System” (EV-CIS).

Table 3-14 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 3-15 Approximate numbers of engine families certified, by model year and age group, for 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."

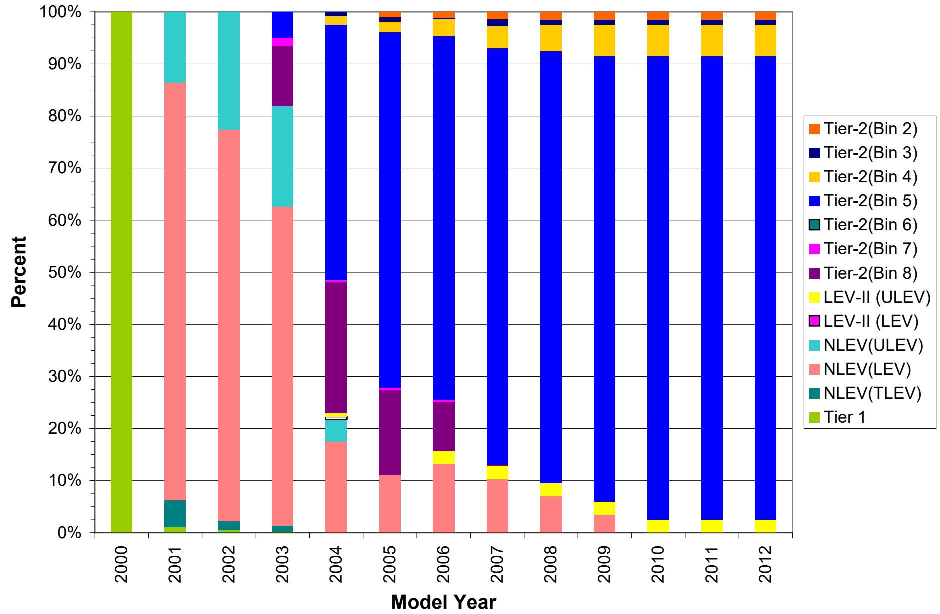


Figure 3-17 Phase-in assumptions for Tier 1, NLEV, and Tier 2 standards, for LDV and LDT1

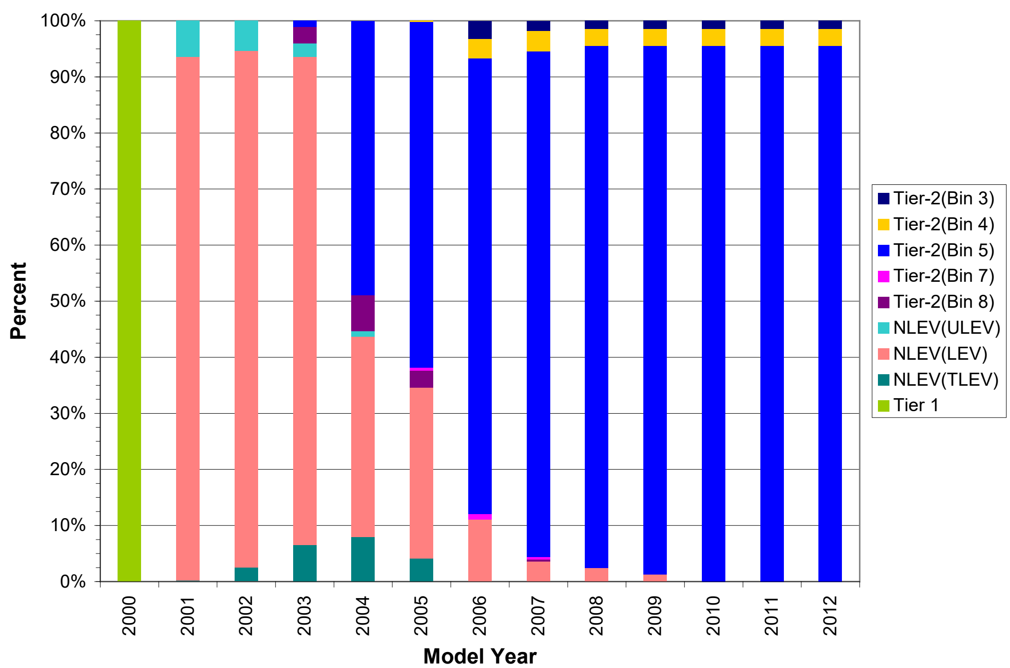


Figure 3-18 Phase-in assumptions for Tier 1, NLEV and Tier 2 standards, for LDT2

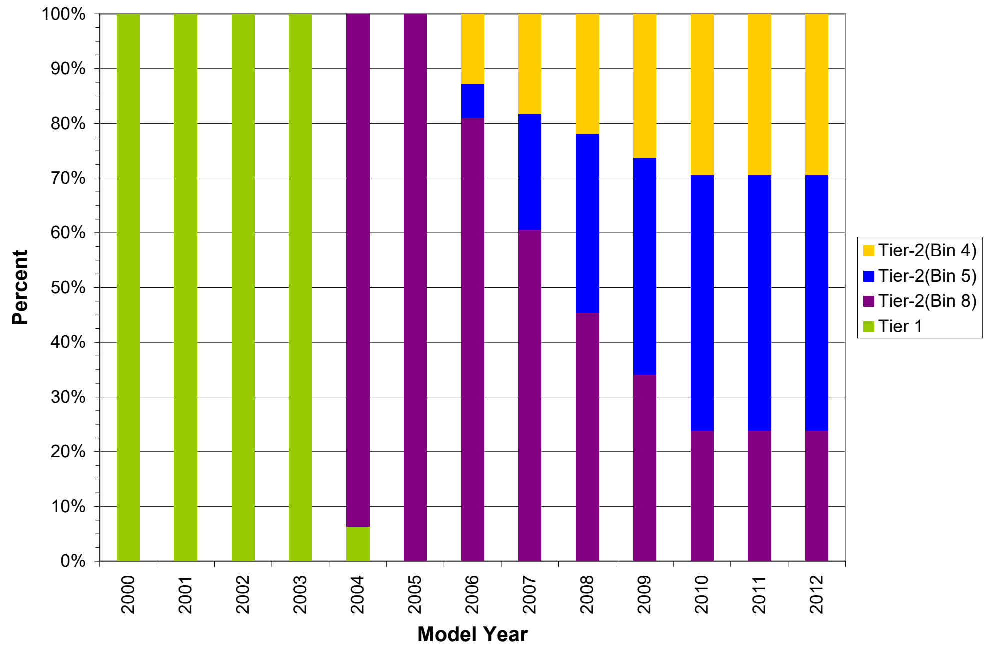


Figure 3-19 Phase-in assumptions for Tier 1 and Tier 2 standards, for LDT3

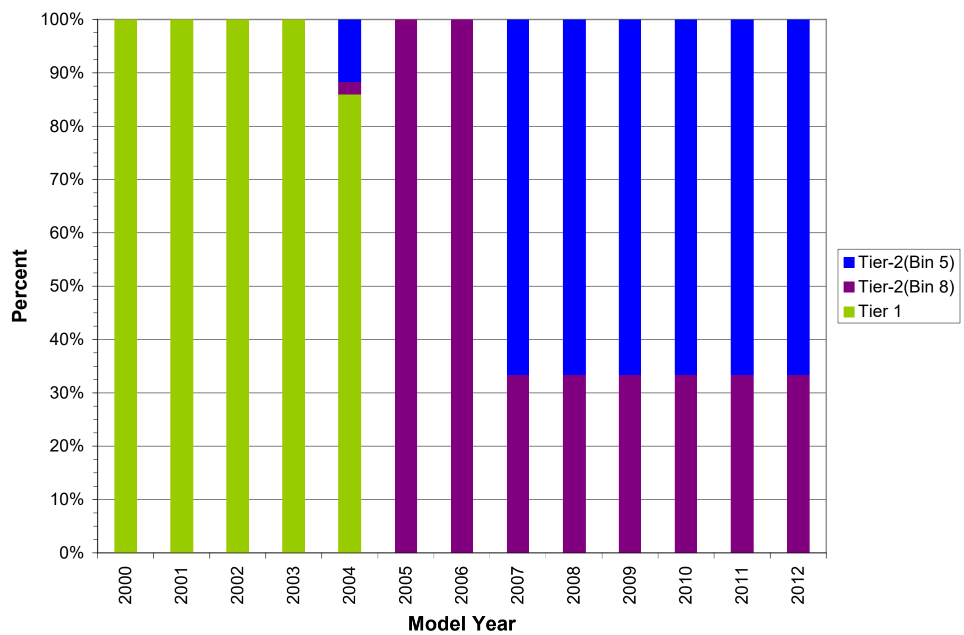


Figure 3-20 Phase-in assumptions for Tier 1 and Tier 2 standards, for LDT4

3.3.2.3 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 3-21.

Figure 3-22 shows an example of the phase-in calculation for NO_x 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 3-16 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 (for 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 3-23 to Figure 3-25 below.

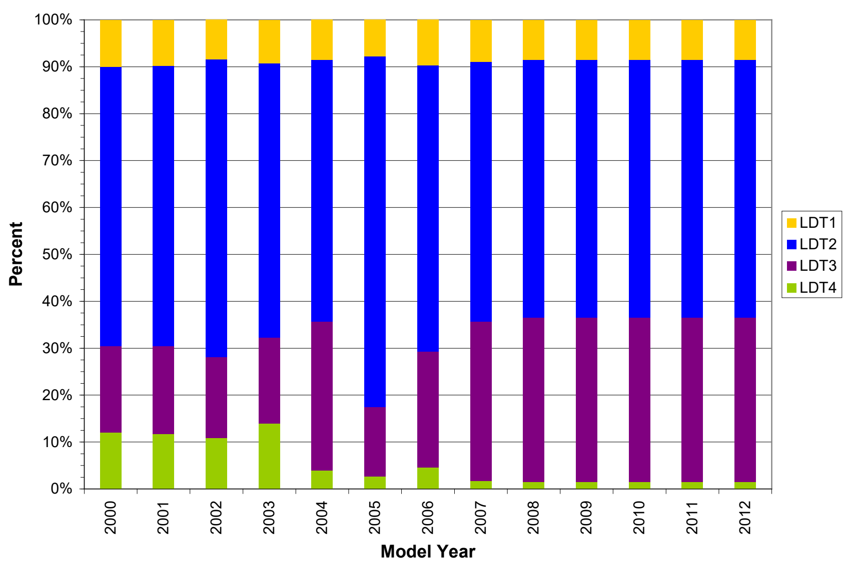


Figure 3-21 Relative fractions of truck classes, by model year

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*

Figure 3-22 Example of phase-in calculation, for NO_x from cars (LDV), for MY 2000-2010

Table 3-16 Weighted average FTP values for trucks and cars for MY 2001-2010

regClass	MY	CO			THC			NO_x		
		Comp. (g/mi)	Start (g)	Running (g/mi)	Comp. (g/mi)	Start (g)	Running (g/mi)	Comp. (g/mi)	Start (g)	Running (g/mi)
Reference[1]	2000	1.62	11.4	0.805	0.126	1.53	0.0571	0.209	0.888	0.127
Trucks	2001	1.43	12.6	0.566	0.0965	1.23	0.0400	0.171	0.843	0.0876
	2002	1.41	12.4	0.552	0.0942	1.21	0.0376	0.169	0.836	0.0865
	2003	1.47	12.7	0.586	0.1004	1.25	0.0424	0.181	0.863	0.0934
	2004	0.923	7.92	0.393	0.0535	0.786	0.0123	0.0849	0.473	0.0434
	2005	0.783	7.05	0.315	0.0440	0.703	0.00574	0.0596	0.367	0.0291
	2006	0.697	6.12	0.296	0.0378	0.612	0.00511	0.0381	0.264	0.0183
	2007	0.664	5.85	0.281	0.0361	0.587	0.00490	0.0315	0.226	0.0148
	2008	0.647	5.75	0.270	0.0356	0.580	0.00479	0.0285	0.208	0.0130
	2009	0.632	5.67	0.260	0.0350	0.571	0.00470	0.0258	0.192	0.0115
	2010	0.618	5.58	0.251	0.0345	0.564	0.00461	0.0233	0.177	0.0101
Cars	2001	0.8561	7.68	0.287	0.0361	0.954	0.00508	0.0948	0.586	0.0457
	2002	0.8206	7.27	0.284	0.0333	0.893	0.00451	0.0898	0.573	0.0421
	2003	0.8076	7.05	0.300	0.0340	0.839	0.00462	0.0824	0.530	0.0394
	2004	0.7141	6.16	0.298	0.0360	0.664	0.00488	0.0461	0.315	0.0220
	2005	0.6716	5.91	0.274	0.0358	0.634	0.00477	0.0351	0.248	0.0161
	2006	0.6566	5.85	0.257	0.0350	0.633	0.00462	0.0335	0.239	0.0150
	2007	0.6210	5.63	0.234	0.0341	0.608	0.00443	0.0271	0.201	0.0112
	2008	0.6114	5.55	0.232	0.0341	0.592	0.00443	0.0248	0.187	0.0101
	2009	0.6011	5.47	0.230	0.0339	0.574	0.00442	0.0224	0.172	0.00896
	2010	0.5915	5.38	0.229	0.0339	0.557	0.00442	0.0201	0.158	0.00784

[1]The reference level for calculating ratios is MY 2000, representing cars (LDV) for Tier 1.

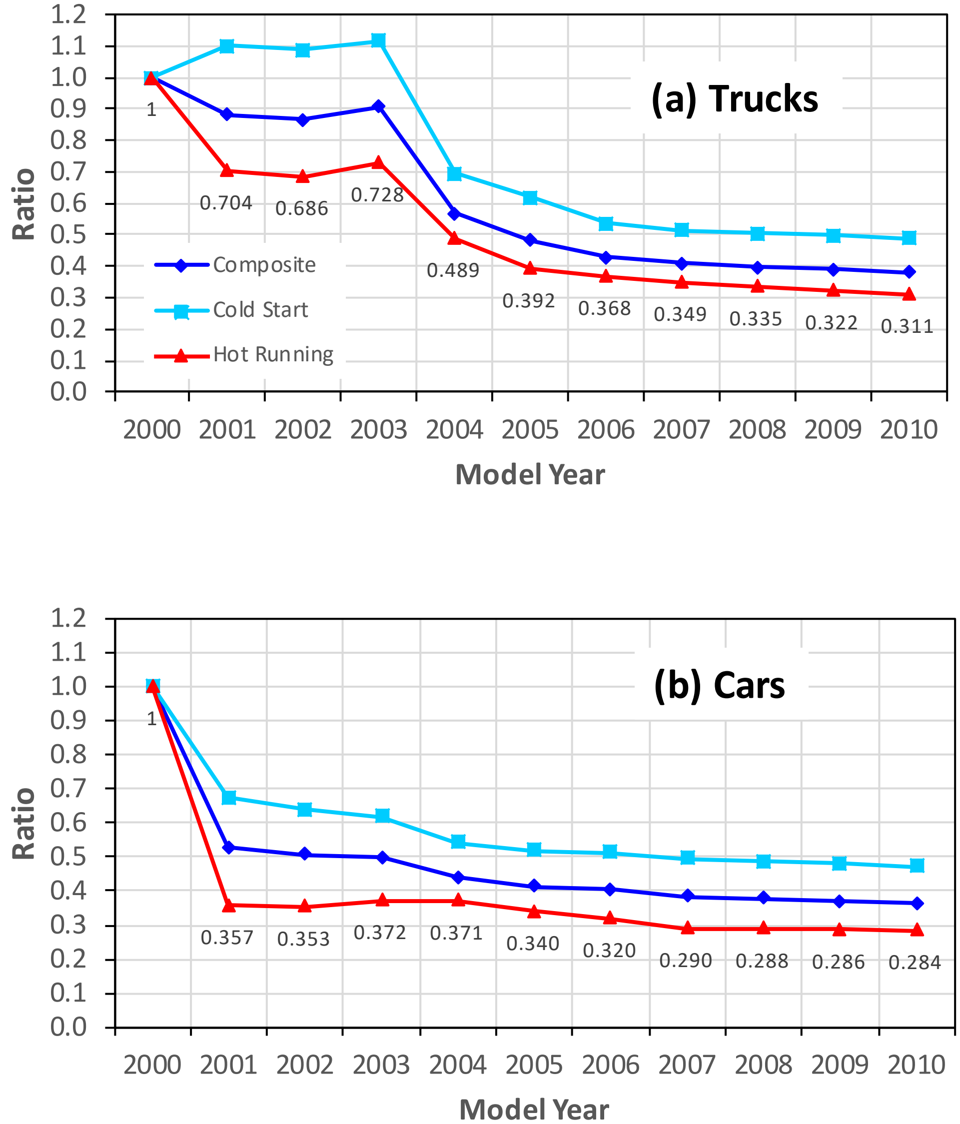


Figure 3-23 Weighted ratios for composite, start and running CO Emissions, for (a) trucks and (b) cars

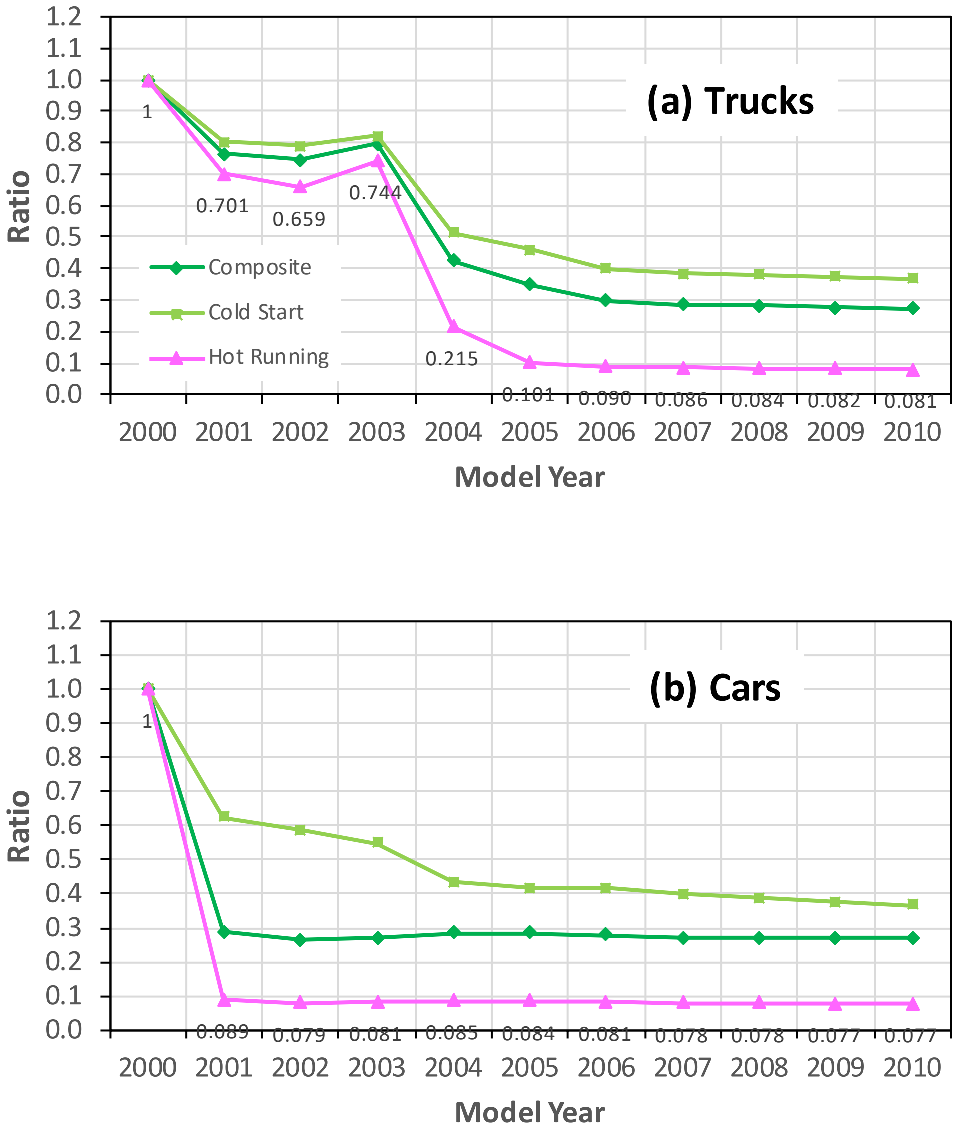


Figure 3-24 Weighted ratios for FTP composite, start and running THC emissions, for (a) trucks and (b) cars

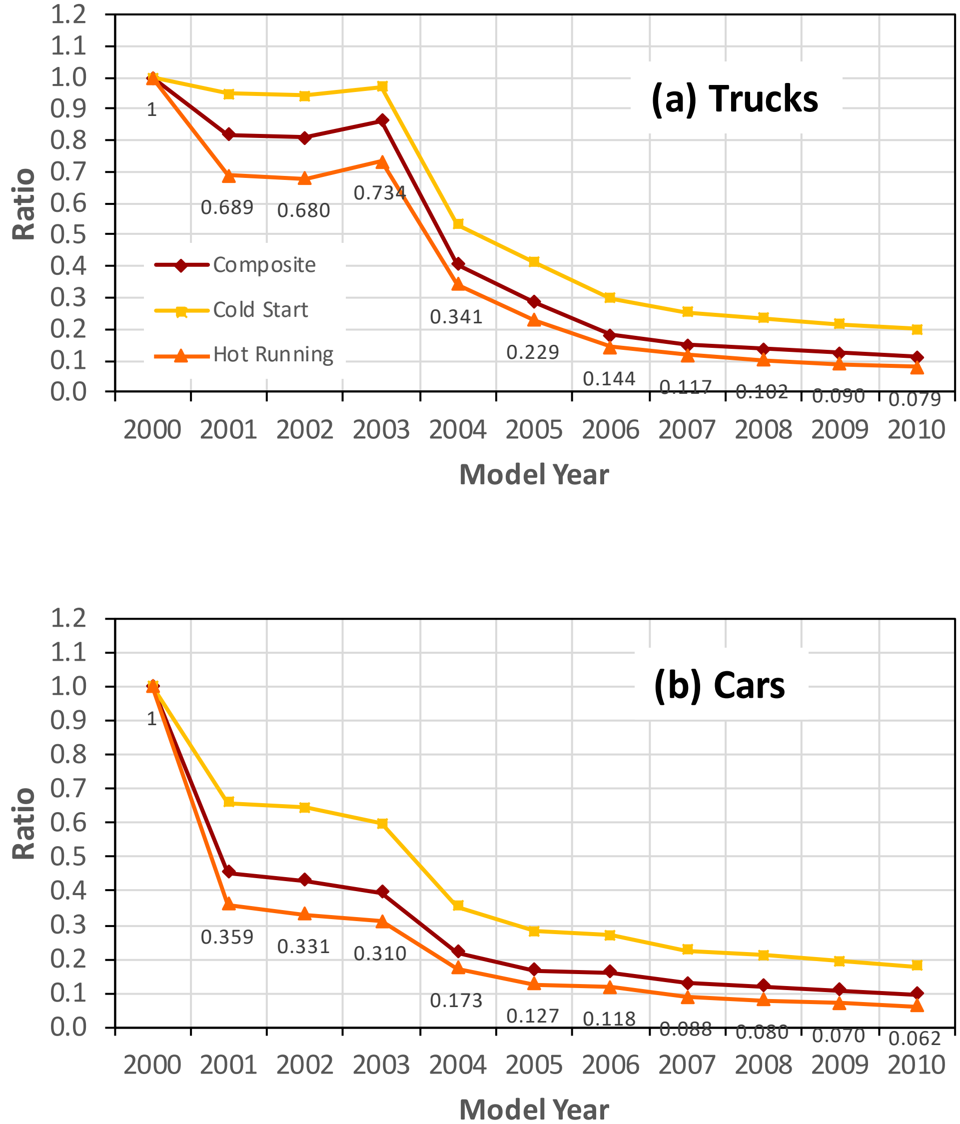


Figure 3-25 Weighted ratios for FTP composite, start and running NO_x emissions, for (a) trucks and (b) cars

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).

In developing rates for use with MOVES2010 and MOVES2014, we attempted to explicitly account for the effects of the SFTP standards. Due to a lack of "second-by-second" data on vehicles certified to the NLEV (or Tier 2) standards at the time, distinct sets of "US06-based" scaling factors were developed to represent emissions during "high-power" operation, which was assumed to occur in a subset of six operating modes (28-30, 38-40).

This approach implied that the interaction of increasing stringent FTP standards (e.g., Bin 3, Bin 2, SULEV) with non-changing SFTP standards would increase the steepness of emissions trends with increasing VSP over approximately 18 kW/Mg.

More recently, the availability of second-by-second data measured on vehicles certified to Tier-2 standards has enabled us to reassess this assumption (see Section 3.3.2.4.1). Our review of these data suggests that the expected offsets in emissions trends with power are not observable. Accordingly, we have modified rates for the current release by removing the 'US06-based' scaling factors.

Thus, in MOVES3 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 all operating modes, we applied a single "hot-running" ratio as listed in Table 3-16 above.

Figure 3-26 and Figure 3-27 show application of the ratios to selected hot-running operating modes in model years 2000 (the reference year), 2005, and 2010, both calculated with respect to 2000. In these figures, the results are presented on both linear and logarithmic scales. The linear plots more clearly display the differences at high-power, but obscure those at lower power. The logarithmic plots supplement the linear plots by making visible the relatively small differences between MY 2005 and 2010 in the lower power modes.

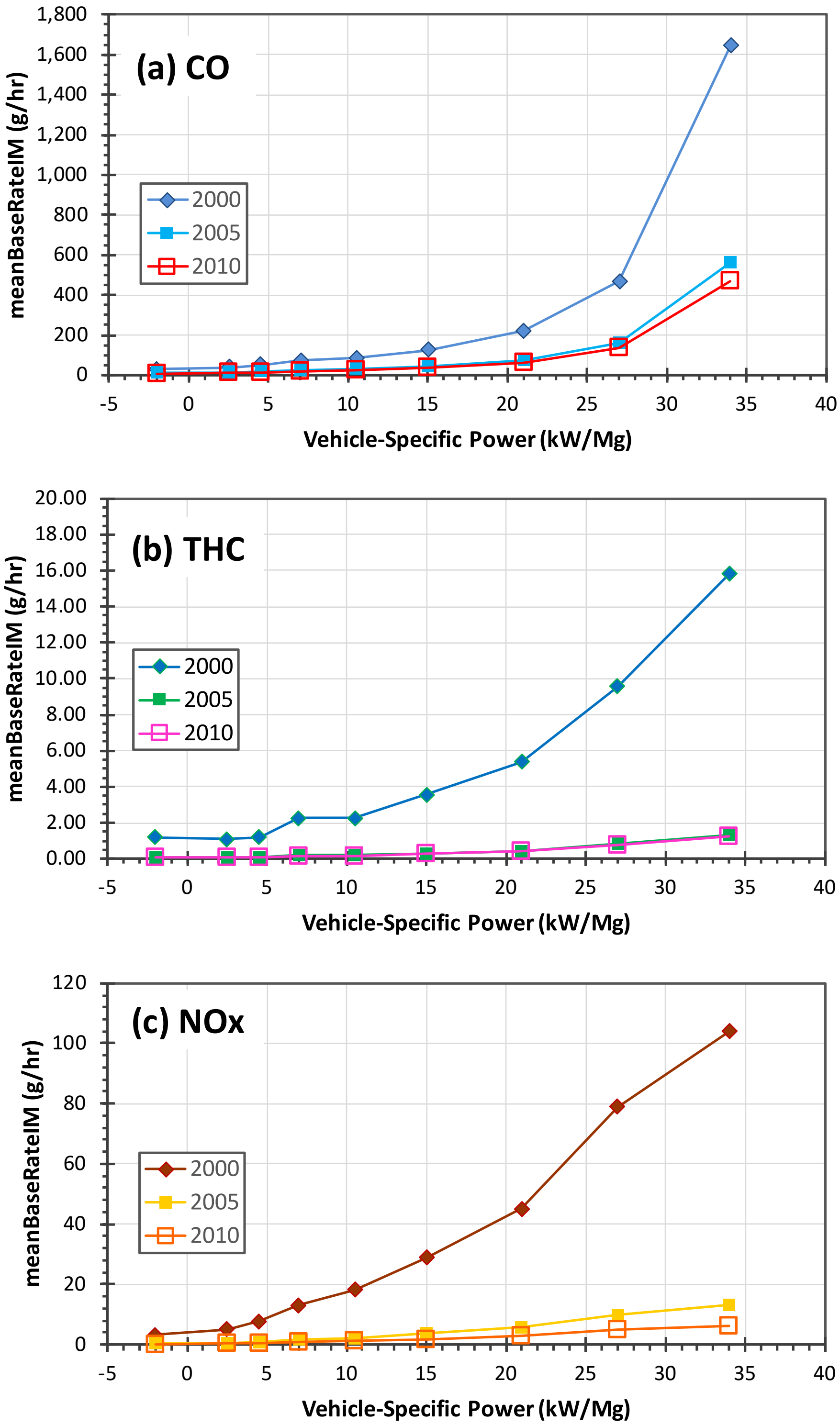


Figure 3-26 Projected emission rates for cars, vs. VSP, for three model years (LINEAR SCALE). (NOTE: rates pictured represent operating modes 21-30 for ages 0-3 years)

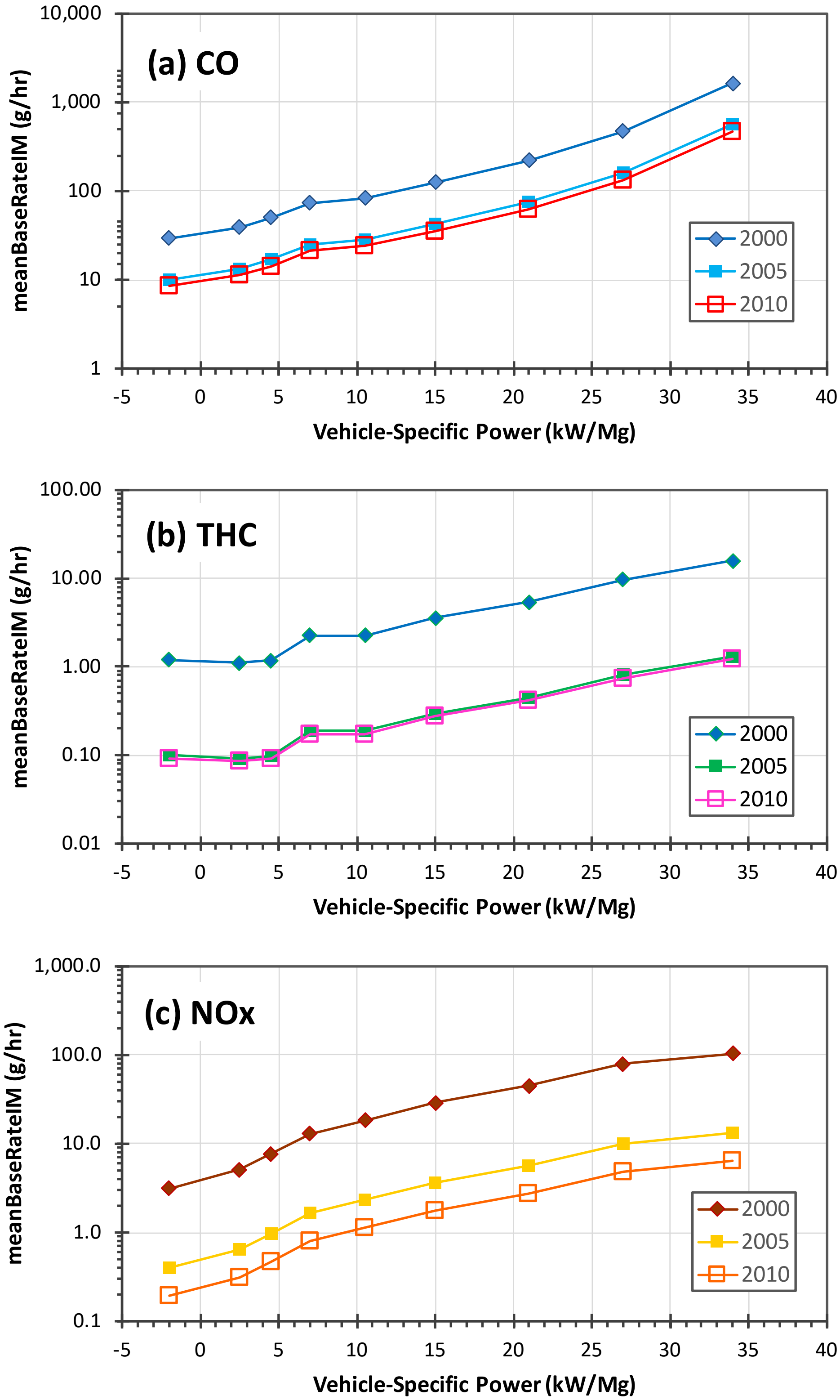


Figure 3-27 Projected emission rates for cars, vs. VSP, for three model years (LOGARITHMIC SCALE) (NOTE: rates pictured represent operating modes 21-30 for ages 0-3 years)

3.3.2.4.1 Evaluation of MOVES2014 "High-Power" Emission Rates

The removal of the MOVES2014 "US06 based" scaling factors described above was based on analysis of recently available second-by-second high-power emission data for vehicles certified to Tier 2 or equivalent standards. While the evaluation was not sufficient to develop new rates, it demonstrated clearly that MOVES would better estimate high-power emissions without the "US06-based" scaling.

One such dataset includes measurements on a set of light-duty vehicles collected by faculty and students at North Carolina State University between 2008 and 2018.[33] The sample includes 205 vehicles. The vehicles range in model year from 1996 to 2018 and incorporate multiple standards, including Tier 1 through Tier 3 and their LEV equivalents. Age and mileage at the time of measurement range from 0 years or miles to 18 years and over 300,000 miles, respectively. Gaseous emissions were measured using Clean Air Technologies (CATI) Montana or Axion portable emissions measurement systems (PEMS) over a set of drive routes in the Raleigh area covering approximately 110 miles.

A second dataset includes measurements on a set of light-duty vehicles taken at the USEPA National Vehicle and Fuel Emissions Laboratory in Ann Arbor, MI. This vehicle sample is much smaller, including 4 cars and 6 trucks. Gaseous emissions were measured using Sensors SEMTECH portable instruments over routes comprising a variety of road types and driving conditions around Ann Arbor, including freeway driving.

Binning and averaging the continuous data by vehicle specific power allows comparison of the results with corresponding trends in MOVES2014 emission rates (see Figure 3-28).   The trends for "NCSU" represent a subsample of vehicles certified to Tier-2 or LEV-II standards, whereas those for "EPA" represent several vehicles each.

For cars, the "NCSU" trend is noticeably lower than the MOVES2014 trend at "high power," i.e., above 20 kW/Mg, and shows a gentler increase in this range. The "EPA" trend increases more aggressively than the "NCSU" trend but is still lower than the MOVES2014 trend. At "low power," i.e., between ~3 to 20 kW/Mg, the "NCSU" trend shows a positive "convex" curve, which is due to the presence of a single "high-emitting" vehicle. Absent this vehicle, the trend would look very similar to that for trucks in this range.

For trucks, the MOVES trend is markedly higher than either of the PEMS trends, although the "EPA" trend is more aggressive than the "NCSU" trend above ~30 kW/Mg.

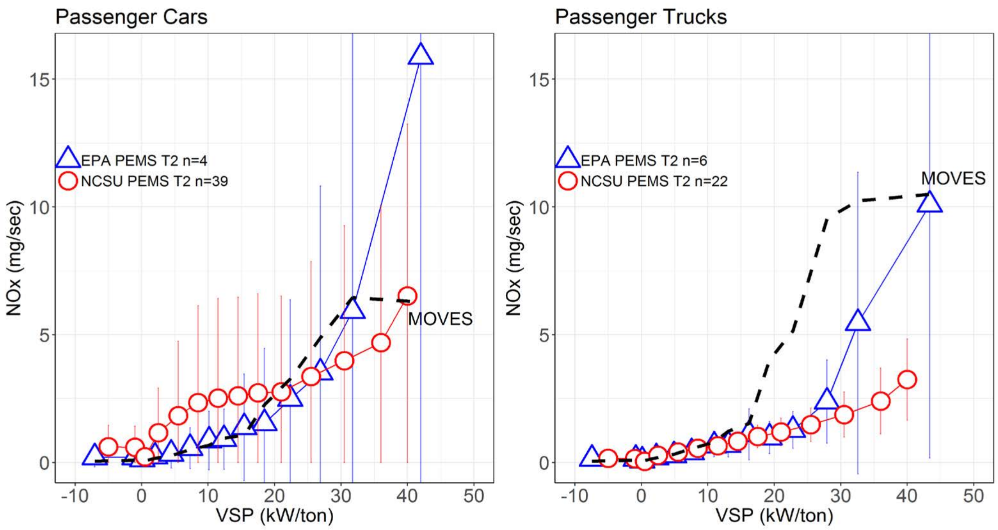


Figure 3-28 Trends in NOx emissions for Cars in trucks, as measured by two PEMS instruments and as represented in MOVES2014 emission rates.

Based on the results of this initial comparison, we compared the "real-world" PEMS results, represented by the "NCSU" trends, to MOVES2014 rates and to a set of MOVES rates modified by removal of the "US06-based" scaling factors, as shown in Figure 3-29 below for CO and NO_x for cars and trucks. In all cases, removal of "US06-based" scaling improved agreement with the PEMS results.

Based on this finding, for MOVES3 we elected to revise the rates by removal of the "US06 scaling" for the subset of "high-power" modes, as described above. Work previously performed to evaluate the projection of NO_x emissions by MOVES2014 had showed that high-power operation contributes substantially to the light-duty NO_x inventory in the National Emissions Inventory.[34,35] Note that some uncertainty remains in the estimation of emissions at high power, as evidenced in part by the differences between measurements by the two PEMS instruments. This topic requires additional evaluation after the release of MOVES3 as more data becomes available.

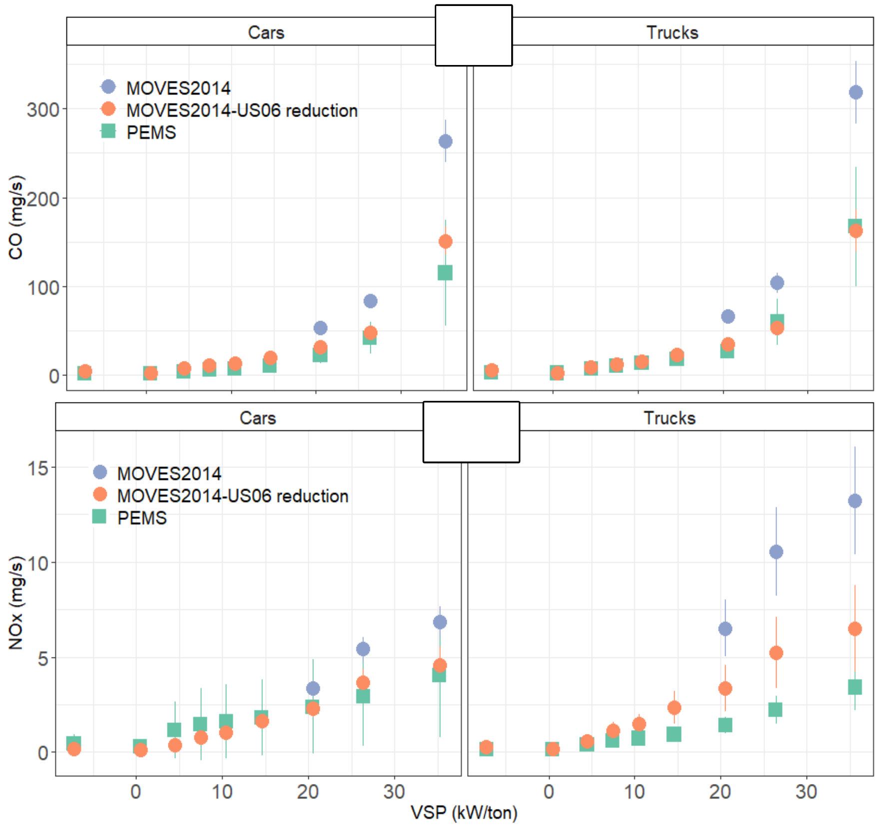


Figure 3-29 Trends in emissions with VSP for two vehicles classes and two pollutants, for MOVES2014 rates, modified MOVES rates and NCSU PEMS results

3.4 MOVES2014 Emission-Rate Development (MY 2017 and later)

This section describes methods used in developing model rates for MOVES2014, representing emissions from vehicles certified to Federal Tier-3 standards, in model years 2017 and later. This material is retained because the MOVES2014 rates provide the basis for the updated MOVES3 rates, after being modified by adjustments as described in Sections 3.6, 3.7, and 3.10 below.

Methods used to develop rates to represent emissions for vehicles certified to Tier 3 standards were identical to those used to develop rates for vehicles certified to NLEV and Tier 2 standards, as described in Section 3.3 above, with several specific modifications. Where no modifications to methods were made, we will refer the reader to the appropriate section of this report.

As previously described, the goal of this process is to represent I/M reference rates for the 0-3 year ageGroup. The rates are estimated by Tier, model year and regulatory class. The process involves six steps previously described, repeated below for convenience.

1. *Average FTP results* by standard level and vehicle class. As before, we made use of data measured on the FTP cycle in the course of the In-use Verification Program (IUVP).

2. *Develop phase-in assumptions* for MY 2017 – 2031, 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 relative to those for cars (LDV) in MY2000, which represent Tier-1 LDV.

4. *Estimate Emissions by Operating Mode*. We calculated emissions by operating mode in each model year by multiplying the MY2000 emission rates by the weighted ratio for each model year.

5. *Apply Deterioration* to estimate emissions for three additional age Groups (4-5, 6-7 and 8-9). for Tier 3 vehicles, we modified deterioration to represent an extended useful life of 150,000 miles, as opposed to the 120,000 mile duration assumed for NLEV and Tier 2 vehicles. We therefore apply ln-linear deterioration to the rates developed in steps 1-4. For the remaining three age groups, emissions are assumed to stabilize as previously described in Section 3.2.2.3 (page 51).

6. Estimate non-I/M reference rates. The rates in steps 1-5 represent I/M references. Corresponding non-I/M references are calculated by applying the ratios applied to the pre-Tier 3 rates.

We followed steps 1-6, with specific modifications to represent Tier 3 rates. In step 1, we developed estimates of FTP results under Tier 3, including composite results, "cold-start" emissions" (Bag1-Bag3) and "hot-running" emissions (Bag 2 FTP). For step 2, we developed phase-in assumptions representing the introduction of Tier 3 standards. Each of these steps and modifications is described in greater detail in the sub-sections below.

3.4.1 Averaging FTP Results (Step 1)

Projecting emissions for Tier 3 vehicles is driven by the NMOG+NO_x standard, set at 30 mg/mi. However, because MOVES projects NO_x and THC emissions separately, we apportioned the aggregate standard into NMOG and NO_x components, which we will refer to as the "effective standards" for each pollutant. For purposes of apportionment, we assumed that NMOG control would pose a greater technical challenge than NO_x control. Accordingly, we assumed "effective standards" for NMOG and NO_x of 20 mg/mi and 10 mg/mi, respectively. To implement this assumption, we further assumed that for NO_x, vehicles would be effectively brought into Tier 2 Bin 2, and that for NMOG, vehicles would be brought to a level between Bin 2 and Bin-3, but closer to Bin 2.

In addition, MOVES models start and running processes separately. It is therefore necessary to translate the composite standard into start and running components. One component represents a "cold start" on the FTP cycle, represented as "Bag1 – Bag3" emissions. A second component represents "hot-running" emissions, represented by the hot-running phase of the FTP (Bag 2).

Estimated FTP emissions levels for hydrocarbons are shown in Table 3-17 for several Tier 2 Bins and for Tier 3. Values for all standards except Tier 3 are identical to those used to develop rates in the default database. The cold start and hot running values for Tier 3 are calculated as a weighted average of those for Bins 2 and 3, using Equation 3-34 with the bin weighting factors selected such that they give the required value for the Tier 3 FTP composite.

$$T3 = 0.775 \cdot B2 + 0.225 \cdot B3 \qquad \text{Equation 3-34}$$

Table 3-17 Hydrocarbons (HC): useful-life FTP standards and associated cold-start and hot-running results on the FTP cycle. Values for the FTP represent NMOG

Bin	Useful-life Standard (mg/mi)	FTP Composite[1] (mg/mi)	FTP Cold Start[1] (mg)	FTP hot Running[1] (Bag 2) (mg/mi)
8	125	41.3	591	3.56
5	90	35.5	534	2.63
4	70	24.8	383	2.28
3	55	21.5	329	1.74
2	10	5.6	87	0.42
Tier 3[2]	20	9.2	142	0.7

[1] Values represent "non-methane organic gases" (NMOG).
[2] Values for Tier 3 calculated using Equation 3-34.

Under a general assumption that CO standards are not forcing, but that CO emissions tend to track NMOG emissions, corresponding values for CO were calculated in the same manner, and are presented in Table 3-18.

Table 3-18 CO: Useful-life FTP standards and associated cold-start and hot-running results on the FTP and US06 Cycles

Bin	Useful-life Standard (mg/mi)	FTP Composite (mg/mi)	Cold Start (mg)	FTP hot Running (Bag 2) (mg/mi)
8	4,200	861	6,680	451
5	4,200	606	5,510	238
4	4,200	537	5,500	201
3	2,100	463	3,470	119
2	2,100	235	1,620	70
Tier 3[1]	2,100	286	2,040	81

[1] Values for Tier 3 calculated using Equation 3-34.

Corresponding results for NO_x are presented in Table 3-19. In contrast to HC and CO, the values for Bin 2 were adopted for Tier 3, as the FTP composite of 5.5 mg/mi suggests that Bin-2 vehicles gives a compliance margin of about 50 percent with respect to the "effective standard" of 10 mg/mi.

Table 3-19 NO_x: Useful-life FTP standards and associated cold-start and hot-running results on the FTP and US06 cycles

Bin	Useful-life Standard (mg/mi)	FTP Composite (mg/mi)	Cold Start (mg)	FTP hot Running (Bag 2) (mg/mi)
8	200	64.2	418	35.1
5	70	21.2	165	8.2
4	40	8.7	90	4.7
3	30	5.7	71	3.8
2	20	5.5	67	0.4
Tier 3	10	5.5	67	0.4

3.4.2 Develop Tier 3 Phase-In Assumptions (Step 2)

We designed phase-in assumptions so as to project compliance with the Tier 3 fleet average NMOG+NO_x requirements. The requirements are shown in Table 3-20 for cars and trucks. The phase-in begins in model year 2017 and ends in model year 2025.

Table 3-20 Target NMOG+NO_x fleet average requirements for the Federal Test Procedure

Model year	FTP Composite, NMOG+NO_x (g/mi)	
	LDV/T1	LDT2[1]
2017	0.086	0.101
2018	0.079	0.092
2019	0.072	0.083
2020	0.065	0.074
2021	0.058	0.065
2022	0.051	0.056
2023	0.044	0.047
2024	0.038	0.038
2025	0.030	0.030

[1] Throughout, these results applied to Federal truck classes LDT2, LDT3 and LDT4.

These results are also pictured in Figure 3-30. Note the sharp drop in emissions at the outset of the Tier 3 phase-in, also that the truck requirements (LDT2,3,4) are slightly higher than those for the lighter vehicles (LDV-T1). After 2017, the reduction in the fleet average is linear, and at the completion of the phase-in, the fleet averages for cars and trucks no longer differ.

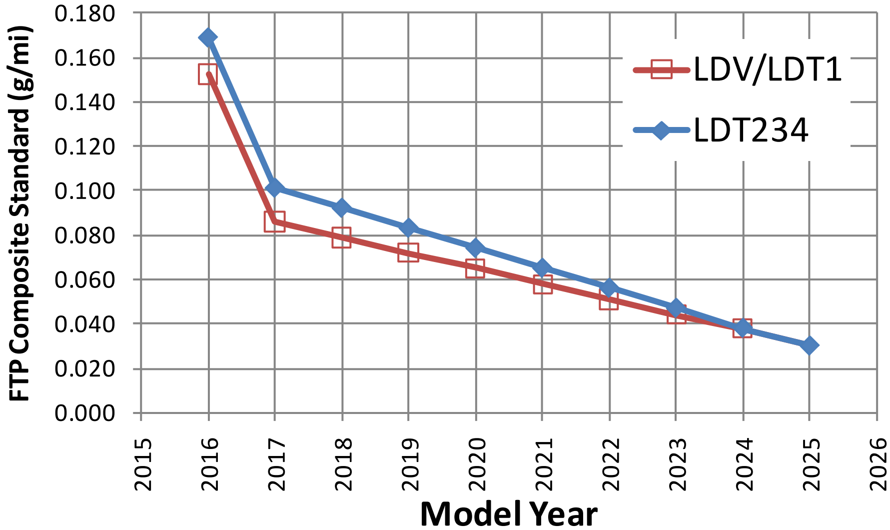


Figure 3-30 NMOG+NO_x FTP fleet average requirements during phase-in of the Tier 3 exhaust emissions standards for light-duty vehicles

In development of MOVES rates, we translated the fleet requirements so as to develop phase-in assumptions representing the introduction of Tier 3 vehicles and concurrent replacement of Tier 2 vehicles. For purposes of model input development, we project phase-ins for four categories of Federally-certified vehicles, LDV-T1, LDT2, LDT3 and LDT4.

These phase-in fractions give emission rates that reproduce the fleet requirements when FTP composites are calculated by combining start and running rates. To represent the fleet requirements, the phase-in assumptions are "linear" and "proportional."

By "linear" we mean that the fractions of Tier 2 vehicles, whether taken together, by vehicle class or by Bin, decline linearly during the Tier 3 phase-in period. We represent them this way because the fleet requirements also decline linearly.

By "proportional," we mean that during the phase-in, the various bins within a vehicle class maintain the same relative proportions as in MY 2016, at the outset of the phase-in. For example, in 2016, we assume that 89 percent and 3.5 percent of LDV-T1 vehicles are in Bins 5 and 3, respectively. This difference implies that the fleet comprises 25.43 times as many Bin-5 vehicles as Bin-3 vehicles (0.89/0.035). This ratio holds in any given model year during the phase-in. In MY 2023, the remaining fractions of Bin 5 and Bin 3 are 10.18 percent and 0.40 percent, which give the same ratio as in MY 2016.

The same proportional approach was applied to LDT2, LDT3 and LDT4. Phase-in assumptions, expressed as the relative composition of Bins within each vehicle class, are presented in Figure 3-31 through Figure 3-34.

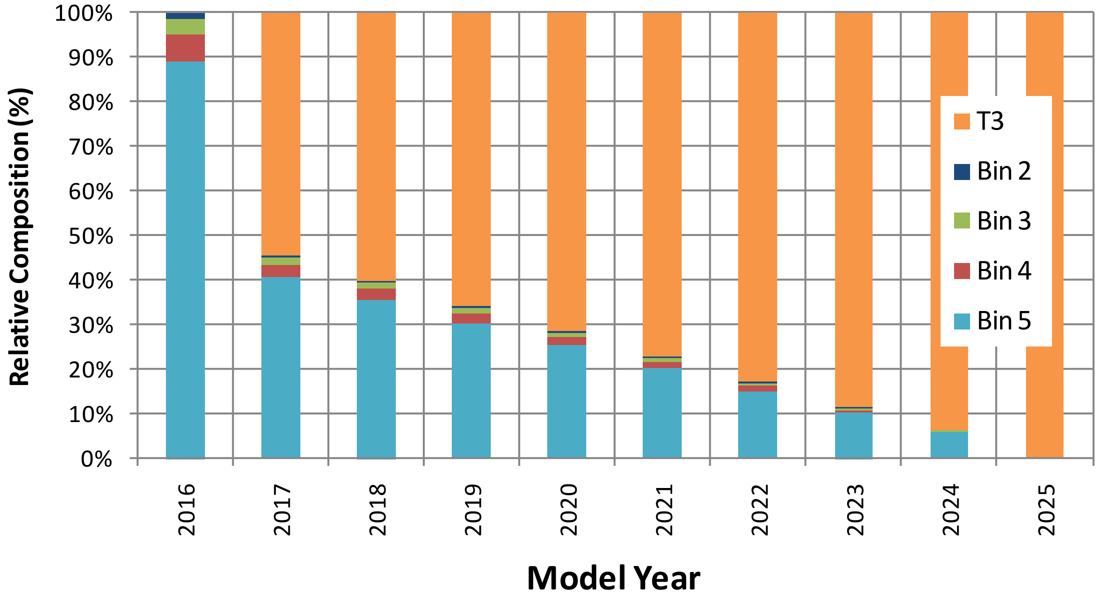


Figure 3-31 Phase-in assumptions, by standard and bin, for LDV-T1 vehicles

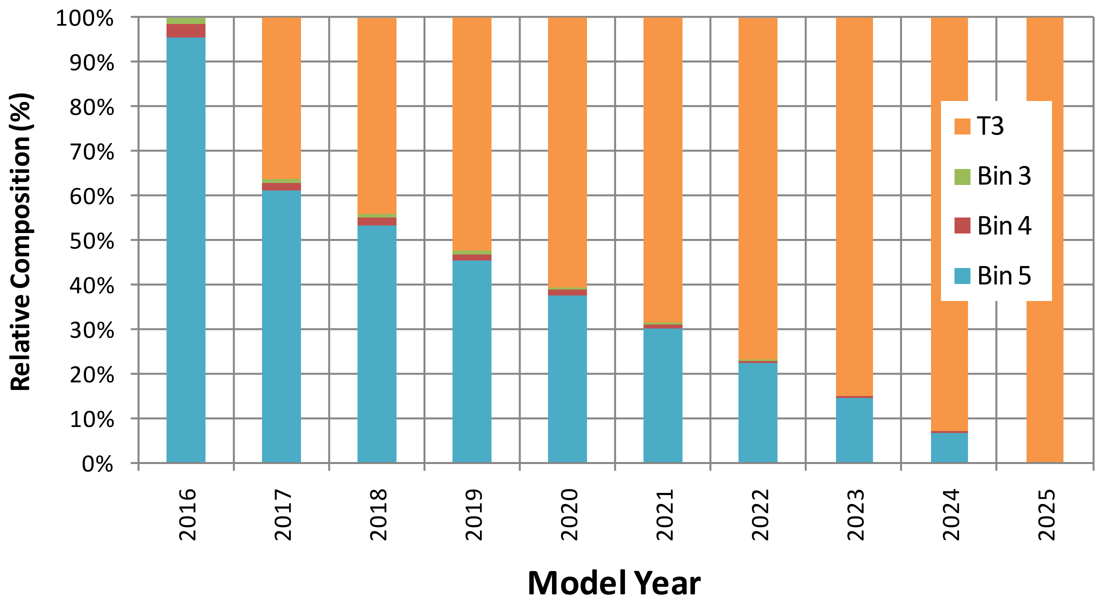


Figure 3-32 Phase-in assumptions, by standard and bin, for LDT2 vehicles

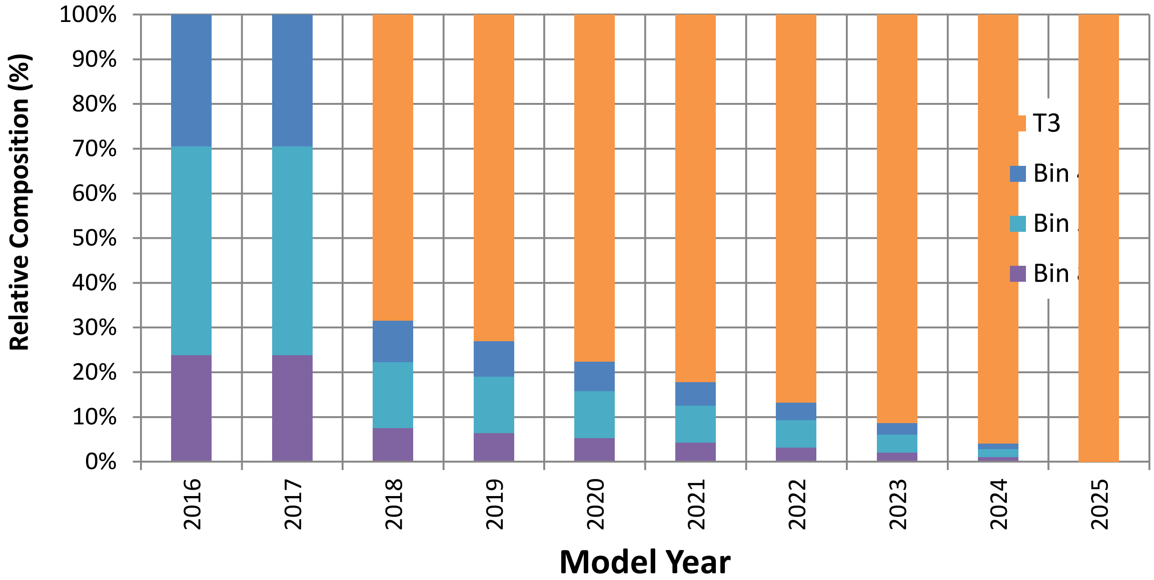


Figure 3-33 Phase-in assumptions, by standard and bin, for LDT3 vehicles

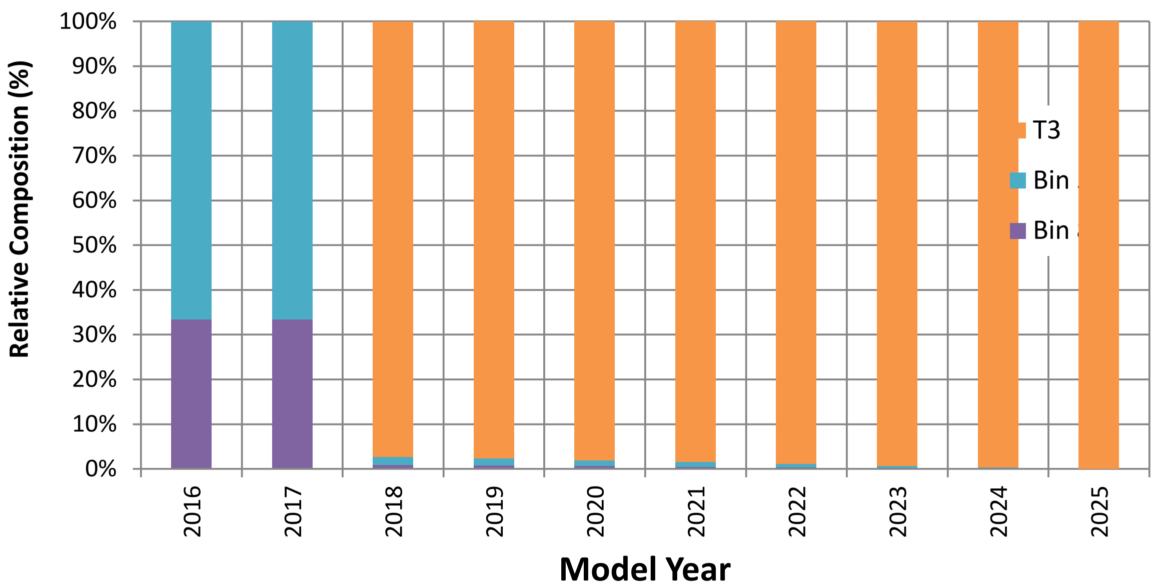


Figure 3-34 Phase-in assumptions, by standard and bin, for LDT4 vehicles

3.4.3 Merge Cycle Results and Phase-In Assumptions (Step 3)

The goal of this step is to calculate weighted averages of the FTP (cold-start and hot-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 weight the four truck classes together using a set of fractions also derived from the weighted sales estimates. See Figure 3-21 (page 68).

Figure 3-35 shows an example of the phase-in calculation for NO_x from cars between model years 2016 and 2025. The figure shows cold-start and hot-running FTP values for Tier-1, Tier 2 and Tier 3 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 3-21 shows weighted average values for model-years 2016-2025 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 3-36 to Figure 3-38 below.

Standard		Cold Start (mg)	Hot Running (mg/mi)	Phase-In by Model Year 2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Tier 1	Tier 1	888.00	127.00	0	0	0	0	0	0	0	0	0	0
Tier 2	Bin 8	417.87	35.07	0	0	0	0	0	0	0	0	0	0
	Bin 5	165.42	8.21	0.890	0.407	0.356	0.305	0.254	0.204	0.153	0.102	0.058	0
	Bin 4	89.72	4.69	0.060	0.027	0.024	0.021	0.017	0.014	0.010	0.007	0.004	0
	Bin 3	70.89	3.78	0.010	0.016	0.014	0.012	0.010	0.008	0.006	0.004	0.002	0
	Bin 2	67.18	0.38	0.015	0.007	0.006	0.005	0.004	0.003	0.003	0.002	0.001	0
Tier 3	Tier 3	67.18	0.38	0.000	0.543	0.600	0.657	0.714	0.771	0.829	0.886	0.935	1.000
			Cold Start (mg)	154.32	107.85	102.76	97.69	92.60	87.52	82.43	77.35	72.99	67.18
			Hot Running (mg/mi)	7.64	3.74	3.32	2.90	2.48	2.06	1.64	1.22	0.86	0.38
			RATIO to Tier 1	***0.0601***	***0.0295***	***0.0262***	***0.0228***	***0.0195***	***0.0162***	***0.0129***	***0.00961***	***0.00677***	***0.00299***

Figure 3-35 Example of phase-in calculation, for NO_x from LDV-T1, for MY 2016-2025

Table 3-21 Weighted average FTP values projected for trucks and cars for MY 2017-2025

regClass	MY	CO			THC			NO_x		
		Composite (mg/mi)	Start (mg)	Running (mg/mi)	Composite (mg/mi)	Start (mg)	Running (mg/mi)	Composite (mg/mi)	Start (mg)	Running (mg/mi)
Ref.[1]	2000	1,620	11,400	805	126	1,530	57.1	209	888	127
Trucks	2017	541	4,749	213	28.3	462	3.82	19.6	154	8.24
	2018	434	3,625	155	20.7	341	2.76	13.1	114	4.45
	2019	412	3,395	144	19.0	314	2.54	12.0	108	3.86
	2020	391	3,164	134	17.3	287	2.32	10.9	101	3.27
	2021	369	2,934	123	15.7	260	2.10	9.82	93.9	2.68
	2022	348	2,704	112	14.0	233	1.88	8.72	87.0	2.09
	2023	327	2,474	101	12.3	206	1.66	7.62	80.2	1.50
	2024	305	2,246	91	10.7	179	1.45	6.53	73.4	0.91
	2025	286	2,037	81	9.2	154	1.25	5.54	67.2	0.38
Cars	2017	426	3,566	149	20.5	339	2.70	12.0	108	3.74
	2018	408	3,375	140	19.1	316	2.52	11.2	103	3.32
	2019	391	3,184	132	17.7	293	2.34	10.4	97.7	2.90
	2020	373	2,993	123	16.3	270	2.16	9.60	92.6	5.48
	2021	356	2,802	115	14.8	247	1.97	8.77	87.5	2.06
	2022	338	2,610	106	13.4	224	1.79	7.96	82.4	1.64
	2023	321	2,419	98	12.0	201	1.61	7.16	77.4	1.22
	2024	306	2,255	91	10.8	181	1.46	6.46	73.0	0.86
	2025	286	2,037	81	9.2	154	1.25	5.54	67.2	0.38

[1] The reference level represents Tier-1 LDV-T1.

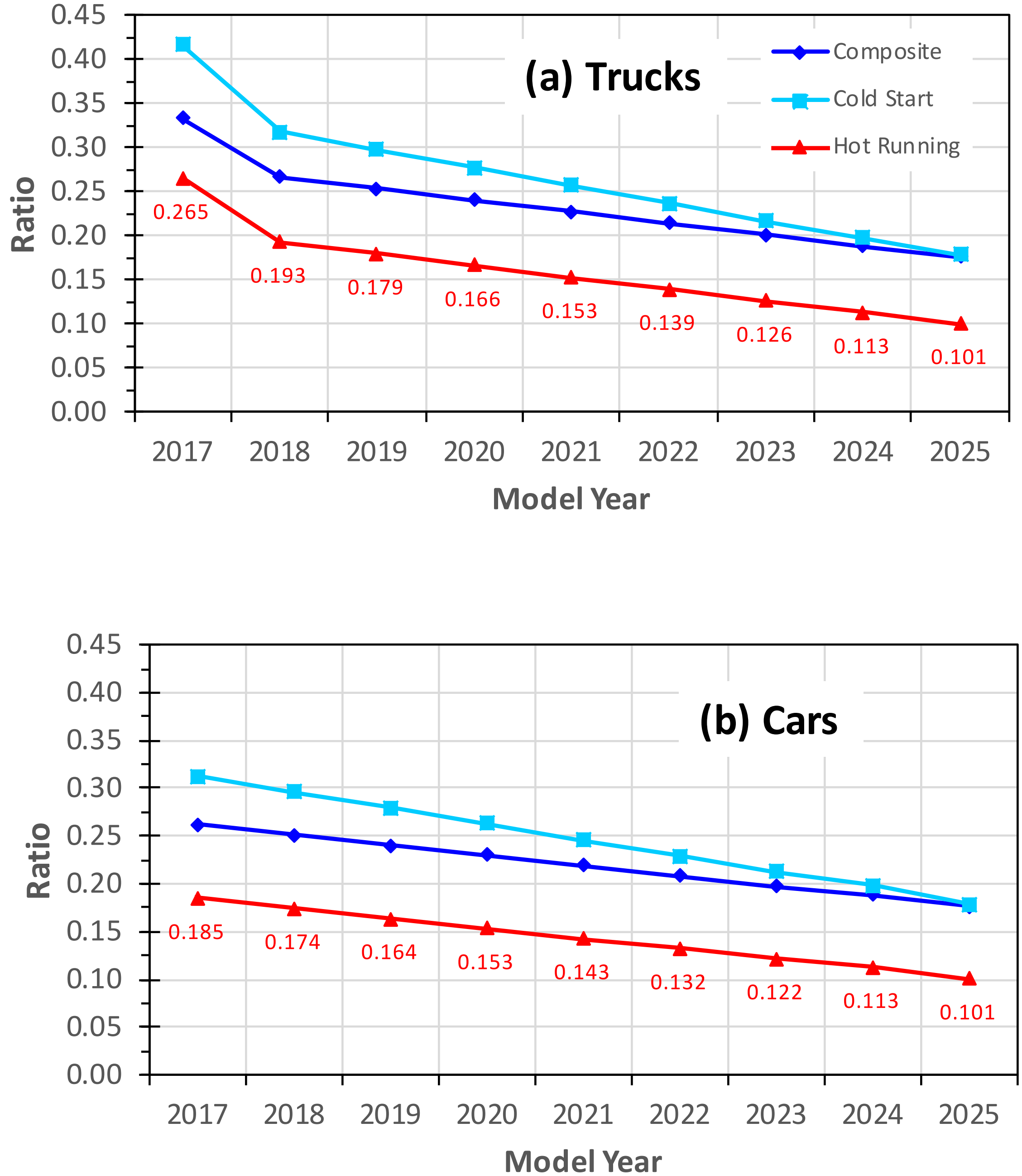


Figure 3-36 Weighted ratios for composite, start and running CO emissions, for (a) trucks and (b) cars

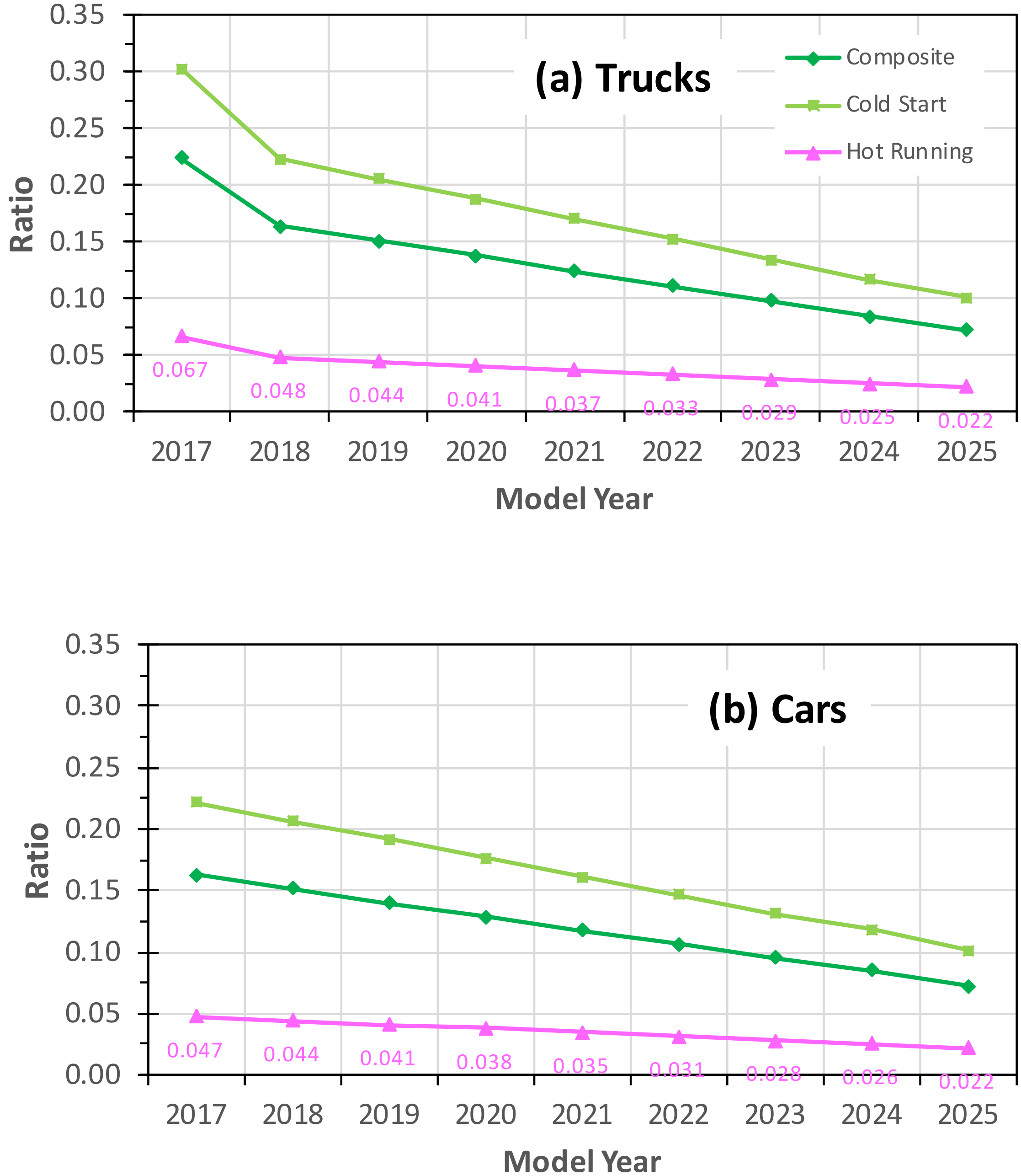


Figure 3-37 Weighted ratios for composite, start and running THC emissions, for (a) trucks and (b) cars

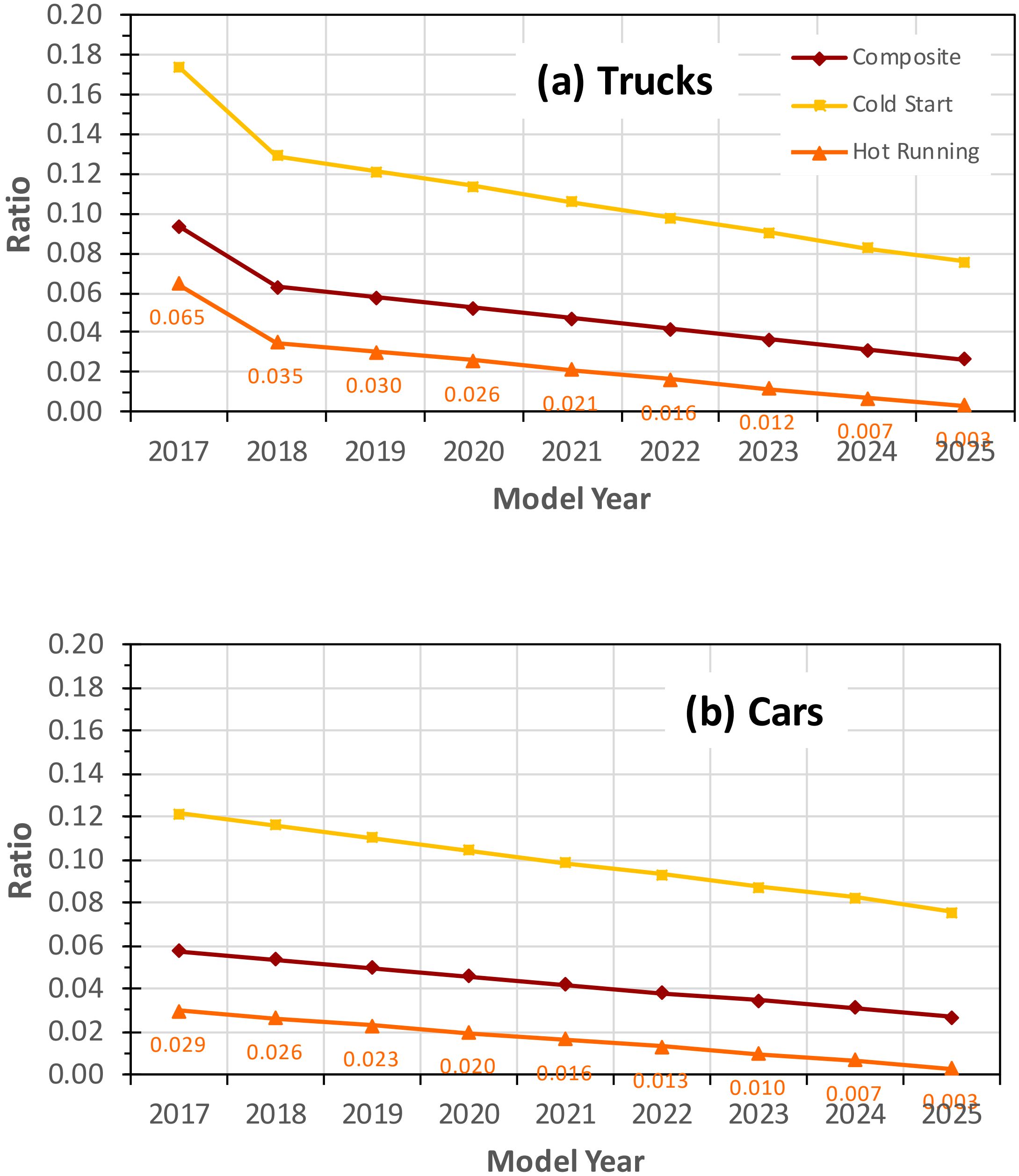


Figure 3-38 Weighted ratios for composite, start and running NO_x emissions, for (a) trucks and (b) cars

3.4.4 Estimating Emissions by Operating Mode (Step 4)

To project modal emissions for Tier 2 and Tier 3 vehicles, the approach was to multiply the emission rates for MY 2000, representing Tier 1, by a specific ratio for each model year from 2016 to 2025, to represent emissions for that model year. For all operating modes, we applied the ratios shown in the three figures immediately above.

Figure 3-39 and Figure 3-40 show application of the ratios for cars in model years 2000, 2005, 2010, 2017, and 2025, representing Tier 1 standards, partially phased-in Tier 2 standards, fully phased-in Tier 2 standards, an interim year during the Tier 3 phase-in, and the fully phased-in Tier 3 standards, respectively. Rates for all five model years are calculated with respect to rates for cars in model-year 2000 (using reduction ratios described above, applied to selected operating modes for running operation. 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 in the lower power modes. In addition, the logarithmic plots include the level for MY2000, which represents Tier-1 standards. Thus, these plots display the degree of running-emissions reduction between Tier1 and Tier 2 (MY2000: MY2010), and between Tier 2 and Tier 3 (MY2010: MY2025), across the full range of vehicle-specific power. Note that for simplicity, these figures represent rates for operating modes 21-30, covering a wide range of power for vehicles operating at speeds between 25 and 50 mph.

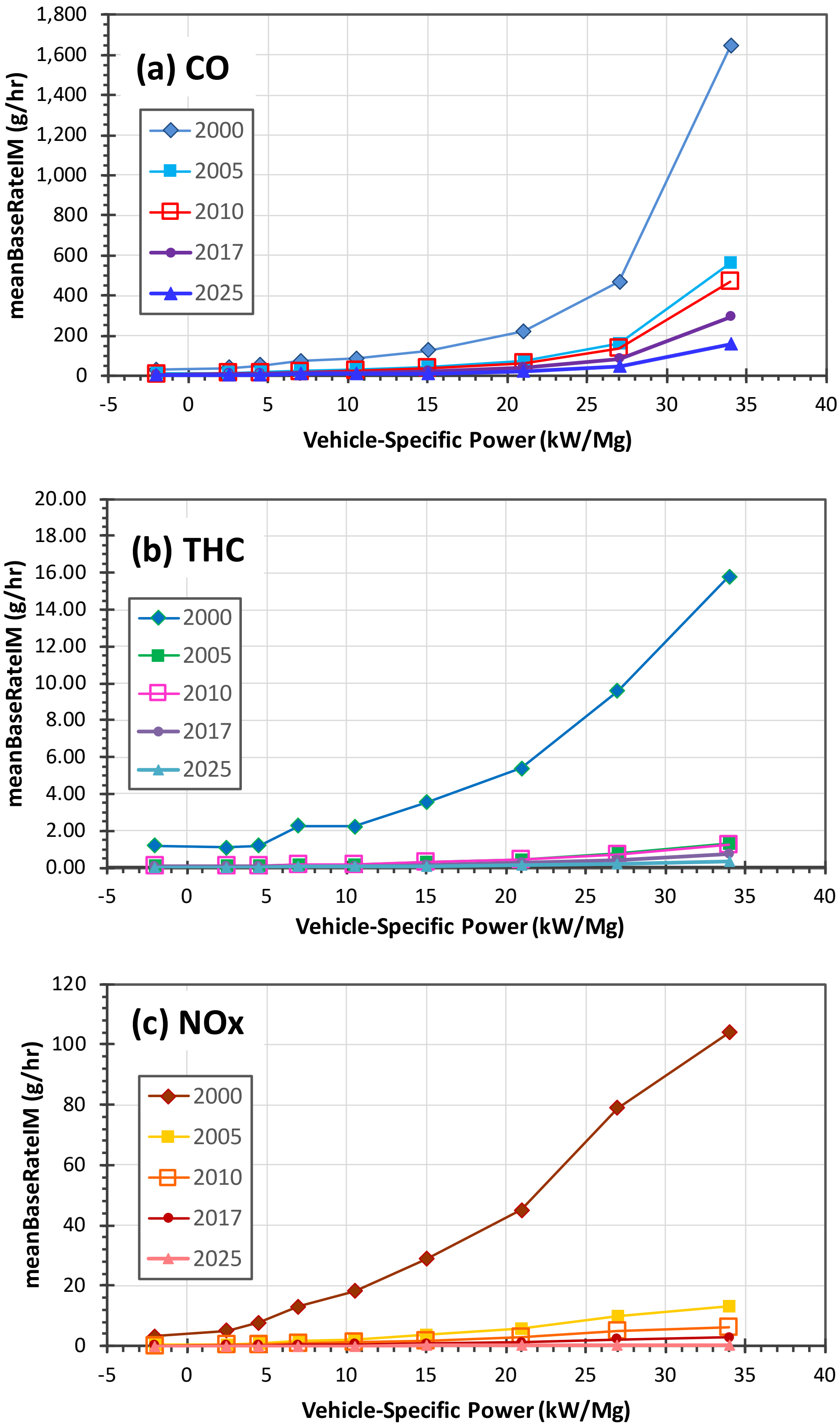


Figure 3-39 Projected emission rates for cars in operating modes 21-30, vs. VSP, in ageGroup 0-3 years, for five model years, for (a) CO, (b) THC and (c) NO_x (LINEAR SCALE)

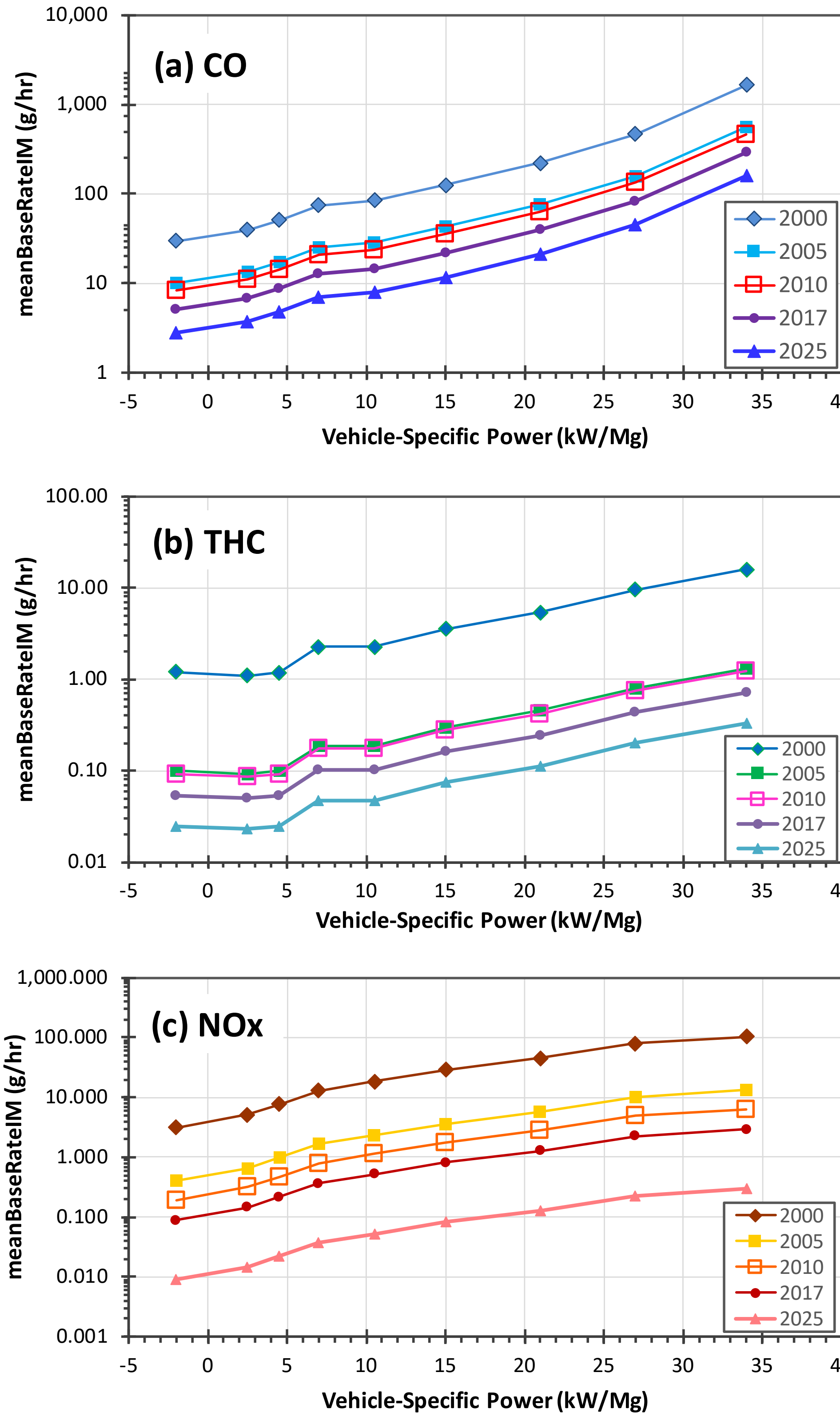


Figure 3-40 Projected emission rates for cars in operating modes 21-30, vs. VSP, in ageGroup 0-3 years, for five model years, for (a) CO, (b) THC and (c) NO_x (LOGARITHMIC SCALE)

3.4.5 Apply Deterioration (Step 5)

Based on review and analysis of data from the Phoenix Inspection-and-Maintenance Program, 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 their respective logarithmic means 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 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.

3.4.5.1 Recalculate the Logarithmic Mean

Starting with the values of the arithmetic mean (x_a) calculated as described in step 4 above, we calculate a logarithmic mean (x_l), as previously shown in Equation 3-28 (page 40).

3.4.5.2 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), using Equation 3-29 (page 40).

The values of the logarithmic slope are adapted from values developed for the 1996-98 model – year group. The values applied to Tier 2 and Tier 3 vehicles are shown in Table 3-22. The reduced slopes for Tier 3 were calculated by reducing the Tier 2 values by 27 percent for THC and CO and by 14 percent for NO_x. These values were estimated empirically so as to implement the assumption of reduced deterioration for the extended useful life. 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.

Table 3-22 Values of the logarithmic deterioration slope applied to running-exhaust emission rates for MY following 2000.

Pollutant	Logarithmic Slope (m_l)	
	Tier 2	***Tier 3***
CO	0.13	0.0949
THC	0.09	0.0657
NO_x	0.15	0.129

3.4.5.3 Apply the Reverse Transformation

After the previous step, the values of $x_{l,\text{age}}$ were reverse-transformed, as shown in Equation 3-28 (page 40).

3.4.6 Estimate Non-I/M References (Step 6)

Completion of the preceding steps provided a set of rates representing I/M reference rates for MY 2016-2025. As a final step, we estimated non-I/M reference rates by applying the same ratios applied to the I/M references for default rates (Section 3.5, page 95).

3.4.7 Start Emissions

The values for "FTP Cold-start" shown in Table 3-16 (page 70) and Table 3-21 (page 87) were used to represent cold-start emissions (opModeID=108). Rates for "warm" or "hot" starts following a range of soak periods were estimated as for the default rates (see Section 3.9.2, page 170). Deterioration was applied to start emissions, relative to that for running emissions, also as described (see below in Section 3.9.3.3, page 198).

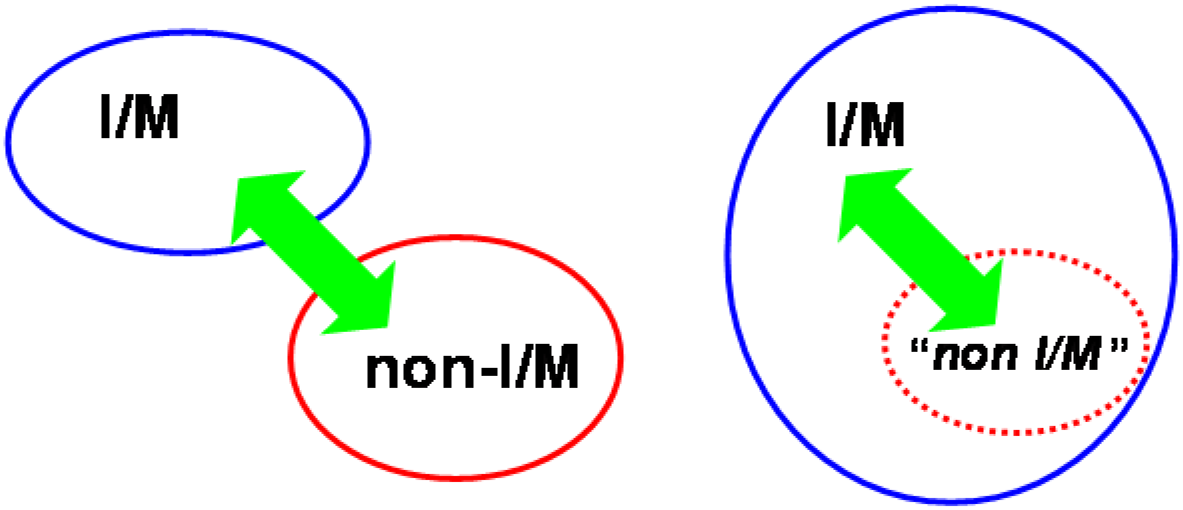
3.5 Estimating Rates for Non-I/M Areas

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 MOVES, 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.

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, as shown in Figure 3-41(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, as shown in Figure 3-42(b).



(a) Comparison between a program Area and a non-program area

(b) Comparison within a program Area

Figure 3-41 General approaches to estimating differences attributable to I/M programs: (a) comparison of subsets of vehicles between two geographic areas, 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 and entering that program. Characteristics of the Phoenix program during 1995-2005 are listed below.

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

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 3-23.

Table 3-23 Criteria used to identify vehicles migrating into the Phoenix program

logic	Criterion
	The vehicle comes 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 the 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.[36]

Figure 3-42 shows the distribution of incoming non-I/M vehicles by Census Region. Most vehicles migrating to Phoenix came from the Midwest (47 percent), followed by the South (32 percent), the West (20 percent) and the Northeast (1 percent). The low incidence from the NE may be attributable to the large number of I/M programs in that region.

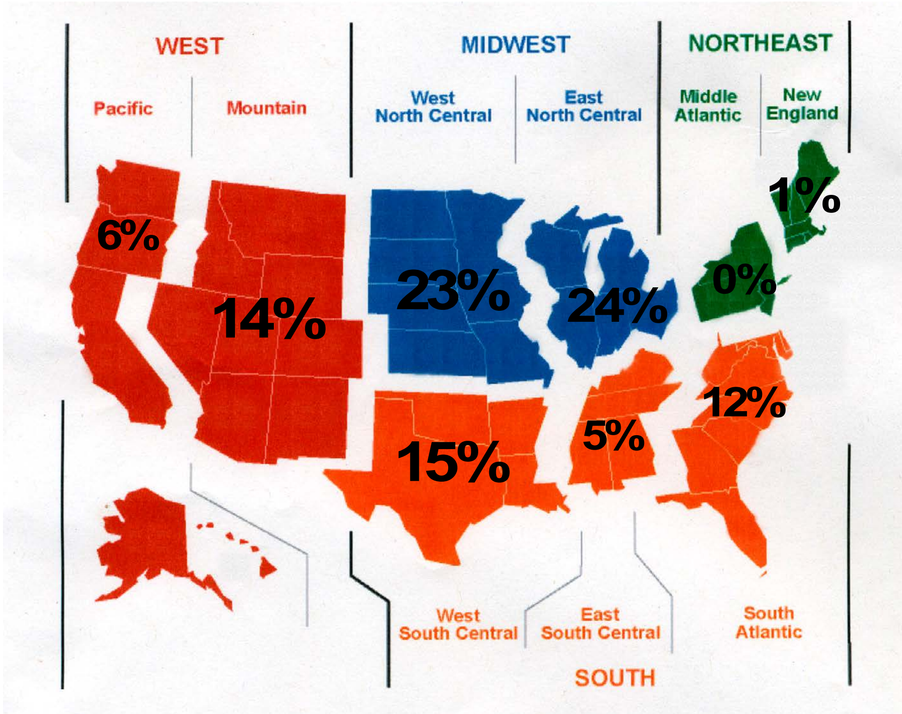


Figure 3-42 Geographic distribution of non-I/M vehicles migrating into the Phoenix I/M area, 1995-2005

To assess the emissions 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 3-35. 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.

$$\text{Ratio} = \frac{\overline{E}_{\text{non-I/M}}}{\overline{E}_{\text{I/M}}}$$ **Equation 3-35**

For purposes of verification, we compared our results to previous work. An initial and obvious comparison was to previous work by Thomas Wenzel based on an out-of-state fleet migrating into Phoenix that provided a model for our own analysis.[37] 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 3-35.

Another valuable source for comparison was remote-sensing data collected in the course of the Continuous Atlanta Fleet Evaluation (CAFE) Program.[38,39] Unlike our own analysis, this program involves a comparison between two geographic areas. The "I/M area" is the thirteencounty Atlanta area, represented by measurements for approximately 129,000 vehicles. The other area is the twelve-county “non-I/M area,” surrounding Atlanta, represented by measurements for approximately 28,000 vehicles. Both areas had 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 remote-sensing 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 3-43. 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 THC and NO_x, 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 THC, but not for NO_x. 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 in addition, the second reason is that the ratios themselves increase with age (**Figure 3-43**). And, because these ratios are applied to calculate non-I/M rates for all model year groups in MOVES, a third implication is the absolute differences would be smaller for successive model-year groups as tailpipe emissions decline with more stringent standards.

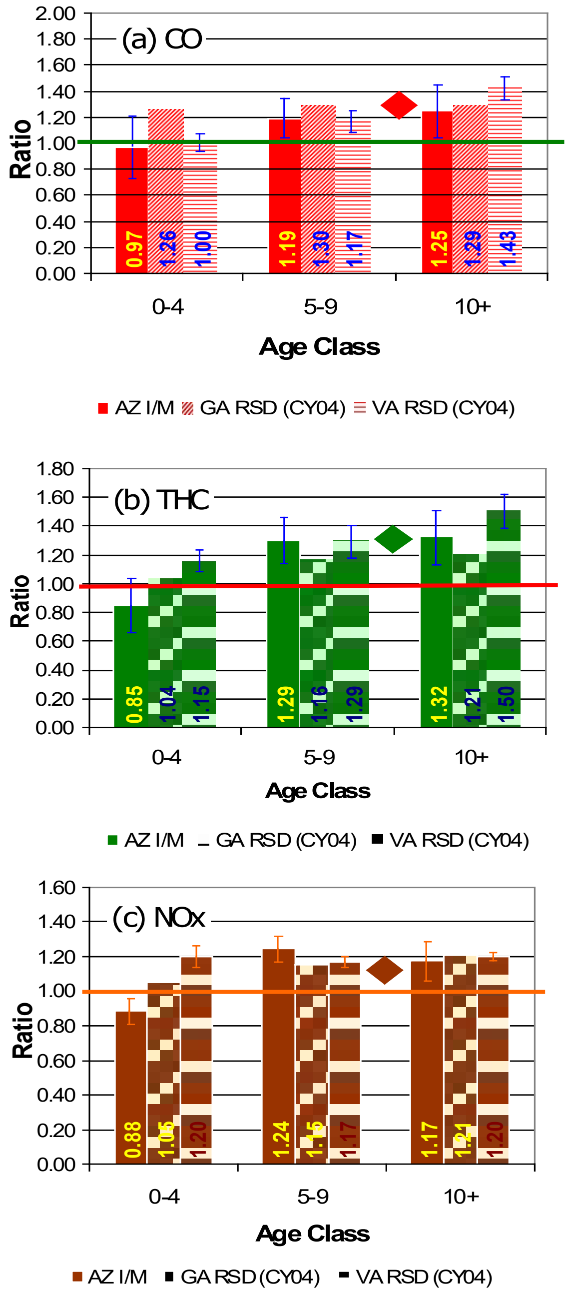


Figure 3-43 Non-I/M: I/M ratios for CO, THC and NO_x for the Phoenix area (this analysis) compared to remote-sensing results for Atlanta and N. Virginia, and previous work in Phoenix (diamonds)

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 3-44. 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.

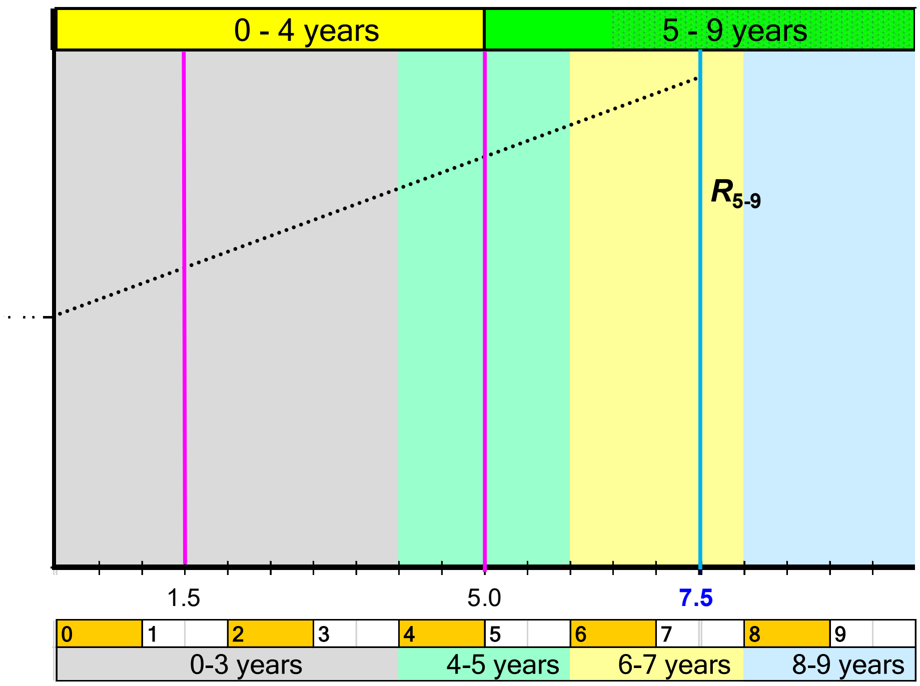


Figure 3-44 Imputation of non-I/M ratios for the 0-3 and 4-5 year MOVES ageGroups by linear interpolation from the midpoint of the 5-9 year analysis age group

Figure 3-45 shows final values of the non-I/M ratios for CO, THC and NO_x, with error-bars representing 95 percent confidence intervals. The values for each pollutant start at 5.0 percent and increase with age, stabilizing at maximum values at 6 years (for NO_x) and 10 years (for THC and CO).

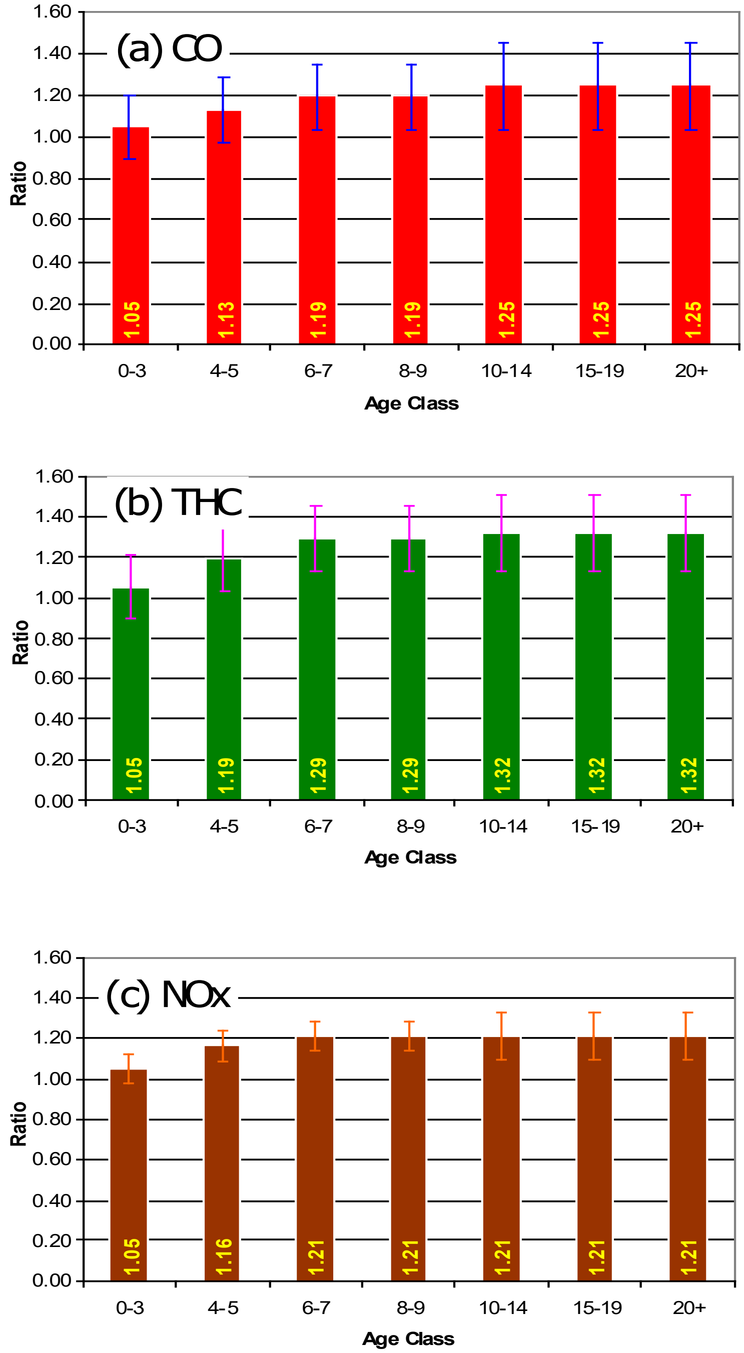


Figure 3-45 Final non-I/M ratios for all model years for CO, THC and NO_x, by MOVES ageGroups, with 95 percent confidence intervals

The ratios shown in **Figure 3-45** are applied to the I/M reference rates to derive non-I/M reference rates.

$$E_{h,\text{non-I/M}} = \text{Ratio} * E_{h,\text{I/M}}$$ **Equation 3-36**

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 $E_{h\text{I/M}}$.

$$s^2_{E_{h,\text{non-I/M}}} = \left(\frac{\partial E_{h,\text{non-I/M}}}{\partial R}\right)^2 s_R^2 + \left(\frac{\partial E_{h,\text{non-I/M}}}{\partial E_{h,\text{I/M}}}\right)^2 s^2_{E_{h,\text{I/M}}}$$
$$s^2_{E_{h,\text{non-I/M}}} = E^2_{h,\text{I/M}} s_R^2 + R^2 s^2_{E_{h,\text{I/M}}}$$ **Equation 3-37**

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.

3.6 MOVES3 Running Exhaust Emission Rates (THC and NO_x for MY 1990 and later)

For MOVES3, light-duty THC and NO_x emission rates for MY 1990-and-later were updated by applying adjustments to the rates used in MOVES2014.[40] We developed and applied two sets of adjustments for these model years. The first is a set of adjustments that we applied to rates in the first ageGroup, 0-3 years. For convenience, we will refer to the rates in the 0-3 year ageGroup as "young vehicles," and the adjustments applied to them as "young-vehicle" adjustments. The second set was applied to adjusted rates for young vehicles to project modified deterioration assumptions for the remaining six ageGroups. Thus, the second set of adjustments will be referred to as "deterioration adjustments."

We chose to modify the existing rates by adjustment so that the update could be completed in time for release with MOVES3. The key motivators for this update was to reevaluate and modify the deterioration assumptions in the MOVES2014 rates, which are very aggressive in some cases.

However, at the time this update was initiated, the relevant datasets were not ready for use in directly developing modal rates, i.e., the supporting analyses to evaluate time series alignment, calculate vehicle-specific power and assign operating modes had not been completed.

Nonetheless, it was possible to analyze deterioration in these datasets on a non-modal basis, and using the results, to propose modifications to the existing rates. These analyses and their application are described in Section 3.6 for THC and NO_x, and in Section 3.7 for CO.

3.6.1 Data Source

While the MOVES2014b rates for MY 1990-and-later were based on the same data and analysis described above for the 1989-and-earlier model years, the MOVES3 updates for MY 1990-and-later are based primarily on the Evaluation Sample for the Denver Metropolitan I/M program.

This source is recent, having been collected during the past decade, and includes a large body of data directly measured on vehicles certified to Tier-2 standards. In addition, the Denver program remains one of the very few programs that performs transient tailpipe testing and that has compiled a random evaluation sample over a period long enough to enable a deterioration analysis. During the past decade, most programs have transitioned to use of scans of the onboard diagnostic system (OBD) as the basis for I/M tests. For example, the program in Chicago, which was considered for MOVES2010, discontinued tailpipe testing by 2010.

As the name implies, "evaluation samples" are collected to provide a basis for evaluation of a program's effectiveness. They involve the collection of vehicle samples at random, to ensure representativeness, and the application of "full duration" tests with replication, to ensure that results represent "hot running," or "fully conditioned" operation.

In addition, full-duration tests, in which the test cycle is run to completion (e.g., 240 sec on the IM240 cycle) are needed to avoid the bias inherent in program test data in which the duration of the test is proportional to vehicles' emissions levels. Such "fast-pass" or "fast-fail" bias is a major obstacle to the use of program data, and precluded the use of data from the St. Louis program in MOVES2010 (see 3.2.1, page 23).

The data from the Denver evaluation sample used in the MOVES3 update was collected between CY 2008 and 2017. The vehicle sample includes model years ranging from the early nineties through 2010. The sample incorporates vehicle emission standards from Tier 1, National LEV, and Tier 2, as well as their California counterparts LEV-I and LEV-II. In the evaluation sample, vehicles selected at random receive two additional full-duration transient tests on the IM240 cycle, in addition to their official test. For purposes of analysis, we used only the second replicate, to ensure that the data represented fully conditioned vehicles.

3.6.2 Vehicle classes

We analyzed emissions results for three classes of vehicles, which include passenger cars and two classes of trucks, distinguished on the basis of gross-vehicle weight. These vehicle classes are defined in Table 3-24.

Table 3-24 Definitions for Vehicle Classes in the Denver Evaluation Sample

Category	Vehicle Class	Description	GVWR (lb)	No. Tests
Cars	LDV	Light-Duty Vehicles		55,506
Trucks	LLDT	Light Light-Duty Trucks	0 < GVW <= 6,000	43,901
Trucks	HLDT	Heavy Light-Duty Trucks	6,000 < GVW <= 8,500	17,184
Total				116,591

The table shows totals numbers of vehicles in each class, for the subsets of data used for analysis, spanning model years 1990-2010. These totals include hot-conditioned "second replicates" only, following some exclusions for purposes of quality assurance. The total samples are largest for cars, followed by the trucks, with HLDT having the smallest sample, roughly one third of the total for cars.

The model-year by age distributions of the vehicle samples for each of these classes are shown in Table 3-25 to Table 3-27 below. For each model year, the sample spans an age trend of nine years. Note that the sampling effort is uneven throughout, but is highest for model years 2004 and later, during calendar years 2012-2016.

Table 3-25 Sample of Passenger Cars (LDV) in the Denver Evaluation Sample

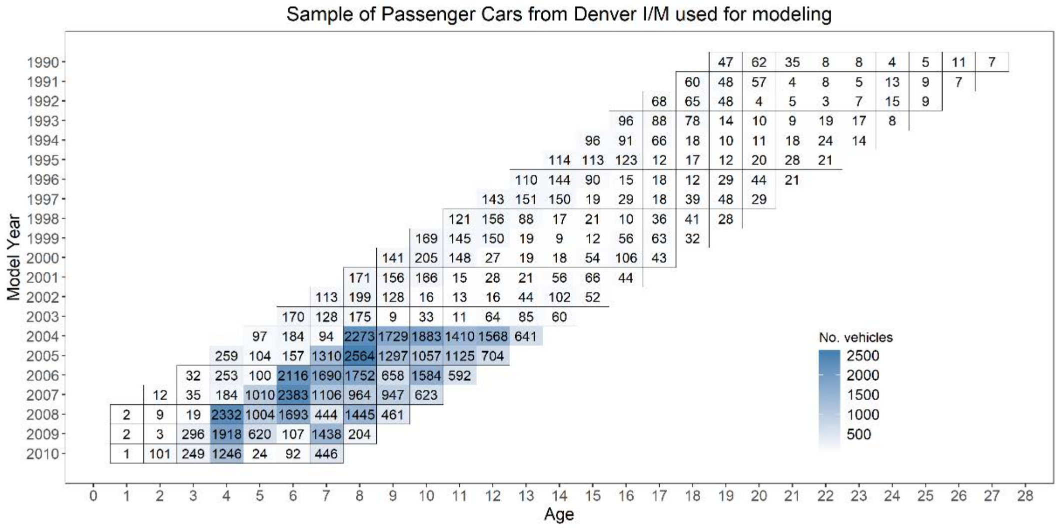


Table 3-26 Sample of Light Light-Duty Trucks in the Denver Evaluation Sample

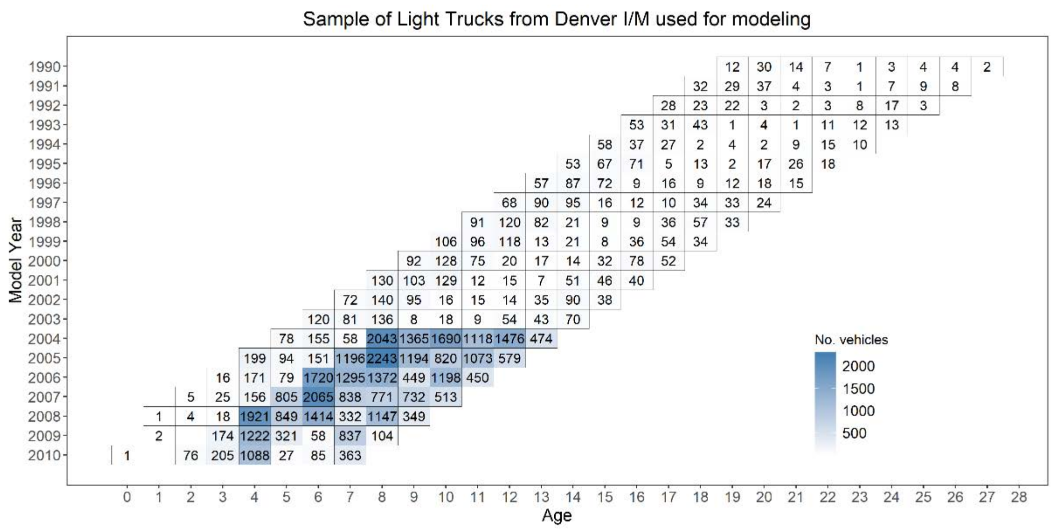
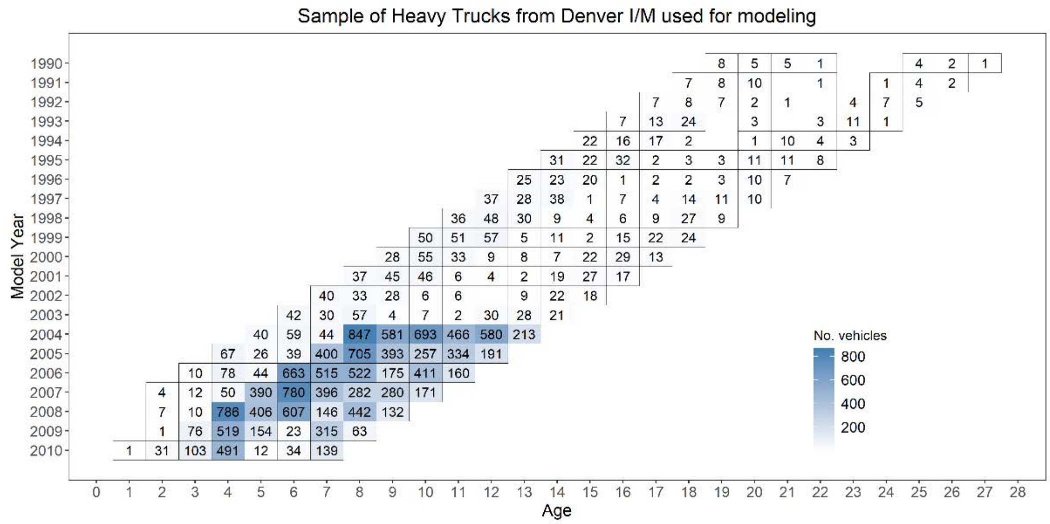


Table 3-27 Sample of Heavy Light-Duty Trucks in the Denver Evaluation Sample



3.6.2.1 Clean Screen

In the Denver metropolitan area, a 'clean-screen' program is used to reduce the testing burden in the inspection stations. This goal is achieved by performing remote sensing throughout the area on an ongoing basis. Vehicles identified as "clean" are eligible to forgo the emissions inspection at their next scheduled registration. Thus, the net effect of "clean-screen" should be to bias the mean emissions levels for the measured fleet somewhat high, as "clean" vehicles are preferentially screened out of the fleet reporting to the centers for regularly scheduled biennial inspections.

We accounted for "clean-screen" by treating it as a secondary *de facto* sampling process, in which the selection would be proportional to vehicles' emissions levels as measured by remote sensing.

We estimated counts of vehicles eligible for clean screen that show up for testing. There are two classes of such eligible vehicles. The first class includes vehicles in the evaluation sample identified as "clean-screen" eligible but whose owners are intentionally not notified. This "hold-back" sub-sample is intended to allow estimation of the emissions levels of eligible vehicles. The second class includes eligible vehicles whose owners were notified that they need not report for emissions inspections but who nonetheless reported to lanes and received inspections, i.e., "came in anyway."

Within the evaluation sample, the fractions of eligible vehicles in a given model year that receive emissions tests, out of the total of clean-screen eligible vehicles, is given by Equation 3-38,

$$f = \frac{n_H + n_C}{n_H + n_C + n_P} \qquad \text{Equation 3-38}$$

where:

n_H = eligible vehicles retained for program evaluation, i.e., "holdback" vehicles,

n_C = eligible vehicles that received tests, i.e., "came in anyway,"

n_P = eligible vehicles exempted from testing, i.e., "clean-screen participants."

After calculating the fractions of clean-screen eligible vehicles undergoing tests, clean-screen weights (w_C) are calculated as their reciprocals, as shown in Equation 3-39:

$$w_C = \frac{1}{f} \qquad \text{Equation 3-39}$$

These calculations were performed on the basis of model year, as shown in Table 3-28. This reciprocal sample-weighting approach can be seen as an analog to non-response weighting in analysis of a sample survey. The weights represent the numbers of eligible vehicles represented by each eligible vehicle that underwent emissions measurements. For example, for model years since 2004, each measured eligible vehicle, in group $n_H + n_C$, represents approximately five eligible vehicles that were exempted from the emissions inspection and were thus not measured. All other vehicles in the evaluation sample not designated as clean-screen eligible were assigned weights of 1.0, i.e., they represent "only themselves."

Table 3-28 Clean-Screen fractions and weights constructed for use with the Denver Evaluation Sample

Model Year	Clean-screen Fraction (f)	Clean-screen Weight (w_C)
1990	0.182	5.49
1991	1.000	1.00
1992	0.167	5.99
1993	0.206	4.85
1994	0.023	43.5
1995	0.222	4.50
1996	0.108	9.26
1997	0.120	8.33
1998	0.112	8.93
1999	0.099	10.10
2000	0.113	8.85
2001	0.099	10.10
2002	0.095	10.53
2003	0.095	10.53
2004	0.221	4.52
2005	0.189	5.29
2006	0.200	5.00
2007	0.180	5.56
2008	0.208	4.81
2009	0.198	5.05
2010	0.197	5.08

3.6.3 Data Review

Prior to analysis, we plotted the data for each combination of pollutant and vehicle class on both linear and logarithmic scales. Review of the plots informs the process of model building and selection.

The plots show four views of the data. In subplots (a) and (b), we plot individual measurements for the entire dataset on linear and logarithmic scales, with simple linear trendlines by model year. These trend lines give a sense of central tendency, i.e., where the means are situated within the clouds of points, which are very broad.

The plots on linear scale demonstrate the strong degree of right skew within the emissions data. They also display that small fractions of extreme high-emitting vehicles report to the lanes for testing. Despite the undoubted tendency of some fraction of drivers to avoid or evade I/M testing, large numbers of vehicle owners report to the lanes with high to very high emissions. The plots also show that extremely high emissions can occur in vehicles that are quite young, certified to low standards, and ostensibly within their regulatory useful lives.

The plots on logarithmic scale are more informative for modeling purposes. They display the remarkably high degree of variability in emissions data, spanning several orders of magnitude. In addition, the trendlines show the general parallelism in trends for successive model years. Another important feature is that the trendlines give a broad indication of the shapes of long-term emissions trends, showing how emissions first increase with age and then gently decline with increasing age.

Review of these plots, supplemented by preliminary modeling of smaller subsets of model years, led to the formulation of the spline model described below.

We also average the data by model year and age (panels (c) and (d)) and present the averages. On the whole, the trends in means also reflect the broad picture in the plots of all measurements. However, the trends in individual means are erratic, due to variation in sample sizes, and treating each model-year × age combination as independent.

3.6.3.1 Oxides of Nitrogen (NO_x)

For NO_x, sets of plots for the three vehicle classes are shown in Figure 3-46 for Passenger Cars, Figure 3-47 for Light Light-Duty Trucks, and Figure 3-48 for Heavy Light-Duty trucks.

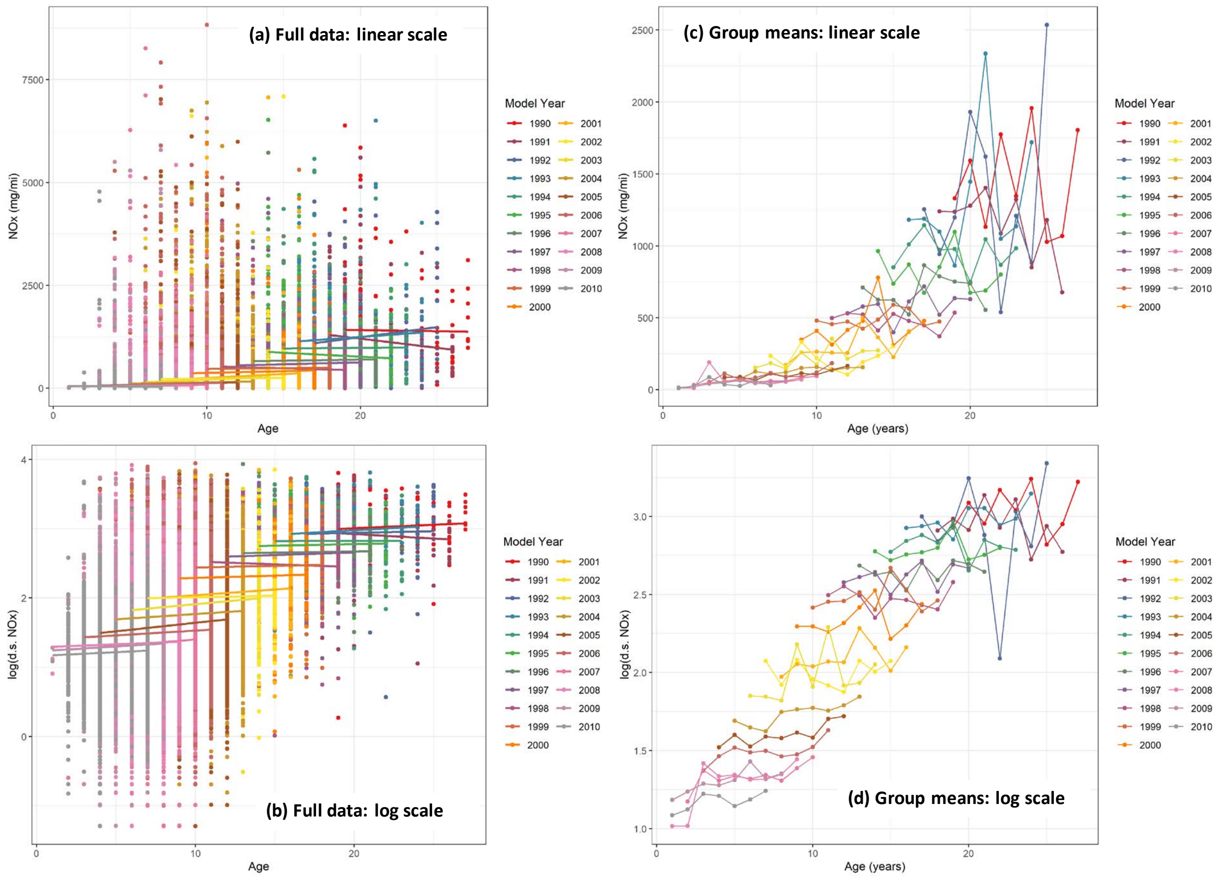


Figure 3-46 NO_x for Passenger Cars (LDV): IM240 Emissions (mg/mi) vs. age: (a) full data set, linear scale, with simple trendlines by model year; (b) full dataset, common logarithmic scale, with simple trendlines by model year; (c) means by model year and age, linear scale; (d) means by model year and age, common logarithmic scale

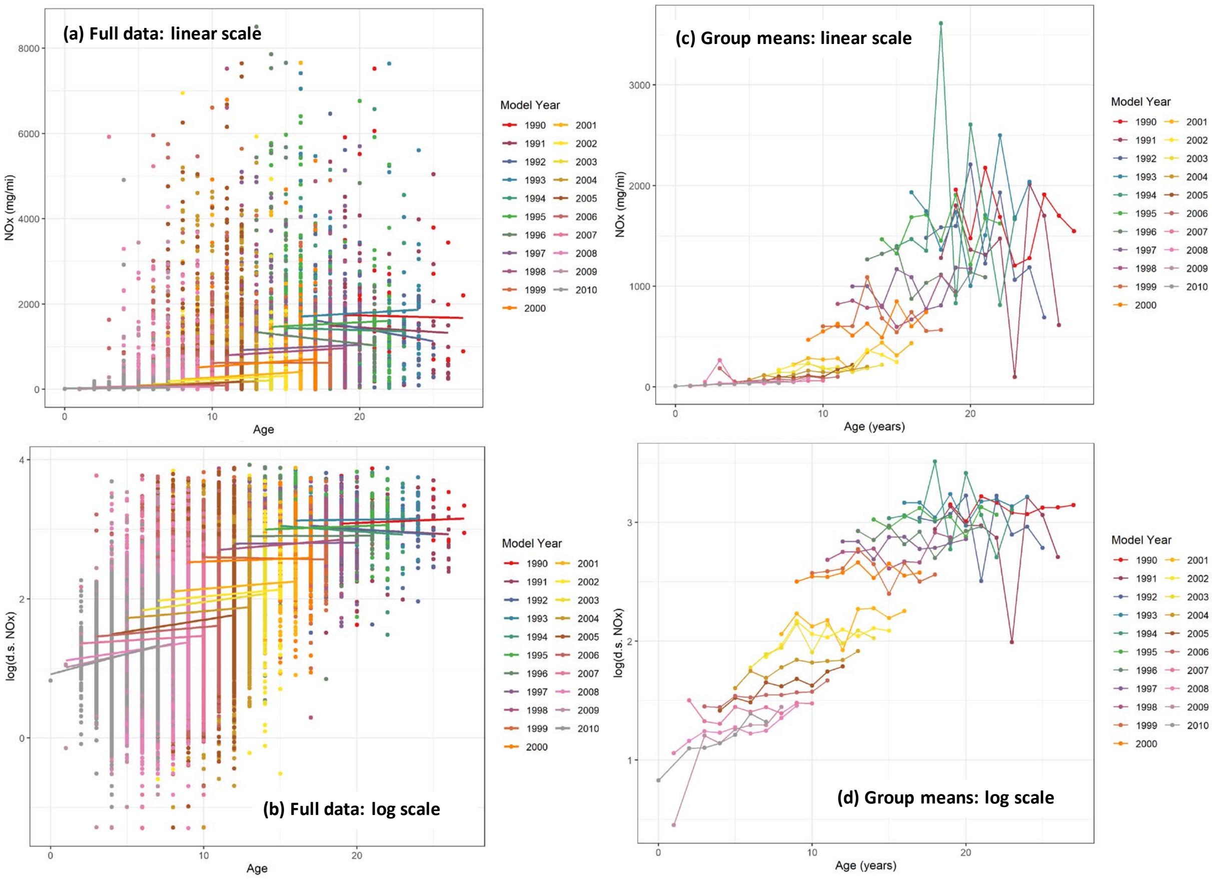


Figure 3-47 NO_x for Light Light-Duty Trucks (LLDT): IM240 Emissions (mg/mi) vs. age: (a) full data set, linear scale, with simple trendlines by model year; (b) full dataset, common logarithmic scale, with simple trendlines by model year; (c) means by model year and age, linear scale; (d) means by model year and age, common logarithmic scale

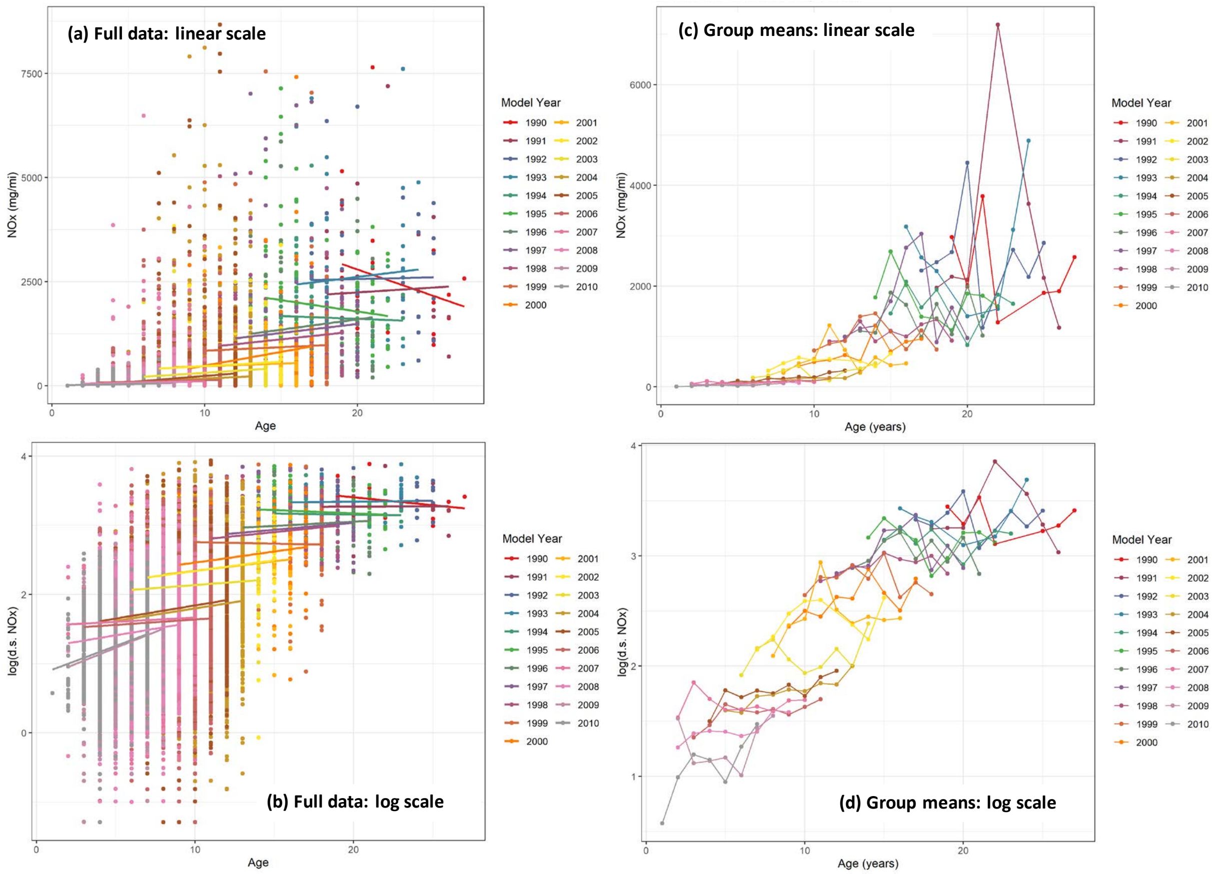


Figure 3-48 NO_x for Heavy Light-Duty Trucks (HLDT): IM240 Emissions (mg/mi) vs. age: (a) full data set, linear scale, with simple trendlines by model year; (b) full dataset, common logarithmic scale, with simple trendlines by model year; (c) means by model year and age, linear scale; (d) means by model year and age, common logarithmic scale

3.6.3.2 Total Hydrocarbons (THC)

For THC, sets of plots for the three vehicle classes are shown in Figure 3-49 for passenger cars, Figure 3-50 for Light Light-Duty Trucks and Figure 3-51 for Heavy Light-Duty Trucks.

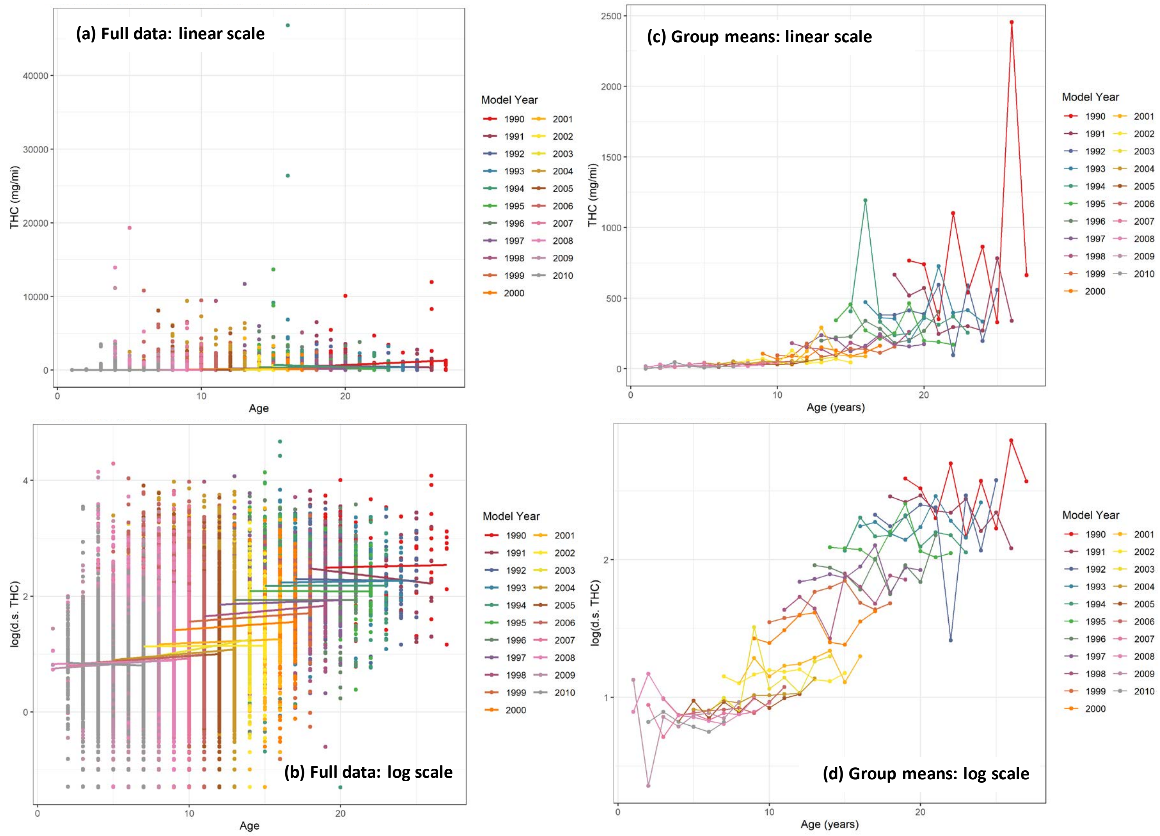


Figure 3-49 THC for Passenger Cars (LDV): IM240 Emissions (mg/mi) vs. age: (a) full data set, linear scale, with simple trendlines by model year; (b) full dataset, common logarithmic scale, with simple trendlines by model year; (c) means by model year and age, linear scale; (d) means by model year and age, common logarithmic scale

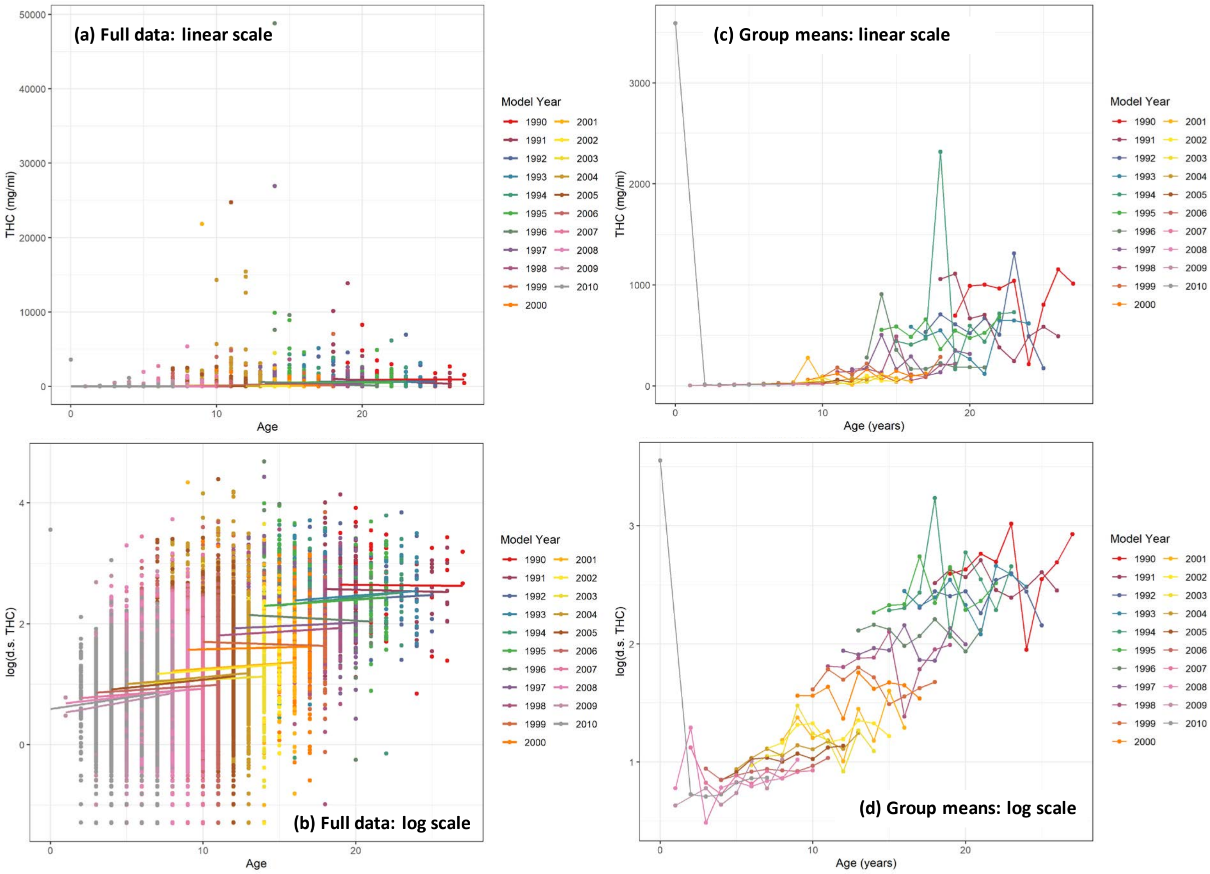


Figure 3-50 THC for Light Light-Duty Trucks (LLDT): IM240 Emissions (mg/mi) vs. age: (a) full data set, linear scale, with simple trendlines by model year; (b) full dataset, common logarithmic scale, with simple trendlines by model year; (c) means by model year and age, linear scale; (d) means by model year and age, common logarithmic scale

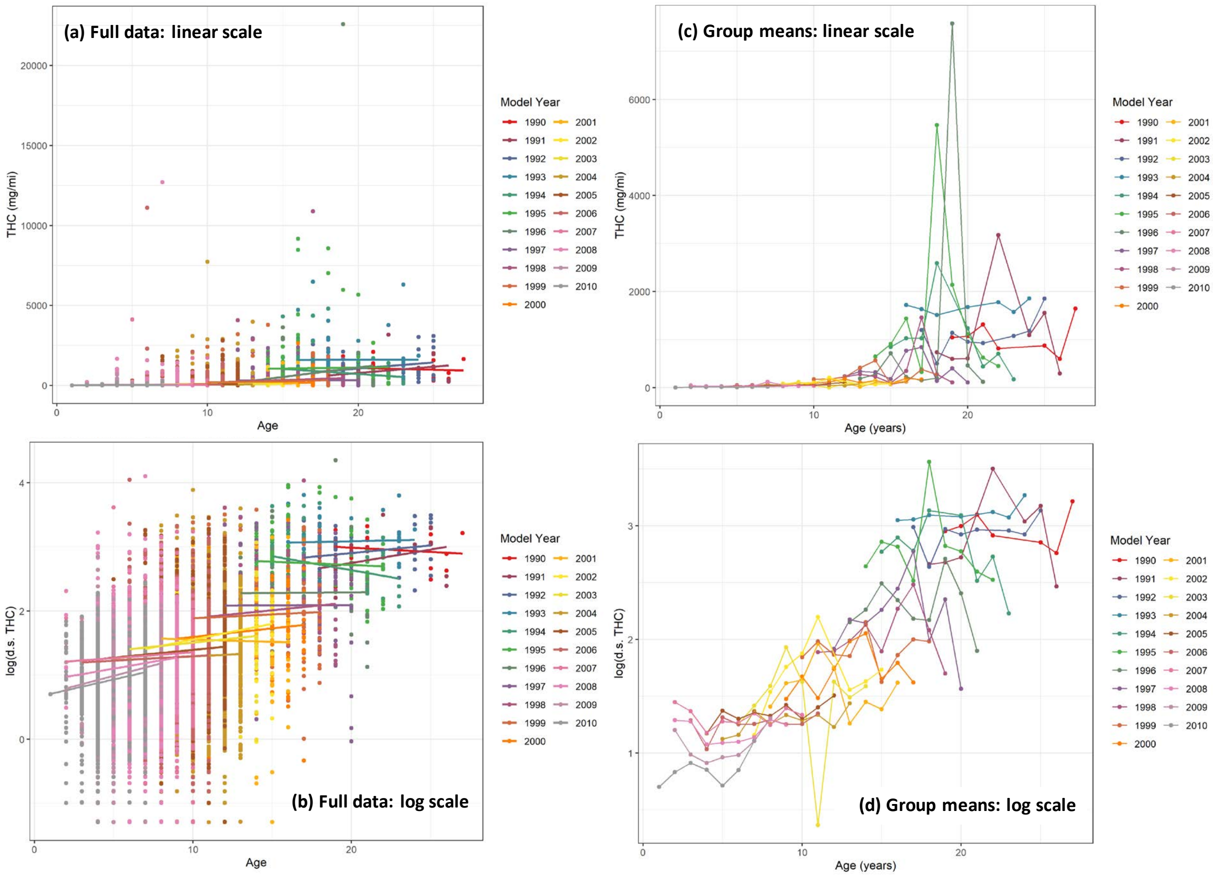


Figure 3-51 THC for Heavy Light-Duty Trucks (HLDT): IM240 Emissions (mg/mi) vs. age: (a) full data set, linear scale, with simple trendlines by model year; (b) full dataset, common logarithmic scale, with simple trendlines by model year; (c) means by model year and age, linear scale; (d) means by model year and age, common logarithmic scale

3.6.4 Model structure

The models were fit as three-piece linear splines, or as piece-wise multiple regressions with three segments to describe the curvilinear shape of a long-term deterioration trend, as shown in Figure 3-52. The points where the segments meet are called "knots." For a three-segment spline it is necessary to define two knots.

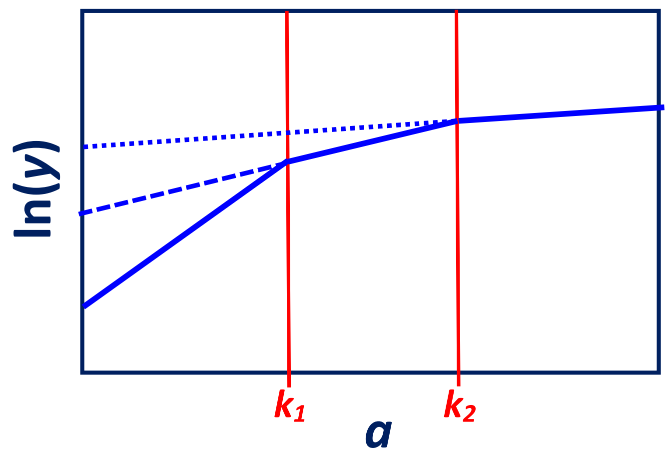


Figure 3-52 Generic structure of the three-piece linear spline model, showing two knots

For a single model year, the three-piece model is defined by the equation

$$\ln y = b_0 + b_{1,}m + b_2a + b_3(a - k_1)d_2 + b_4(a - k_2)d_3 + \varepsilon \qquad \text{Equation 3-40}$$

where:

$\ln y$ = natural logarithm of IM240 cycle aggregate emissions (mg/mi),
b_0 = grand intercept for a reference model year, assigned as the most recent model year, 2010,
$b_{1,\mathrm{m}}$ = incremental intercept coefficient for model year m, as difference from b_0,
m = model year as a class or categorical (dummy) variable,
b_2 = coefficient for age at test (a) as a continuous predictor (yr),
k_1, k_2 = knots where linear segments meet,
b_3 = incremental difference in slope for predictor a between k_1 and k_2,
b_4 = incremental difference in slope for predictor a above k_2,
d_2 = 1, if $a > k_1$, else = 0,
d_3 = 1, if $a > k_2$, else = 0.

The predictor variables are age and model year, with age (a) fit as a continuous variable and model year (m) fit as a class or categorical variable. The model structure assumes that the logarithmic age trend is uniform across model years within a segment, and that each model year has a distinct intercept.

Resolving the equation for each segment gives expressions for intercepts and slopes within each of the three segments, as shown in Table 3-29.

Table 3-29 Expressions for intercept and slope parameters in the three-piece spline model

Segment	d_1	d_2	Intercept	Slope
$0 < a \le k_1$	0	0	$b_0 + b_1$	b_2
$k_1 < a \le k_2$	1	0	$b_0 + b_1 - b_3k_1$	$b_2 + b_3$
$k_2 < a$	1	1	$b_0 + b_1 - b_3k_1 - b_4k_2$	$b_2 + b_3 + b_4$

3.6.4.1 Optimizing the Assignment of Knots

We fit the models repeatedly to test series of combinations for values of the two knots k_1 and k_2. For each model in the search grid, $k_1 \times k_2$, we compiled information for goodness of fit (*F*-statistics or -2 log likelihood) and tests of effect (*t*-tests for individual coefficients).

We found that criteria typically used for model selection based on overall goodness of fit, such as partial *F* tests, were not helpful in that the differences in *F* statistics among the various models were not large enough to be meaningful. Accordingly, we devised an alternative criterion for selecting models with the optimal assignment of knots.

The criterion we settled upon was to sum the *p*-values for the *t*-tests for the three slope coefficients, as shown in Equation 3-41. In each case, we selected the model with the minimum value of the summed *p*-values, as the model with the most significant values for the slope terms.

$$\boldsymbol{criterion = p_{b2} + p_{b3} + p_{b4}} \qquad \textbf{Equation 3-41}$$

Values of the criterion for all models fit during optimization are shown in Table 3-30 for NO_x and Table 3-31 for THC. In each table the minimum value of the criterion is indicated. The assignments of knots for each vehicle class for NO_x and THC is summarized in Table 3-32.

Table 3-30 NO_x: Optimization of knot assignments

Passenger Cars (LDV)

k_2	k_1					
	6	*7*	*8*	*9*	*10*	*11*
11	0.42	0.014	0.00035	0.0012	0.0019	---
12	0.37	0.010	**0.00021**	0.0060	0.019	0.18
13	0.33	0.0093	0.00034	0.017	0.061	0.36
14	0.29	0.011	0.0010	0.053	0.21	0.92
15	0.26	0.020	0.0044	0.181	0.67	0.69

Light Light-Duty Trucks (LLDT)

k_2	k_1					
	6	*7*	*8*	*9*	*10*	*11*
11	0.0044	0.0031	0.19	0.14	0.24	---
12	0.00087	0.00037	0.030	0.017	0.56	0.51
13	0.00034	0.00010	0.0093	0.0041	0.17	0.20
14	0.000092	**0.000048**	0.0015	0.0033	0.023	0.51
15	0.000050	0.00012	0.00058	0.0059	0.021	0.52

Heavy Light-Duty Trucks (HLDT)

k_2	k_1					
	5	*6*	*7*	*8*	*9*	*10*
11	0.74	0.54	0.54	0.25	0.84	---
12	0.58	0.38	0.22	0.13	0.52	---
13	0.48	0.29	0.12	0.078	0.33	---
14	0.39	0.21	0.079	0.038	0.15	---
15	0.33	0.16	0.044	0.019	0.073	---
16	0.26	0.10	0.026	**0.0087**	0.026	---
17	0.19	0.068	0.011	0.015	0.035	---

Table 3-31 THC: Optimization of knot assignments

Passenger Cars (LDV)

k_2	k_1					
	6	*7*	*8*	*9*	*10*	*11*
11	0.43	0.117	0.0018	0.048	0.035	---
12	0.49	0.087	0.0024	0.067	0.082	0.36
13	0.49	0.083	**0.0010**	0.036	0.034	0.070
14	0.51	0.074	0.0012	0.048	0.055	0.12
15	0.56	0.063	0.0027	0.10	0.15	0.40

Light Light-Duty Trucks (LLDT)

k_2	k_1					
	6	*7*	*8*	*9*	*10*	*11*
11	0.14	0.13	0.97	0.80	0.14	NA
12	0.049	0.055	0.29	0.268	0.58	0.04
13	0.037	**0.033**	0.22	0.1570	0.38	0.52
14	0.042	0.063	0.15	0.2513	0.479	0.32
15	0.072	0.12	0.16	0.3860	0.653	0.29

Heavy Light-Duty Trucks (HLDT)

k_2	k_1					
	5	*6*	*7*	*8*	*9*	*10*
11	0.92	0.24	0.071	0.22	0.79	0.98
12	0.61	0.11	0.081	0.21	0.94	0.78
13	0.56	0.090	0.030	0.076	0.41	0.36
14	0.52	0.077	0.017	0.043	0.24	0.22
15	0.48	0.065	0.012	0.027	0.14	0.14
16	0.44	0.055	**0.0082**	0.018	0.083	0.091
17	0.38	0.043	0.018	0.034	0.12	0.11

Table 3-32 Assignment of knots for three-piece spline models, by emission and vehicle class

Vehicle Class	k_1	k_2
NOx		
Passenger Cars (LDV)	8	12
Light Light-Duty Trucks	7	14
Heavy Light-Duty Trucks	8	16
THC		
Passenger Cars (LDV)	8	13
Light Light-Duty Trucks	7	13
Heavy Light-Duty Trucks	7	16

3.6.5 Model Results

Model fitting results for NO_x and THC are presented below. The left-hand portions of the tables, "*Coefficients*," present coefficients, standard errors and tests of effect (i.e., *t*-tests) as output by the model fitting procedure. In this case, the models were fit by ordinary least squares (OLS) using the lm() function in R.

The "Intercept" parameter represents the intercept for the reference model year, assigned as the most recent model year, 2010. The intercept parameter for all other model years is fit as an incremental difference between the reference model year and the given model year.

The tables also present slope terms. The slope parameter for "Age" is the b_2 coefficient in Equation 3-40 and represents the slope below the first knot ($a \leq k_1$). The second slope parameter, which applies to the term $(a - k_1)d_1$, is the b_3 coefficient and represents an incremental difference in slope between the two knots. The third slope parameter, which applies to the term $(a - k_2)d_2$, is the b_4 coefficient and represents an incremental difference in slopes above the second knot.

The upper right-hand portions of the tables, "*Intercepts*," presents intercepts (at age = 0) for each of the three linear segments of the model, calculated as defined in Table 3-32. As shown in the table, the calculated intercepts for the first segment ($a \leq k_1$), are simply the sums of the intercept coefficients b_0 and b_1. Those for the second segment ($k_1 < a \leq k_2$) build on the those for first segment by including adjustments based on the incremental slope difference for the second segment (b_3) and the location of the first knot. Slopes for the third segment build on those for the second segment by including adjustments based on the incremental slope difference for the third segment (b_4) and the location of the second knot.

The lower right-hand portions of the tables "Slopes" present slopes for each of the three model segments as shown in Table 3-32. The slopes for each segment are calculated simply as the sums of the slope coefficients for the current and preceding segments.

3.6.5.1 Oxides of Nitrogen (NO_x)

Model fitting results for NO_x for the three vehicle classes are shown in Table 3-33, Table 3-34 and Table 3-35 below, respectively. The models are also applied to predict trends as shown in Figure 3-53.

The figures are depicted in logarithmic scale. However, for clarity of presentation, they are presented as common logarithms, i.e., base 10, despite the fact that the models were fit as natural logarithms. On logarithmic scale, the parallelism of trends by model year, within the three segments is easy to see.

However, the sequencing of trends by MY is not always monotonic. For example, for cars, model year 2002 is slightly higher than 2001. For LLDT, the sequencing is consistent throughout. For HLDT, there are cases where model years do not always decrease in sequence. This outcome is not surprising due to the vagaries of sampling, the variability of emissions, and the fact that we need not assume that emission levels must always change meaningfully from model year to model year.

For trucks, the steepness of the age slopes declines with age from segment to segment. In fact, the slopes become negative in the third segment, giving declining mean emissions after approximately 14-16 years of age. We may interpret these declines as resulting from small and erratic subsamples for the oldest vehicles. Alternatively, the declines may indicate that older vehicles with higher emission rates are dropping from the population over time.

For cars, however, the slope is steeper in the middle segment (7-14 years) than in the first. In the third segment, the slope is still positive, but very gentle. Reasons for these differences are not clear. They may be artifacts of particular subsets of data.

Table 3-33 NO_x for Passenger Cars (LDV): Intercept and slope coefficients for the selected spline model

Coefficients

Parameter	Estimate	Std Err	t-value	Pr > |t|
Intercept	2.7013	0.0378	71.4980	< 2e-16
Model Year = 1990	3.8343	0.1279	29.9810	< 2e-16
Model Year = 1991	3.6080	0.1212	29.7770	< 2e-16
Model Year = 1992	3.6118	0.1125	32.1120	< 2e-16
Model Year = 1993	3.6946	0.0956	38.6320	< 2e-16
Model Year = 1994	3.3822	0.0897	37.7150	< 2e-16
Model Year = 1995	3.2332	0.0797	40.5830	< 2e-16
Model Year = 1996	2.9455	0.0759	38.8200	< 2e-16
Model Year = 1997	2.9309	0.0667	43.9730	< 2e-16
Model Year = 1998	2.6974	0.0685	39.4000	< 2e-16
Model Year = 1999	2.5712	0.0619	41.5610	< 2e-16
Model Year = 2000	2.2527	0.0588	38.3330	< 2e-16
Model Year = 2001	1.5781	0.0560	28.1860	< 2e-16
Model Year = 2002	1.6699	0.0573	29.1360	< 2e-16
Model Year = 2003	1.4395	0.0544	26.4640	< 2e-16
Model Year = 2004	1.0891	0.0369	29.5200	< 2e-16
Model Year = 2005	0.7816	0.0361	21.6630	< 2e-16
Model Year = 2006	0.5565	0.0348	15.9920	< 2e-16
Model Year = 2007	0.2810	0.0345	8.1540	0.0000
Model Year = 2008	0.2463	0.0332	7.4270	0.0000
Model Year = 2009	0.1965	0.0353	5.5650	0.0000
Model Year = 2010	0.0000			
Age	0.02052	0.00536	3.82600	0.00013
Age $(a - k_1)d_1$	0.03384	0.00858	3.94500	0.00008
Age $(a - k_2)d_2$	-0.04943	0.01060	-4.66500	0.00000

Intercepts

Model Year	$b_0 + b_1$	$b_0 + b_1 - b_3k_1$	$b_0 + b_1 - b_3k_1 - b_4k_2$
1990	6.5356	6.2649	6.8580
1991	6.3093	6.0386	6.6317
1992	6.3131	6.0424	6.6355
1993	6.3959	6.1252	6.7183
1994	6.0835	5.8128	6.4059
1995	5.9345	5.6638	6.2569
1996	5.6469	5.3761	5.9692
1997	5.6322	5.3615	5.9546
1998	5.3987	5.1280	5.7211
1999	5.2725	5.0018	5.5949
2000	4.9540	4.6833	5.2764
2001	4.2794	4.0087	4.6018
2002	4.3712	4.1005	4.6936
2003	4.1409	3.8701	4.4633
2004	3.7904	3.5197	4.1128
2005	3.4829	3.2122	3.8053
2006	3.2578	2.9871	3.5802
2007	2.9823	2.7116	3.3047
2008	2.9477	2.6769	3.2701
2009	2.8978	2.6271	3.2202
2010	2.7013	2.4306	3.0237

Slopes

b_2	$b_2 + b_3$	$b_2 + b_3 + b_4$
0.02052	0.05436	0.00493

Table 3-34 NO_x for Light Light-Duty Trucks (LLDT): Intercept and slope coefficients for the selected spline model

Coefficients

Parameter	Estimate	Std Err	t-value	Pr > |t|
Intercept	2.3289	0.0443	52.5590	< 2e-16
Model Year = 1990	3.9166	0.1760	22.2560	< 2e-16
Model Year = 1991	3.6634	0.1422	25.7570	< 2e-16
Model Year = 1992	3.6749	0.1450	25.3450	< 2e-16
Model Year = 1993	3.9974	0.1158	34.5110	< 2e-16
Model Year = 1994	3.6904	0.1171	31.5190	< 2e-16
Model Year = 1995	3.6680	0.0933	39.3090	< 2e-16
Model Year = 1996	3.2522	0.0832	39.0800	< 2e-16
Model Year = 1997	3.2091	0.0773	41.5150	< 2e-16
Model Year = 1998	3.1372	0.0716	43.8040	< 2e-16
Model Year = 1999	2.7283	0.0664	41.0850	< 2e-16
Model Year = 2000	2.7060	0.0638	42.4170	< 2e-16
Model Year = 2001	1.9002	0.0617	30.7730	< 2e-16
Model Year = 2002	1.5970	0.0611	26.1530	< 2e-16
Model Year = 2003	1.4452	0.0579	24.9530	< 2e-16
Model Year = 2004	1.1163	0.0373	29.9090	< 2e-16
Model Year = 2005	0.7889	0.0366	21.5490	< 2e-16
Model Year = 2006	0.6042	0.0359	16.8510	< 2e-16
Model Year = 2007	0.3873	0.0352	11.0020	< 2e-16
Model Year = 2008	0.0713	0.0335	2.1290	0.0332
Model Year = 2009	0.0230	0.0379	0.6080	0.5430
Model Year = 2010	0.0000			
Age	0.08814	0.0074	11.8510	< 2e-16
Age $(a - k_1)d_1$	-0.04130	0.0095	-4.3320	0.0000
Age $(a - k_2)d_2$	-0.05328	0.0128	-4.1500	0.0000

Intercepts

Model Year	$b_0 + b_1$	$b_0 + b_1 - b_3k_1$	$b_0 + b_1 - b_3k_1 - b_4k_2$
1990	6.2455	6.5346	7.2804
1991	5.9923	6.2814	7.0272
1992	6.0038	6.2929	7.0387
1993	6.3263	6.6154	7.3612
1994	6.0193	6.3084	7.0542
1995	5.9969	6.2860	7.0318
1996	5.5811	5.8702	6.6160
1997	5.5379	5.8270	6.5729
1998	5.4661	5.7552	6.5010
1999	5.0572	5.3462	6.0921
2000	5.0349	5.3240	6.0698
2001	4.2291	4.5181	5.2640
2002	3.9259	4.2150	4.9608
2003	3.7741	4.0632	4.8091
2004	3.4452	3.7343	4.4801
2005	3.1178	3.4069	4.1528
2006	2.9331	3.2222	3.9680
2007	2.7162	3.0053	3.7512
2008	2.4002	2.6893	3.4351
2009	2.3519	2.6410	3.3869
2010	2.3289	2.6180	3.3638

Slopes

b_2	$b_2 + b_3$	$b_2 + b_3 + b_4$
0.08814	0.04684	-0.006434

Table 3-35 NO_x for Heavy Light-Duty Trucks (HLDT): Intercept and slope coefficients for the selected spline model

Coefficients

Parameter	Estimate	Std Err	t-value	Pr > |t|
Intercept	2.3721	0.0695	34.1140	< 2e-16
Model Year = 1990	4.4626	0.3546	12.5850	< 2e-16
Model Year = 1991	4.1824	0.3129	13.3660	< 2e-16
Model Year = 1992	4.3503	0.2893	15.0390	< 2e-16
Model Year = 1993	4.2614	0.2315	18.4090	< 2e-16
Model Year = 1994	3.8143	0.2058	18.5360	< 2e-16
Model Year = 1995	3.9178	0.1690	23.1810	< 2e-16
Model Year = 1996	3.3442	0.1789	18.6920	< 2e-16
Model Year = 1997	3.2845	0.1468	22.3790	< 2e-16
Model Year = 1998	3.2281	0.1323	24.3950	< 2e-16
Model Year = 1999	2.8004	0.1223	22.8920	< 2e-16
Model Year = 2000	2.4822	0.1307	18.9880	< 2e-16
Model Year = 2001	2.0237	0.1143	17.7130	< 2e-16
Model Year = 2002	2.4084	0.1237	19.4690	< 2e-16
Model Year = 2003	1.7058	0.1078	15.8280	< 2e-16
Model Year = 2004	0.9004	0.0685	13.1520	< 2e-16
Model Year = 2005	0.9378	0.0681	13.7690	< 2e-16
Model Year = 2006	0.6373	0.0647	9.8480	< 2e-16
Model Year = 2007	0.7342	0.0634	11.5900	< 2e-16
Model Year = 2008	0.4001	0.0600	6.6670	0.0000
Model Year = 2009	0.0208	0.0679	0.3060	0.7597
Model Year = 2010	0.0000			
Age	0.09457	0.01054	8.97300	< 2e-16
Age $(a - k_1)d_1$	-0.04084	0.01525	-2.67800	0.00741
Age $(a - k_2)d_2$	-0.10121	0.03139	-3.22400	0.00127

Intercepts

Model Year	$b_0 + b_1$	$b_0 + b_1 - b_3k_1$	$b_0 + b_1 - b_3k_1 - b_4k_2$
1990	6.8347	7.1614	8.7808
1991	6.5545	6.8812	8.5006
1992	6.7224	7.0491	8.6685
1993	6.6335	6.9603	8.5796
1994	6.1864	6.5131	8.1325
1995	6.2899	6.6167	8.2360
1996	5.7163	6.0431	7.6624
1997	5.6566	5.9833	7.6027
1998	5.6002	5.9270	7.5463
1999	5.1725	5.4992	7.1186
2000	4.8543	5.1810	6.8004
2001	4.3958	4.7226	6.3419
2002	4.7806	5.1073	6.7266
2003	4.0779	4.4046	6.0240
2004	3.2725	3.5992	5.2186
2005	3.3099	3.6367	5.2560
2006	3.0094	3.3361	4.9555
2007	3.1064	3.4331	5.0524
2008	2.7722	3.0990	4.7183
2009	2.3929	2.7196	4.3390
2010	2.3721	2.6988	4.3182

Slopes

b_2	$b_2 + b_3$	$b_2 + b_3 + b_4$
0.09457	0.05373	-0.047480

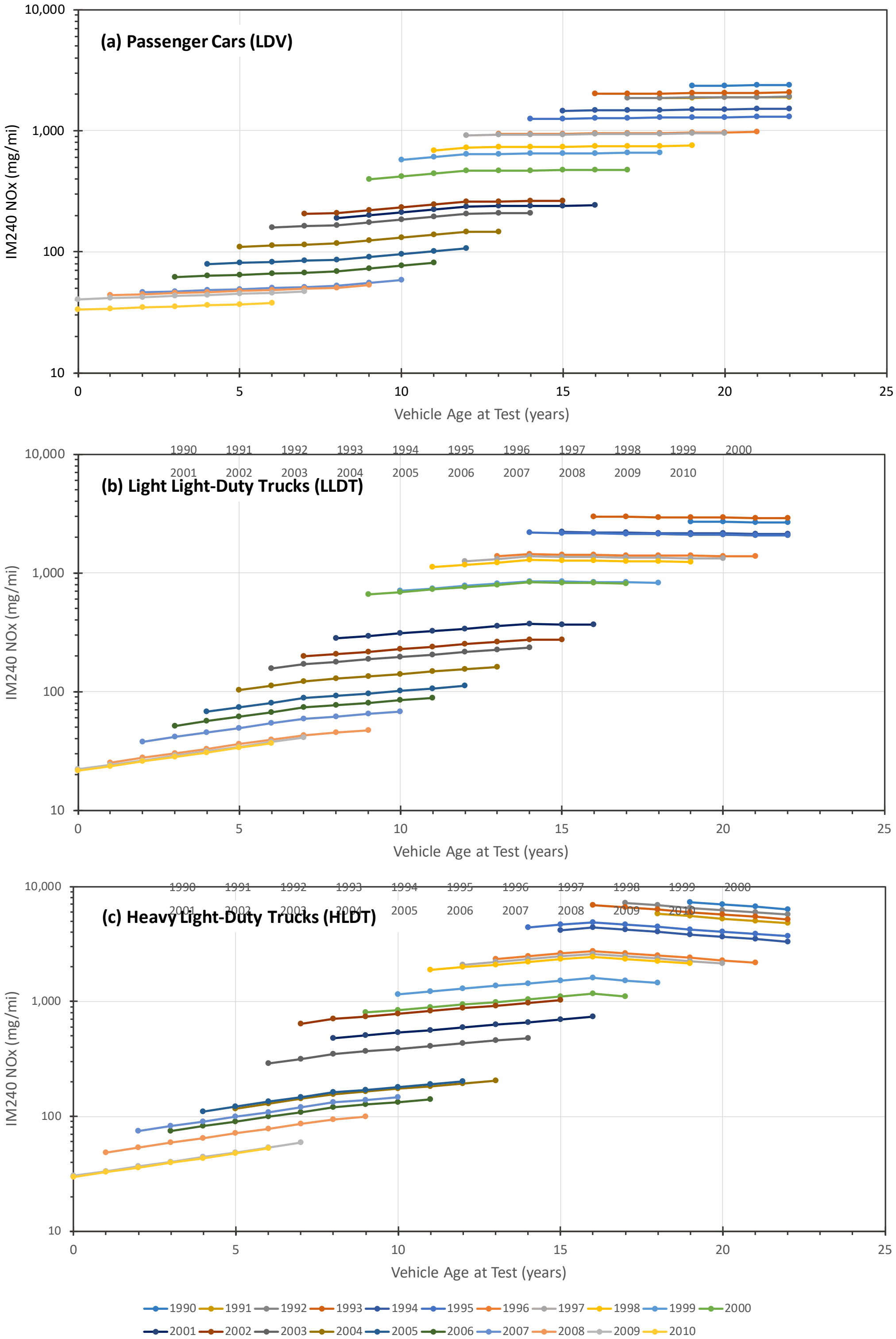


Figure 3-53 NO$_x$: Three-piece linear spline deterioration models for three vehicle classes: (a) Passenger cars, (b) Light Light Duty Trucks, and (c) Heavy Light-Duty Trucks. Note that emissions are expressed on common logarithmic scale

3.6.5.2 Total Hydrocarbons (THC)

Model fitting results for THC for the three vehicle classes are shown in Table 3-36, Table 3-37 and Table 3-38 above, respectively. Trends are also shown graphically in Figure 3-54.

The figures are depicted in logarithmic scale. However, for clarity, they are presented as common logarithms, i.e., base 10, despite having fit the models as natural logarithms. At logarithmic scale, the parallelism of trends by model year within the three segments is easy to see.

However, the sequencing of trends by MY is not always monotonic. For cars, the sequencing is generally consistent throughout. For LLDT and HLDT, there are cases where model years do not always decrease in sequence.

Patterns of steepness in the slopes by segment are similar to the NO_x models. The slope in the youngest segment is very gentle, and that in the second steeper. Slopes in the third segment are gently positive for cars and LLDT, and negative for HLDT.

Table 3-36 THC for Passenger Cars (LDV): Intercept and slope coefficients for the selected spline model

Coefficients

Parameter	Estimate	Std Err	t-value	Pr > |t|
Intercept	1.7881	0.0460	38.8920	< 2e-16
Model Year = 1990	3.4132	0.1534	22.2550	< 2e-16
Model Year = 1991	3.2188	0.1449	22.2200	< 2e-16
Model Year = 1992	2.8936	0.1340	21.5960	< 2e-16
Model Year = 1993	2.8477	0.1137	25.0350	< 2e-16
Model Year = 1994	2.6462	0.1064	24.8730	< 2e-16
Model Year = 1995	2.5205	0.0945	26.6780	< 2e-16
Model Year = 1996	2.0756	0.0902	23.0150	< 2e-16
Model Year = 1997	1.9756	0.0798	24.7520	< 2e-16
Model Year = 1998	1.7102	0.0827	20.6690	< 2e-16
Model Year = 1999	1.4418	0.0745	19.3530	< 2e-16
Model Year = 2000	1.1036	0.0707	15.6010	< 2e-16
Model Year = 2001	0.6765	0.0679	9.9640	< 2e-16
Model Year = 2002	0.4631	0.0690	6.7110	0.0000
Model Year = 2003	0.2334	0.0661	3.5310	0.0004
Model Year = 2004	0.2075	0.0448	4.6280	0.0000
Model Year = 2005	0.1400	0.0439	3.1900	0.0014
Model Year = 2006	0.1392	0.0423	3.2890	0.0010
Model Year = 2007	0.0786	0.0419	1.8750	0.0608
Model Year = 2008	0.0676	0.0404	1.6750	0.0939
Model Year = 2009	0.0181	0.0430	0.4210	0.6738
Model Year = 2010	0.0000			
Age	0.0237	0.0065	3.6450	0.0003
Age $(a - k_1)d_1$	0.0348	0.0100	3.4810	0.0005
Age $(a - k_2)d_2$	-0.0491	0.0133	-3.6830	0.0002

Intercepts

Model Year	$b_0 + b_1$	$b_0 + b_1 - b_3k_1$	$b_0 + b_1 - b_3k_1 - b_4k_2$
1990	5.2013	4.9232	5.5610
1991	5.0069	4.7288	5.3666
1992	4.6817	4.4036	5.0415
1993	4.6358	4.3576	4.9955
1994	4.4343	4.1561	4.7940
1995	4.3086	4.0305	4.6683
1996	3.8637	3.5856	4.2234
1997	3.7637	3.4856	4.1234
1998	3.4983	3.2202	3.8580
1999	3.2299	2.9518	3.5896
2000	2.8917	2.6135	3.2514
2001	2.4646	2.1865	2.8243
2002	2.2512	1.9730	2.6109
2003	2.0215	1.7434	2.3813
2004	1.9956	1.7175	2.3553
2005	1.9281	1.6499	2.2878
2006	1.9273	1.6491	2.2870
2007	1.8667	1.5886	2.2264
2008	1.8557	1.5776	2.2155
2009	1.8062	1.5281	2.1659
2010	1.7881	1.5100	2.1478

Slopes	b_2	$b_2 + b_3$	$b_2 + b_3 + b_4$
	0.0237	0.05844	0.00938

Table 3-37 THC for Light Light-Duty Trucks (LLDT): Intercept and slope coefficients for the selected spline model

Coefficients

Parameter	Estimate	Std Err	t-value	Pr > |t|
Intercept	1.4111	0.0541	26.1010	< 2e-16
Model Year = 1990	3.8269	0.2111	18.1280	< 2e-16
Model Year = 1991	3.6516	0.1703	21.4410	< 2e-16
Model Year = 1992	3.2634	0.1739	18.7610	< 2e-16
Model Year = 1993	3.2756	0.1399	23.4180	< 2e-16
Model Year = 1994	3.2273	0.1413	22.8390	< 2e-16
Model Year = 1995	3.2101	0.1132	28.3630	< 2e-16
Model Year = 1996	2.6421	0.1001	26.3920	< 2e-16
Model Year = 1997	2.2638	0.0929	24.3570	< 2e-16
Model Year = 1998	2.1779	0.0862	25.2690	< 2e-16
Model Year = 1999	1.7882	0.0797	22.4270	< 2e-16
Model Year = 2000	1.6094	0.0769	20.9400	< 2e-16
Model Year = 2001	0.8705	0.0747	11.6480	< 2e-16
Model Year = 2002	0.9834	0.0736	13.3580	< 2e-16
Model Year = 2003	0.5677	0.0705	8.0530	0.0000
Model Year = 2004	0.5374	0.0454	11.8340	< 2e-16
Model Year = 2005	0.4522	0.0445	10.1620	< 2e-16
Model Year = 2006	0.2491	0.0436	5.7120	0.0000
Model Year = 2007	0.0976	0.0428	2.2790	0.0226
Model Year = 2008	0.0599	0.0408	1.4670	0.1425
Model Year = 2009	-0.1038	0.0462	-2.2460	0.0247
Model Year = 2010	0.0000			
Age	0.0716	0.0090	7.9090	0.0000
Age $(a - k_1)d_1$	-0.0285	0.0117	-2.4310	0.0151
Age $(a - k_2)d_2$	-0.0330	0.0140	-2.3600	0.0183

Intercepts

Model Year	$b_0 + b_1$	$b_0 + b_1 - b_3k_1$	$b_0 + b_1 - b_3k_1 - b_4k_2$
1990	5.2380	5.4373	5.8668
1991	5.0627	5.2621	5.6915
1992	4.6746	4.8739	5.3034
1993	4.6867	4.8860	5.3155
1994	4.6384	4.8378	5.2672
1995	4.6212	4.8206	5.2500
1996	4.0533	4.2526	4.6821
1997	3.6749	3.8742	4.3037
1998	3.5890	3.7884	4.2178
1999	3.1993	3.3987	3.8281
2000	3.0206	3.2199	3.6494
2001	2.2816	2.4809	2.9104
2002	2.3945	2.5938	3.0233
2003	1.9788	2.1782	2.6077
2004	1.9485	2.1479	2.5774
2005	1.8633	2.0627	2.4922
2006	1.6602	1.8595	2.2890
2007	1.5087	1.7081	2.1376
2008	1.4710	1.6703	2.0998
2009	1.3073	1.5066	1.9361
2010	1.4111	1.6105	2.0399

Slopes

b_2	$b_2 + b_3$	$b_2 + b_3 + b_4$
0.0716	0.04309	0.01005

Table 3-38 THC for Heavy Light-Duty Trucks (HLDT): Intercept and slope coefficients for the selected spline model

Coefficients

Parameter	Estimate	Std Err	t-value	Pr > |t|
Intercept	1.6683	0.0781	21.3670	< 2e-16
Model Year = 1990	4.6073	0.3464	13.3020	< 2e-16
Model Year = 1991	4.1024	0.3056	13.4230	< 2e-16
Model Year = 1992	4.4423	0.2826	15.7220	< 2e-16
Model Year = 1993	4.7289	0.2260	20.9230	< 2e-16
Model Year = 1994	3.9220	0.2009	19.5250	< 2e-16
Model Year = 1995	3.9106	0.1650	23.6960	< 2e-16
Model Year = 1996	2.7202	0.1749	15.5570	< 2e-16
Model Year = 1997	2.3602	0.1436	16.4380	< 2e-16
Model Year = 1998	2.0586	0.1296	15.8820	< 2e-16
Model Year = 1999	1.8609	0.1202	15.4790	< 2e-16
Model Year = 2000	1.4066	0.1281	10.9800	< 2e-16
Model Year = 2001	1.1281	0.1122	10.0570	< 2e-16
Model Year = 2002	1.1582	0.1218	9.5080	< 2e-16
Model Year = 2003	1.1536	0.1062	10.8620	< 2e-16
Model Year = 2004	0.6204	0.0673	9.2230	< 2e-16
Model Year = 2005	0.8415	0.0672	12.5170	< 2e-16
Model Year = 2006	0.6840	0.0646	10.5850	< 2e-16
Model Year = 2007	0.7443	0.0634	11.7410	< 2e-16
Model Year = 2008	0.4792	0.0596	8.0430	0.0000
Model Year = 2009	0.2349	0.0674	3.4870	0.0005
Model Year = 2010	0.0000			
Age	0.0849	0.0134	6.3620	0.0000
Age $(a - k_1)d_1$	-0.0569	0.0170	-3.3500	0.0008
Age $(a - k_2)d_2$	-0.0807	0.0301	-2.6780	0.0074

Intercepts

Model Year	$b_0 + b_1$	$b_0 + b_1 - b_3k_1$	$b_0 + b_1 - b_3k_1 - b_4k_2$
1990	6.2755	6.6740	7.9650
1991	5.7706	6.1691	7.4601
1992	6.1106	6.5090	7.8001
1993	6.3971	6.7956	8.0866
1994	5.5902	5.9887	7.2797
1995	5.5789	5.9773	7.2684
1996	4.3884	4.7868	6.0779
1997	4.0285	4.4269	5.7179
1998	3.7269	4.1253	5.4163
1999	3.5292	3.9276	5.2187
2000	3.0749	3.4733	4.7644
2001	2.7964	3.1948	4.4859
2002	2.8265	3.2249	4.5160
2003	2.8219	3.2203	4.5113
2004	2.2887	2.6871	3.9781
2005	2.5097	2.9081	4.1992
2006	2.3522	2.7507	4.0417
2007	2.4125	2.8110	4.1020
2008	2.1475	2.5459	3.8369
2009	1.9032	2.3016	3.5927
2010	1.6683	2.0667	3.3577

Slopes

b_2	$b_2 + b_3$	$b_2 + b_3 + b_4$
0.0849	0.02800	-0.05269

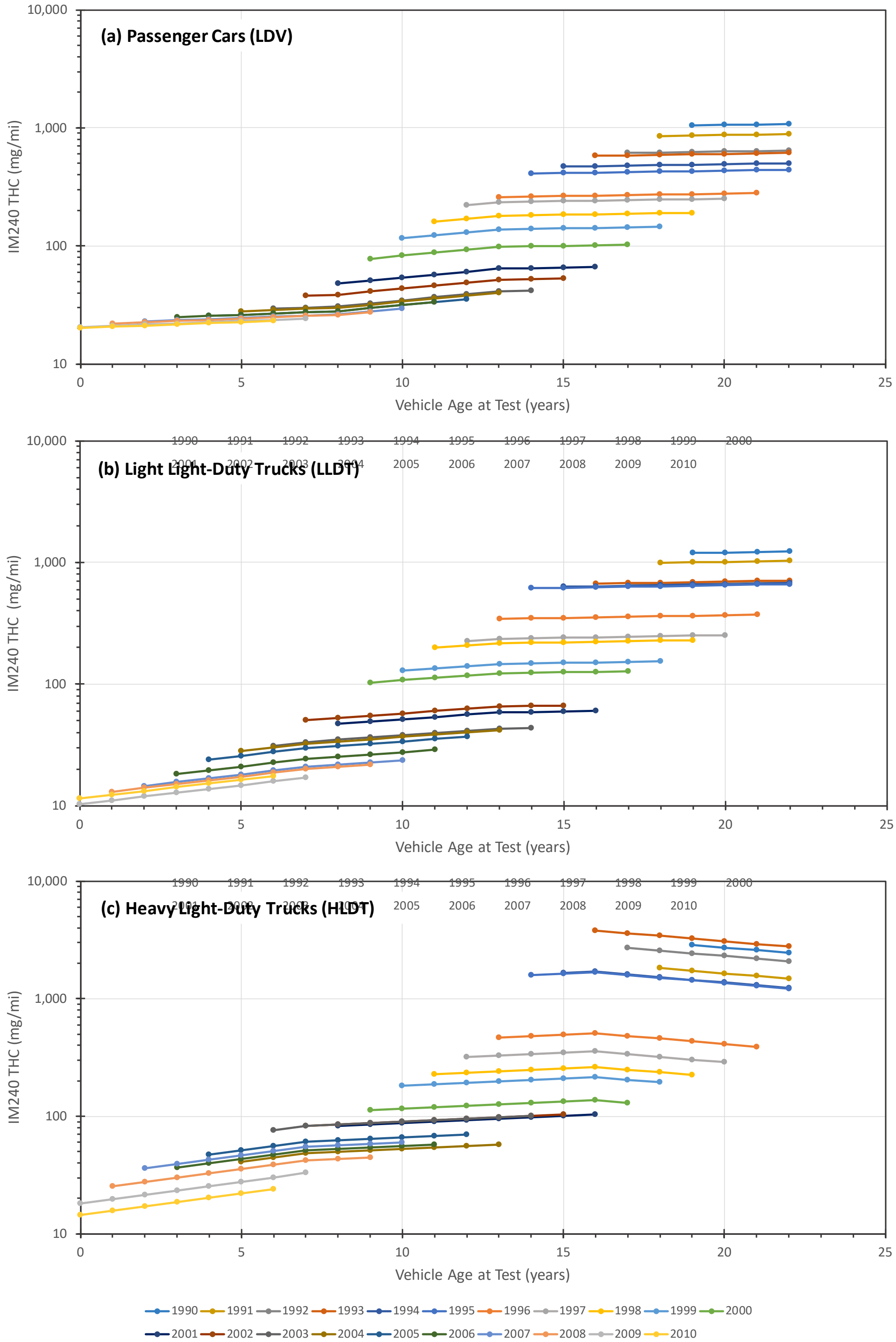


Figure 3-54 THC: Three-piece linear spline deterioration models for three vehicle classes: (a) Passenger cars, (b) Light Light Duty Trucks, and (c) Heavy Light-Duty Trucks. Note that emissions are expressed on common logarithmic scale

3.6.6 Reverse Transformation

Despite the fact that all parameters in all models are highly significant, the main purpose for these analyses is not hypothesis testing, but developing emission rates. It is therefore necessary to reverse transform the logarithmic model results for purposes of prediction.

As the response variable for the models is ln y, we exponentiate the results to estimate emissions in original units (mg/mi).

$$y = e^{\ln y} \qquad \text{Equation 3-42}$$

However, under the assumption that the emissions are lognormally distributed, this initial step returns not the mean emissions level, but rather the "geometric mean" emissions level, which we can effectively treat as the "median" level, denoted as y_g. This level is of general interest in that it indicates the emissions level of a "typical" vehicle.

However, for estimation of an emissions inventory, the parameter to be estimated is not the "geometric mean" but rather the "arithmetic mean," as the arithmetic mean relates directly to total emissions, e.g., kg, Mg. To estimate the arithmetic mean, which we will denote as y_a, we add a second term including the "logarithmic variance" (s^2):

$$y_a = e^{\ln y} e^{0.5s^2} = y_g e^{0.5s^2} \qquad \text{Equation 3-43}$$

The implication is that underestimating s^2 would lead to underestimation of the arithmetic mean y_a. In the models, we estimate the logarithmic variance as the residual error variance. The OLS models estimate a uniform error variance for residuals throughout the parameter space. The logarithmic variance is of interpretive interest as it provides an index of the degree of right skew in the lognormal distribution. In fact, the second term in the equation gives the ratio of the arithmetic to the geometric mean (y_a/y_g).

However, as the sample sizes by model year and age are not uniform throughout the dataset, neither is the variance. The variance is related to sample size, as in random sampling, the probability of pulling in the extremes of the distribution is proportional to sample size. In addition, we observed as noted above that the sampling effort was higher for MY since 2004 (see Table 3-25, Table 3-26 and Table 3-27 above).

To investigate patterns in s^2 with model year, we fit a second set of models. Rather than classic OLS regressions, we used mixed-factor models to take advantage of the capability of these procedures to estimate heterogeneous error variances by subgroups in the data. We used the lme() function in the R nlme library.

The resulting variance estimates are in Table 3-39 for NO_x and Table 3-40 for THC. The same results are presented graphically in Figure 3-55 for NO_x and Figure 3-56 for THC. While variances vary from model year to model year, it is clear that they are highest in the model years with the largest sample sizes, e.g., $n > 800$.

The task then was to decide how to select values of s^2 to use for the reverse transform. We proceeded on the assumption that the largest samples come closest to capturing the full range of variability in the population distributions. Conversely, we assume that lower variances in the smaller samples fail to capture the expected variability.

Another important question concerned whether the error variance might be expected to decline as vehicles age. In this dataset, the data for older "Tier-1" model years, e.g., prior to 2000, were collected when the vehicles were older than 10 years. As the models would be used to hindcast emissions for these vehicles when less than five years of age, a key question is whether their variances when young would be similar to those for the young Tier 2 vehicles (e.g., MY 2004 and later) directly observed in this dataset.

We answered this question in the affirmative, based on remote-sensing data collected by the University of Denver. There results showed that variances for Tier 1 vehicles measured while young were as large or larger than any measured for young Tier 2 vehicles.

For the reverse transformation, we assigned a uniform value of s^2 for use with each model, which we applied to all model years. These values were calculated as averages of a subset of model years for which samples were reasonably large and during which the variances were in a relatively uniform range. The subsets of model years used for each vehicle class indicated by gray shading, with the values obtained shown at the bottom of the tables.

For NO_x, the values of s^2 for LLDT are lower than those for cars, while those for HLDT are higher. For THC, values of s^2 for both truck classes are lower than that for cars and are nearly equal.

Seeing no obvious reasons based on engine or emissions control technology why the variances for cars would be highest, we suggest it may reflect the fact that the cars have the largest samples. Offhand, we would assume that variances would be similar for different vehicle classes, if all populations were adequately characterized. Nonetheless, for each vehicle class, we applied the variance estimates obtained from their respective datasets.

Table 3-39 NO_x: Logarithmic variances by model year for three vehicle classes (NOTE: the gray cells include those in the 10-yr average below, used for reverse transformation)

Model Year	LDV	LLDT	HLDT
1990	0.8225	0.7676	0.1901
1991	0.9789	0.9840	0.4173
1992	0.8384	0.9304	0.3448
1993	0.6629	0.5316	0.3489
1994	0.9073	0.7264	0.2559
1995	0.8543	0.8819	0.4171
1996	0.7815	1.0679	0.6668
1997	0.7021	1.0168	0.7426
1998	1.1197	0.9893	0.7794
1999	1.1566	1.0418	1.1740
2000	1.4283	1.1173	1.4467
2001	1.5954	1.5210	2.0158
2002	1.5699	2.0570	2.2738
2003	1.7353	1.3071	1.9447
2004	1.6167	1.6073	2.0701
2005	1.6636	1.5316	2.4124
2006	1.8533	1.3472	2.3662
2007	1.8132	1.2774	1.5647
2008	1.4856	1.5210	1.9682
2009	1.4589	1.3820	1.9847
2010	1.3648	1.3353	1.7527

10-yr Average	1.6157	1.4887	2.0353

Table 3-40 THC: Logarithmic variances by model year for three vehicle classes (NOTE: the gray cells include those in the averages below, used for reverse transformation)

Model Year	LDV	LLDT	HLDT
1990	1.7266	1.8780	0.3119
1991	1.5770	1.6869	0.7567
1992	1.4231	1.9454	0.6442
1993	1.7927	1.5504	0.6614
1994	2.3794	1.9607	0.9015
1995	1.8040	1.7387	1.1649
1996	1.9471	1.4782	1.3296
1997	1.7056	1.5644	2.1978
1998	2.4316	1.6758	1.9049
1999	2.3307	1.5439	2.0212
2000	2.5899	1.8922	2.2248
2001	2.6940	2.3209	2.7090
2002	2.7358	2.1830	1.9808
2003	2.7920	2.1026	2.0720
2004	2.6518	2.1217	1.7764
2005	2.2630	1.9287	1.7155
2006	2.2861	1.7526	1.6746
2007	2.2471	1.9959	1.3231
2008	2.3235	2.0149	2.3402
2009	2.1573	2.0544	1.9051
2010	2.1265	2.0754	2.0691
Average	2.4330	2.0550	1.9939

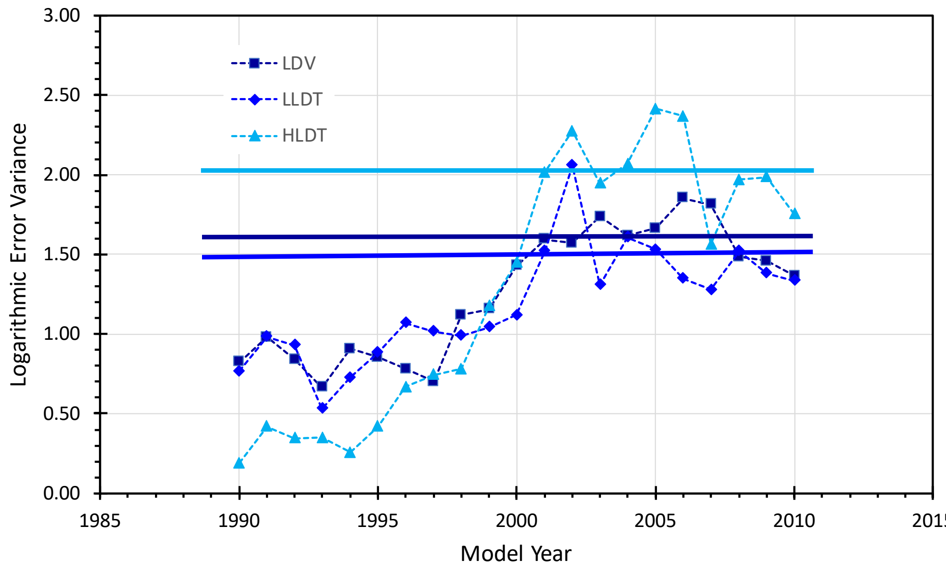


Figure 3-55 NO_x: Logarithmic variance (s^2) by model year for three vehicle classes. Solid horizontal lines represent values selected for reverse-transformation

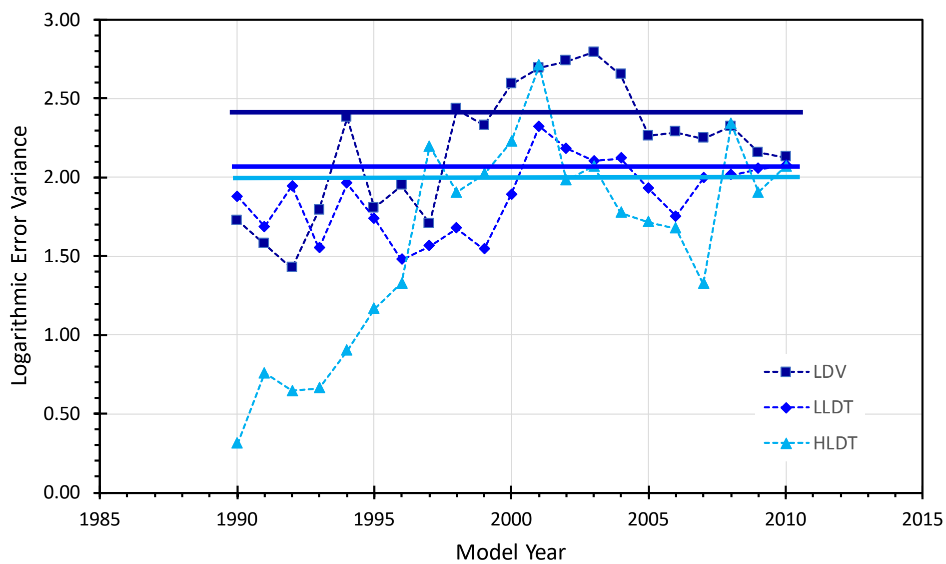


Figure 3-56 THC: Logarithmic variance (s^2) by model year for three vehicle classes. Solid horizontal lines represent values selected for reverse-transformation

Deterioration trends as predicted by the models following the reverse transformation are shown in Figure 3-57 for NO_x and Figure 3-58 for THC.

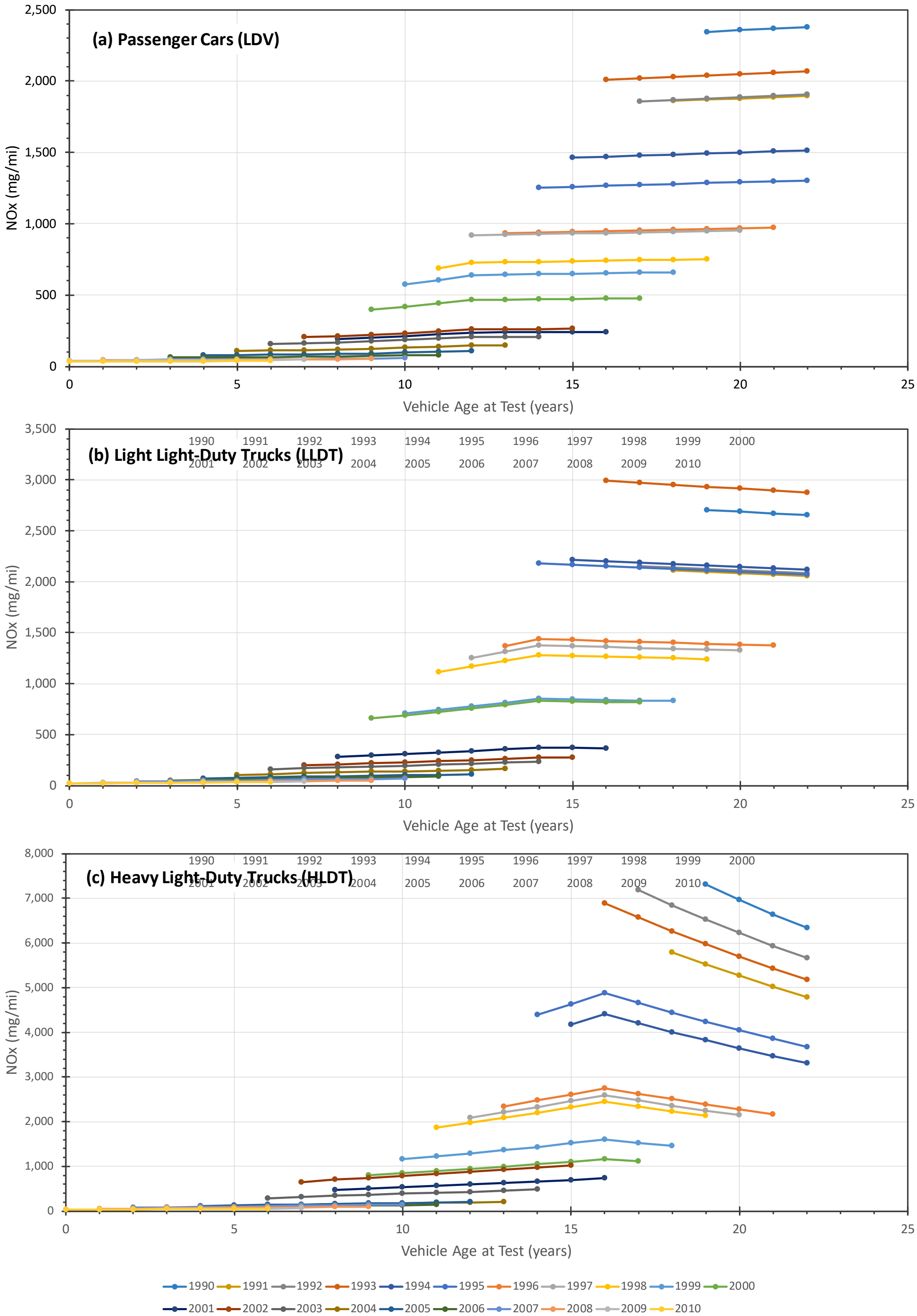


Figure 3-57 NO_x: Trends in emissions vs. age as predicted by reverse-transformed three-piece ln-linear spline models

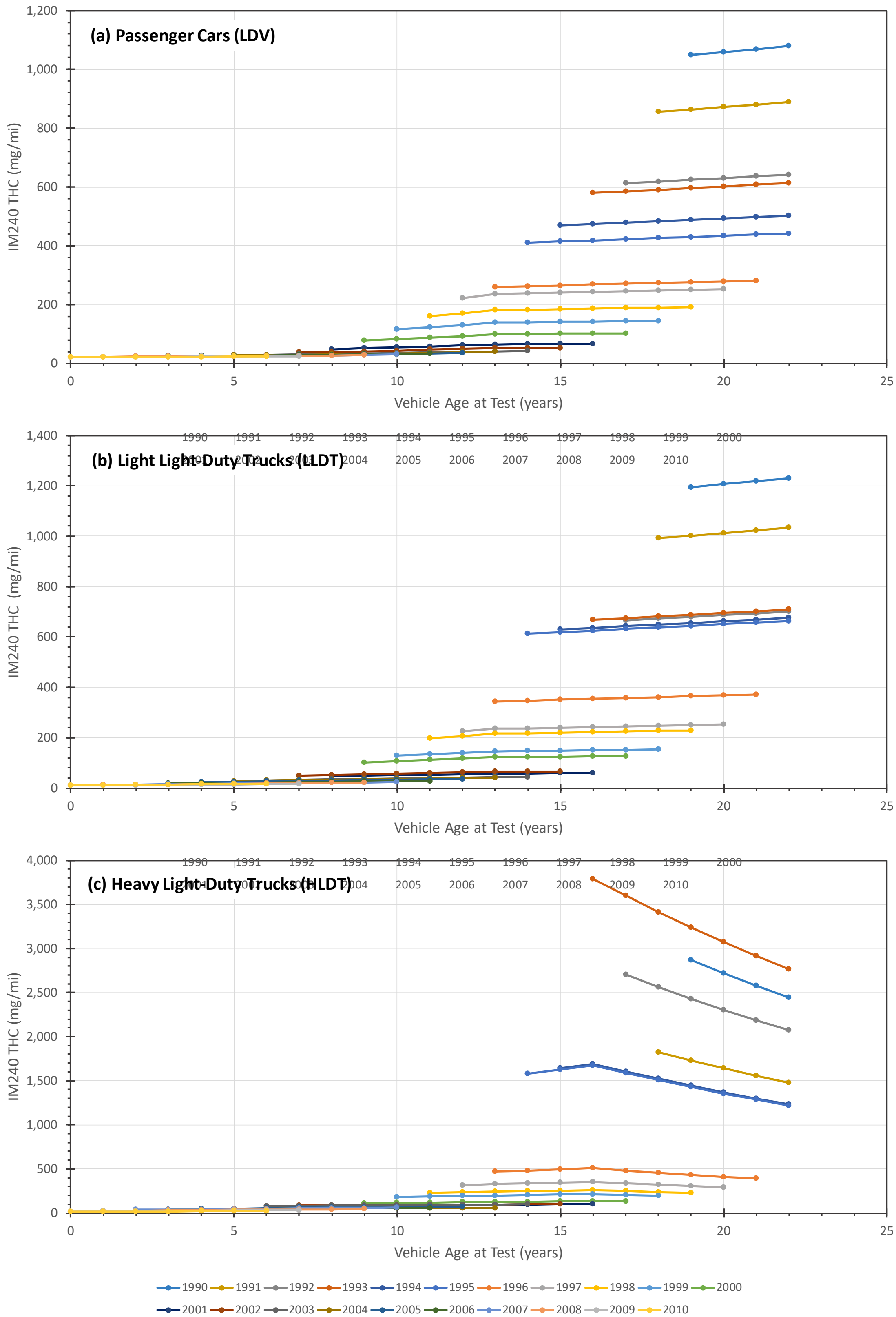


Figure 3-58 THC: Trends in emissions vs. age as predicted by reverse-transformed three-piece ln-linear spline models

3.6.7 "Young Vehicle" Adjustments

The adjustments for "young vehicles" were developed by using the spline models to estimate average IM240 levels at 2 years of age for all model years. The result is a trend in emissions with model year at age = 2. Two years of age was selected because it represents the midpoint of the 0-3 year ageGroup, which is actually 4 years in length, i.e., vehicles are three years old until their "fourth birthday." This rate at age 2 is later used as the basis for applying deterioration.

For comparison, a corresponding trend to represent the MOVES2014 rates for the 0-3 year ageGroup was constructed by simulating the IM240 cycle using the MOVES2014b rates for the hot-running emissions process. This step was achieved by calculating sums of rates weighted by an operating mode distribution for the IM240 cycle. The total (g) is the sum of time-in-mode (hr) times emission rate (g/hr).

3.6.7.1 Adjustments for NO_x

3.6.7.1.1 Cars

For NO_x, estimates from the spline models based on the Denver IM240s are consistently higher than the simulated MOVES2014 IM240s, as shown in Figure 3-59.

Also, the Denver IM240 results show a steady decline in emissions from 1994 through 2000, which years include the phase-in and duration of the Tier 1 emissions standards. This pattern contrasts with that in the MOVES rates, which assume stable emissions during MY 1996-2000, while the Tier 1 standards were in effect. In other words, the MOVES2014 rates assumed that emission rates remain stable if the emissions standards are unchanging. However, the evidence from the Denver data suggest otherwise--that emissions may decline without corresponding declines in standards. Design features contributing to the declines could include the introduction of oxygen sensors and on-board diagnostic systems (OBD).

Nonetheless, the chief salient feature is that the Denver IM240 levels are consistently higher than the simulated MOVES IM240s. This pattern holds over the entire model year range, even during and after the phase-in of Tier 2 standards, as clearly shown in Figure 3-59.

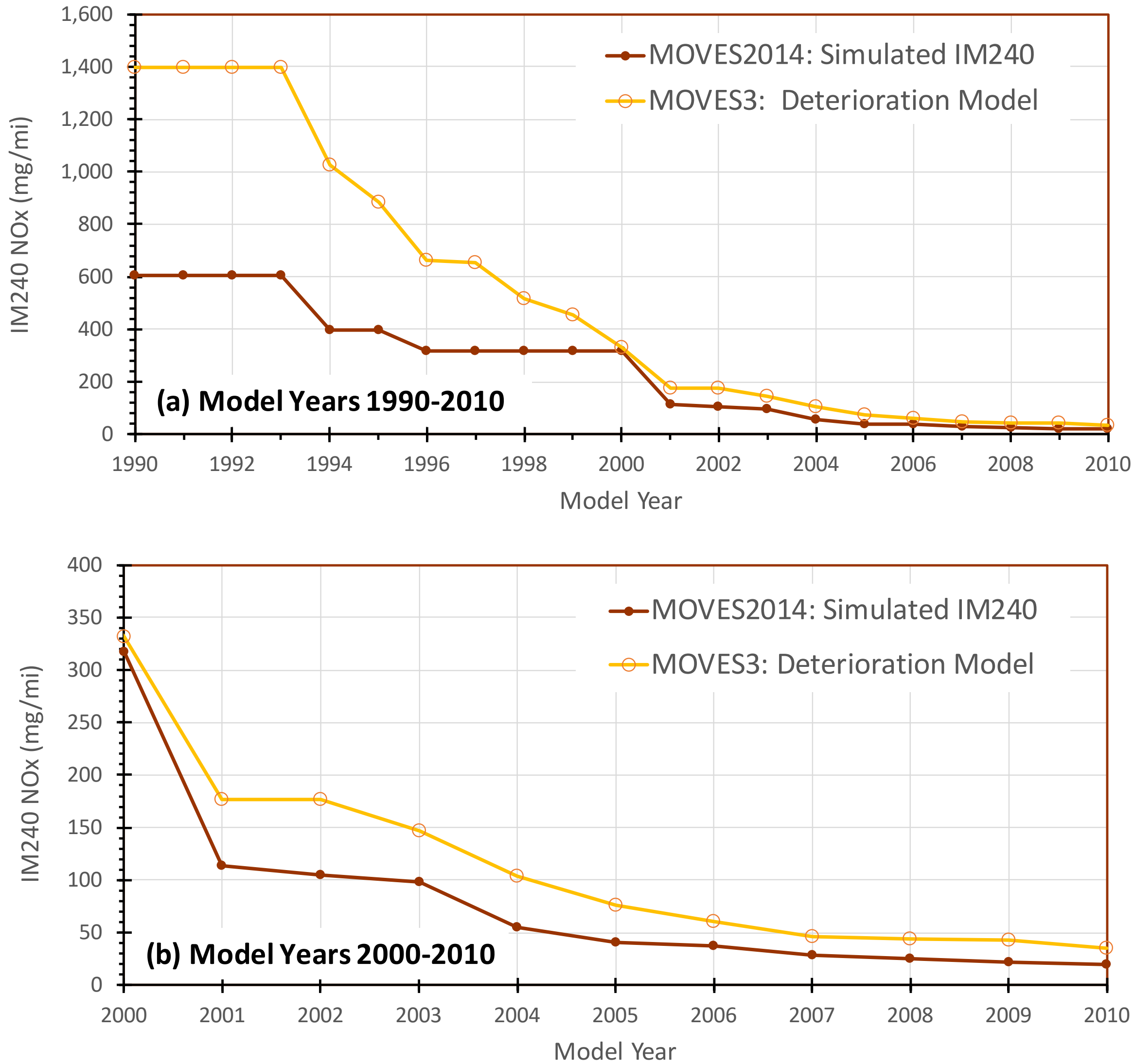


Figure 3-59 NO_x for Cars: Trends by model year IM240 emissions simulated from MOVES2014 rates and estimated from Denver IM240 at age = 2 years: (a) Overview for MY 1990-2010; (b) CLOSEUP on National LEV (2001-2003) and Tier 2 (2004-2010) standards

3.6.7.1.2 Trucks

The picture for trucks is more complicated. As discussed above, we modeled the Denver data for two truck classes, whereas MOVES treats all trucks as a single class.

Accordingly, we needed to resolve the spline model results into a single truck class. We did this by weighting them. We used fractions derived in development of rates for MOVES2010 and MOVES2014. Originally, the fractions were applied to individual truck classes LDT1-LDT4. In the current analysis, fractions for LLDT were calculated by summing fractions for LDT1 and LDT2, and fractions for HLDT by summing fractions for LDT3 and LDT4 (Table 3-41).

The summed fractions were used to construct a combined single trend for all trucks, designated at "LDT," as shown in Figure 3-60.

Table 3-41 Truck Class fractions in the light-duty fleet, by model year

Model Year	LDT1	LDT2	LDT3	LDT4	LLDT	HLDT
1990	0.100	0.595	0.185	0.120	0.695	0.305
1991	0.100	0.595	0.185	0.120	0.695	0.305
1992	0.100	0.595	0.185	0.120	0.695	0.305
1993	0.100	0.595	0.185	0.120	0.695	0.305
1994	0.100	0.595	0.185	0.120	0.695	0.305
1995	0.100	0.595	0.185	0.120	0.695	0.305
1996	0.100	0.595	0.185	0.120	0.695	0.305
1997	0.100	0.595	0.185	0.120	0.695	0.305
1998	0.100	0.595	0.185	0.120	0.695	0.305
1999	0.100	0.595	0.185	0.120	0.695	0.305
2000	0.100	0.595	0.185	0.120	0.695	0.305
2001	0.098	0.598	0.187	0.117	0.696	0.304
2002	0.085	0.634	0.172	0.109	0.719	0.281
2003	0.093	0.585	0.183	0.140	0.677	0.323
2004	0.085	0.558	0.316	0.040	0.644	0.356
2005	0.078	0.748	0.147	0.027	0.826	0.174
2006	0.097	0.610	0.247	0.046	0.707	0.293
2007	0.089	0.554	0.340	0.017	0.644	0.356
2008	0.085	0.550	0.350	0.015	0.635	0.365
2009	0.085	0.550	0.350	0.015	0.635	0.365
2010	0.085	0.550	0.350	0.015	0.635	0.365

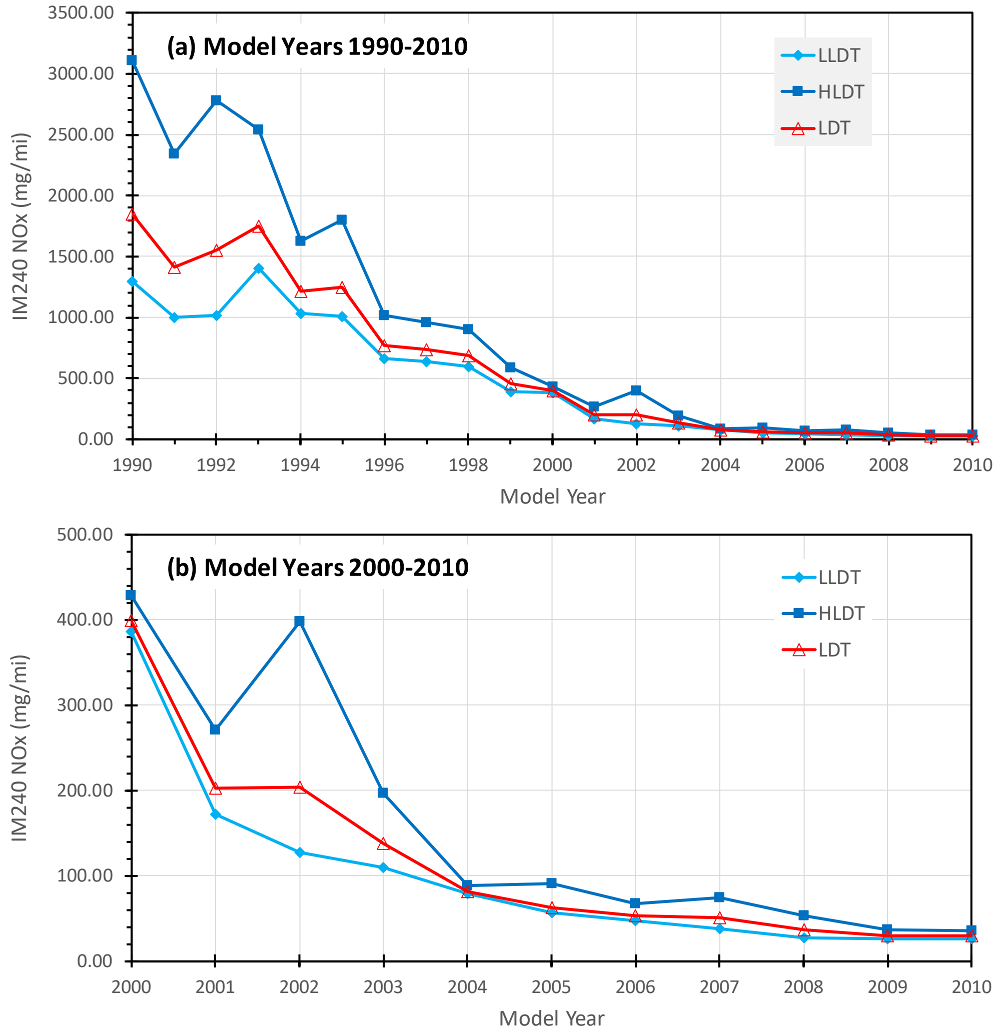


Figure 3-60 NO_x: Estimated IM240 emissions vs. model year at age 2, for individual and weighted truck classes: (a) full model-year range (1990-2010); (b) Closeup on model-years (2000-2010)

Trends in predicted and simulated IM240 emissions for combined trucks (LLDT + HLDT = LDT) are shown in Figure 3-61. Like the trends for cars, the predicted Denver results show a steady decline in truck emissions from 1993 to 2001. During this period, however, the differences between the Denver and MOVES2014 values are not as prominent as those for cars. In addition, the Denver results show a gradual decline from 2001-2004, whereas the MOVES2014 values remain stable. In this interval, the MOVES rates reflect the assumption that the heavier trucks (HLDT) remain at elevated Tier-1 levels, while the lighter trucks (LLDT) have come under reduced National LEV standards. During the adoption of Tier 2 standards (2004-2010) the Denver trend is consistently higher than the MOVES trend, as it is for cars, although differences are relatively small.

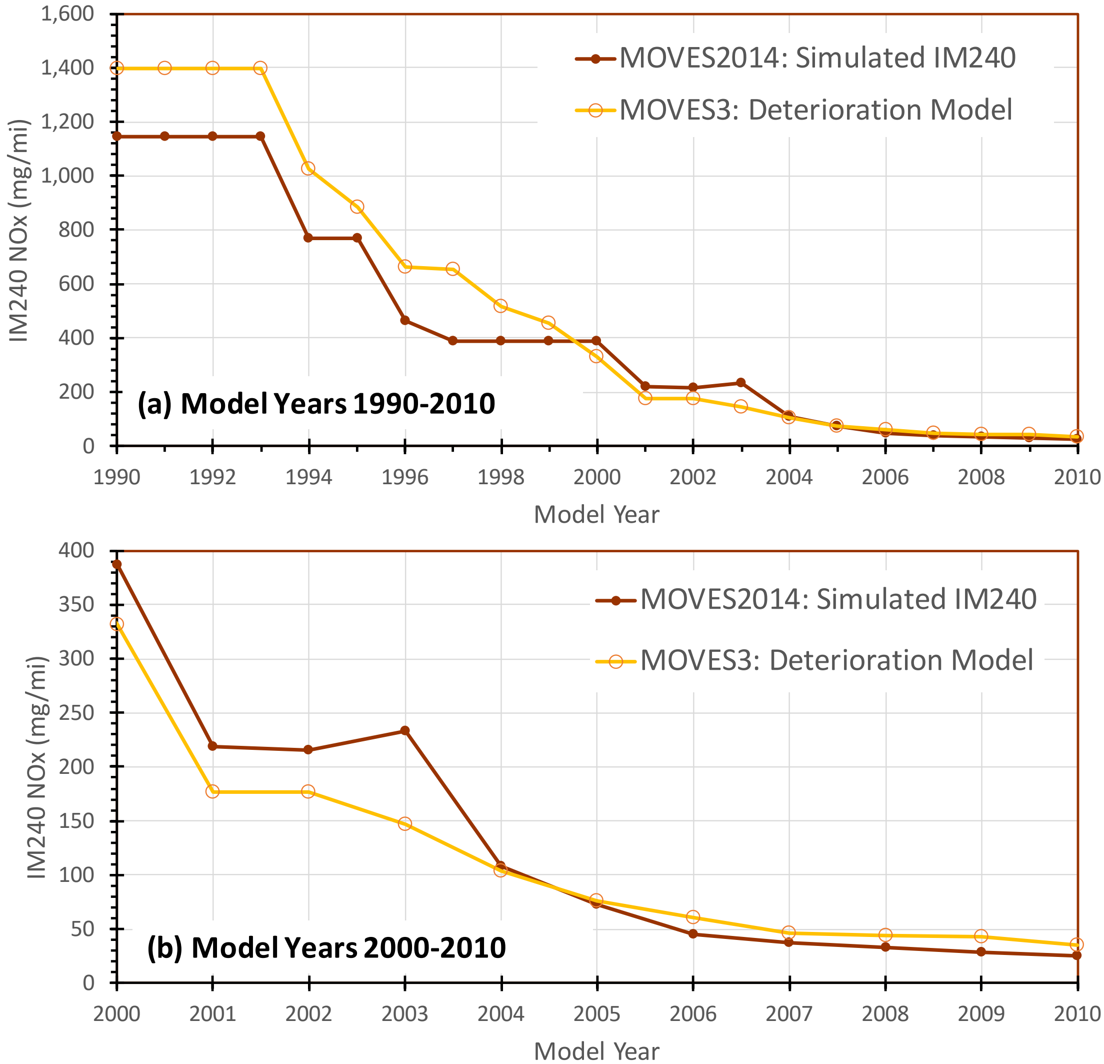


Figure 3-61 NO_x for Trucks (LDT): Trends by model year IM240 emissions simulated from MOVES2014 rates and estimated from Denver IM240 at age = 2 years: (a) Overview for MY 1990-2010; (b) CLOSEUP on National LEV (2001-2003) and Tier 2 (2004-2010) standards

3.6.7.2 Calculating NO_x Adjustments

Based on these trends, as shown in Figure 3-60 for cars and Figure 3-61 for trucks, the "young-vehicle" adjustments for each model year were calculated as the ratio

$$A_{young} = \frac{\text{predicted Denver IM240}}{\text{simulated MOVES IM240}} \qquad \text{Equation 3-44}$$

The adjustments for cars and trucks are shown in Figure 3-62. The adjustments for cars are generally larger (> 2.0) for model years prior to 1997 and between about 1.5 and 2.0 for model years after 2005. The adjustments for cars are consistently > 1.0, except for model year 2000, where the value is very close to 1.0.

The adjustments for trucks are generally smaller than those for cars, always < 2.0 for model years prior to 2000, and < 1.5 for all model years after 2006. In the intervening years, 2001-2005, the adjustments are < 1.0, ranging as low as 0.50.

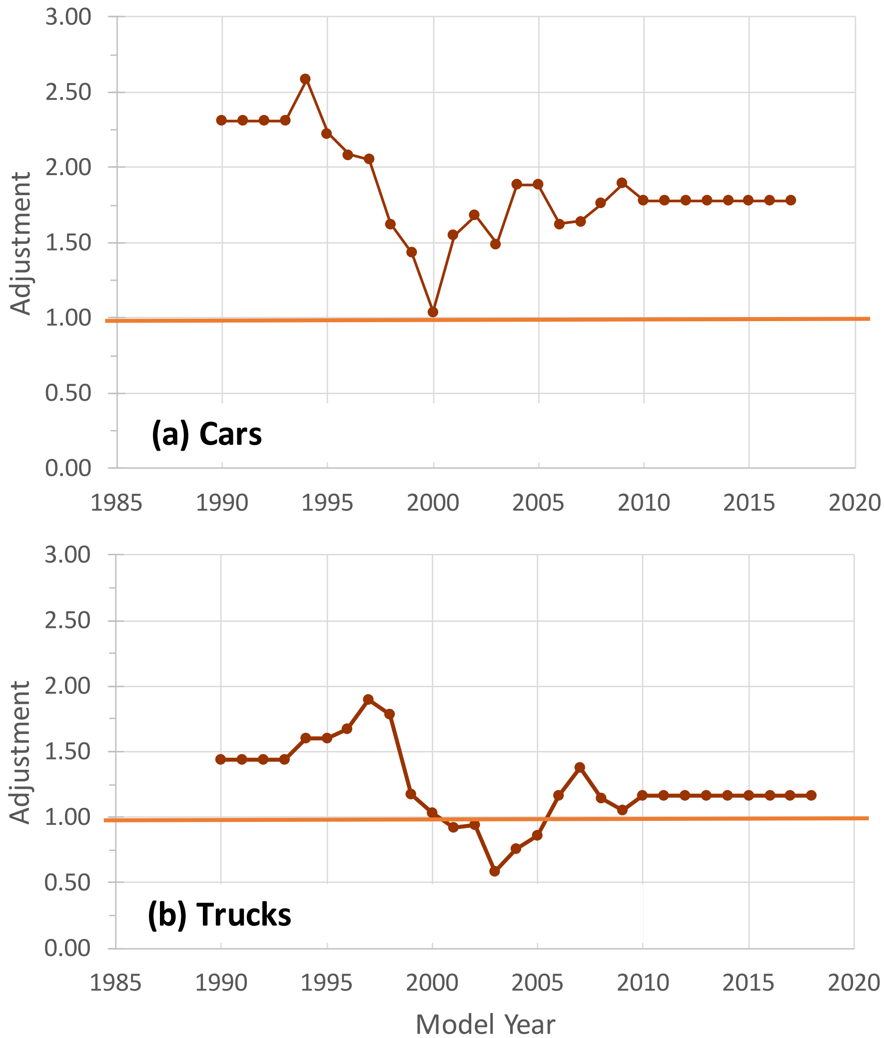


Figure 3-62 NO_x: "Young-vehicle" adjustments for (a) Cars and (b) Trucks

3.6.7.3 Adjustments for THC

3.6.7.3.1 Cars at Age 2

As with NO_x, estimates from the spline models based on the Denver IM240s are consistently higher than the simulated MOVES IM240s, as shown in Figure 3-63 below.

Like the trends for NO_x, the Denver IM240 results show a steady decline in emissions from 1994 through 2000 (Figure 3-63 (a)), which years include the phase-in and duration of the Tier 1 emissions standards. The MOVES rates for THC also assume stable emissions during MY 1996-2000. During the second decade (2000-2010) the striking feature is that the predicted Denver

IM240s exceed the MOVES rates by a larger margin than for NO_x (~5-fold rather than ~2-fold) as shown in Figure 3-63 (b).

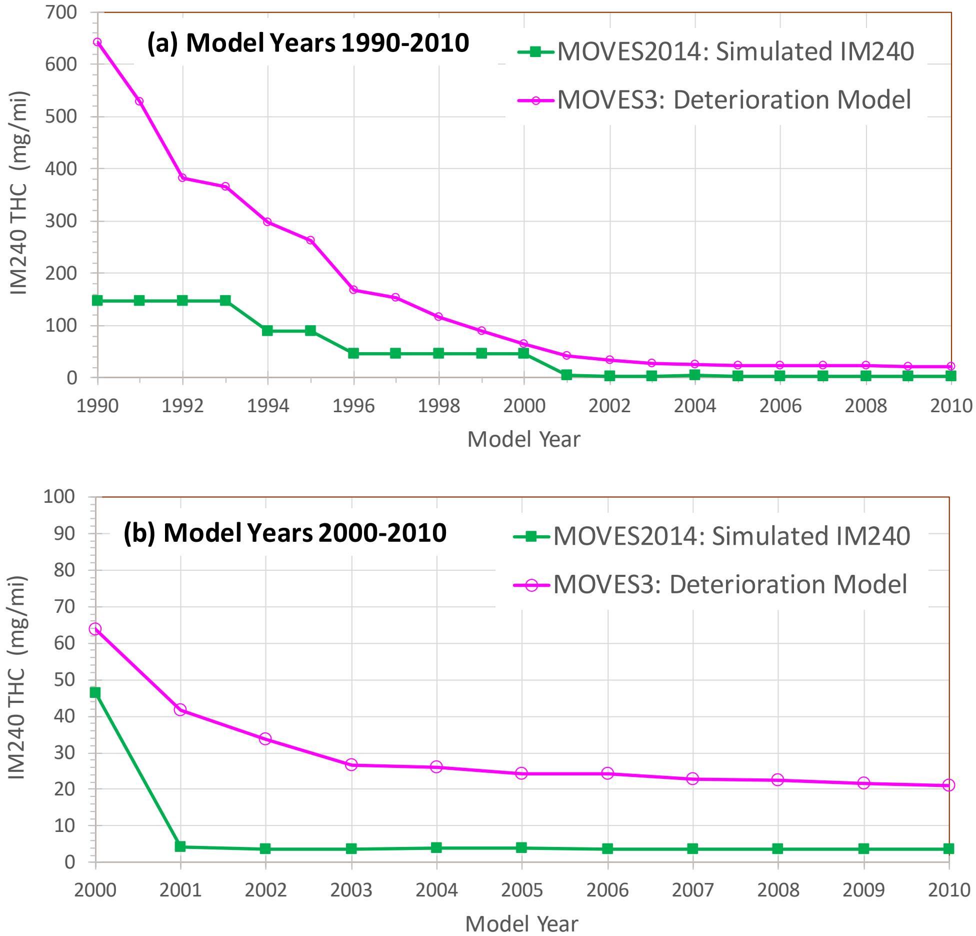


Figure 3-63 THC for Cars: Trends in IM240 emissions simulated from MOVES2014 rates and estimated from Denver IM240 vs. model year at age = 2 years: (a) full model year range (1990-2010); (b) CLOSEUP on model year range (2000-2010)

3.6.7.3.2 Trucks at Age 2

A single trend for trucks was constructed by taking a weighted average of the trends for LLDT and HLDT, using the weights shown in Table 3-41 above. The summed fractions were used to construct a combined single trend for all trucks, designated at "LDT," as shown in Figure 3-64.

Hydrocarbon emissions for both classes show a marked drop at the outset of the Tier 1 standards (1995-1996) (Figure 3-63 (a)). During this period, the emissions for HLDT are noticeably higher than those for LLDT. In addition, and contrast to NO_x, the trend for HLDT remains higher than that for LLDT throughout the Tier-2 phase-in (2004-2010) (Figure 3-64 (b)).

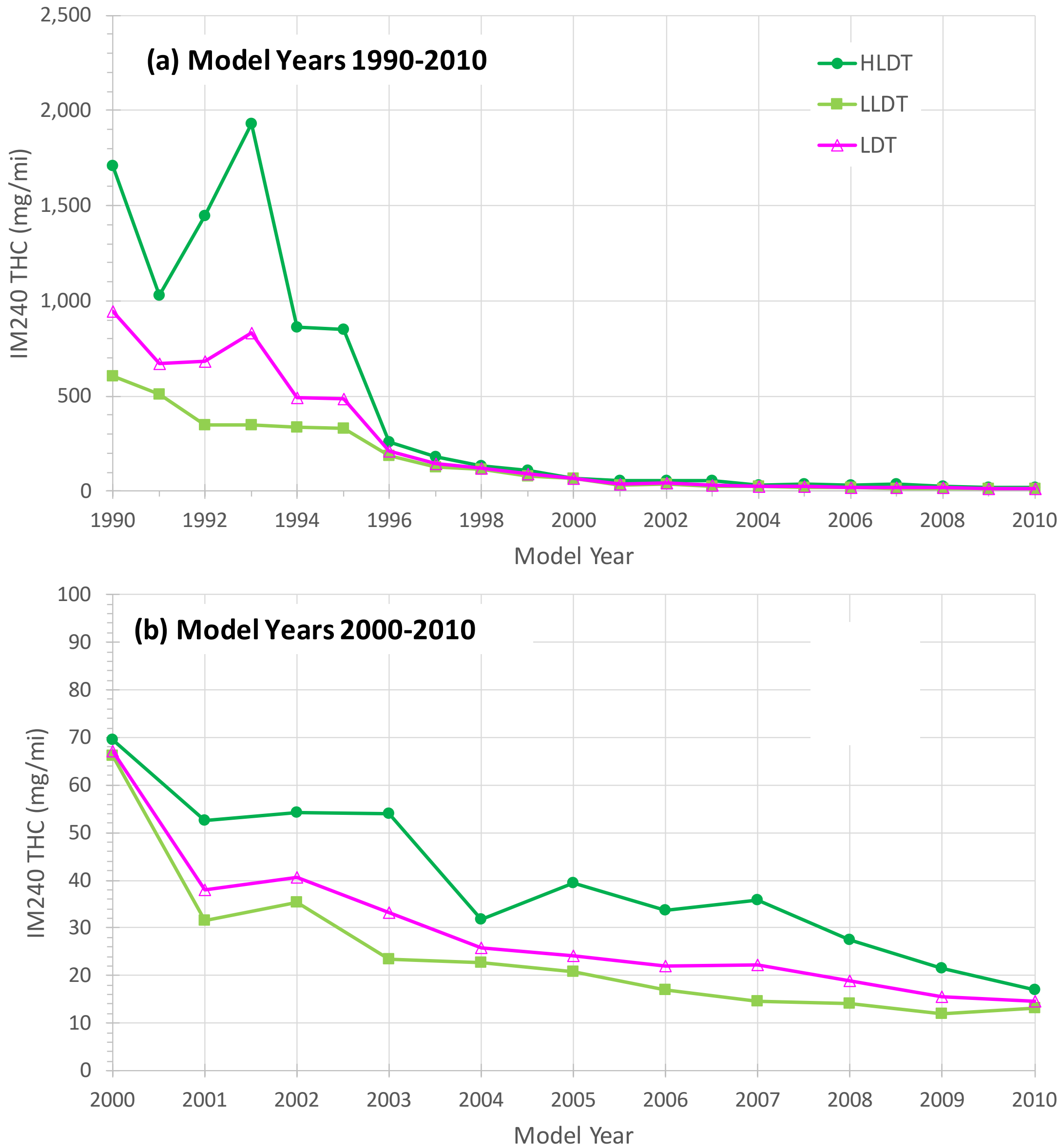


Figure 3-64 THC: Estimated IM240 emissions vs. model year at age 2, for individual and weighted truck classes: (a) full model-year range (1990-2010); (b) Closeup on model-years (2000-2010)

Trends in predicted and simulated IM240 emissions for combined trucks (LLDT + HLDT = LDT) are shown in Figure 3-65. Like the trends for cars, the predicted Denver results show a steep decline in truck emissions from 1993 to 2001. During this period, however, the differences between the Denver and MOVES values are greater than a factor of 2. In 2004, at the outset of the Tier 2 phase-in, the MOVES2014 rates drop by a factor of 3, whereas the estimates based on Denver data continue a gradual but steady decline. During this period, the Denver estimates remain ~3-5 times higher than the MOVES2014 rates.

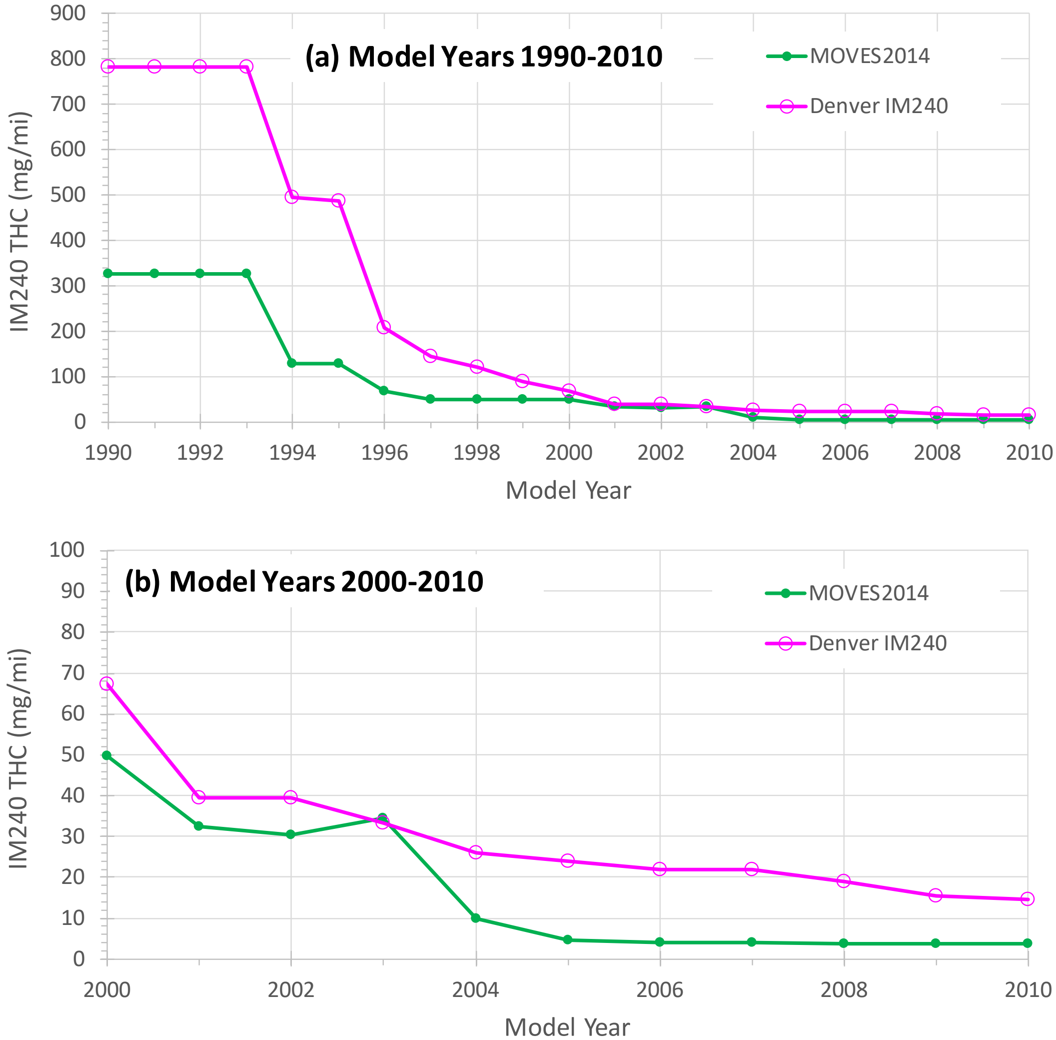


Figure 3-65 THC for Trucks (LDT): Trends in estimated and simulated IM240 emissions vs. model year at age = 2 years: (a) Overview for MY 1990-2010; (b) CLOSEUP on National LEV (2001-2003) and Tier 2 (2004-2010) standards

3.6.7.4 Calculating THC Adjustments

Based on these trends, as shown in for cars and for trucks, the "young-vehicle" adjustments for each model year were calculated as for NO_x, using Equation 3-44.

The adjustments are cars are shown in (a). For model years prior to 2000, the adjustments are always > 1.0, and below a maximum of 4.5. In 2000, the adjustment peaks at 10.0 as the two trends diverge at the outset of the National LEV standards. In successive model years, the adjustment declines, stabilizing at ~6.0 in 2004 and thereafter.

The adjustments for trucks are smaller than those for cars, always < 4.0 for model years prior to 2000, and < 5.0 for all model years after 2005. In the intervening years, 2001-2005, the adjustments are smaller, ranging as low as 1.0 in 2003.

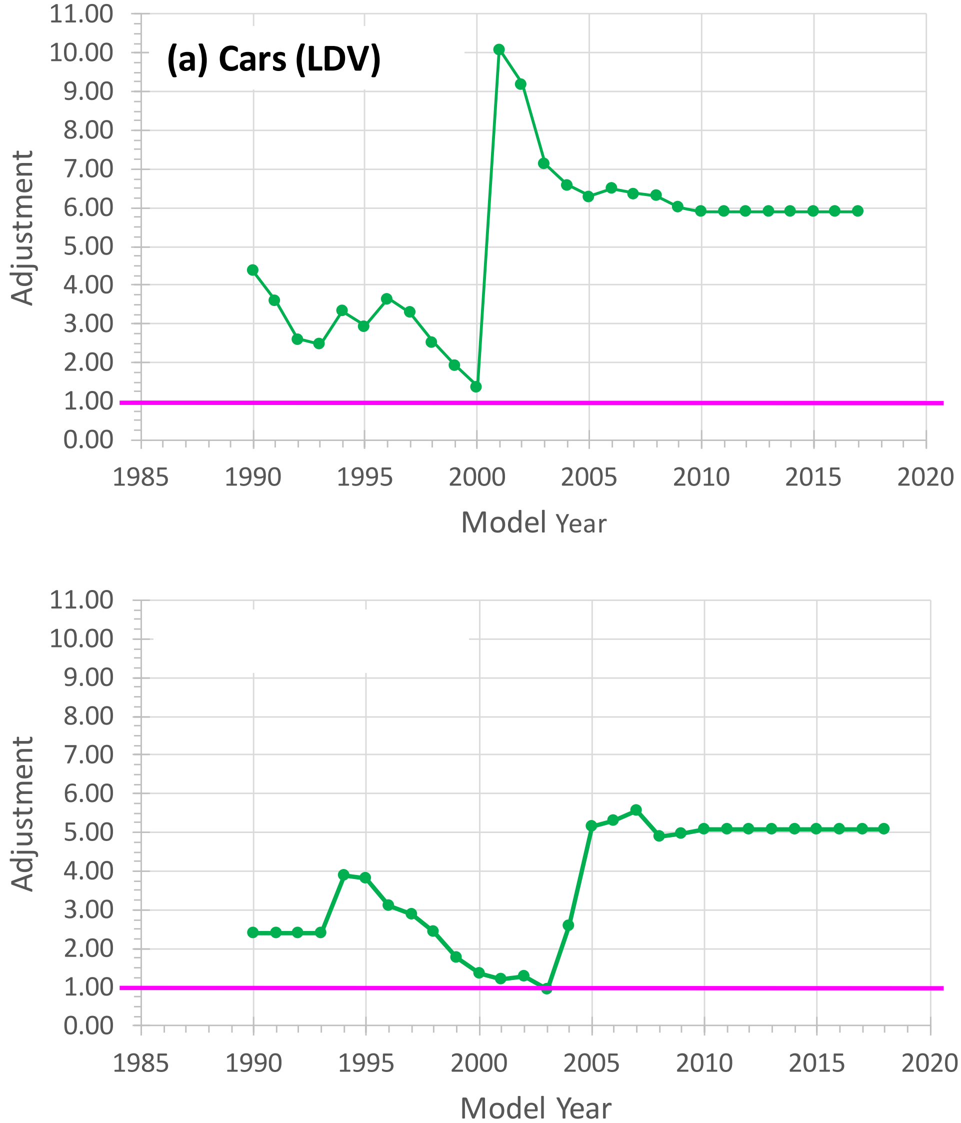


Figure 3-66 THC: "Young-vehicle" adjustments for (a) Cars and (b) Trucks

3.6.8 Deterioration Adjustments

3.6.8.1 Running Process for NO_x

We also used the spline models to project emissions trends vs. age for model years 1990-and-later.

For trucks it is necessary to construct a single trend, as MOVES treats light-duty trucks as a single class. We achieved this goal by calculating a weighted average of the trends for LLDT and HLDT. For this purpose, we used the trends for MY 2000, as the fractions for this model year (0.695, 0.305) are close to the averages for the entire model year range 1990-2010 (0.689, 0.311). For cars, LLDT, HLDT and LDT, deterioration trends for MY 2000 are shown in Figure 3-67.

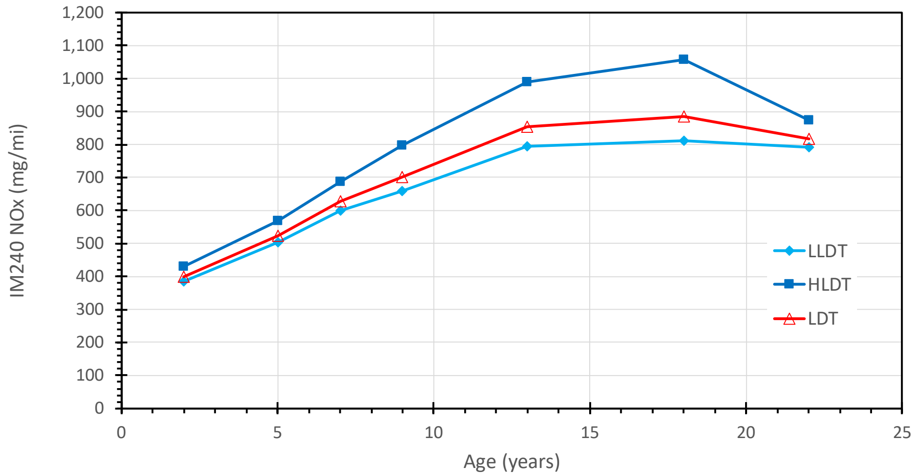


Figure 3-67 NO_x: Trends in emissions vs. age for trucks in model year 2000, by class

We also assembled mean simulated MOVES IM240s by Age Group for model years 1990-and-later, which we plotted against the midpoints of the ageGroups. Alongside the MOVES rates, we plot the Denver results against ages coinciding with or close to the midpoints of the ageGroups, i.e., 2, 5, 7, 9, 12.5, 17.5 and 23 years, respectively.

In Figure 3-68, we've plotted examples for a "Tier 1" model year (1998) and a "Tier 2" model year (2008) for both cars and trucks. The differences at age = 2 reflect the effects of the "young vehicle" adjustments as described above. For the remaining ages, the Denver trends reflect the age slopes for the spline models and those for the MOVES2014 values reflect the deterioration assumptions in the MOVES2014 rates. For ages after 5 years (ageGroup 4-5 years), the patterns vary with the Denver predictions exceeding the MOVES rates in some cases and the reverse in others.

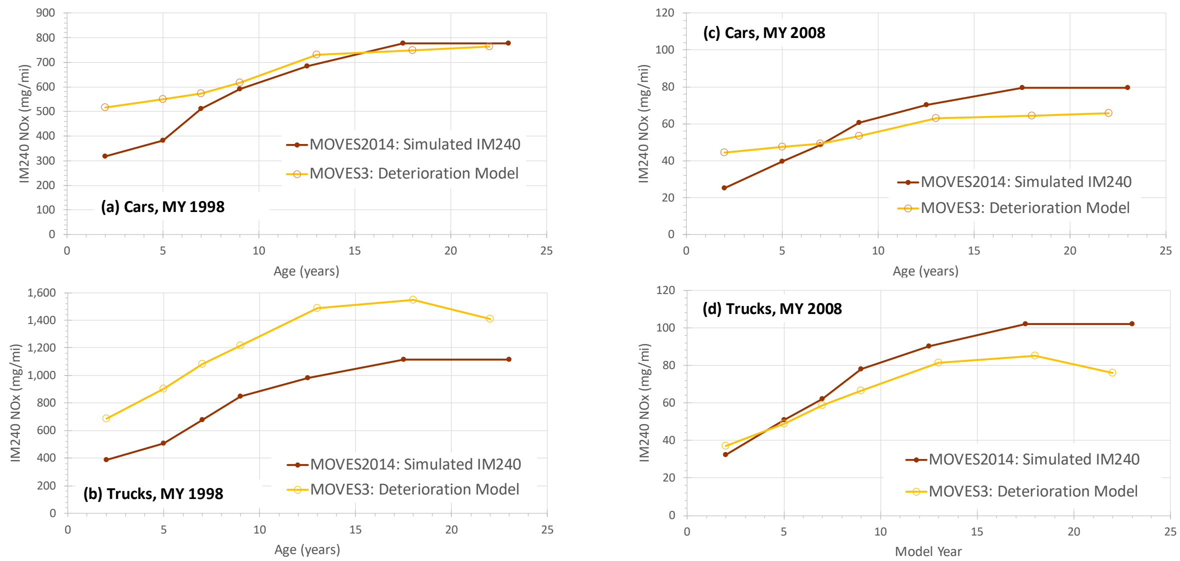


Figure 3-68 NO_x: Predicted trends in IM240 emissions vs age for cars and trucks in two model years

To express the deterioration shown in in proportional or relative terms, we can normalize the trends in Figure 3-68 to the first age group (age = 2). The values at age = 2 are converted to 1.0 and those for the remaining age groups to ratios relative to the first group, as shown in Figure 3-69. Note that the relative trends in the Denver-based values are identical in both model years for cars and trucks as this outcome is an implication of the premises of the spline models.

The trends show clearly that proportional deterioration in the MOVES2014 rates is substantially higher than in the Denver IM240 dataset. This point is conspicuous in the case of cars. The MOVES rates increase by factors of 2.5 and 3.0 in 1998 and 2008, respectively. In contrast, the Denver-based values increase by only a factor of 1.5. For trucks the result is somewhat less marked, with MOVES2014 rates increasing by about a factor of 3.0 and the Denver-based values by about 2.25.

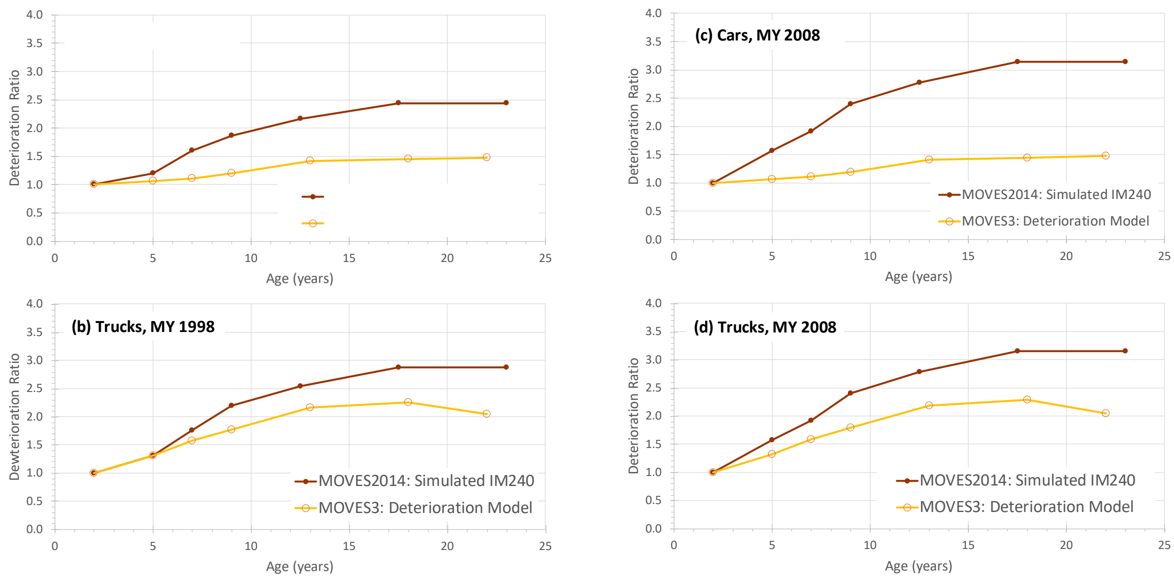


Figure 3-69 NO_x: Deterioration ratios for cars and trucks in two model years

3.6.8.2 Running Process for THC

For trucks, we constructed a single trend for trucks (LDT) as a weighted average of the trends for LLDT and HLDT, using the MY2000 LLDT & HLDT weighting factors, as described for NO_x, above. The individual and combined trends are shown in Figure 3-70.

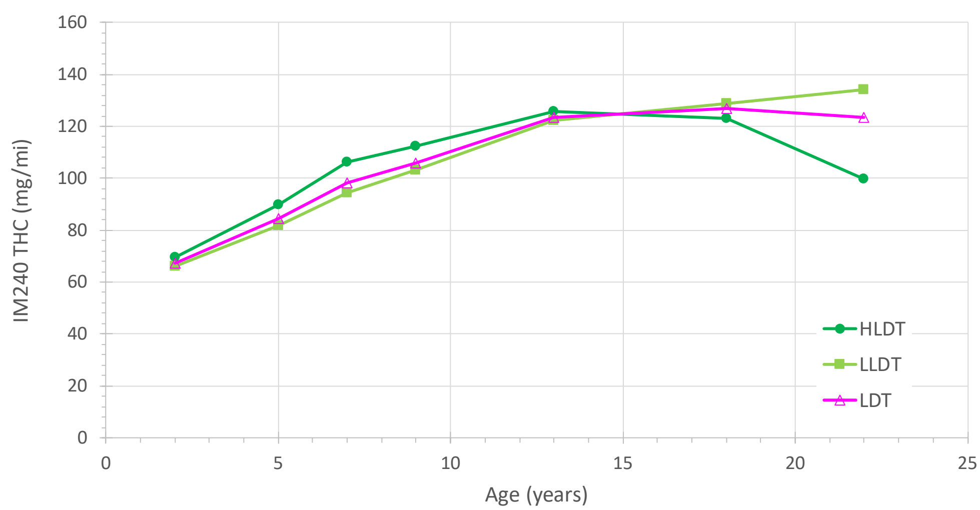


Figure 3-70 THC: Trends in emissions vs. age for trucks in model year 2000, by class

As with NO_x, we plotted mean simulated MOVES IM240s and Denver-based values against ages coinciding with or close to the midpoints of the ageGroups, i.e., 2, 5, 7, 9, 12.5, 17.5 and 23 years, respectively.

In Figure 3-71, we show results for MY 1998 and 2008 for both cars and trucks. The differences at age = 2 reflect the effects of the "young vehicle" adjustments as described above. In 1998 (Figure a and b), the deterioration trends in the MOVES2014 rates are aggressive enough that the MOVES2014 rates are higher than the Denver-based values after 9 years of age (the 8-9 year ageGroup). In 2008 (Figure c and d), the Denver rates are higher than the MOVES2014 rates at all ages.

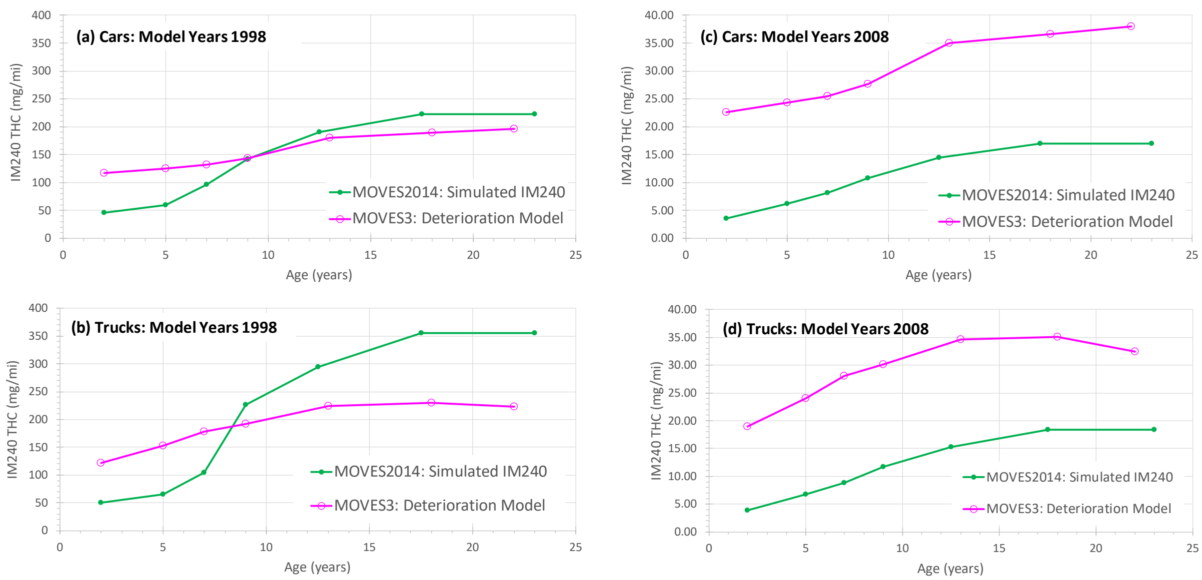


Figure 3-71 THC: Predicted trends in IM240 emissions vs age for cars and trucks in two model years

Deterioration trends normalized to 2 years are shown in Figure 3-72. Like NO_x, the trends show clearly that proportional deterioration in the current MOVES rates is substantially higher than in the Denver IM240 dataset. However, for THC, the differences are more pronounced than for NO_x. The MOVES rates increase by maximum factors of 5-7 in both model years. In contrast, the Denver-based values increase by factors between 1.7-2.0 for both cars and trucks.

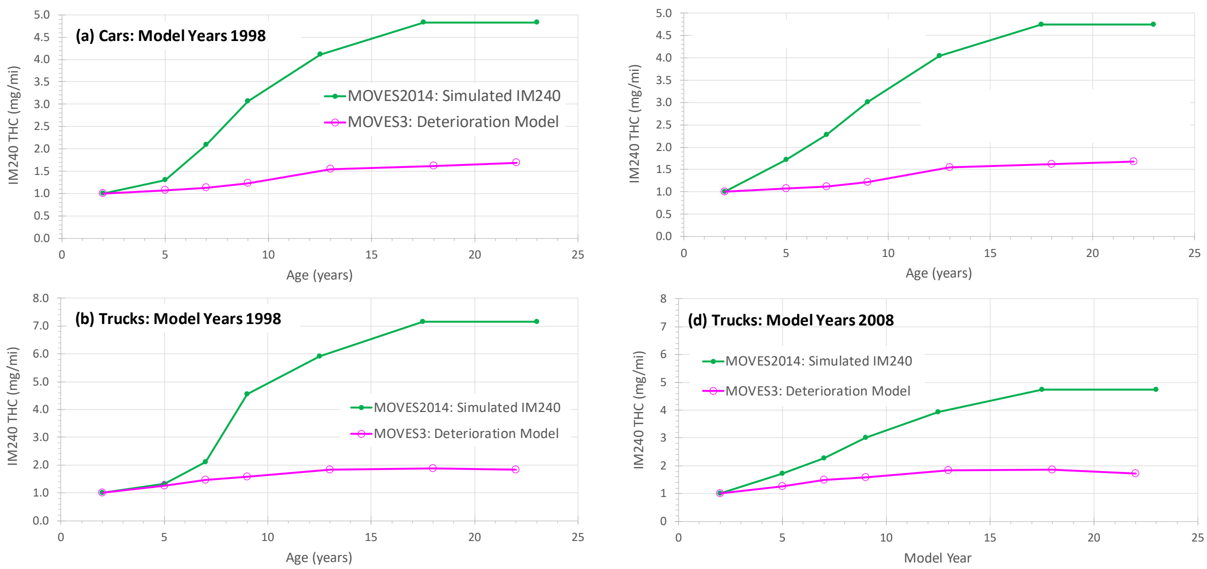


Figure 3-72 THC: Deterioration ratios for cars and trucks in two model years

3.7 Running Exhaust Emission Rates (CO for MY 1990 and Later)

3.7.1 Data Source

For CO, we did not use the Denver IM240 dataset as we did for HC and NO_x. When reviewing the Denver IM240 data, we saw that emission trends with model year were contrary to expectations. The averages for model years 2007-2010 were higher than those for MY 2004-6, despite advances in technology over that time. For the current update, time was not available to adequately evaluate the issue and rule out CO measurement issues.

Instead, we used a large set of remote-sensing data compiled by the Colorado Department of Public Health and Environment (CDPHE). This dataset was collected to serve the Clean-screen program for the Denver Metropolitan Inspection and Maintenance Program, described above. The data is collected through the deployment of remote-sensing equipment around the city on an ongoing basis. The scope of the dataset is similar to the Denver IM240 dataset used for HC and NO_x.

We elected to use a subset of the data that included CY2009-2014, a six-year period for which the instruments and data processing were consistent. We excluded the two most recent calendar years because the remote sensing contractor adopted a newer instrument and modified data processing procedures which may have affected the observed trends over time. For modeling purposes, we used a data subset including model years 1990-2010.

We are continuing to evaluate the RSD data and measurement methods to inform our analysis for future versions of MOVES.

3.7.2 Vehicle Classes

We relied on vehicle classes as defined by CDPHE. Vehicles are classified simply as "Cars" (LDV) or "Trucks" (LDT). We did not attempt to distinguish "Light" from "Heavy" light trucks as we did with the IM240 dataset.

The samples are very large, containing millions, rather than thousands of data points (Table 3-42). However, it is important to bear in mind that the sample sizes reflect individual measurements, approximately 1 sec in duration, rather than the I/M test cycles which are 240 secs in duration.

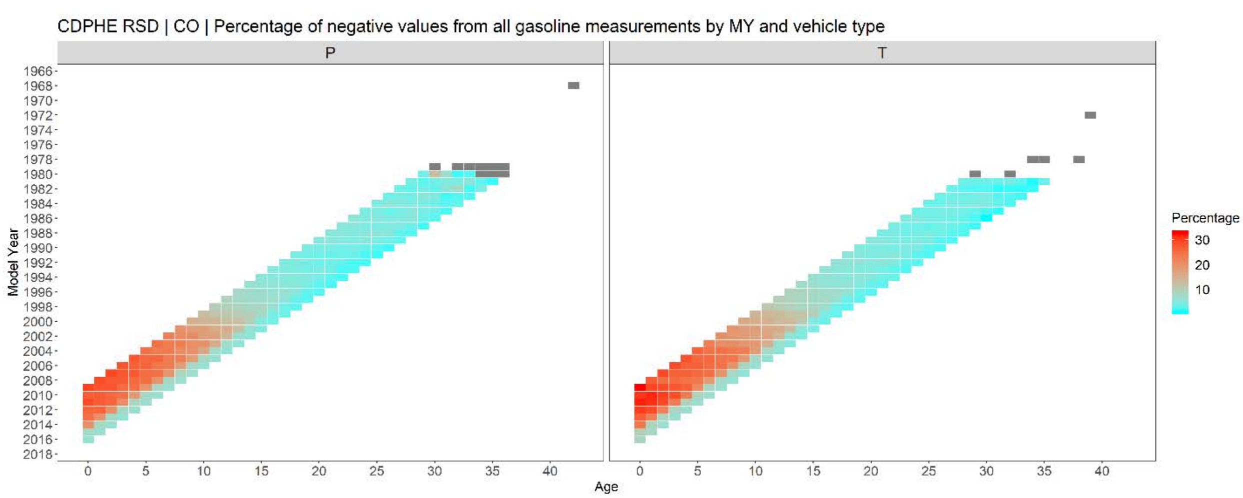
In addition, a feature in remote sensing data is that some fraction of the measurements take values that are zero or negative. Because negative emission rates are physically impossible, we interpret the negative values as "missing." The numbers of negative values increase with model year, as vehicles become cleaner and more difficult for the remote-sensing instrument to quantify.

Table 3-42 Definitions for Vehicle Classes in the Denver Evaluation Sample

Category	Vehicle Class	Description	No. Meas. (incl. negatives)	No. Meas. (excl. negatives)
Cars	LDV	Light-Duty Vehicles	14,965,000	13,385,000
Trucks	LDT	Light-Duty Trucks	19,860,000	17,608,000
Total			34,825,000	30,993,000

The table shows total numbers of measurements, including and excluding negative. For the entire sample, the prevalence of negatives is approximately 11% for both cars and trucks. However, the numbers of negatives vary throughout the sample, as shown in Table 3-43 For the oldest vehicles (model year ca. 1990), the fractions of zero/negative values are < 5%, whereas in the newest model years (ca. 2010) the fractions exceed 25%.

Table 3-43 CO: Samples of Passenger Cars (P) and Light Trucks (T) in the Denver Evaluation Sample



3.7.3 Data Review

For the remote-sensing data, the datasets were so large that plotting all points proved impractical. However, we did average the data to obtain trends by model year and age and plotted these trends on linear and logarithmic scales. Note that the data shown in the plots were averaged after excluding negative values. While biasing the results, this approach ensures that the means on linear scale would match those on logarithmic scale, as the negative values cannot be included when the logarithmic transforms are performed.

As neglecting the negative values is incorrect and leads to positive bias in the results, the impression given by these plots must be discounted. Nonetheless, they are helpful in giving an impression that guides the modeling of the dataset.

The trends in means are broadly similar to those viewed above for HC and NO_x. Due to the extremely large samples, the trends look less erratic and better behaved. The linear trends show the characteristic fan behavior and the logarithmic trends show the parallelism evident in the IM240 results. Between 1995 and 1996, the trucks show a larger gap at the outset of the Tier 1 standards than evident in the cars.

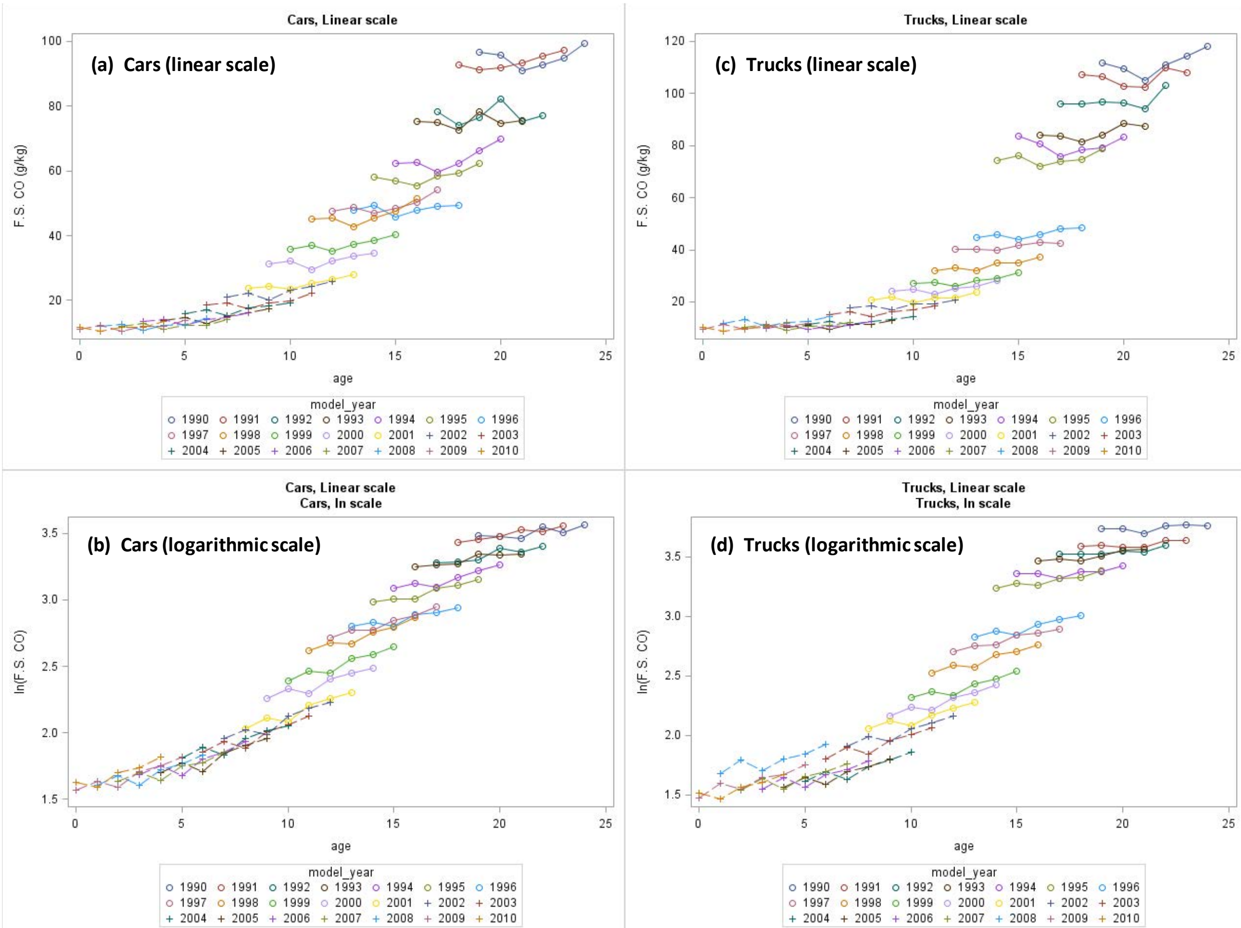


Figure 3-73 CO for Passenger Cars (LDV) and Light Trucks (LDT): Fuel-specific remote-sensing emissions (g/kg), means by model year and age: (a) Cars, linear scale; (b) Cars, natural logarithmic scale; (c) Trucks, linear scale; (d) Trucks, natural logarithmic scale

3.7.4 Model Structure

Despite the differences in data sources, the model structure for CO is identical to that used for HC and NO_x. We fit 3-piece linear splines, as previously shown in Figure 3-52, Equation 3-40 and Table 3-29. It was, however, necessary to modify the approach to assignment of knots, as described below.

3.7.4.1 Optimizing Assignment of Knots

A surprising outcome in fitting models to such large datasets is that statistical tests could not be used in the usual way to select among parameters and models. The reason is that all tests were highly significant in all models. This finding necessitated a different approach to assign the knots in the CO model.

The first step was to fit what we called "overlapping regressions." Each of these regressions is a non-spline regression to a subset of data for five model years. The model was fit with a single slope term and a separate intercept for each model year, as shown in Equation 3-45

$$\ln y = b_0 + b_1 m + b_2 a + \varepsilon \qquad \text{Equation 3-45}$$

where:

$\ln y$ = natural logarithm of fuel-specific remote-sensing emissions (g/kg),

b_0 = grand intercept for a reference model year,

b_1 = intercept coefficient for model year, as difference from b_0,

m = model year as a class or categorical variable,

b_2 = coefficient for age at measurement (a) as a continuous predictor (yr),

If the earliest model year was m, a model would be fit including intercepts for the set of model years $\{m, m+1, m+2, m+3, m+4\}$. We call the models "overlapping" because the second model would include intercepts for the set of model years {m+1, m+2, m+3, m+4, m+5}, and so on, for successive models, through $\{m+16, m+17, m+18, m+19, m+20\}$. As mentioned, in our dataset, m = 1990 and m+20 = 2010.

To account for the presence of the zero and negative values, we employed "left-censored" Tobit regressions. These models were fit, not by OLS, but rather by maximum likelihood, with the likelihood function modified to incorporate the negative values, treated as "censored." Each censored value is assumed to represent some unknown positive value between 0 and an effective "limit of quantitation." For each model, the effective limit of quantitation was assumed to be the minimum positive measured value of lnCO in the current subset of data. We fit the models using the Lifereg procedure in SAS9.4, assuming normal distributions.[d]

In the compiled results, the parameters of interest are the slope terms for age and the "scale" parameters, summarized in Table 3-44. When the Tobit model assumes a normal distribution, the "scale" parameter represents the standard deviation of the residual errors, or the logarithmic standard deviation of the ln-transformed CO data. Squaring this parameter gives the logarithmic variance needed for the reverse transformation, further discussed below. Note that the scale parameters are more uniform for the series of regressions than the corresponding variance estimates based on the IM240 data. See Table 3-39 (page 131) and Table 3-40 (page 132).

[d] The options on the model statement are set to "nolog d=normal."

Table 3-44 CO: Slope terms and logarithmic standard deviations for overlapping regressons, for cars and trucks

Model-year Range	Slope Terms		Logarithmic Std. Dev.	
	Cars	Trucks	Cars	Trucks
1990 -1994	0.03258	0.02064	1.628	1.726
1991 -1995	0.03668	0.02766	1.622	1.730
1992 -1996	0.03776	0.03590	1.625	1.699
1993 -1997	0.04388	0.04336	1.635	1.666
1994 -1998	0.04979	0.05106	1.652	1.635
1995 -1999	0.05664	0.05699	1.665	1.622
1996 -2000	0.06166	0.06319	1.683	1.612
1997 -2001	0.06983	0.06454	1.692	1.610
1998 -2002	0.07606	0.06655	1.703	1.604
1999 -2003	0.08017	0.06789	1.704	1.604
2000 -2004	0.08097	0.06756	1.696	1.586
2001 -2005	0.08378	0.06695	1.681	1.564
2002 -2006	0.08233	0.06673	1.662	1.544
2003 -2007	0.07861	0.06542	1.635	1.529
2004 -2008	0.07529	0.06381	1.611	1.531
2005 -2009	0.07564	0.06541	1.593	1.531
2006 -2010	0.07399	0.06519	1.576	1.535

To lay the basis for assignment of knots, the next step was to assign the slope terms for each model year range to the "parallelogram" shaped MY × Age blocks to which they applied, as shown for a limited set of examples in Table 3-45. With all blocks thus vertically arranged, the slope terms for each age level were averaged across all model years, including all repetition within and across blocks, to produce a single slope composite slope trend by age, one for cars and a second for trucks as shown in Figure 3-74(a) and (c).

Within the trends for cars and trucks we calculated the first differential of the composite slopes at age *a* ($\Delta m^c{}_a$) as shown in Equation 3-46.

$$\Delta m_a^c = m_a^c - m_{a-1}^c \qquad \text{Equation 3-46}$$

The slope differentials for cars and trucks are presented graphically in Figure 3-74 (b) and (d). The plots for trends show the slopes for the youngest vehicles start relatively low, then increase to very broad peaks at 8-9 years, and decline thereafter. The differential plots identify points of inflection in the composite trends. The plots (Figure 3-74, (b) and (d)) show broad inflections at 5-7 years for cars and 7-9 years for trucks. Both cars and trucks have sharp inflections at 15 years. Based on the differentials, knots were assigned for the spline models as shown in Table 3-46.

Table 3-45 CO for cars: Averaging blocks of slope terms for three model-year ranges: 1990-1994, 1999-2003 and 2006-2010

Model Year	Age (years)																								
	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
1990																				0.033	0.033	0.033	0.033	0.033	0.033
1991																			0.033	0.033	0.033	0.033	0.033	0.033	
1992																		0.033	0.033	0.033	0.033	0.033	0.033		
1993																	0.033	0.033	0.033	0.033	0.033	0.033			
1994																0.033	0.033	0.033	0.033	0.033	0.033				
1995																									
1996																									
1997																									
1998																									
1999											0.080	0.080	0.080	0.080	0.080	0.080									
2000										0.080	0.080	0.080	0.080	0.080	0.080										
2001									0.080	0.080	0.080	0.080	0.080	0.080											
2002								0.080	0.080	0.080	0.080	0.080	0.080												
2003							0.080	0.080	0.080	0.080	0.080	0.080													
2004																									
2005																									
2006				0.074	0.074	0.074	0.074	0.074	0.074																
2007			0.074	0.074	0.074	0.074	0.074	0.074																	
2008		0.074	0.074	0.074	0.074	0.074	0.074																		
2009	0.074	0.074	0.074	0.074	0.074	0.074																			
2010	0.074	0.074	0.074	0.074	0.074																				

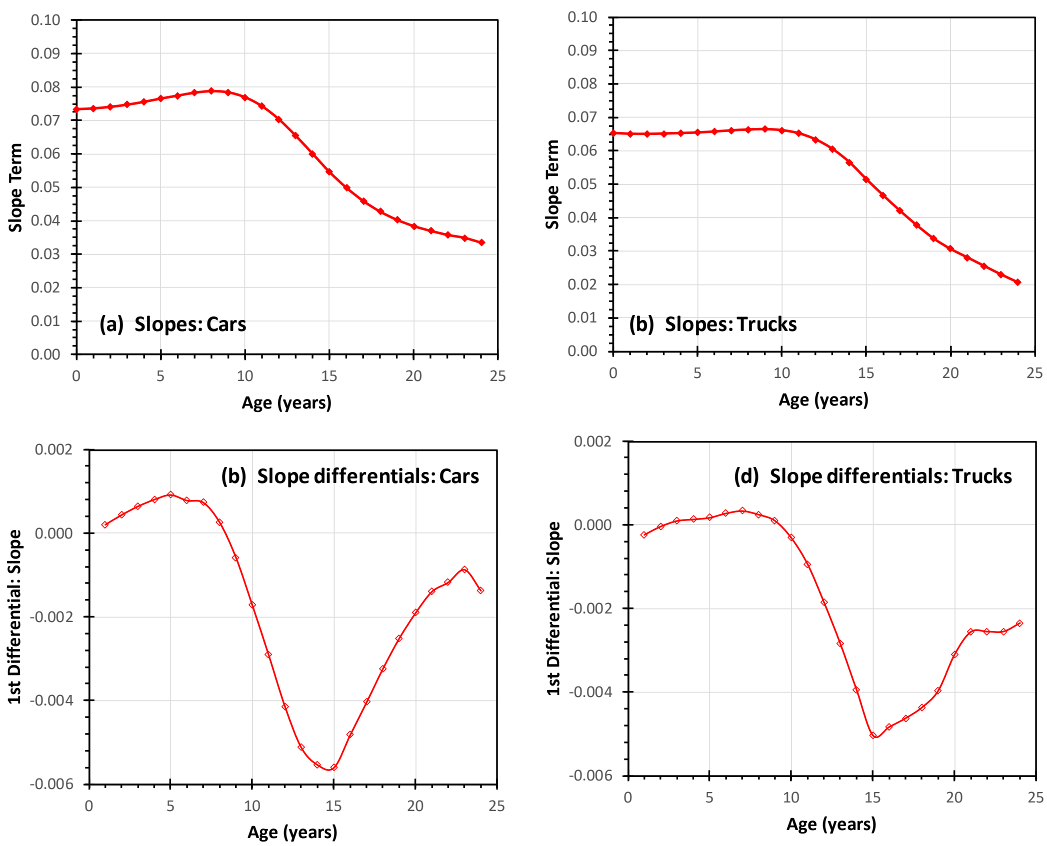


Figure 3-74 CO: composite trends in age slopes and 1st differential of slope from overlapping regresssions for cars and trucks

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Table 3-46 CO: Assignment of knots for three-piece linear spline models

Vehicle Class	k_1	k_2
Passenger Cars (LDV)	7	15
Light Trucks (LDT)	8	15

3.7.5 Model Results

Model fitting results for CO for cars and trucks are shown in Table 3-47 and Table 3-48 above, respectively. The application of the models to predict logarithmic trends is shown graphically in Figure 3-75.

The figures are depicted in logarithmic scale. However, for clarity of presentation, they are presented as common logarithms, i.e., base 10, despite the fact that the models were fit to natural logarithms. On logarithmic scale, the parallelism of trends by model year, within the three segments is easy to see. However, just as with the IM240 data, the sequencing of trends by MY is not always monotonic.

The patterns in slopes for both CO models are similar to those for cars with NO_x and THC, although less pronounced. The slope terms for CO in the first segment are steeper than those for HC and NO_x cars, e.g., ~0.07 as opposed to ~0.025. The slope terms in the center segment are slightly steeper than in the first, but the increase is smaller than for HC and NO_x, e.g., ~0.005 as opposed to ~0.03. In the right-hand segment, the slopes are steeper than those for HC and NO_x, and do not decline. The outcome is that based on the remote-sensing data, mean CO emission levels continue to increase at moderate rates, even after 20 years of age.

Table 3-47 CO for Passenger Cars (LDV): Intercept and slope coefficients for the selected spline model

Coefficients

Parameter	Estimate	Std Error	χ^2	Pr{> χ2 }
Intercept	0.8595	0.002507	117,578.27	0.00000000
Model Year = 1990	1.1215	0.008563	17,152.52	0.00000000
Model Year = 1991	1.1539	0.007702	22,444.15	0.00000000
Model Year = 1992	1.0126	0.006910	21,475.93	0.00000000
Model Year = 1993	1.0056	0.006352	25,060.45	0.00000000
Model Year = 1994	0.8715	0.005875	22,004.53	0.00000000
Model Year = 1995	0.7923	0.005419	21,372.50	0.00000000
Model Year = 1996	0.6199	0.005192	14,258.17	0.00000000
Model Year = 1997	0.6134	0.004865	15,896.99	0.00000000
Model Year = 1998	0.5525	0.004620	14,303.17	0.00000000
Model Year = 1999	0.3628	0.004361	6,920.33	0.00000000
Model Year = 2000	0.2244	0.004120	2,965.97	0.00000000
Model Year = 2001	-0.0051	0.003982	1.66	0.19694683
Model Year = 2002	-0.0624	0.003875	259.05	0.00000000
Model Year = 2003	-0.1409	0.003786	1,385.64	0.00000000
Model Year = 2004	-0.1132	0.003639	966.83	0.00000000
Model Year = 2005	-0.2093	0.003475	3,627.59	0.00000000
Model Year = 2006	-0.1695	0.003274	2,679.87	0.00000000
Model Year = 2007	-0.1782	0.003109	3,285.36	0.00000000
Model Year = 2008	-0.1243	0.002979	1,740.48	0.00000000
Model Year = 2009	-0.0792	0.003142	635.32	0.00000000
Model Year = 2010	0	0		
Age	0.07418	0.000487561	23,145.96	0.00000000
Age $(a - k_1)d_2$	0.004263	0.00067944	39.36	0.00000000
Age $(a - k_2)d_3$	-0.04531	0.001056919	1,837.51	0.00000000
Scale	1.656	0.000350825		
Logarithmic Variance	2.743			

Intercepts

Model Year	$b_0 + b_1$	$b_0 + b_1 - b_3k_1$	$b_0 + b_1 - b_3k_1 - b_4k_2$
1990	1.9810	1.9511	2.6307
1991	2.0134	1.9836	2.6631
1992	1.8721	1.8423	2.5218
1993	1.8651	1.8353	2.5149
1994	1.7310	1.7011	2.3807
1995	1.6518	1.6219	2.3015
1996	1.4794	1.4496	2.1292
1997	1.4729	1.4430	2.1226
1998	1.4120	1.3821	2.0617
1999	1.2223	1.1924	1.8720
2000	1.0839	1.0540	1.7336
2001	0.8544	0.8245	1.5041
2002	0.7971	0.7673	1.4469
2003	0.7186	0.6887	1.3683
2004	0.7463	0.7165	1.3961
2005	0.6502	0.6204	1.3000
2006	0.6900	0.6602	1.3397
2007	0.6813	0.6514	1.3310
2008	0.7352	0.7054	1.3850
2009	0.7803	0.7505	1.4301
2010	0.8595	0.8297	1.5092

Slopes

b_2	$b_2 + b_3$	$b_2 + b_3 + b_4$
0.0742	0.0784	0.0331

Table 3-48 CO for Light-duty Trucks (LDT): Intercept and slope coefficients for the selected spline model

Coefficients

Parameter	Estimate	Std Error	χ^2	Pr{> χ2 }
Intercept	0.6743	0.0018	141,025.61	0.00000000
Model Year = 1990	1.6983	0.0089	36,698.98	0.00000000
Model Year = 1991	1.5661	0.0077	41,844.13	0.00000000
Model Year = 1992	1.5099	0.0069	48,461.88	0.00000000
Model Year = 1993	1.5173	0.0059	66,848.94	0.00000000
Model Year = 1994	1.3885	0.0052	72,623.62	0.00000000
Model Year = 1995	1.3307	0.0047	80,753.59	0.00000000
Model Year = 1996	0.9477	0.0044	46,428.13	0.00000000
Model Year = 1997	0.8857	0.0040	47,826.48	0.00000000
Model Year = 1998	0.7590	0.0037	41,551.27	0.00000000
Model Year = 1999	0.5106	0.0035	21,795.84	0.00000000
Model Year = 2000	0.4085	0.0032	16,000.66	0.00000000
Model Year = 2001	0.2809	0.0031	8,241.98	0.00000000
Model Year = 2002	0.2192	0.0029	5,537.81	0.00000000
Model Year = 2003	0.1404	0.0028	2,450.39	0.00000000
Model Year = 2004	-0.0685	0.0027	666.46	0.00000000
Model Year = 2005	-0.0772	0.0025	952.89	0.00000000
Model Year = 2006	-0.0490	0.0024	430.76	0.00000000
Model Year = 2007	-0.0022	0.0022	1.02	0.31367070
Model Year = 2008	0.2270	0.0021	11,262.74	0.00000000
Model Year = 2009	0.0469	0.0025	365.85	0.00000000
Model Year = 2010	0	0	0	0.00000000
Age	0.06487	0.00033	38,076.22	0.00000000
Age $(a - k_1)d_2$	0.00464	0.00056	69.36	0.00000000
Age $(a - k_2)d_3$	-0.04186	0.00107	1,543.73	0.00000000
Scale	1.58545	0.00030		
Logarithmic Variance	2.514			

Intercepts

Model Year	$b_0 + b_1$	$b_0 + b_1 - b_3k_1$	$b_0 + b_1 - b_3k_1 - b_4k_2$
1990	2.3726	2.3355	2.9633
1991	2.2404	2.2033	2.8311
1992	2.1842	2.1471	2.7749
1993	2.1916	2.1544	2.7823
1994	2.0629	2.0257	2.6536
1995	2.0050	1.9679	2.5957
1996	1.6221	1.5849	2.2128
1997	1.5600	1.5228	2.1507
1998	1.4333	1.3962	2.0240
1999	1.1850	1.1478	1.7757
2000	1.0828	1.0457	1.6735
2001	0.9552	0.9180	1.5459
2002	0.8935	0.8564	1.4842
2003	0.8147	0.7775	1.4054
2004	0.6058	0.5686	1.1965
2005	0.5971	0.5600	1.1878
2006	0.6253	0.5882	1.2160
2007	0.6721	0.6349	1.2628
2008	0.9013	0.8641	1.4920
2009	0.7212	0.6841	1.3119
2010	0.6743	0.6372	1.2650

Slopes

b_2	$b_2 + b_3$	$b_2 + b_3 + b_4$
0.06487	0.06951	0.02765

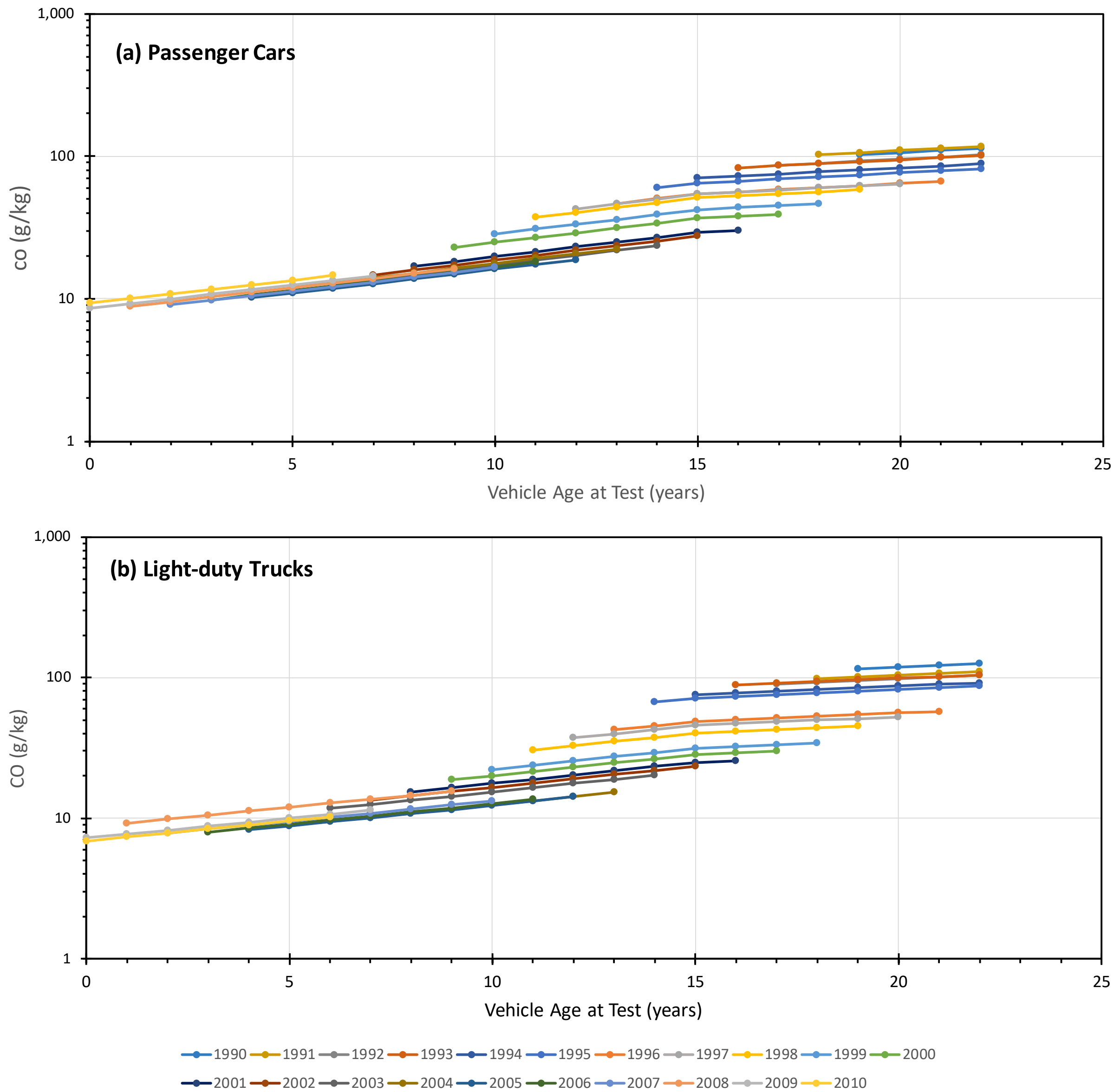

Figure 3-75 CO: Three-piece linear spline deterioration models for two vehicle classes: (a) Passenger cars and, (b) Light Duty Trucks. Note that emissions are expressed on common logarithmic scale

3.7.6 Reverse Transformation

The Tobit regression procedure cannot fit multiple variance terms as the mixed-factor model used with HC and NO_x can. For the reverse transformation with CO, we used the uniform scale parameters fit by the spline models, shown in Table 3-47 and Table 3-48, at bottom. Previously in Table 3-44, we saw that the multiple scale parameters fit in the sets of "overlapping" regressions are fairly uniform. We concluded that using a uniform scale parameter is a reasonable assumption. As the scale parameters represent standard deviations, we squared them to represent logarithmic variances. As with the HC and NO_x models, we performed the reverse transformation using Equation 3-43.

After transformation, the gentle positive increases in slope at the first knot (7-8 years) gives the CO trends an appearance of gentle upwards curvature. The decline in slope at the second knot (15 years) is more abrupt and pronounced.

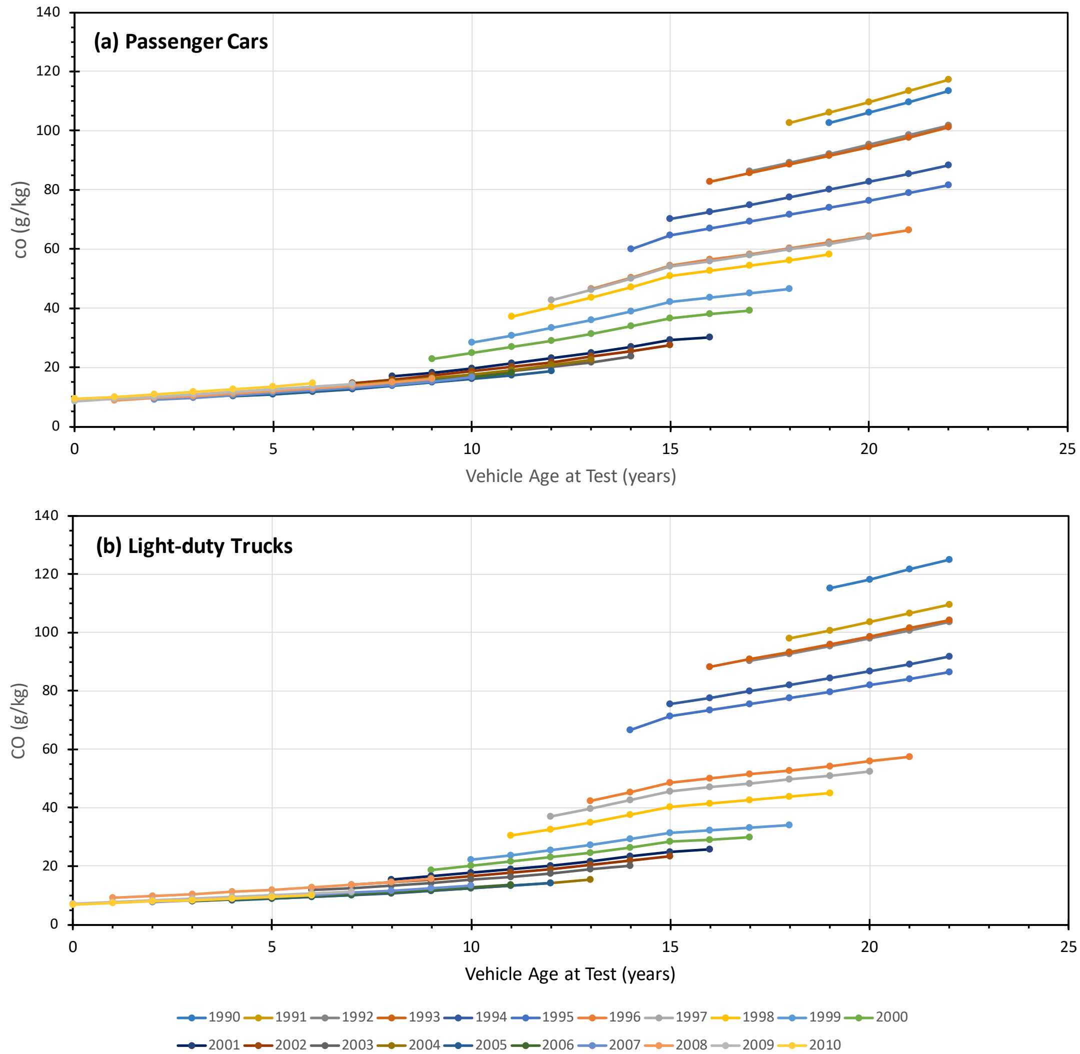

Figure 3-76 CO: Trends in emissions vs. age as predicted by reverse-transformed three-piece ln-linear spline models

3.7.6.1 Translation from Fuel to Distance Bases

Following the reverse transformation, the results still represent fuel-specific emissions, i.e., g/kg. For use in developing MOVES emission rates, it was necessary to express the fuel-specific emissions as mean IM240 results in mg/mi. To achieve this step, is was necessary to multiply the fuel-specific means by corresponding fuel-consumption estimates.

We assumed that the appropriate estimates would represent fuel consumption on the IM240 cycle. To obtain such estimates, we extracted energy-consumption rates for running operation from the MOVES emissionRate table. After translating the energy rates to fuel-consumption, using an appropriate heating value (41.762 kJ/g), we estimated total fuel consumed on the cycle as a weighted sum of fuel consumption rate (kg/hr) by time-in-mode (hr) over the cycle, based on an operating-mode distribution for the cycle. Finally, we divided the total fuel by the total distance of the IM240 cycle (1.96 miles) to get a final result in kg fuel/mile. As MOVES does not represent an age effect for energy or fuel consumption, we simulated IM240 fuel consumption rates by model year, as shown for cars and trucks in Figure 3-77.

This final result was multiplied by fuel-specific CO rates (g/kg) to estimate mg CO/mi on the IM240 cycle.

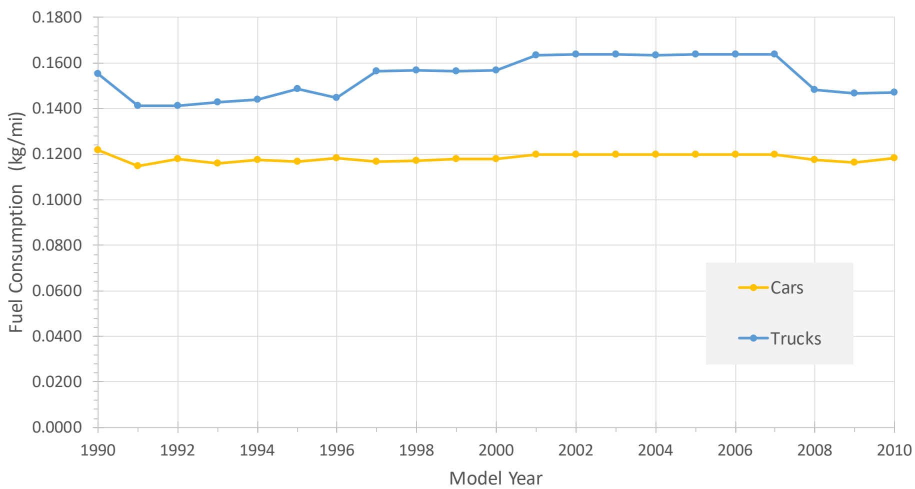

Figure 3-77 Fuel consumption on the IM240 cycle, as estimated from MOVES energy-consumption rates

3.7.7 "Young Vehicle Adjustments"

Estimates from the spline models based on the remote-sensing data are consistently higher than the simulated MOVES2014 IM240s. For cars, the spline-model values are higher than the simulated MOVES2014 results except for the first several model years (Figure 3-78). Between 1994 and 2000, the spline predictions are higher, but the differences are smaller than those for HC. After 2000, both trends are similar in that they settle to stable levels, but with the RSD-based spline predictions slightly more than twice as high.

The trends for trucks are similar to those for cars, with the exception that the trends for trucks in the final eight models years show gentle declines not evident in the trends for cars (Figure 3-79).

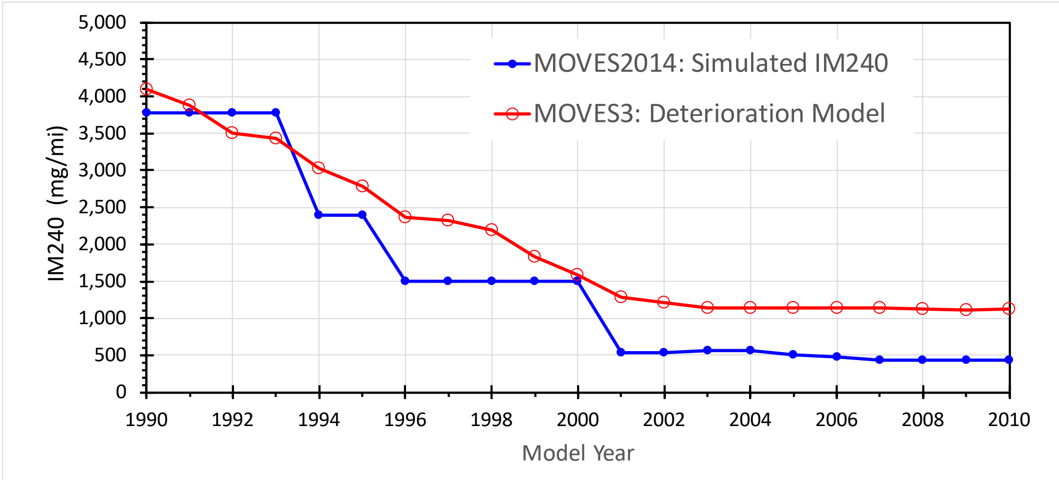

Figure 3-78 CO for Cars: Trends in estimated and simulated IM240 emissions vs. model year at age = 2 years

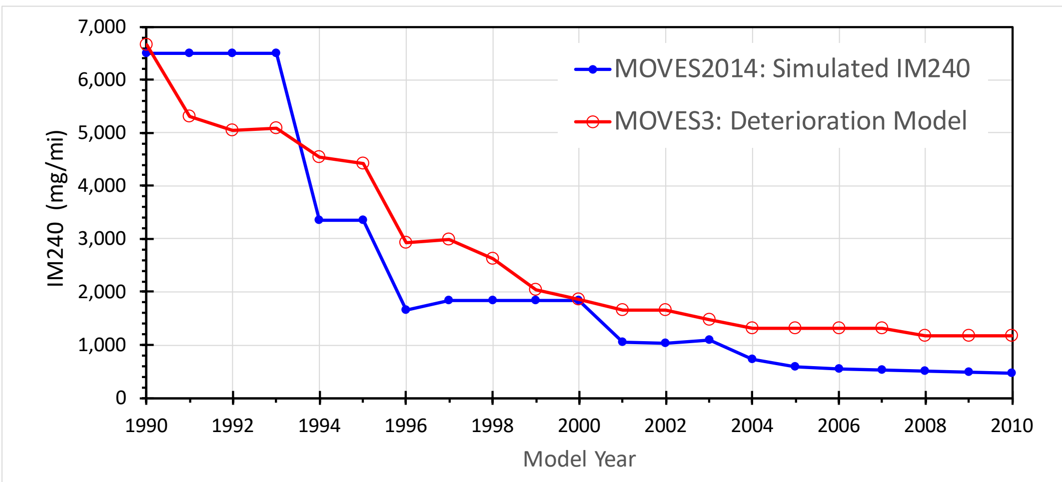

Figure 3-79 CO for Trucks: Trends in estimated and simulated IM240 emissions vs. model year at age = 2 years

3.7.7.1 Calculating Adjustments

Based on these trends, as shown in for cars and for trucks, the "young-vehicle" adjustments for each model year were calculated as for NO_x, using Equation 3-44. Generally, the adjustments for CO are larger than those for NO_x, but less than half of those for HC.

The adjustments are cars are shown in Figure 3-80(a). For model years prior to 2000, the adjustments are variable, ranging from slightly < 1.0 to ~1.6. After model year 2000, the adjustments are larger, between 2.0 and 2.6.

Prior to 2000, the adjustments for trucks follow a similar trend, but with wider variability, ranging from ~0.8 to ~1.8 Figure 3-80(b). After 2000, the truck adjustments also follow a trend similar to cars, but are slightly smaller, reaching maximum values of ~2.5.

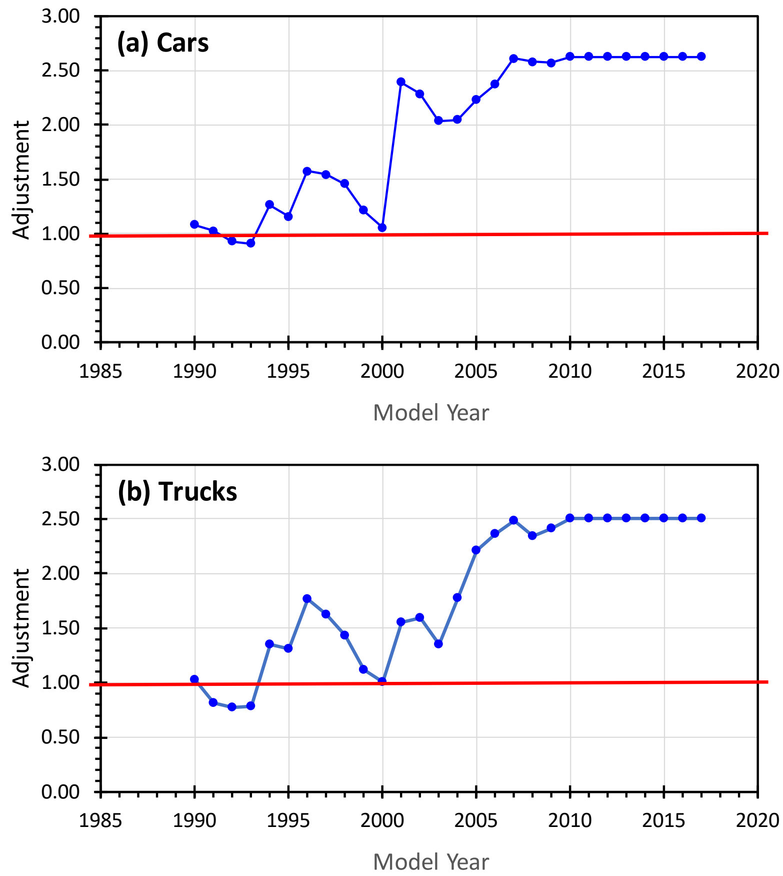

Figure 3-80 CO: "Young-vehicle" adjustments for (a) Cars and (b) Trucks

3.7.8 Deterioration Adjustments

3.7.8.1 Running Process for CO

As with NO_x and THC, we plotted mean simulated MOVES2014 IM240s and Denver-data-based values against ages coinciding with or close to the midpoints of the ageGroups, i.e., 2, 5, 7, 9, 12.5, 17.5 and 23 years, respectively.

Figure 3-81 show results for 1998 and 2008 for both cars and trucks. In all cases except that for trucks in 1998, the spline-model values are higher than the MOVES2014 results at all ages. As mentioned, the updated trends do not decline and stabilize as the current rates do. For trucks in 1998 Figure 3-81(b), the MOVES2014 trend increases aggressively from 7 to 9 years, at which point the MOVES2014 values are higher than the spline-based values.

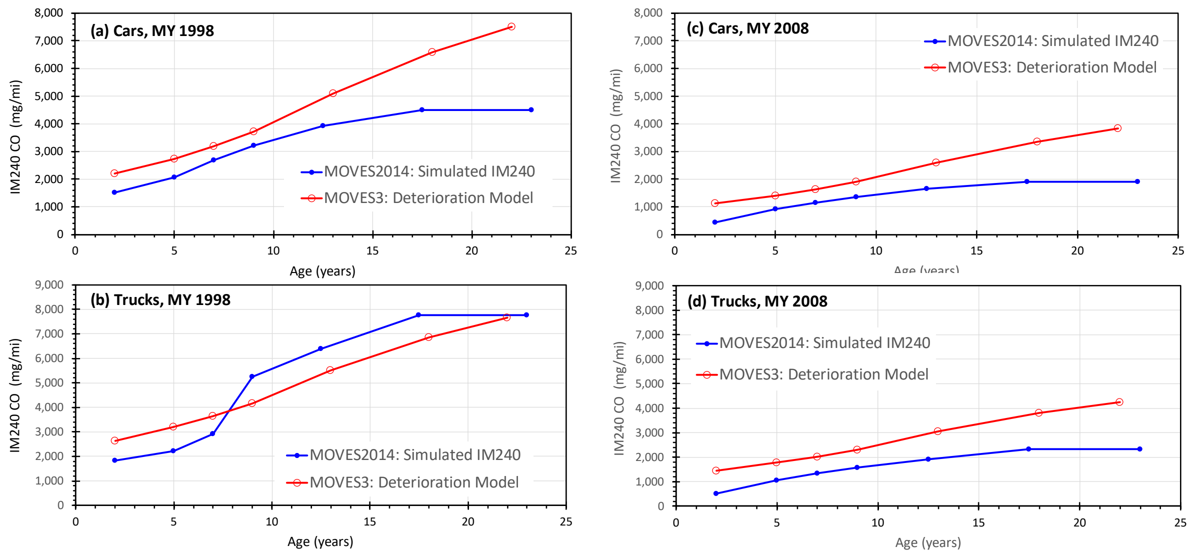

Figure 3-81 CO: Predicted trends in IM240 emissions vs age for cars and trucks in two model years

As shown in Figure 3-82, when viewing deterioration in relative terms (that is, with emissions at all ages normalized to emissions at age 2), the overall picture is similar to that for NO_x and HC. Generally, the spline-based trends have notably lower relative deterioration than the MOVES2014 rates, reaching maximum ratios of 3.5 for cars and 3.0 for trucks. In contrast, for cars in 2008 and trucks in both years, the relative deterioration in the MOVES2014 rates reaches maxima of 4.0 to 4.5. The single exception is MY2008 cars as shown in Figure 3-82(b), in which the relative deterioration is similar for both MOVES and the proposed update.

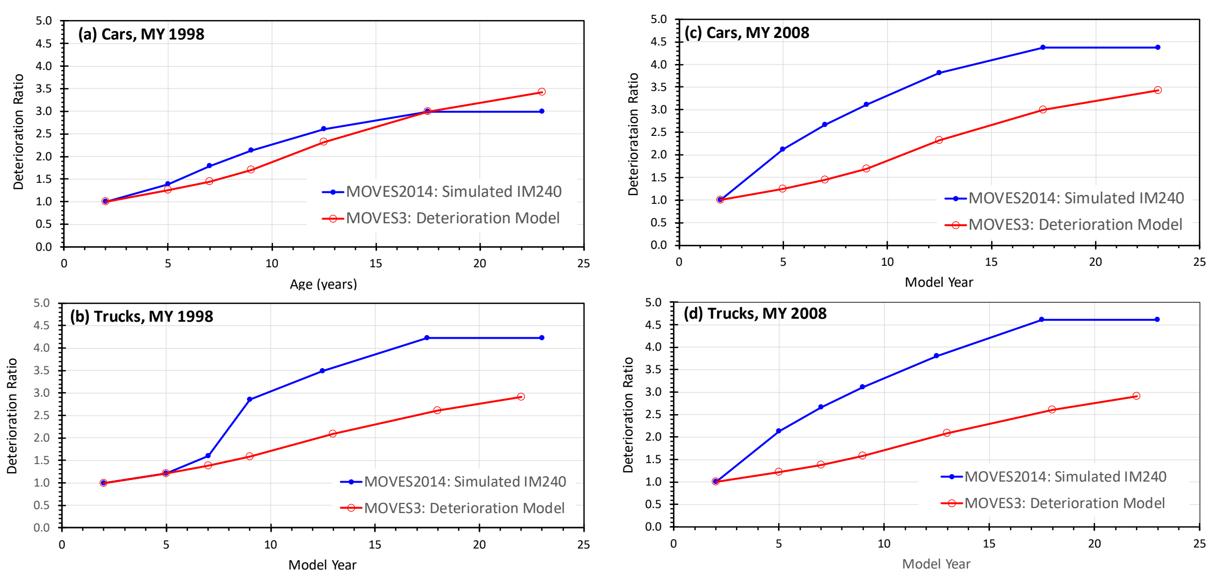

Figure 3-82 CO: Predicted deterioration ratios vs. age for cars and trucks in two model years

3.8 Estimation of Emission Rates for Cold Starts

Within the MOVES modal structure, operating modes for start emissions are defined in terms of soak time (preceding the engine start), as described above in 2.4 (page 20). This section discusses the development of base rates for "cold starts" (operating mode 108).

Activity for start emissions are defined in terms of numbers of start events per day, combined with distributions of soak time, both described in a separate report.[41]

Note that the data sources described in previous sections to estimate rates for running operation do not include results for start emissions. Datasets available for analysis of start emissions are more limited in size and scope.

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

Base start emissions for passenger cars and light-duty trucks, are dependent upon two factors:

1. the (base) emissions level at approximately 75 degrees Fahrenheit,[42]
2. an adjustment based on the length of soak time[43]

These emissions were derived for MOVES2010 and have not been updated.

3.8.1.1 Data Sources

Data used in these analyses were acquired 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 large numbers of vehicles under various conditions.

   We identified (in the MSOD) 549 gasoline-fueled vehicles (494 passenger cars and 55 light-duty 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.[44]
3. 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.[45]
4. During 2004-05, USEPA Office of Transportation and Air Quality (OTAQ) and Office of Research Development (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.[51]

3.8.1.2 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.[46] Based on these data, we derived a correction factor "A" as shown in Equation 3-47 and Table 3-49.

$$\text{Cold Start Emissions} = \frac{(\text{Bag 1 - Bag 3})}{1 - A} \qquad \textbf{Equation 3-47}$$

Table 3-49 Correction factor *A* for application in Equation 3-47 (MY 1995 and earlier)

Vehicle Type	THC	CO	NO_x
No Catalyst	0.37101	0.34524	1.57562
Catalyst Equipped	0.12090	0.11474	0.39366
Heated Catalyst	0.05559	0.06937	1.05017

Model-year groups used to calculate start rates for vehicles in model year 1995 and earlier are shown in Table 3-50. In some cases, model-year groups were adjusted to compensate for sparsity of data in narrower groups. For example, the average NO_x start emissions for MY 1983-1985 trucks are slightly negative. This result is possible if emissions are truly higher in FTP phase 3 than phase 1, 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 MY1994-1995 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 3-50 Cold-start emissions (Bag 1 – Bag 3, adjusted) for gasoline-powered cars and trucks

Model-year Group	*n*	Mean (g)			Standard deviation (g)			CV-of-the-Mean (RSE)		
Years		***THC***	***CO***	***NO_x***	***THC***	***CO***	***NO_x***	***THC***	***CO***	***NO_x***
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	1,192	3.804	45.918	2.107	2.298	36.356	2.152	0.017	0.023	0.030
1990-1995	1,755	3.288	40.927	2.192	4.211	42.478	2.158	0.031	0.025	0.024

3.8.2 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 In-use Verification Program (IUVP), as with running rates for MY2001 and later (see Section 3.3, page 57).

For model years 1996-2000, rates for vehicles at 0-3 years of age (ageGroup=0003) are shown above in Table 3-16, in the row for MY2000.

For MY 2001 and later, cold-start rates (opModeID=108) were estimated as described in 3.3 above, using the data and approaches described in steps 1-4 and step 6. As with running emissions, Figure 3-22 (page 69) and Figure 3-35 (page 86) illustrate the calculation of weighted average FTP results for NO_x by model year.

3.9 Estimation of Emission Rates for Hot to Warm Starts

Within the MOVES modal structure, operating modes for start emissions are defined in terms of soak time (preceding an engine start). The following section discusses the development of base rates for "warm" or "hot" starts following seven soak periods of varying length defined in MOVES (operating modes 101-107).

3.9.1 Subgroup 1: Model Years 2003 and earlier

3.9.1.1 Relationship between Soak Time and Start Emissions

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 soak-time/start relationships described below. The specific values used are adapted from the MOBILE6 soak-effect curves for 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.

For model years 1995 and earlier, we adapted and applied the soak-time adjustments used in MOBILE6.2 for gasoline-fueled vehicles, as shown in Table 3-51. Additionally, all pre-1981 model year passenger cars and trucks use the same catalyst-equipped soak curve adjustments, although some of these vehicles were not catalyst-equipped.

Table 3-51 Calculated soak-time adjustments, derived from MOBILE6 soak-time coefficients for catalyst-equipped vehicles (MY 1995 and earlier)

opModeID	Soak period midpoint (min)	Adjustment		
		THC	CO	NO_x
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

For model years 1996-2003, soak fractions were also adapted from the approach applied in the MOBILE model.[20] Specifically, the piece-wise regression equations used in MOBILE6 for "conventional catalyst" engines were evaluated at the midpoint of the soak period for each operating mode (Table 3-51). For each mode, the start rate is the product of the cold-start rate and the corresponding soak fraction. Figure 3-83 shows the soak fractions for THC, CO and NO_x, with each value plotted at the midpoint of the respective soak period.

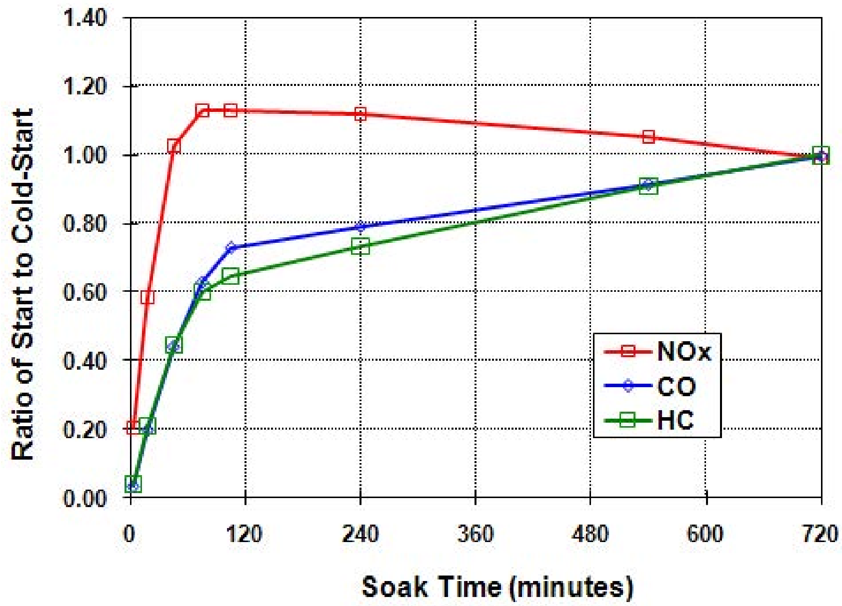

Figure 3-83 Soak fractions applied to cold-start emissions (opModeID = 108) to estimate emissions for shorter soak periods (operating modes 101-107, applied to MY 1996-2003)

3.9.2 Subgroup 2: Model Years 2004 and Later

The soak fractions adapted from MOBILE6 are based on data collected in the early 1990's. More recently, the question arose as to whether they could be considered applicable to vehicles designed to comply with Tier 2 (or LEV-II) and Tier 3 exhaust emissions standards. To address this question, we initiated a research program during the summers of 2016 and 2017, with the goal of examining the relationships between soak time and start emissions for a set of light-duty vehicles certified to Tier 2 or Tier 3 standards.

Data collected by the California Air Resources Board (CARB) was also included in order to increase the number of vehicles influencing the new soak curves.

3.9.2.1 Measuring Start Emissions using PEMS

This work differed from previous efforts in that it represents a first attempt for EPA to estimate start emissions using portable emissions measurement systems (PEMS), rather than by using the FTP cycle on a chassis dynamometer. During July-September, 2016, the test vehicles, outfitted with Sensors SEMTECH-D instruments, were repeatedly driven over a 2.7-mile route in Ann Arbor, MI, starting and ending at the National Vehicle and Fuel Emissions Laboratory (NVFEL). The route and drive times were designed to minimize variability in trip time and idling due to traffic conditions.

Measurements were collected on six vehicles, one to seven years old at the time of measurement (Table 3-52). A typical speed trace of the route is shown in Figure 3-84.

Table 3-52 EPA-Tested Light-Duty Vehicles for the Start/Soak Project

Make and Model	Model Year	Engine Displacement	Standard	Number of Trips
Ford Explorer	2009	4.0 L	Bin 4	42
Ford F150	2011	3.5 L	Bin 4	20
Saturn Outlook	2009	3.6 L	Bin 5 (ULEV)	47
Toyota Camry	2009	2.4 L	Bin 5 (ULEV)	19
Ford F150	2017	3.5 L	Bin 5 (ULEV)	13
Toyota Camry	2017	2.5 L	Tier 3 Bin 125	20

Vehicles were soaked indoors at 72° F prior to driving each repeat trip on the route. For purposes of this analysis, only trips when the outdoor ambient outdoor temperature was above 50°F were used. Repeat trips were performed for soak periods targeted to the midpoint times of each MOVES operating mode (Table 3-51, page 169).

During each repeat route, the PEMS measured continuous CO_2, CO, THC and NO_x emissions at a time-interval of approximately 1.0 Hz. For purposes of quality assurance, time series were viewed to identify irregularities and measurement issues.

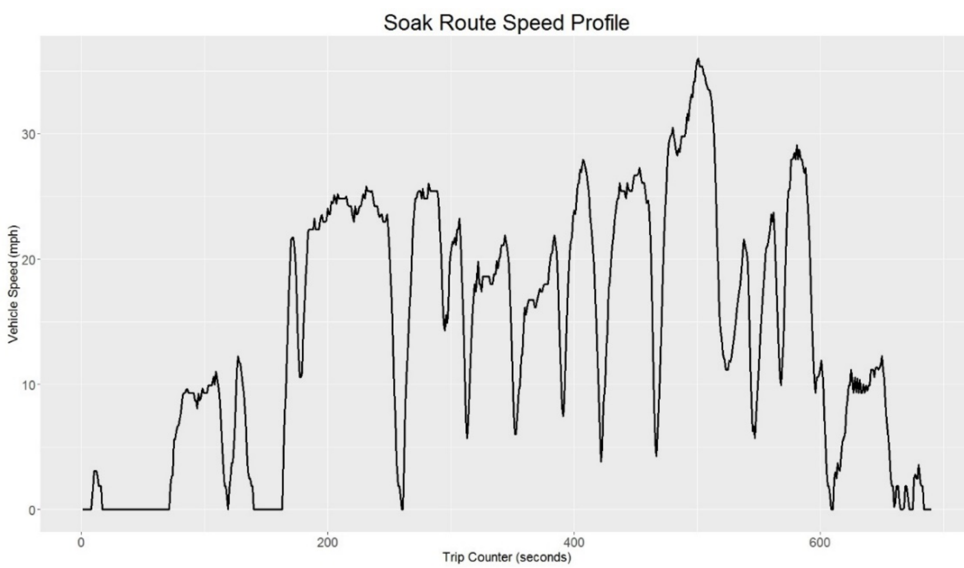

Figure 3-84 An Example Speed Trace for the Drive Route

In analysis of the data, it was important to verify that the route was long enough for engines to warm up fully. To examine this question, we summarized and viewed results for catalyst and coolant temperatures. Trends in catalyst temperatures for the measured soak periods for one vehicle (the Explorer) are shown in Figure 3-85. These results for selected individual drives suggest that the catalyst temperature stabilizes at 300°C or higher between 300 to 400 seconds after engine start, depending on the duration of engine soak prior to the start. Similar results for coolant temperatures are shown for the Toyota Camry in Figure 3-86.

An interesting result is that the catalyst takes more time to come to operating temperature for intermediate soaks (45-240 min, operating modes 103-106) than for the longest soak period (720 min, operating mode 108). However, the coolant temperature shows the opposite pattern, with coolant reaching operating temperature more quickly for the intermediate soaks than for the longer soaks.

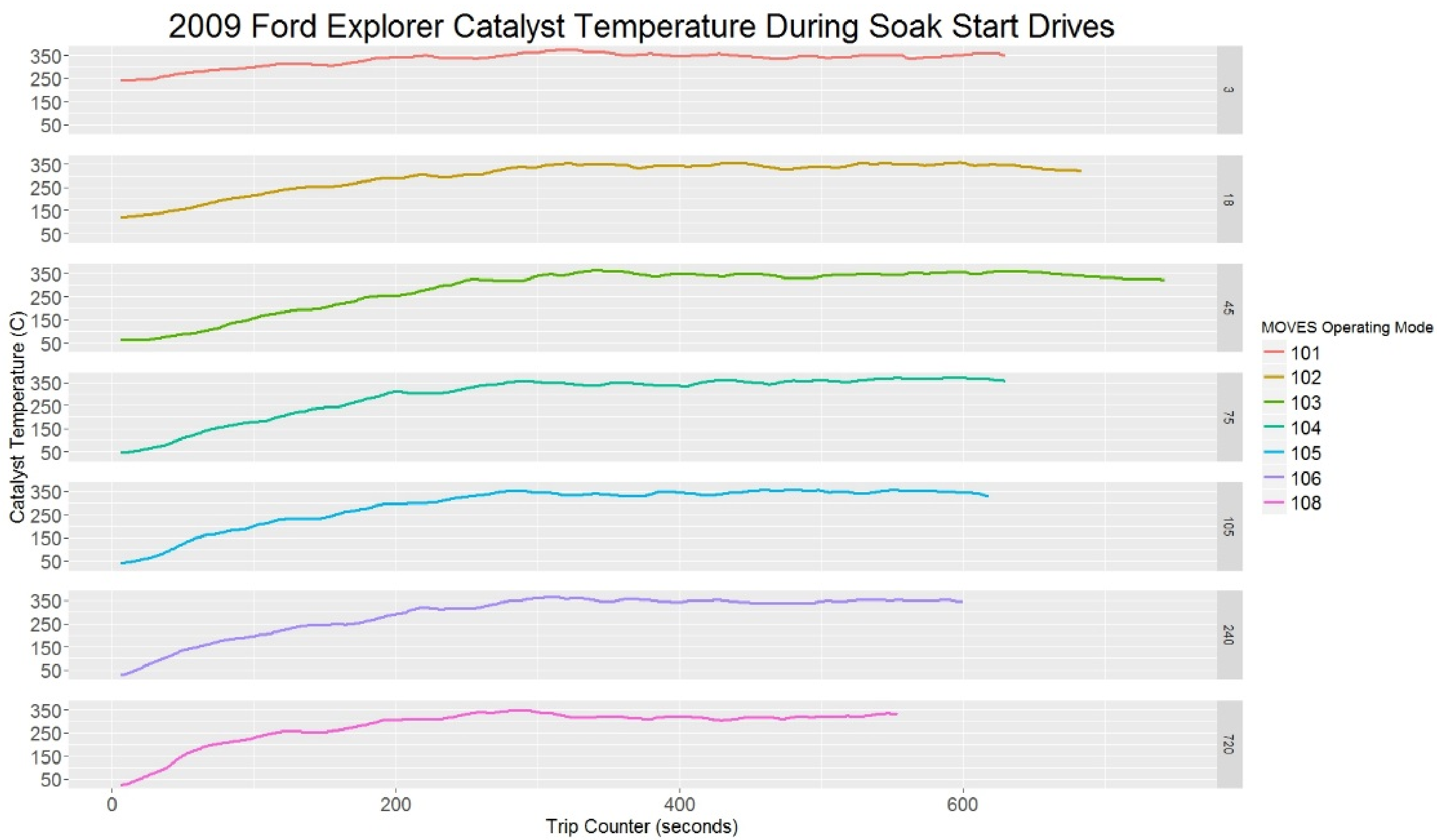

Figure 3-85 Mean catalyst temperature trends for the Ford Explorer, by soak period

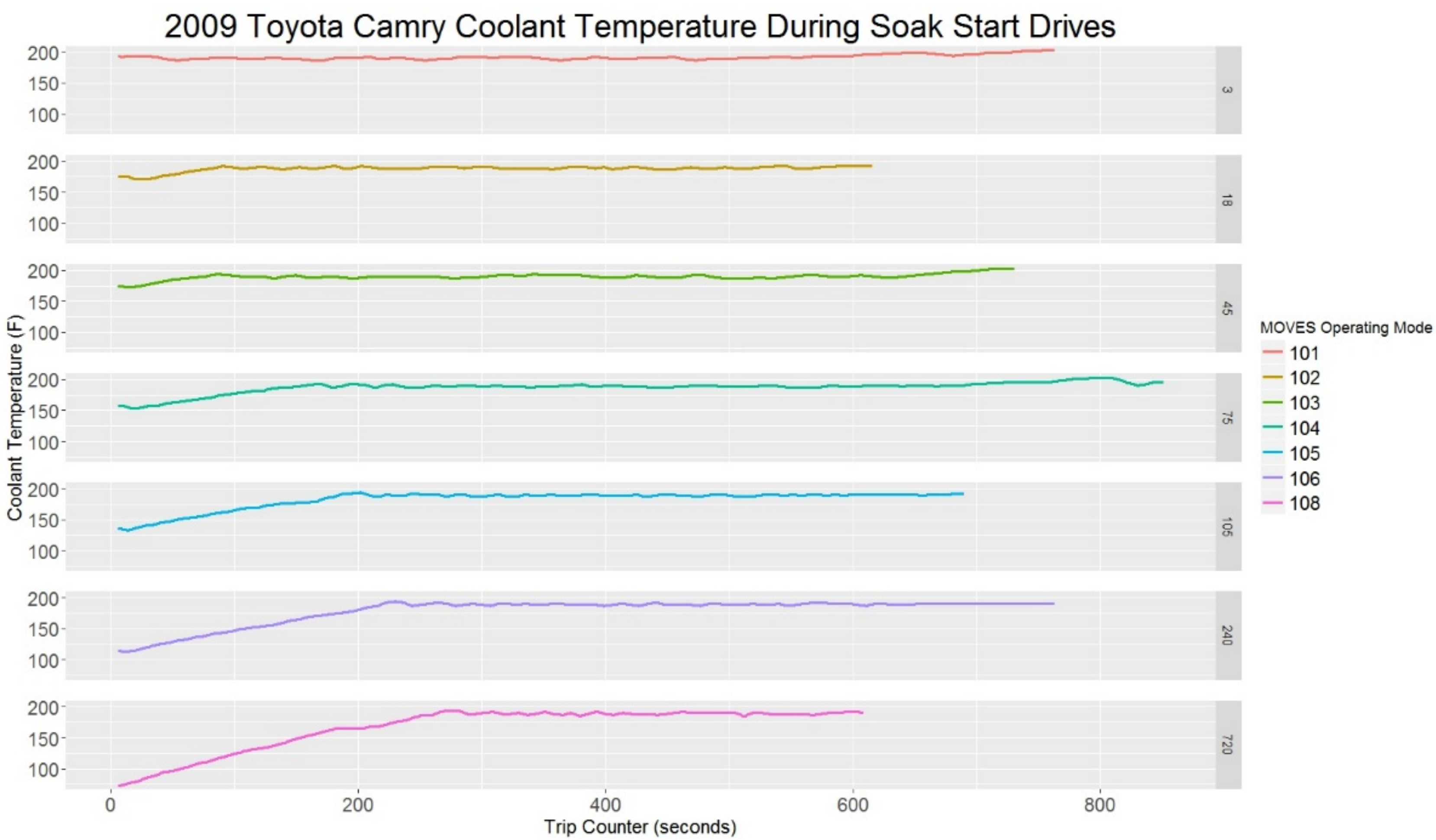

Figure 3-86 Mean trends in coolant temperature for the Toyota Camry, by soak period

3.9.2.2 Measuring Soak-time Relationships on the Dynamometer

The data collected by EPA using PEMS was supplemented by a dataset collected by the California Air Resources Board and used to update start emission rates for EMFAC2017.[47] These data were measured as cycle aggregates on the California Unified Cycle. We made use of data from Phase 1 of the cycle for 32 vehicles certified to LEV-II standards. The start phase of the Unified cycle is approximately 300 sec in duration.

To make use of the CARB data, we assigned the soak periods used in its collection to soak periods corresponding to MOVES start operating modes.

3.9.2.3 Comparing Dynamometer and PEMS Measurements

To obtain a broad overview of the data from both sources, we first averaged all sets of results by vehicle and soak period.

Emissions trends by vehicle and method are shown in for THC, CO and NO_x in Figure 3-87, Figure 3-88, and Figure 3-89, respectively.

As is typical with emissions data, the trends in start emissions with soak period are highly variable across individual vehicles in both datasets. The CARB dataset is much larger and hence the range of variability is wider, capturing more vehicles with emissions at the low end of the range, as well as small numbers of vehicles with unusually high emissions.

With these considerations in mind, it appears the CARB and EPA datasets are broadly similar, both in terms of emissions levels and in the shapes of trends by pollutant. However, we can also conclude that results derived solely from the smaller PEMS dataset would be biased high. We also note that the PEMS dataset is limited in that only one vehicle was measured at the nine-hour soak period (540 min). The CARB data is also valuable in covering this period, which represents operating mode 107.

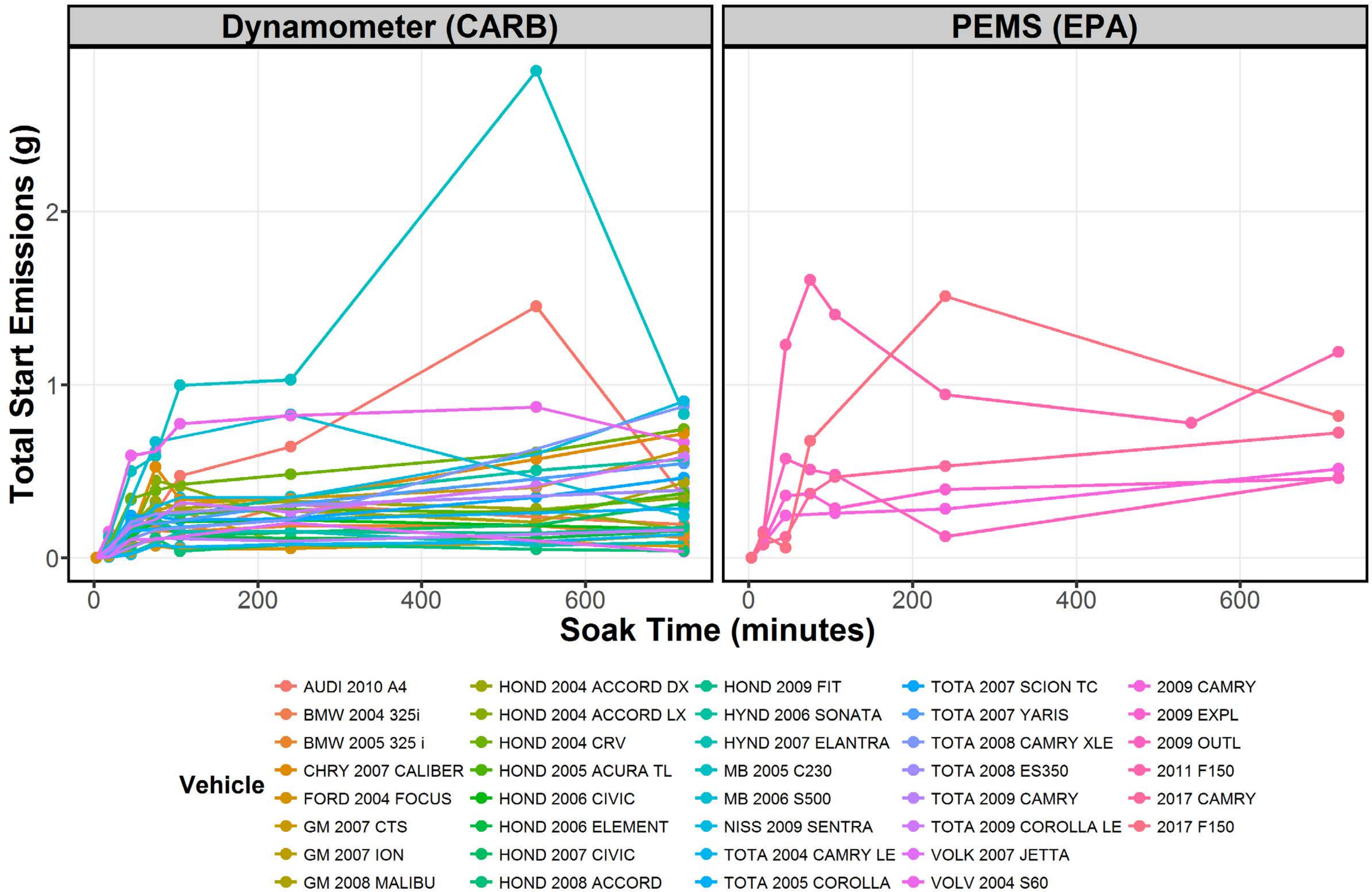

Figure 3-87 THC: Start emissions by soak period and vehicle for dynamometer and PEMS measurement methods

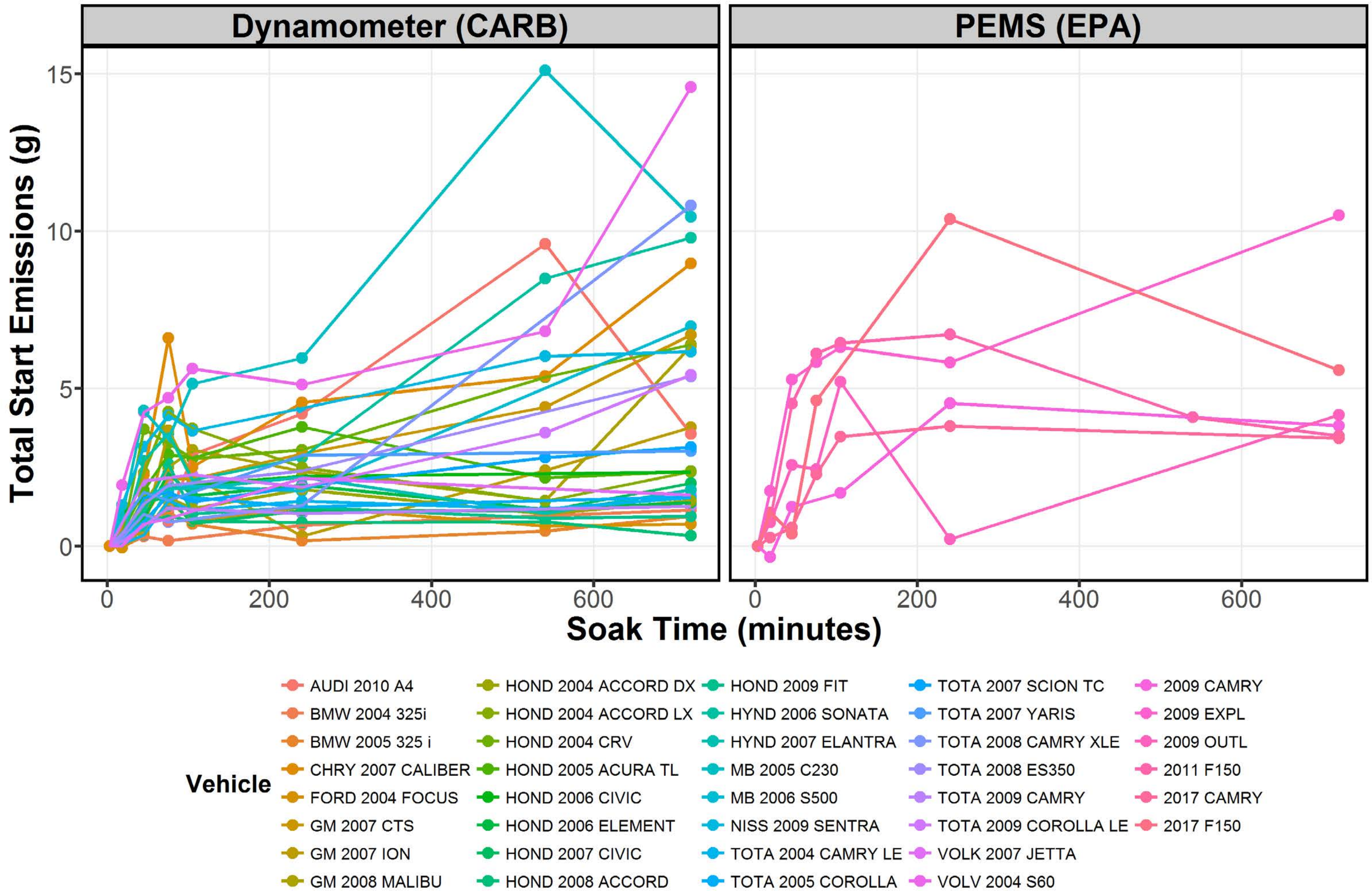

Figure 3-88 CO: Start emissions by soak period and vehicle for dynamometer and PEMS measurement methods

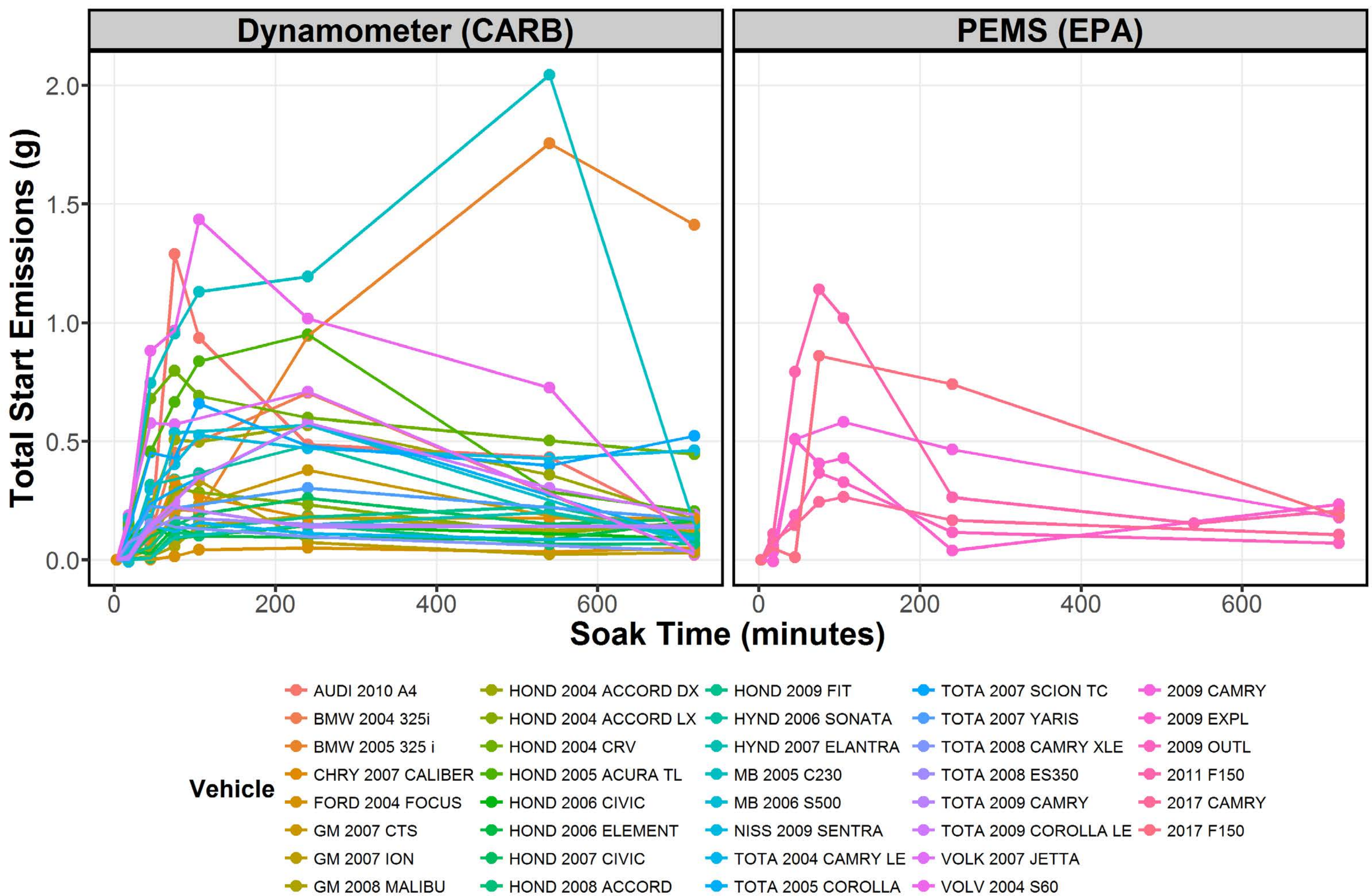

Figure 3-89 NO_x: Start emissions by soak period and vehicle for dynamometer and PEMS measurement methods

After averaging the data by vehicle and soak period, mean soak-time trends were constructed by following several additional steps.

Step 1: Correct for running-exhaust emissions

In addition to the emissions attributed to the excess fuel injected into cylinders during an engine start period, we assume that typical "running emissions" and "hot-start emissions" are included in the total. To isolate the excess emissions attributable to the start condition, we subtracted the results for the 0-6 minute soak period from the measurements for the remaining soak periods. This calculation was performed separately for each vehicle. This step is analogous to subtracting Bag 3 from Bag 1 when estimating FTP start emissions.

Step 2: Average results across vehicles

Next, we averaged the means for individual vehicles across vehicle to obtain average trends. We performed this step separately for the dynamometer and PEMS datasets.

Step 3: Calculate program-specific soak ratios

As in initial step in developing soak-time relationships, we normalized the mean emissions (in grams) at all soak periods to those for the 12-hr soak period, i.e., cold start. We called this step "program-specific" because we performed the normalization separately for the dynamometer and PEMS datasets.

These intermediate ratios are shown for THC, CO and NO_x in Figure 3-90, Figure 3-91 and Figure 3-92 below, respectively. The ratios for the PEMS and dynamometer datasets are labeled "EPA" and "CARB," respectively.

Step 4: Calculate final ratios

In this final step, we averaged the program-specific ratios for the two datasets to obtain a single set of soak-time ratios. For each soak period, the final ratio was calculated as an average of two intermediate ratios, weighted by numbers of vehicles in each data source for that period. The final ratios are also shown in the figures, labelled as "EPA + CARB weighted average."

Due to the subtractions performed in step 1, the ratios for the first operating mode, opModeID 101, could not be directly estimated from the means. After correcting for running and hot-start emissions, operating mode 101 would have had a mass of 0.0 g. To impute the ratios for this mode, the soak ratios for the opModeID 101 was extrapolated. This fraction was estimated by multiplying the fraction at operating mode 102 (soak time = 18 minutes) by 3/18, the proportional difference between the midpoints of the soak periods for these two operating modes.

For comparison, the figures also include the "older" soak curves, previously shown in Figure 3-83, page 170. The comparisons show the largest differences in soak curves for THC and NO_x, especially for soak times less than 240 minutes. Both the THC and NO_x ratios surpass 1.0 before the 720-minute soak mark, indicating that THC and NO_x emissions from starts after less than 240 minutes soaking are greater than after 720 minutes or more.

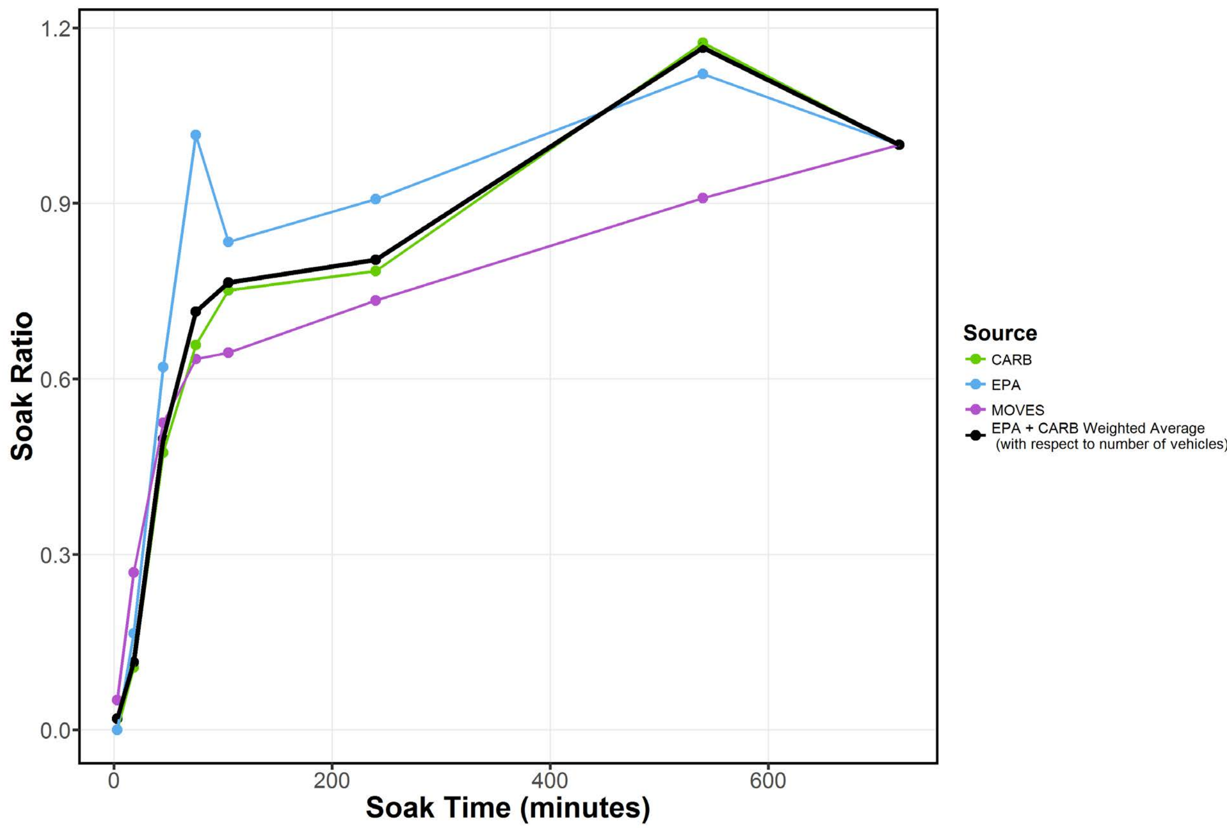

Figure 3-90 THC: Program-specific and final soak-time ratios for Tier-2/LEV-II vehicles. The "MOVES" line refers to values used in MOVES2014 and retained in MOVES3 for MY 2003 and earlier

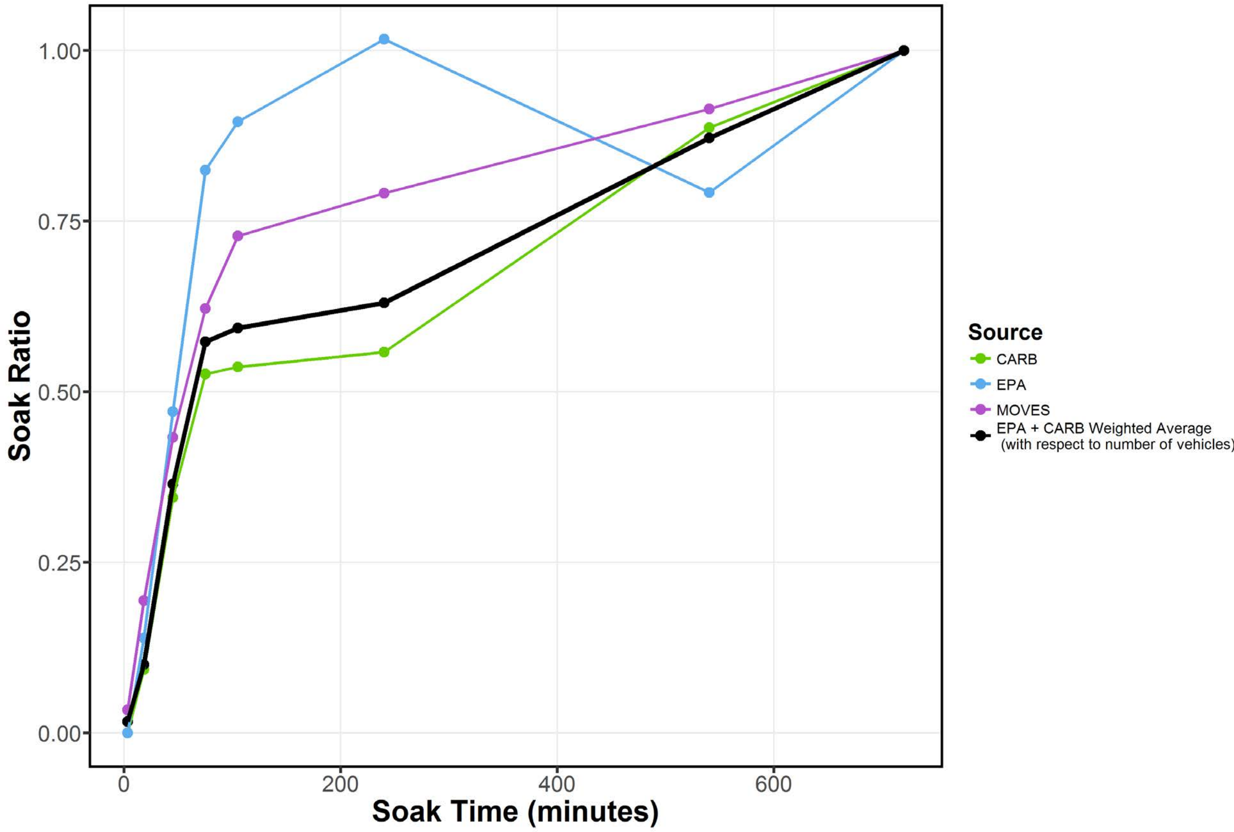

Figure 3-91 CO: Program-specific and final soak-time ratios for Tier-2/LEV-II vehicles. The "MOVES" line refers to values used in MOVES2014 and retained in MOVES3 for MY 2003 and earlier

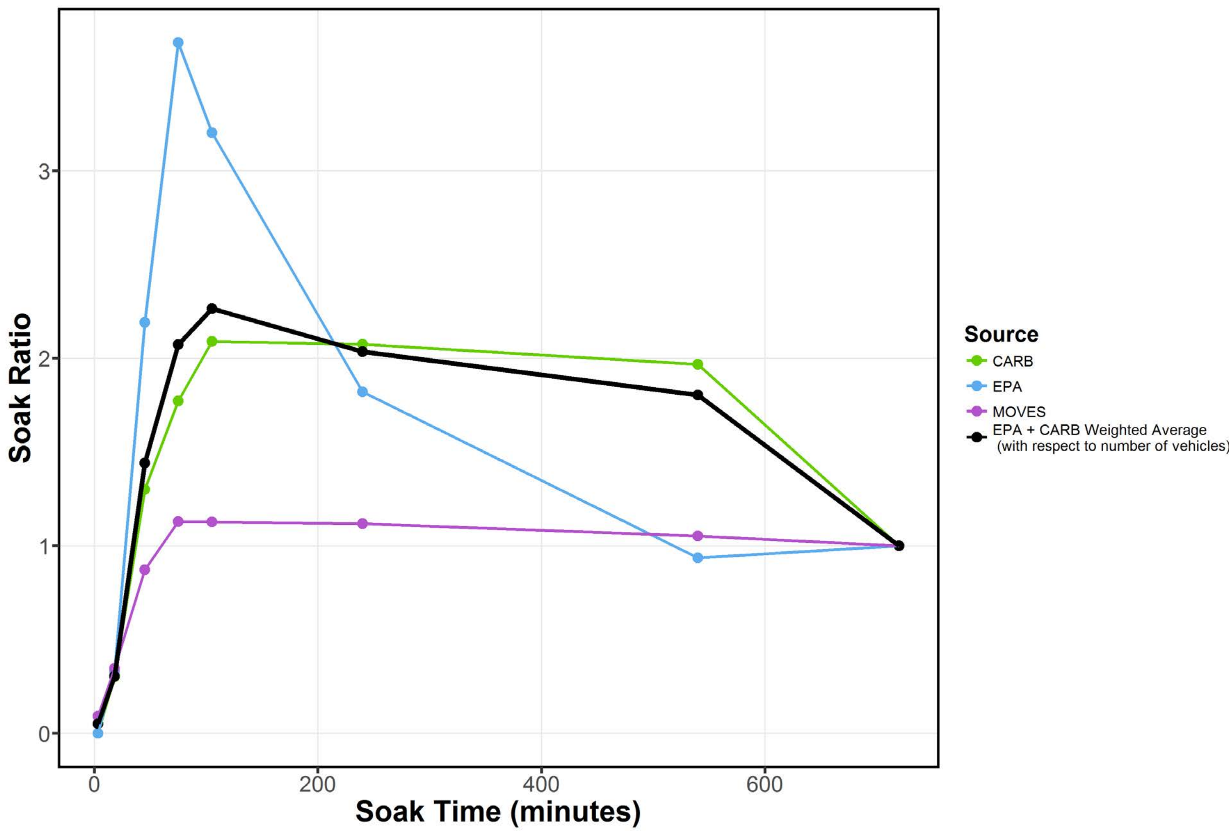

Figure 3-92 NO_x: Program-specific and final soak-time ratios for Tier-2/LEV-II vehicles. The "MOVES" line refers to values used in MOVES2014 and retained in MOVES3 for MY 2003 and earlier

The final results for use in MOVES3 are shown in Table 3-53. As mentioned, these fractions will be applied to model years 2004 and later.

Table 3-53 Revised Soak Fractions for Light-duty Start Emissions, for MY 2004 and later

opModeID	Midpoint Soak time (min)	Soak Fractions		
		THC	CO	NO_x
101	3	0.0193	0.0167	0.0509
102	18	0.1159	0.1003	0.3053
103	45	0.4974	0.3649	1.4425
104	75	0.7149	0.5732	2.0743
105	105	0.7646	0.5931	2.2659
106	240	0.8039	0.6303	2.0355
107	540	1.160	0.8719	1.8055
108	720	1.000	1.000	1.000

3.9.3 Applying Deterioration to Starts

3.9.3.1 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 direct information on deterioration for start emissions. Our best data source for start deterioration was data from the IUVP program, used to develop running rates for NLEV and Tier 2 vehicles (see Section 3.3). However, because the IUVP data is a relatively small data set, and restricted to vehicles in good repair, we were concerned that it would not capture the true variation in emissions. We considered whether it would be better to simply apply the running deterioration rates described in Sections 3.2, 3.6 and 3.7, to start emissions. To investigate this, we compared start and running deterioration in the IUVP data. As described below, we eventually applied adjusted running deterioration rates that accounted for the differences in start and running deterioration as seen in the IUVP data.

A valuable aspect of the IUVP 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 first evaluate trends in emissions vs. mileage and only later convert to the age-based rates needed for MOVES.

Starting with the National LEV standards in MY 2001, the hydrocarbon species used for certification is non-methane organic gases (NMOG), rather than total hydrocarbons (THC). At the outset, we plotted the data for NMOG and NO_x vs. odometer reading, on linear and logarithmic scales. Scatterplots of start and running NMOG emissions are shown in Figure 3-93 and Figure 3-94; corresponding plots for lnNMOG are shown in Figure 3-95 and Figure 3-96. Similarly, scatterplots of start and running NO_x emissions are shown in Figure 3-97 and Figure 3-98; corresponding plots for $lnNO_x$ are shown in Figure 3-99 and Figure 3-100.

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 that the purpose of the IUVP program is compliance assessment, 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. On a logarithmic scale, 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 3-56 and Table 3-57. The model structure includes a grand intercept for all vehicle classes (LDV, LDT1-4), and separate intercepts for each vehicle class. All parameters are highly significant, both for lnNMOG and $lnNO_x$. 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 Bin-5 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 $lnNO_x$. Positive trends in emissions do appear evident in these data, but the increase in emissions with mileage is very gradual. The trends in $lnNO_x$ are steeper than those for lnNMOG, and the trends for running emissions are steeper than those for start emissions. However, the differences between the slopes for start and running are less pronounced for $lnNO_x$ than for lnNMOG. For $lnNO_x$, the running slope is 1.25 times that for starts, and for lnNMOG, the running slope is 1.65 times that for starts.

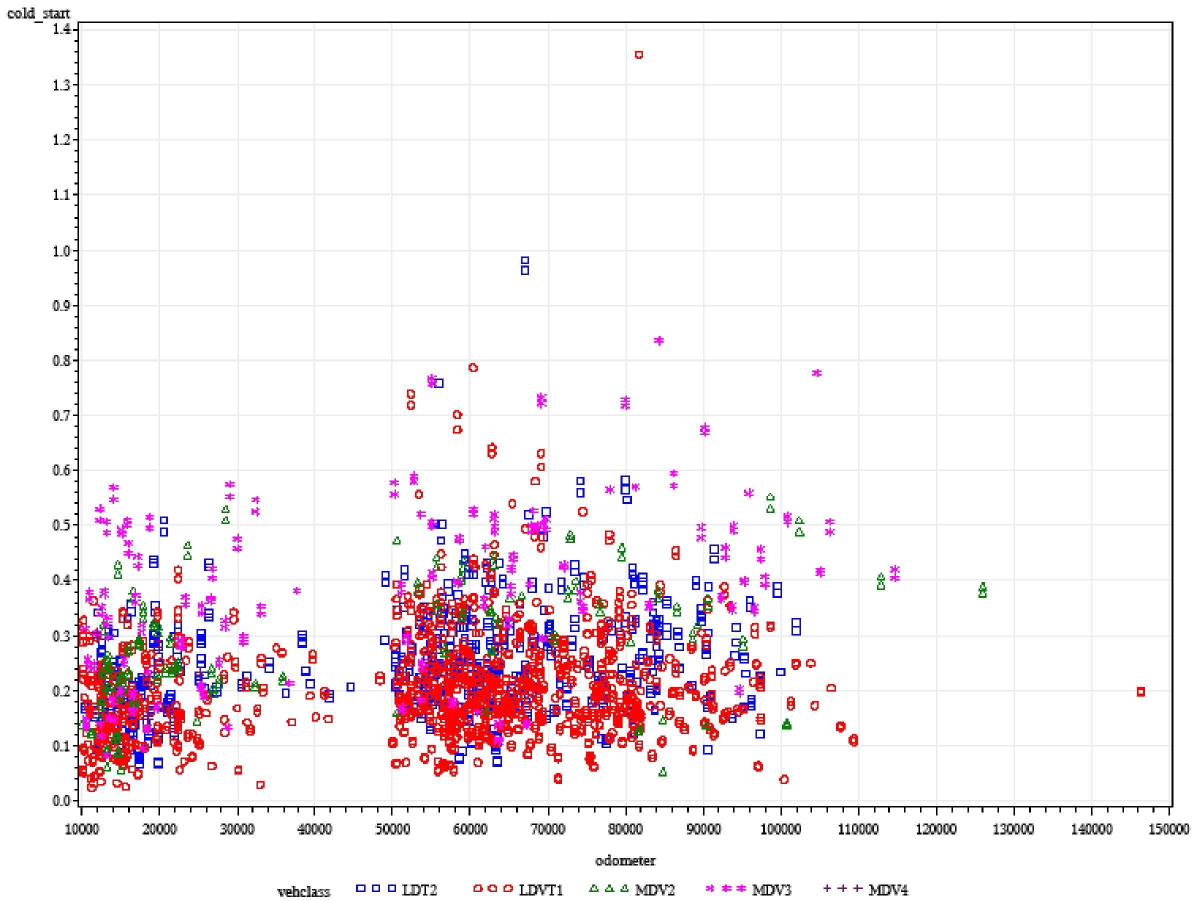

Figure 3-93 Cold-start FTP emissions for NMOG (g) vs. odometer (mi), for LEV vehicles, from the IUVP program

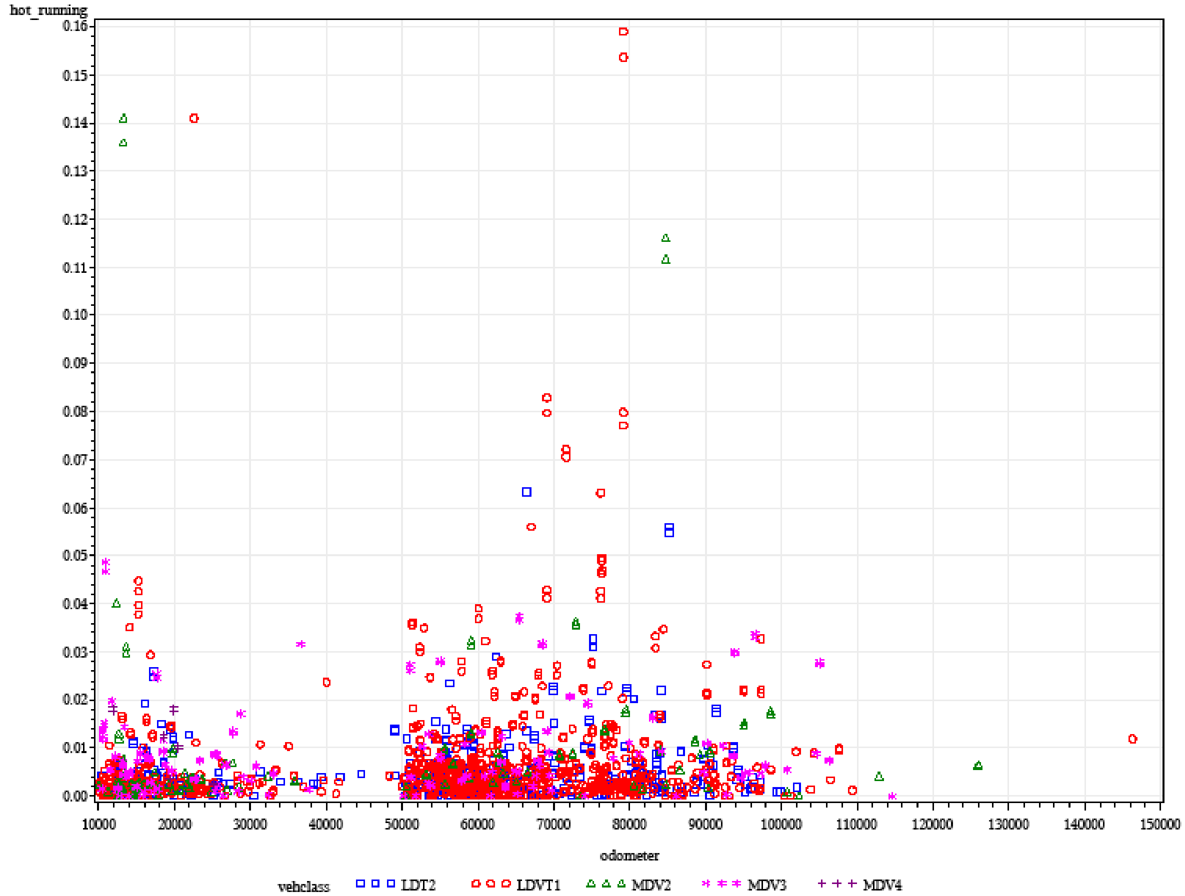

Figure 3-94 Hot-running (Bag 2) FTP emissions for NMOG (g/mi) vs. odometer (mi), for LEV vehicles, from the IUVP program

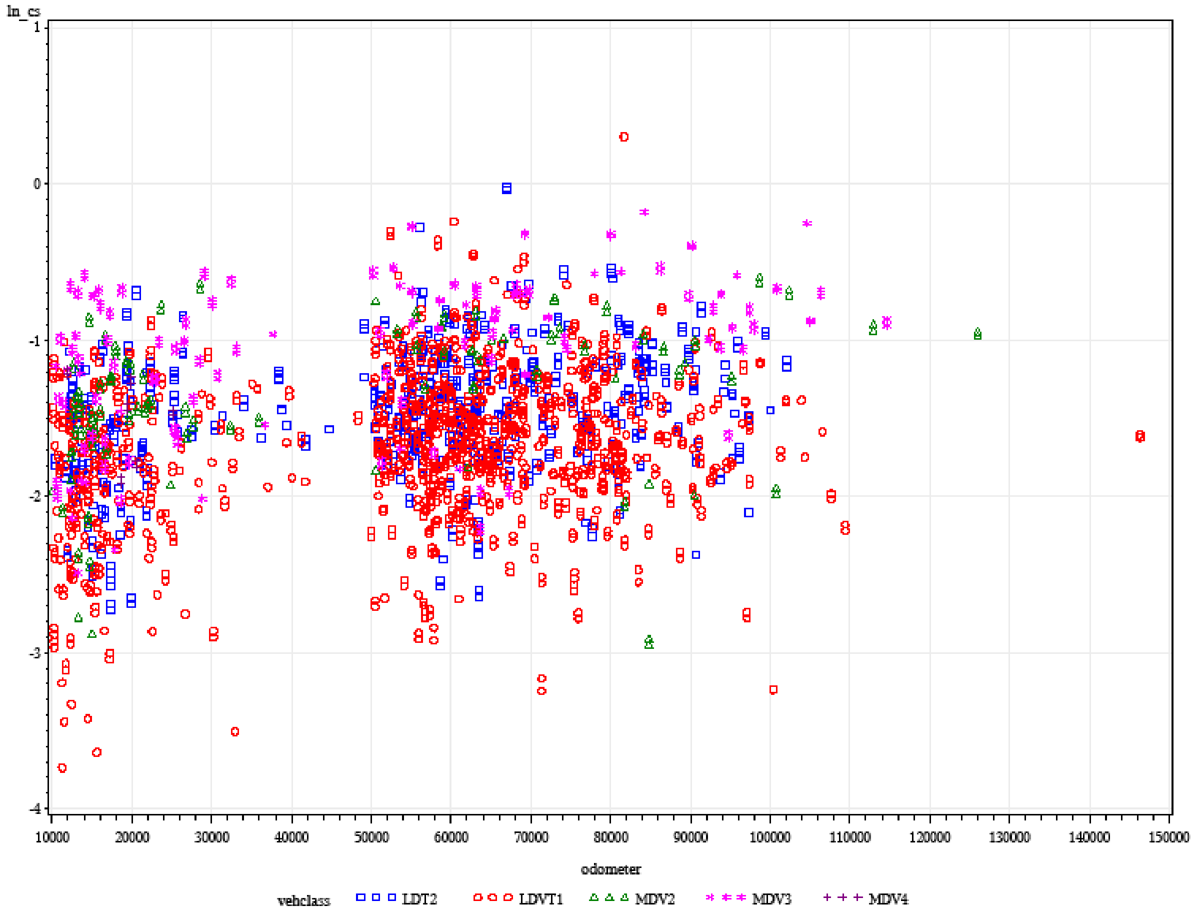

Figure 3-95 Cold-start FTP emissions for ln(NMOG) vs. odometer (mi), for LEV vehicles, from the IUVP program (LOGARITHMIC SCALE)

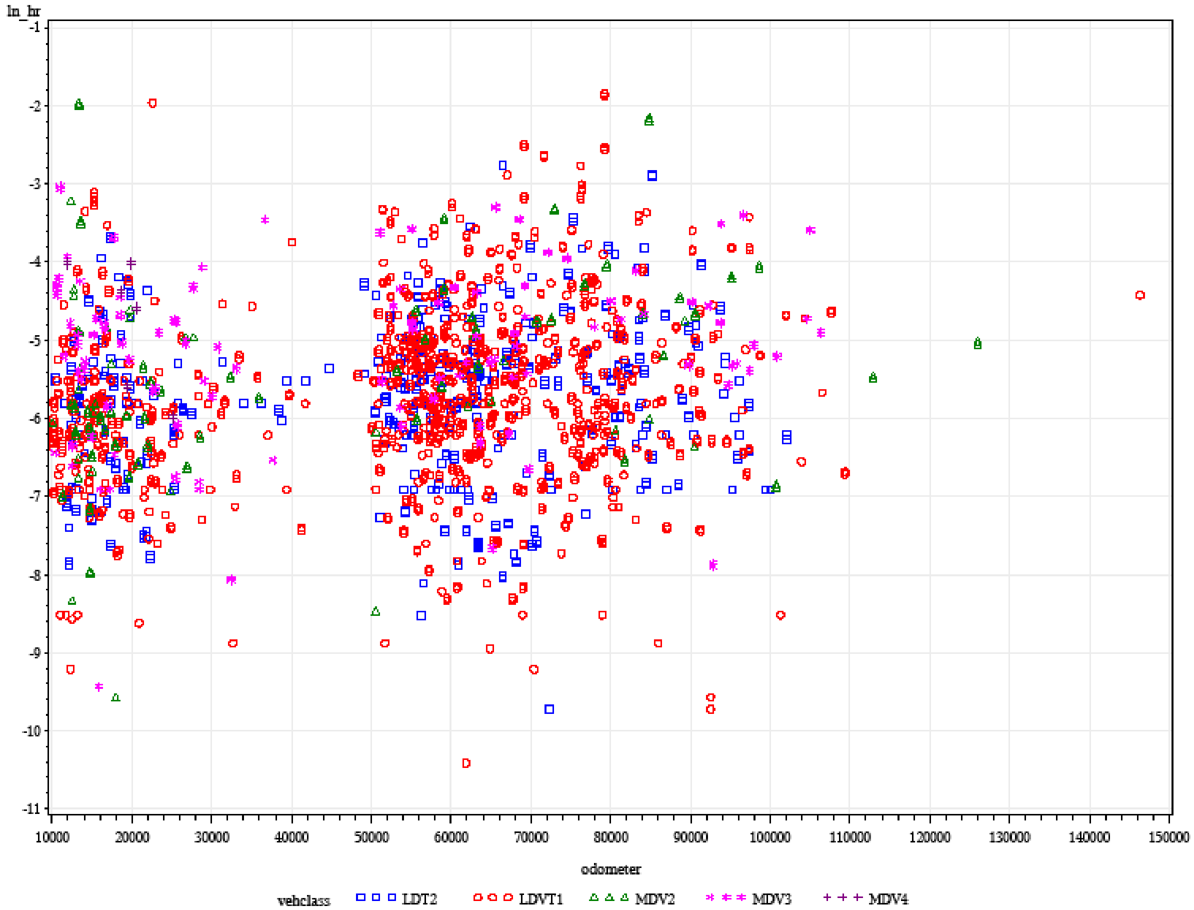

Figure 3-96 Hot-running (Bag 2) FTP emissions for ln(NMOG) vs. odometer (mi), for LEV vehicles, from the IUVP program (LOGARITHMIC SCALE)

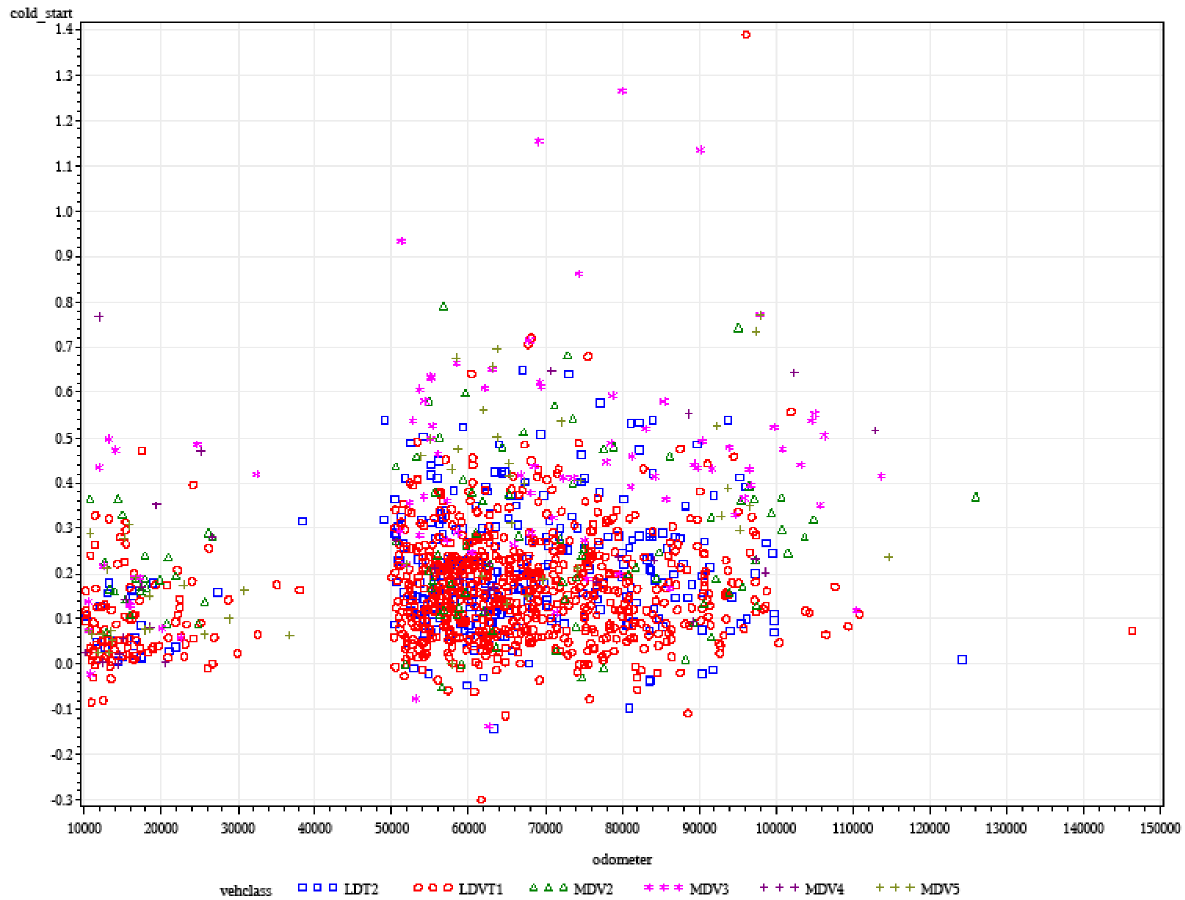

Figure 3-97 Cold-start FTP emissions for NO_x (g) vs. odometer (mi), for LEV and ULEV vehicles, from the IUVP program

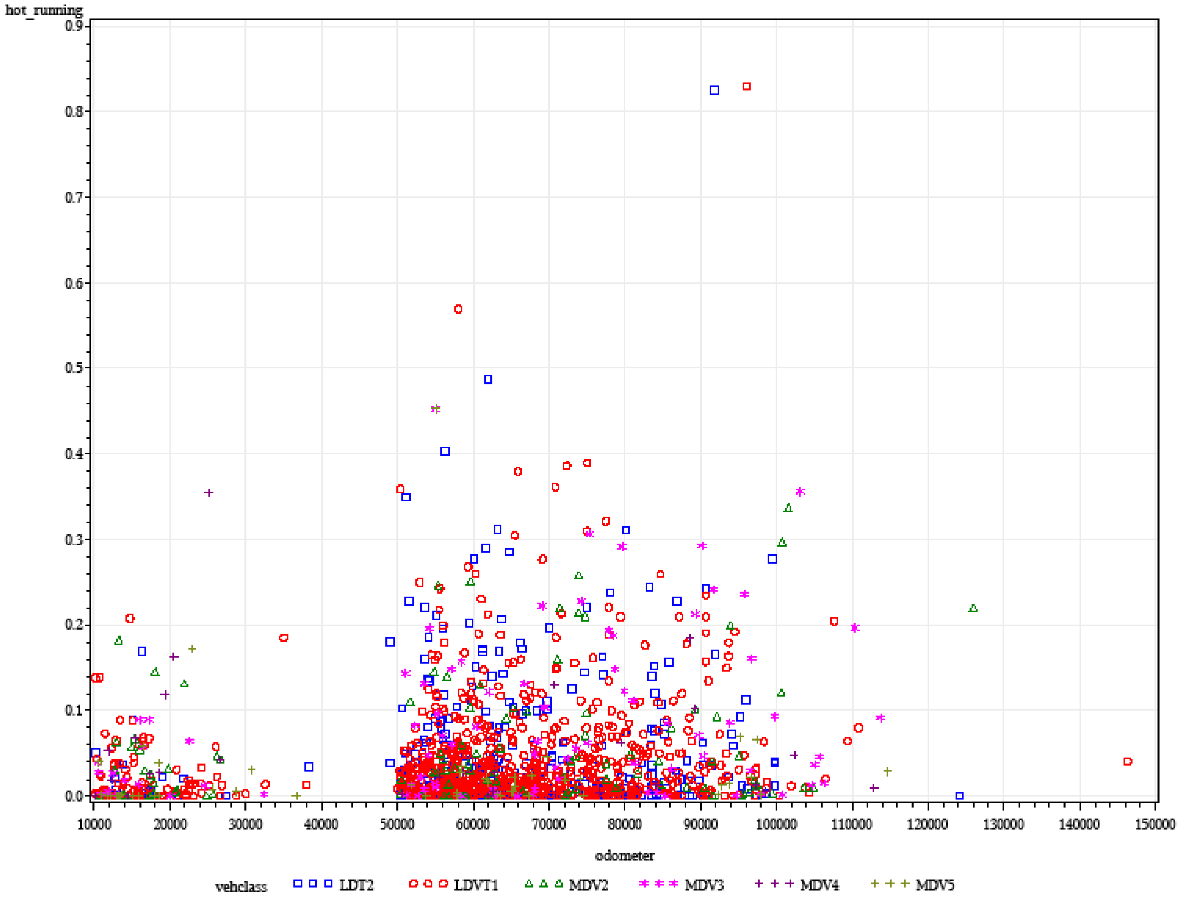

Figure 3-98 Hot-running (Bag 2) FTP emissions for NO_x (g/mi) vs. odometer (mi), for LEV and ULEV vehicles, from the IUVP program

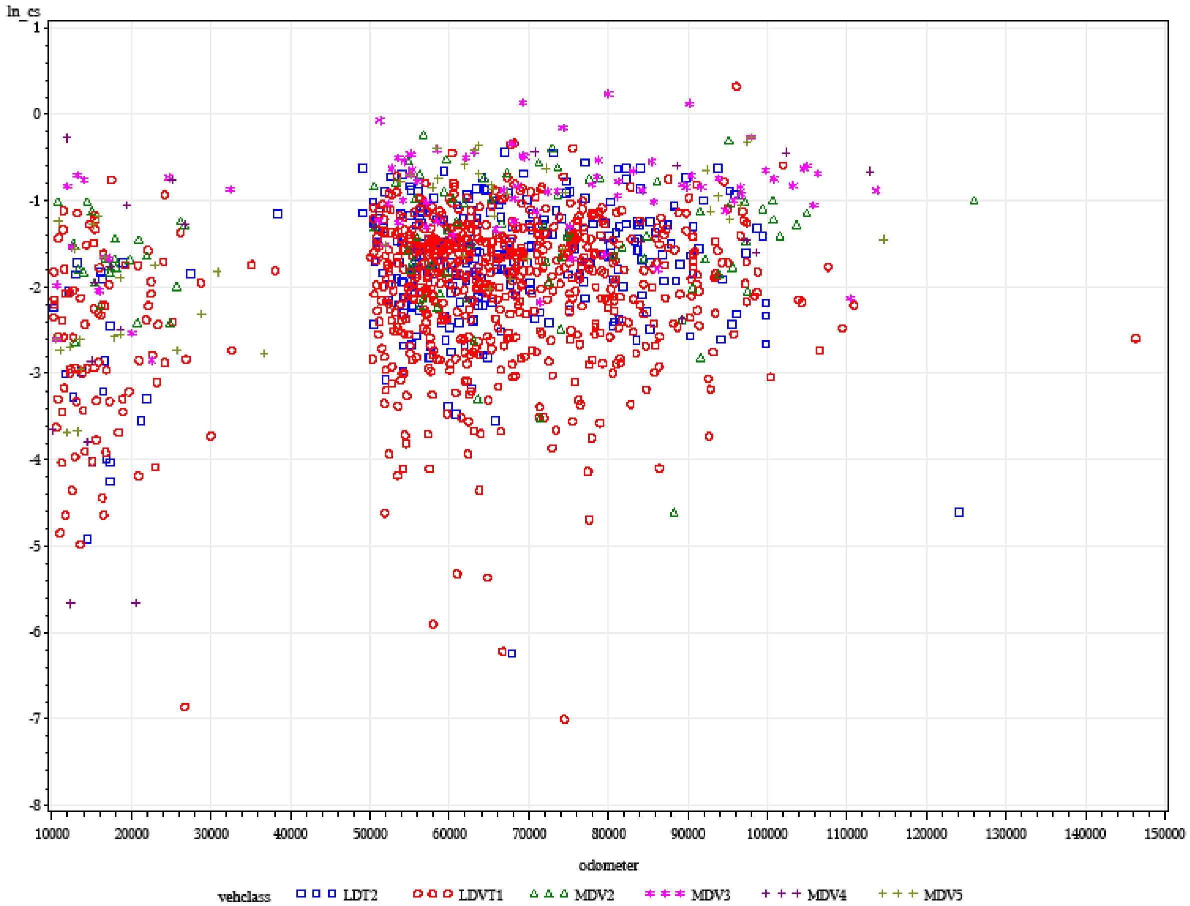

Figure 3-99 Cold-start FTP emissions for ln(NO_x) vs. odometer (mi), for LEV vehicles (Source: IUVP program)

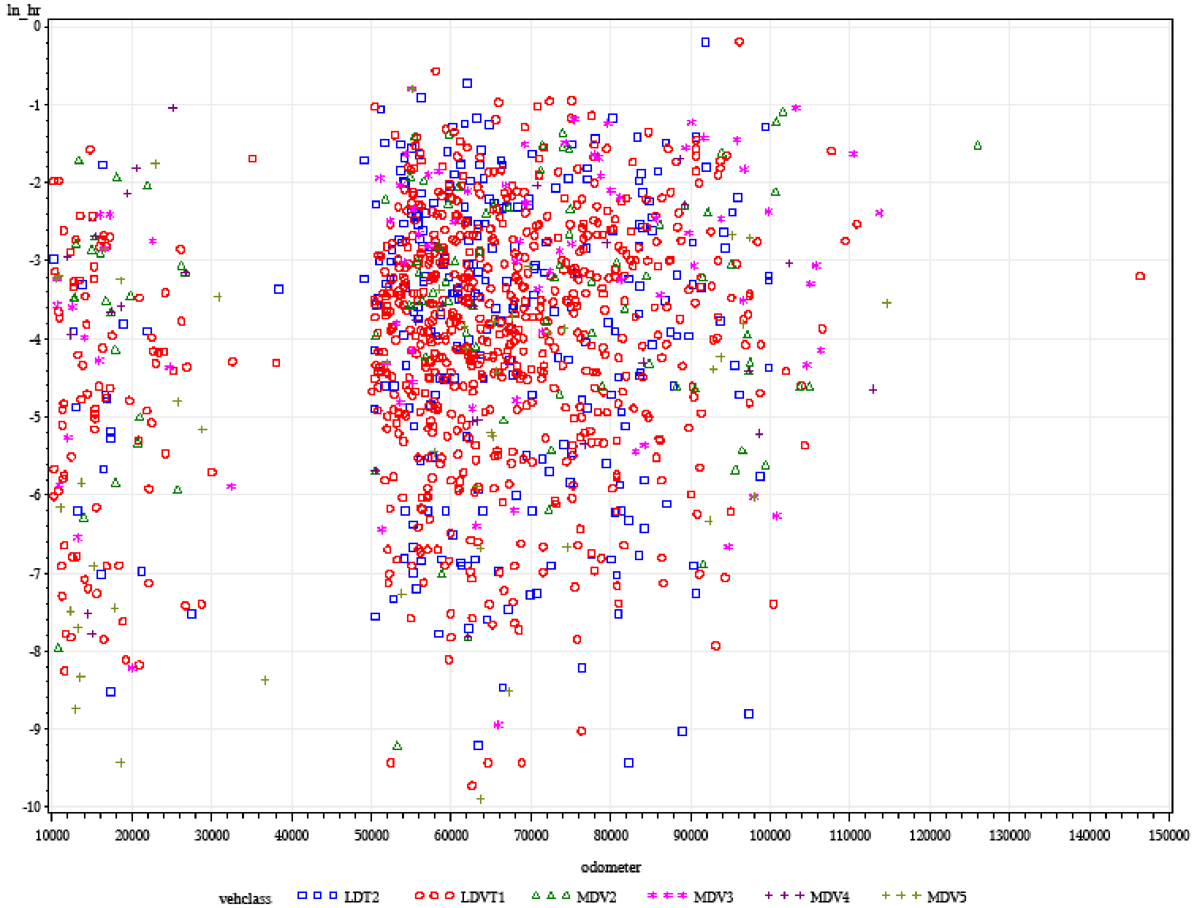

Figure 3-100 Hot-running (Bag 2) FTP emissions for ln(NO_x) vs. odometer (mi), for LEV vehicles from the IUVP program

Table 3-54 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 3-55 Model fit parameters for $\ln NO_x$, 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 $\ln NO_x$ at mileages from 0 (the intercept) to 155,000 miles. We reverse-transformed the models using Equation 3-28 (page 40) to obtain predicted geometric and arithmetic means with increasing mileage, as shown in Table 3-56 for NMOG and Table 3-57 for NO_x.

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 3-48).

$$R_{\text{det}} = \frac{\bar{x}_{a,\text{miles}}}{\bar{x}_{a,0}}$$ **Equation 3-48**

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}

$$R_{\text{rel}} = \frac{R_{\text{det,start}}}{R_{\text{det,running}}}$$ **Equation 3-49**

Values or R_{det} and R_{rel} for NMOG and NO_x are shown in Table 3-56 and Table 3-57, respectively, with corresponding results shown graphically in Figure 3-101 and Figure 3-102, respectively.

Table 3-56 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 3-57 Application of models for NO_x, 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									
$\ln NO_x$	-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									
$\ln NO_x$	-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

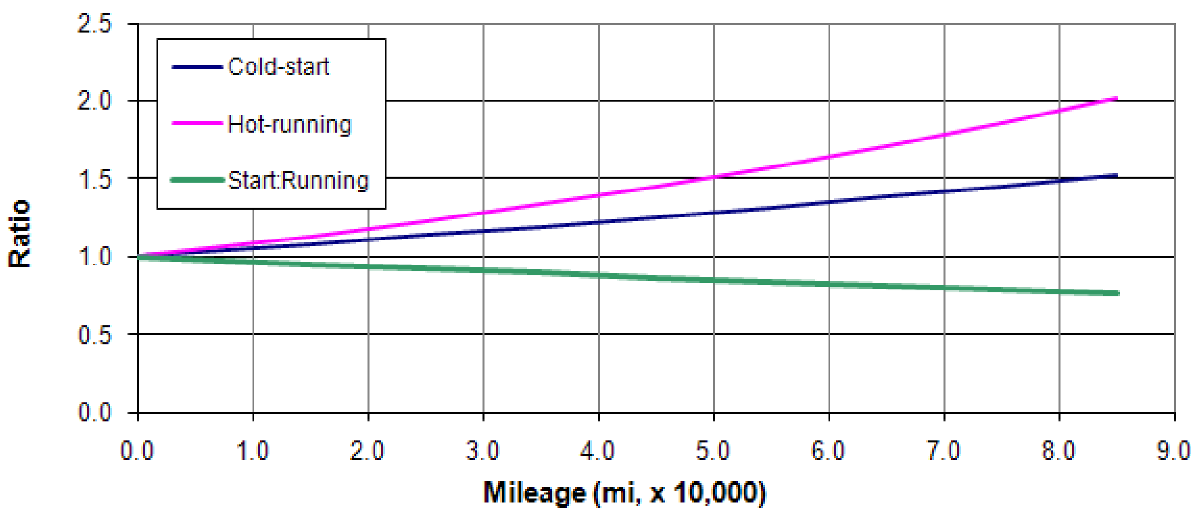

Figure 3-101 LEV deterioration ratios for cold-start and hot-running NMOG emissions, plus the ratio of the two ratios (Start:Running)

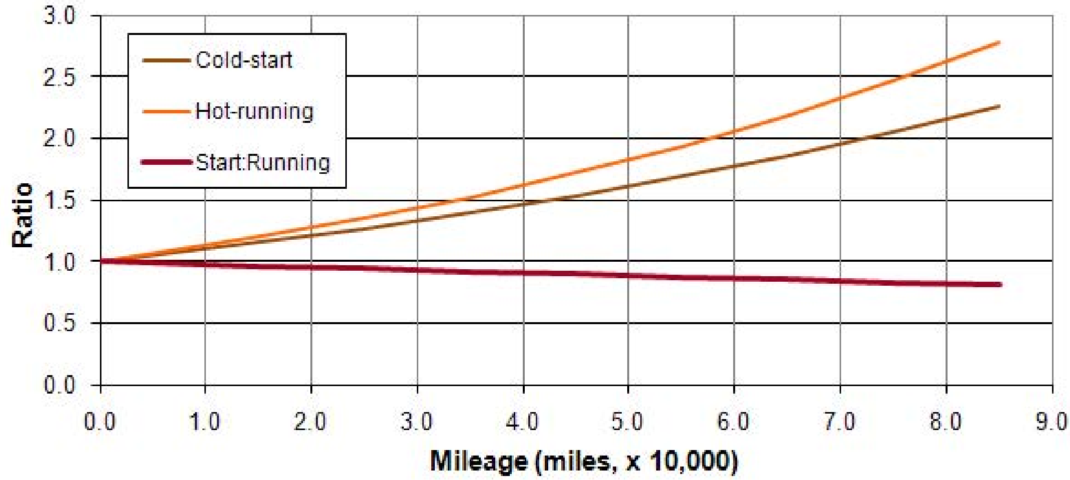

Figure 3-102 LEV deterioration ratios for cold-start and hot-running NO_x emissions, plus the ratio of the two ratios (Start:Running)

For both NMOG and NO_x, the difference between running and start deterioration was large enough that we decided that it was not appropriate to assume that starts deteriorate at the exactly the same rate as running emissions. Instead we elected to use the IUVP data to estimate distinct start deterioration assumptions.

3.9.3.2 Translation from Mileage to Age Basis (MY 1989 and earlier)

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[e,48] 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). Equation 3-50 shows an example of this calculation for NMOG, which is used to represent THC in the emission rates.

[e] The FHWA reports light-duty vehicles traveled on average 11,576 miles per year in 2018[48]. We believe an approximation is sufficient because the average miles traveled per year on reduce as vehicles age, and the use of age groups already requires some approximation.

$$m_{R\text{rel}} = \frac{\Delta R_{\text{rel}}}{\Delta \text{time}} = \frac{0.675 - 1.0}{12.5 - 2} = \frac{-0.325}{10.5} = -0.30952$$ **Equation 3-50**

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

$$R_{\text{rel,age}} = 1.000 - m_{R\text{rel}}\,\text{age}$$ **Equation 3-51**

The results, as applied for hydrocarbons and NO_x, are shown in Table 3-58 and Figure 3-103. The net result is a 15-40 percent reduction in multiplicative start deterioration, relative to running deterioration. The ratios for hydrocarbons were also applied for CO, as the results of analyses with CO were similar.

Table 3-58 Relative deterioration ratios (R_{rel}), for THC and NO_x, assigned to each ageGroup (Note: ratios for THC also applied to CO)

AgeGroup	Age (years)	Relative Ratio (R_{rel})	
		THC	NO_x
0-3	2	1.000	1.000
4-5	5	0.845	0.892
6-7	7	0.783	0.848
8-9	9	0.721	0.805
10-14	12.5	0.613	0.729
15-19	17.5	0.613	0.729
20 +	23	0.613	0.729

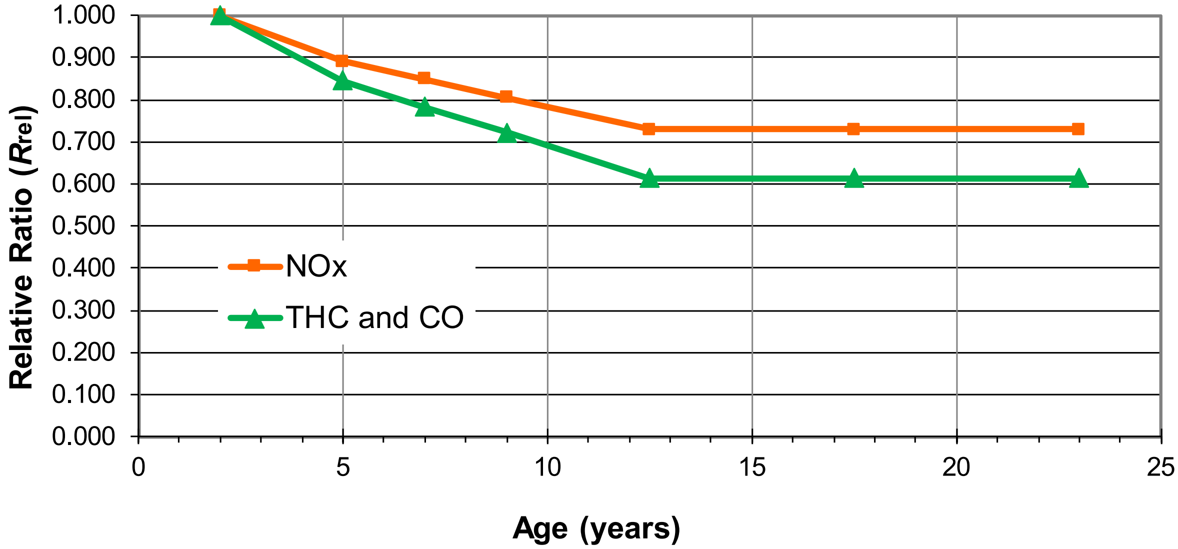

Figure 3-103 Relative deterioration ratios (R_{rel}), for THC and NO, assigned to each ageGroup

3.9.3.3 Translation from Mileage to Age Basis (MY 1990 and later)

3.9.3.3.1 Start Process for NO_x

As we have shown in 3.6.8 and 3.7.8, the revised analysis has yielded meaningful reductions in proportional deterioration compared to the levels in MOVES2014. As in MOVES2014, we propose to model deterioration for start emissions as less than but proportional to that for running emissions. Then, we need to develop emission rates.

As in MOVES2014, the relation between start and running emissions is based on regression analyses of data measured on the FTP cycle through the In-Use Verification Program, described above in 3.9.3.1. As the regressions were performed on the basis of mileage, and MOVES assesses deterioration on the basis of age, it was necessary to relate mileage to age, assuming mileage accumulation of 12,500 mi/year, i.e., at age 1 mileage is 12,500 mi, and at age 2 mileage = 25,000 mi, etc. (Table 3-59).

Based on the regression results, the deterioration ratio for starts (R_{start})is calculated in terms of the ratio for running (R_{run}) as

$$R_{start} = 1 + R_{run}S_{start,run} \qquad \text{Equation 3-52}$$

Where $S_{start,run}$ is the relative sensitivity of start to running emissions, calculated as the ratio of fractional differences in predicted emissions E in each ageGroup a to that at age 2, as shown in Equation 3-53.

$$S_{start,run} = \frac{\frac{E_{a,start}}{E_{2,start}} - 1}{\frac{E_{a,run}}{E_{2,run}} - 1} \qquad \text{Equation 3-53}$$

The calculation of the relative sensitivity is illustrated in Table 3-59. Deterioration ratios for running and start emissions are shown graphically in Figure 3-104.

Table 3-59 NO_x: Calculation of relative sensitivity of cold-start to hot-running emissions

		Cold-Start				Hot-Running				
Age	Mileage	lnNOx	NOx (g/mi)	Norm. 2 yr	frac. diff.	lnNOx	NOx (g/mi)	Norm. 2 yr	frac. diff.	Sensitivity
0	0	-2.6039	0.1039			-4.7396	0.0385			
2	25,000	-2.3654	0.1319	1.0000	0.0000	-4.4396	0.0520	1.0000	0.0000	0.0000
5	62,500	-2.0076	0.1887	1.4302	0.4302	-3.9896	0.0815	1.5683	0.5683	0.7569
7	87,500	-1.7691	0.2395	1.8154	0.8154	-3.6896	0.1100	2.1170	1.1170	0.7300
9	112,500	-1.5305	0.3041	2.3044	1.3044	-3.3896	0.1485	2.8577	1.8577	0.7022
12.5	156,250	-1.1131	0.4616	3.4982	2.4982	-2.8646	0.2510	4.8307	3.8307	0.6522
17.5	218,750	-0.5168	0.8379	6.3507	5.3507	-2.1146	0.5313	10.2267	9.2267	0.5799
23	287,500	0.1391	1.6147	12.2376	11.2376	-1.2896	1.2123	23.3361	22.3361	0.5031

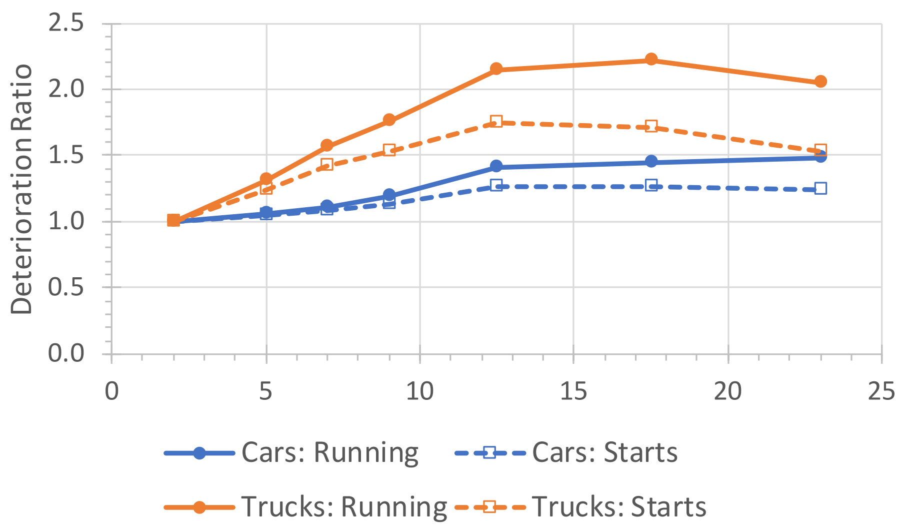

Figure 3-104 NO_x: Deterioration ratios for running and start emissions

3.9.3.3.2 Start Process for THC

For THC, proportional deterioration for starts was calculated in relation to running emissions as for NO_x, using Equation 3-52 and Equation 3-53.

The calculation of the relative sensitivity is illustrated in Table 3-60. Deterioration ratios for running and start emissions are shown graphically in Figure 3-105.

Table 3-60 THC: Calculation of relative sensitivity of cold-start to hot-running emissions

Age	Mileage	Cold-Start lnTHC	Cold-Start THC (g/mi)	Cold-Start Norm. 2 yr	Cold-Start frac. diff.	Hot-Running lnTHC	Hot-Running THC (g/mi)	Hot-Running Norm. 2 yr	Hot-Running frac. diff.	Sensitivity
0	0	-1.9603	0.1556			-6.1604	0.0093			
2	25,000	-1.8358	0.1763	1.0000	0.0000	-5.9545	0.0114	1.0000	0.0000	0.0000
5	62,500	-1.6489	0.2125	1.2054	0.2054	-5.6456	0.0156	1.3619	0.3619	0.5676
7	87,500	-1.5244	0.2407	1.3653	0.3653	-5.4397	0.0191	1.6733	0.6733	0.5425
9	112,500	-1.3998	0.2726	1.5464	0.5464	-5.2337	0.0235	2.0559	1.0559	0.5174
12.5	156,250	-1.1819	0.3390	1.9230	0.9230	-4.8734	0.0337	2.9479	1.9479	0.4738
17.5	218,750	-0.8705	0.4628	2.6255	1.6255	-4.3586	0.0563	4.9329	3.9329	0.4133
23	287,500	-0.5280	0.6518	3.6979	2.6979	-3.7923	0.0993	8.6903	7.6903	0.3508

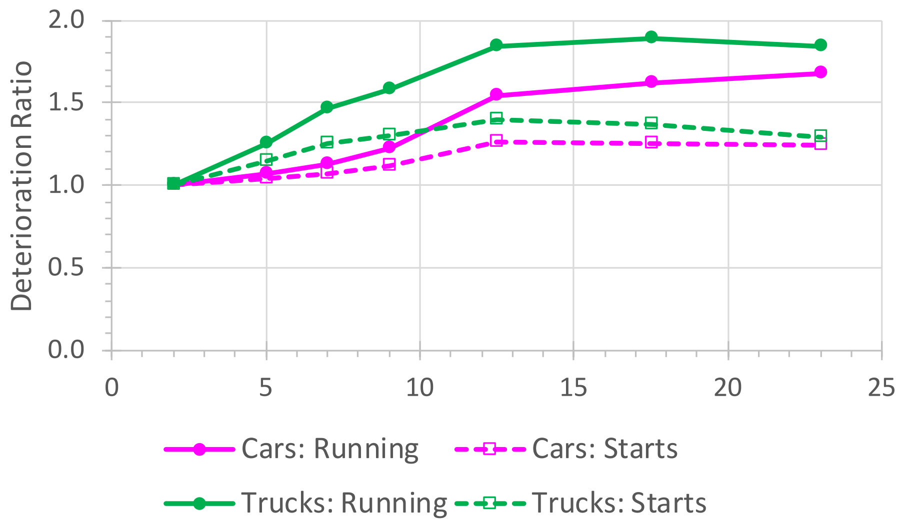

Figure 3-105 THC: Deterioration ratios for running and start emissions

3.9.3.3.3 Start Process for CO

For CO, proportional deterioration for starts was calculated in relation to running emissions as for NO_x, using Equation 3-52 and Equation 3-53 .

The calculation of the relative sensitivity is illustrated in Table 3-61. Deterioration ratios for running and start emissions are shown graphically in Figure 3-106.

Table 3-61 CO: Calculating the relative sensitivity of start to running deterioration

Age	Mileage	Cold-Start lnCO	Cold-Start CO (g/mi)	Cold-Start Norm. 2 yr	Cold-Start frac. diff.	Hot-Running lnCO	Hot-Running CO (g/mi)	Hot-Running Norm. 2 yr	Hot-Running frac. diff.	Sensitivity
0	0	-0.2186	0.9604			-2.7594	0.1828			
2	25,000	-0.0954	1.0863	1.0000	0.0000	-2.5333	0.2292	1.0000	0.0000	0.0000
5	62,500	0.0895	1.3068	1.2030	0.2030	-2.1941	0.3217	1.4038	0.4038	0.5028
7	87,500	0.2127	1.4782	1.3608	0.3608	-1.9680	0.4033	1.7600	0.7600	0.4747
9	112,500	0.3359	1.6721	1.5392	0.5392	-1.7418	0.5057	2.2066	1.2066	0.4469
12.5	156,250	0.5516	2.0745	1.9097	0.9097	-1.3461	0.7512	3.2777	2.2777	0.3994
17.5	218,750	0.8596	2.8229	2.5987	1.5987	-0.7808	1.3221	5.7688	4.7688	0.3352
23	287,500	1.1985	3.9616	3.6468	2.6468	-0.1590	2.4622	10.7436	9.7436	0.2716

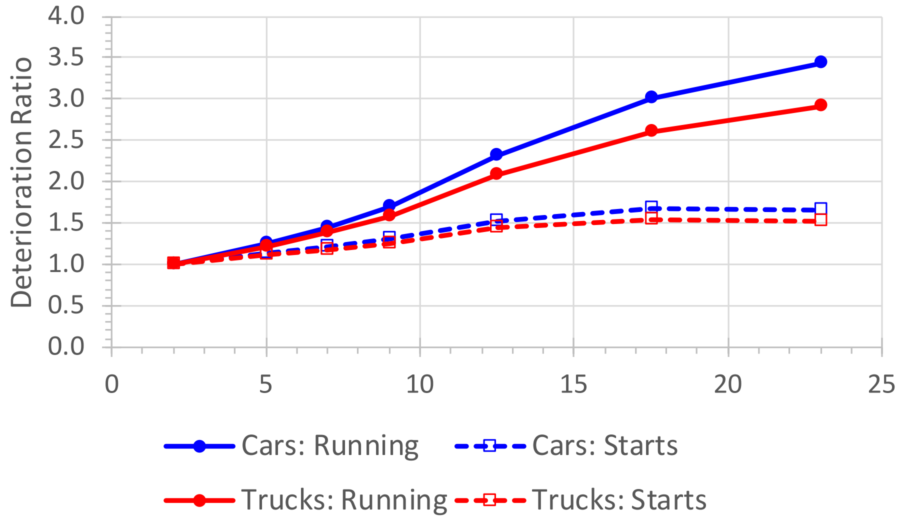

Figure 3-106 CO: Deterioration ratios for running and start emissions

3.10 Constructing Updated Rates (Model Years 1990 and Later)

Having completed the analyses described in 3.6, 3.7, 3.9.2 and 3.9.3.3, we constructed the updated MOVES3 running and start gaseous exhaust rates for light-duty cars and trucks by adjusting the MOVES2014 rates in the emissionRateByAge table. Note that these updates apply only to rates for MY 1990 and later. The rates for MY 1989 and earlier are unchanged.

We did this in several steps, described below.

3.10.1 Step 1: Extract LD gasoline rates from the Input database

We extracted a subset of rates from the emissionRateByAge table in the previous MOVES database. The scope of rates extracted is described below:

Database: MOVESDB20200123.

Pollutant/Process: Running and start exhaust for HC, CO and NO_x (polprocessid = 101, 201, 301 and 102, 202, 302),

Age Group: Ages 0-3 years (ageGroupID = 3),

Operating Modes: 23 Modes for running coast/cruise/acceleration (0, 1, 11-16, 21-30, 33-40), [f] eight modes for start operation (101-108),

Fuel type: Gasoline (fuelTypeID) = 1,

Regulatory Class: light-duty cars (LDV) and trucks (LDT) (regClassID = 20, 30),

Model year: Model year groups from 1990-93 through 2051-2060.

[f] Note that operating modes 26 and 36 do not exist.

3.10.2 Step 2: Apply Young-vehicle Adjustments to Running Rates

We applied the "young vehicle adjustments" described in 3.6.7 and 3.7.7 to calculate revised I/M reference rates (meanBaseRateIM) in the first ageGroup (0-3 years). The adjustments were merged into the emissionRateByAge segment on basis of regulatory class and model year. We applied these adjustments to running rates but not to start rates. The adjustments for model year 2010 were applied to all future model years through 2060.

3.10.3 Step 3: Apply Deterioration Adjustments

We calculated revised I/M reference rates for the remaining six ageGroups, based on results of analyses described in 3.6.8 and 3.7.8 for running emissions and 3.9.3.3 for start emissions. We merged the deterioration adjustments into the rates segment on the basis of pollutant process, regulatory class and ageGroup. The deterioration adjustments were applied multiplicatively and uniformly to both running and start rates in all model years 1990-2060.

3.10.4 Step 4: Apply Non-IM Ratios

We calculated the non-I/M reference rates (meanBaseRate) from the I/M reference rates (meanBaseRateIM) by applying non-I/M ratios. These ratios increase by ageGroup and were merged into the rates segment on basis of pollutant process and ageGroup. These ratios are the same values for all model years (see 3.5) and are applied multiplicatively and uniformly to both running and start rates for both regulatory classes in all model years.

3.10.5 Step 5: Replicate Rates for Additional Fuel Types

After completing Step 4, we replicated the subset of rates for gasoline (fuelTypeID = 1) to generate corresponding subsets for diesel (fuelTypeID = 2) and E85 (fuelTypeID = 5). Because data on E-85 and diesel-fueled LD vehicles is lacking and at least since the introduction of Tier-2 standards, they are required to meet the same emission standards as gasoline vehicles, we found it appropriate to use the same rates in modelling their emissions.

As we do not represent an "I/M difference" for light-duty diesel vehicles, for this fuel only, we reset the meanBaseRateIM to equal the meanBaseRate.

For E85 and diesel, we assigned the dataSourceID as 4900 and 4910, respectively.

3.11 Final Results for Update for MOVES3

Having completed the steps described in 3.10, we have generated a complete set of updated rates for model years 1990 and later, encompassing the Tier 0, Tier 1, National LEV, Tier 2 and Tier 3 emissions standards.

In this section, we present and review the resulting emission rates, including comparison to rates developed for MOVES3 in comparison to the rates used for the previous public release, MOVES2014b. We note trends in the rates from the perspective of key variables in the table structure. These include vehicle-specific power (for running rates), soak time (for start rates), age (for both running and start rates) and I/M status.

Because the rates are generated by applying multiplicative factors, the patterns and trends are generally proportional, so only a few representative examples need be shown.

3.11.1 Trends with Vehicle-Specific Power

The operating modes for most of the rates for the running-exhaust process, with the exception of the idle and deceleration/braking modes, are defined in term of vehicle-specific power (VSP, kW/Mg).

We present rates for a subset of the operating modes, 21-30, which show a complete VSP trend at moderate speed (25-50 mph), from < 0 kW/Mg (coasting) to > 30 kW/Mg (hard acceleration). To give proper scaling, the midpoint values of VSP for each mode are used for plotting, as shown in Table 3-62.

Table 3-62 Midpoint VSP values assigned to selected operating modes for plotting purposes

Operating Mode	Vehicle Specific Power (VSP, kW/Mg)
21	-2
22	2.5
23	4.5
24	7.5
25	10.5
27	15.0
28	21.0
29	27.0
30	34.0

The plots present the "I/M reference rate" (meanBaseRateIM) for cars (regClassID = 20, on left) and trucks (regClassID = 30, on right). The plot shows four model years, taken as cross sections across the long-term trend of improving technology and declining standards. The model years 1998, 2004, 2010 and 2017 represent the "Tier 1", "Onset of Tier 2", "mature Tier 2" and "onset of Tier 3," respectively.

The appearance of all plots is generally similar, because the scaling in the rates is proportional throughout, and because each row in the plots is scaled independently of the others. In viewing the plots, it is important to note the differences in scales by model year.

Plots for THC, CO and NO_x are presented in Figure 3-107, Figure 3-108 and Figure 3-109 below. These figures present rates for "young vehicles" in the 0-3 year ageGroup.

In all cases, the updated MOVES3 rates are higher than the previous rates in all cases at VSP < 15 kW/Mg, and in many but not all cases at VSP > 15 kW/Mg. This difference is largely due to the application of the "young-vehicle" adjustments described above, although it is not always conspicuous at low VSP where the rates are smaller. The difference is the most marked for THC, as the "young-vehicle" adjustments for this pollutant were often more than twice as large as for CO and NO_x. See for 3.6.7.1 for NO_x, 3.6.7.3 for THC, and 3.7.7 for CO.

For CO, the updated rates are higher than the previous rates for both cars and trucks in all model years. Of the three pollutants, CO shows the most marked increase in the steepness of the trend at higher VSP, which may reflect the tendency towards increased CO production as the engine shifts towards rich operation.

For THC and NO_x, however, the updated rates are lower than the previous rates at higher power, with this tendency more pronounced for trucks than cars, and becoming more pronounced for model years after 2004. Note that in the MOVES2014 rates, the trends for THC and NO_x have sharp “elbows” in the trends at 15 kW/Mg. These sharp increases in the trends reflect the assumption that emissions control systems would be less effective at higher VSP, resulting in sharper VSP trends for the “high power” modes. In this update, this assumption has been revised, as review of more recently acquired data did not support it as described in Section 3.3.2.4. Accordingly, the MOVES3 trends in the three more recent model years appear qualitatively similar to that for 1998, although scaled down to represent the more recent technologies and emission standards.

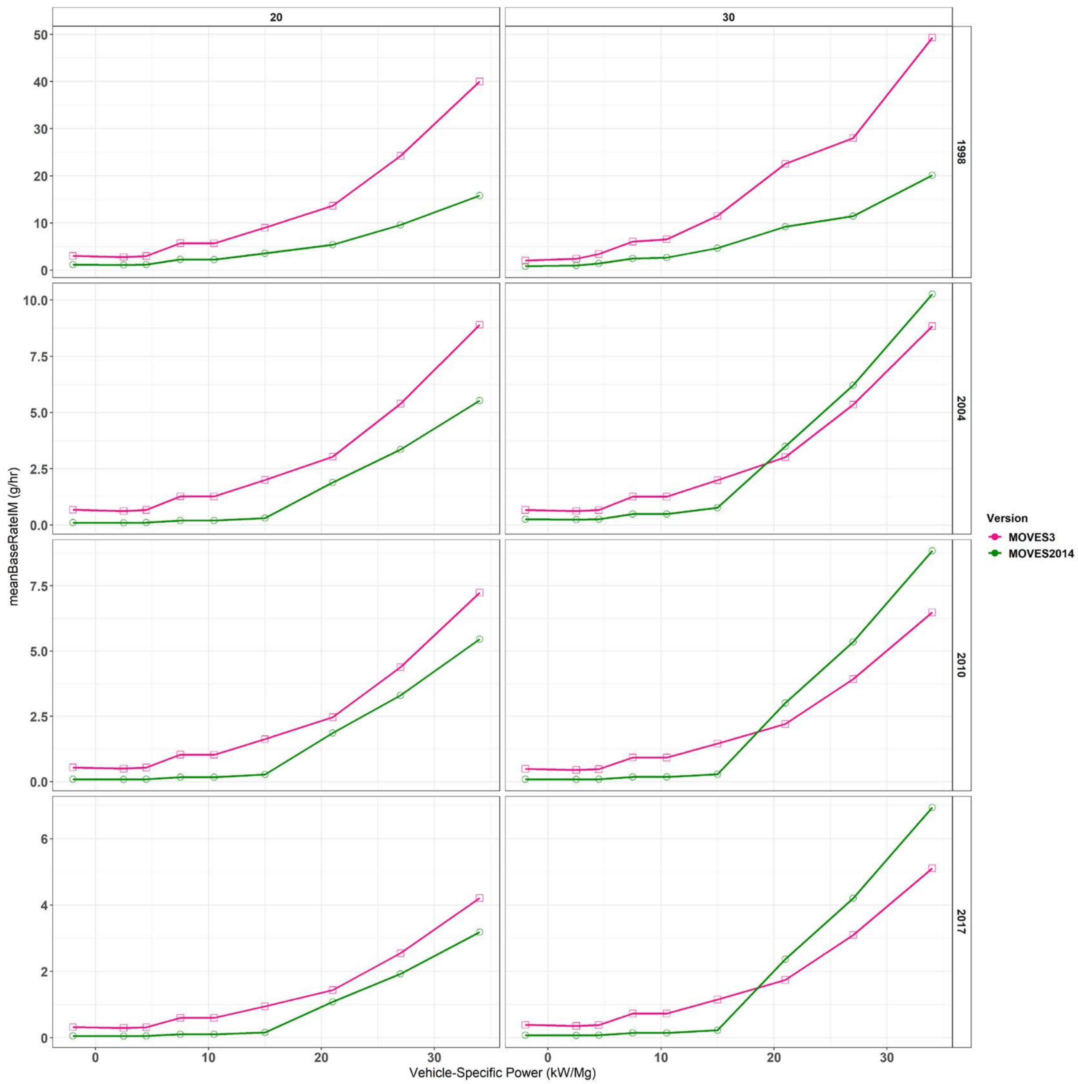

Figure 3-107 THC: Emission rate (meanBaseRateIM in g/hr) vs. VSP for operating modes 21-30, for cars (20) and trucks (30) in four model years (1998, 2004, 2010, 2017), at ages 0-3 (Note that rows are scaled independently)

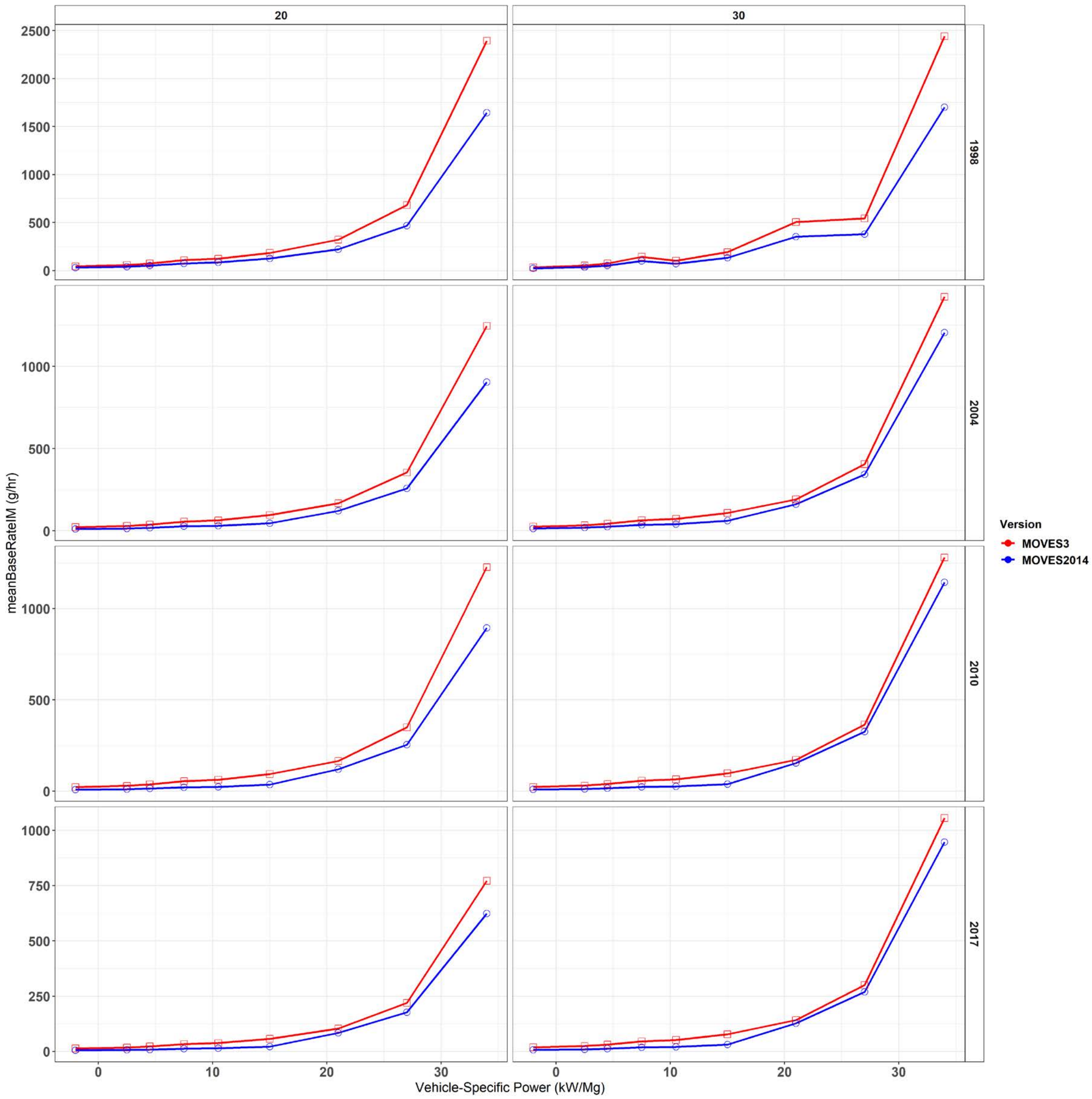

Figure 3-108 CO: Emission rate (meanBaseRateIM in g/hr) vs. VSP for operating modes 21-30, for cars (20) and trucks (30) in four model years (1998, 2004, 2010, 2017), at ages 0-3 (Note that rows are scaled independently)

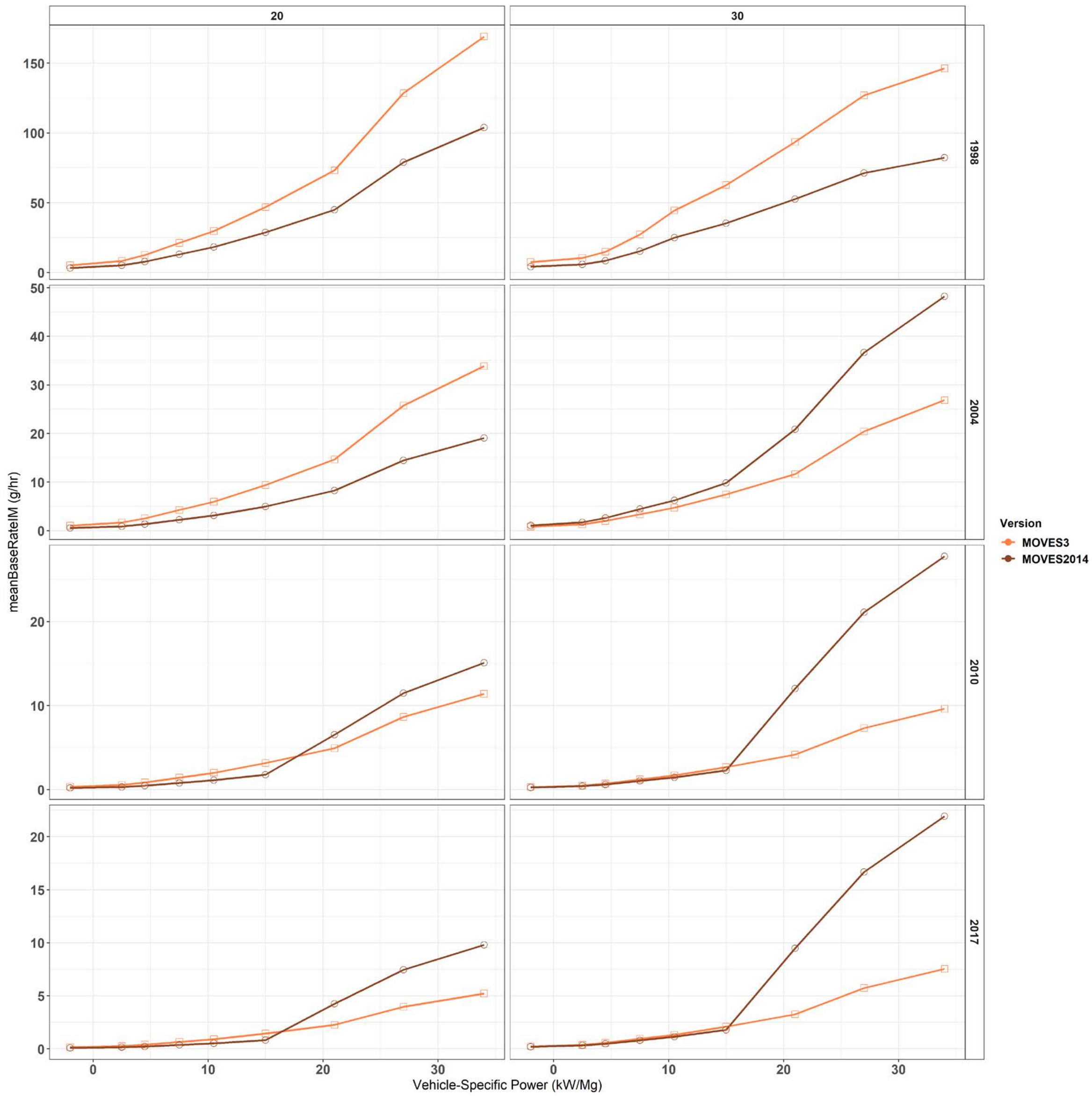

Figure 3-109 NO_x: Emission rate (meanBaseRateIM in g/hr) vs. VSP for operating modes 21-30, for cars (20) and trucks (30) in four model years (1998, 2004, 2010, 2017), at ages 0-3 (Note that rows are scaled independently)

3.11.2 Trends with Soak Time

The operating modes for the rates for the start-exhaust process, are defined in term of soak time, i.e., the time since the engine was last turned off, as described in 3.8.1.2 on page 167.

We present rates for the eight start operating modes, 101-108, which reflect a range in soak time from several minutes to 12 hours (720 min), at which point we assume that the engine is completely "cold". To give proper scaling, the midpoint values of soak time for each mode are used for plotting, as shown in Table 3-63 below.

Table 3-63 Midpoint soak-time values assigned to operating modes for plotting purposes

Operating Mode	Soak time (hr)
101	0.05
102	0.30
103	0.75
104	1.25
105	1.75
106	4.0
107	9.0
108	12.0

The plots present the "I/M reference rate" (meanBaseRateIM) for cars (regClassID = 20, on left) and trucks (regClassID = 30, on right). The plot shows the same four model years used for the VSP trends above.

As with the VSP trends, the appearance of all plots is generally similar, because the scaling in the rates is proportional throughout, and because each row in the plots is scaled independently of the others.

Plots for THC, CO and NO_x are presented in Figure 3-110, Figure 3-111 and Figure 3-112 below, respectively. These figures present rates for "young vehicles" in the 0-3 year ageGroup.

In all three figures, note that the updated and previous trends are identical in MY1998. This pattern follows from the fact that the "young-vehicle" adjustments were not applied to start emissions, and also that the "older" soak-time relationships apply to this model year (see Figure 3-83, page 170). In addition, note that the rates for the "cold starts" (soak time = 12 hr, opModeID=108) are also identical, as the "young-vehicle" adjustments were not applied to start rates. The differences shown for the remaining seven operating modes, i.e., "warm" and "hot" starts, reflect the differences between the "older" and "updated" soak-time relationships (see Figure 3-90 to Figure 3-92, page 180).

For THC, the updated soak-time trends are generally similar to the older trends, but the updated start rates are higher than before for soak times between 1.25 and 9.0 hours. For times < 1 hr, the updated rates are lower, as the updated trend shows a less steep curvature for hot starts.

For CO, the updated trends are also generally similar in shape to the older trends, but the updated rates are lower at all times except 12 hours.

For NO_x, the updated trends differ markedly from the older trends. Rather than increasing gently from the 12-hr soak to a broad peak at the 1.25-hr soak, the updated rates increase more steeply from the 12-hr soak to a sharper peak at the 1.75-hr soak, then declining steeply to the 0.05-hr soak. The updated rates for the two shortest soak times are lower than before.

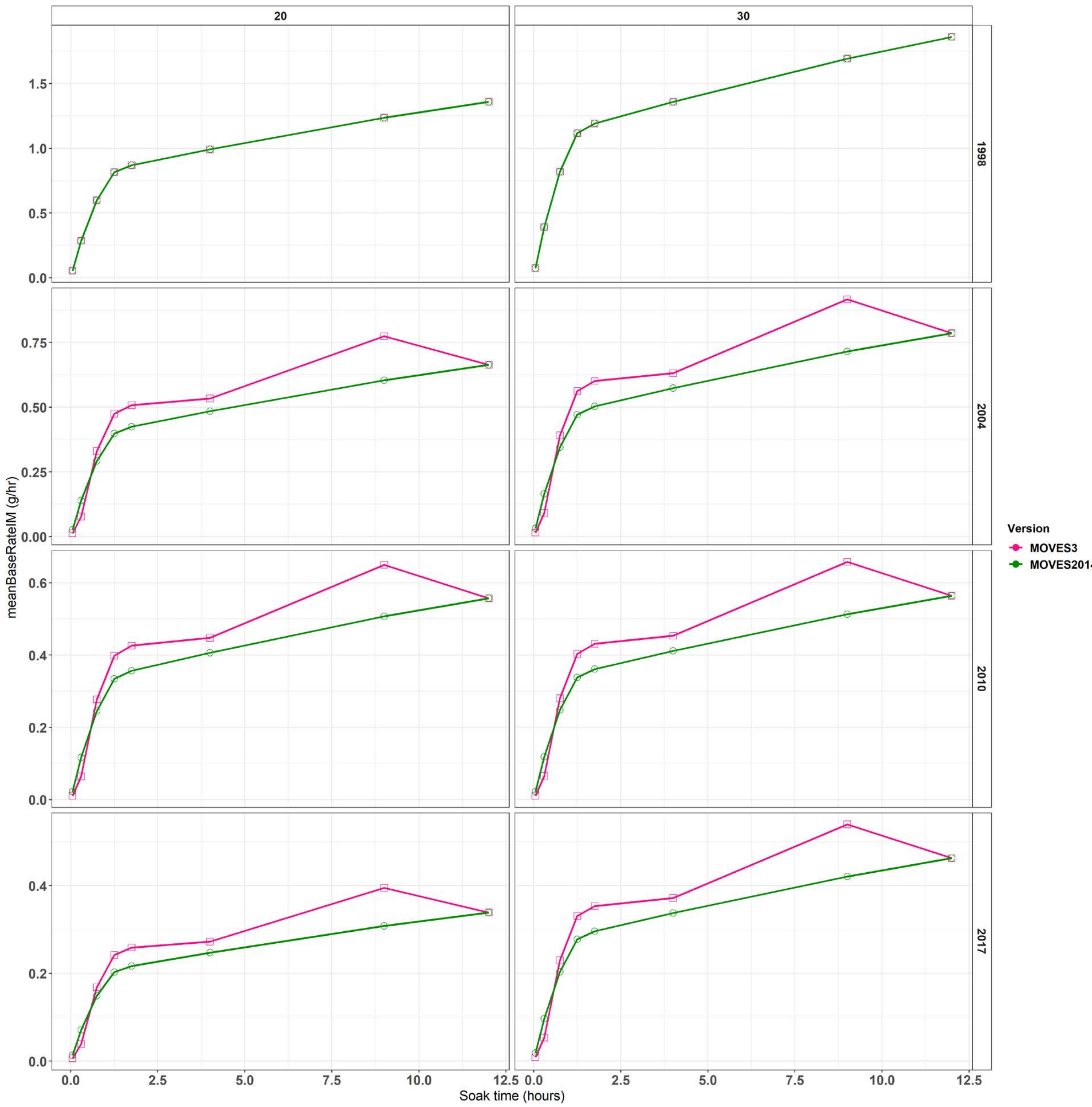

Figure 3-110 THC: Emission rate (meanBaseRateIM, g/start) vs. soak time for operating modes 101-108, for cars (20) and trucks (30) in four model years (1998, 2004, 2010, 2017), at ages 0-3 (Note that rows are scaled independently)

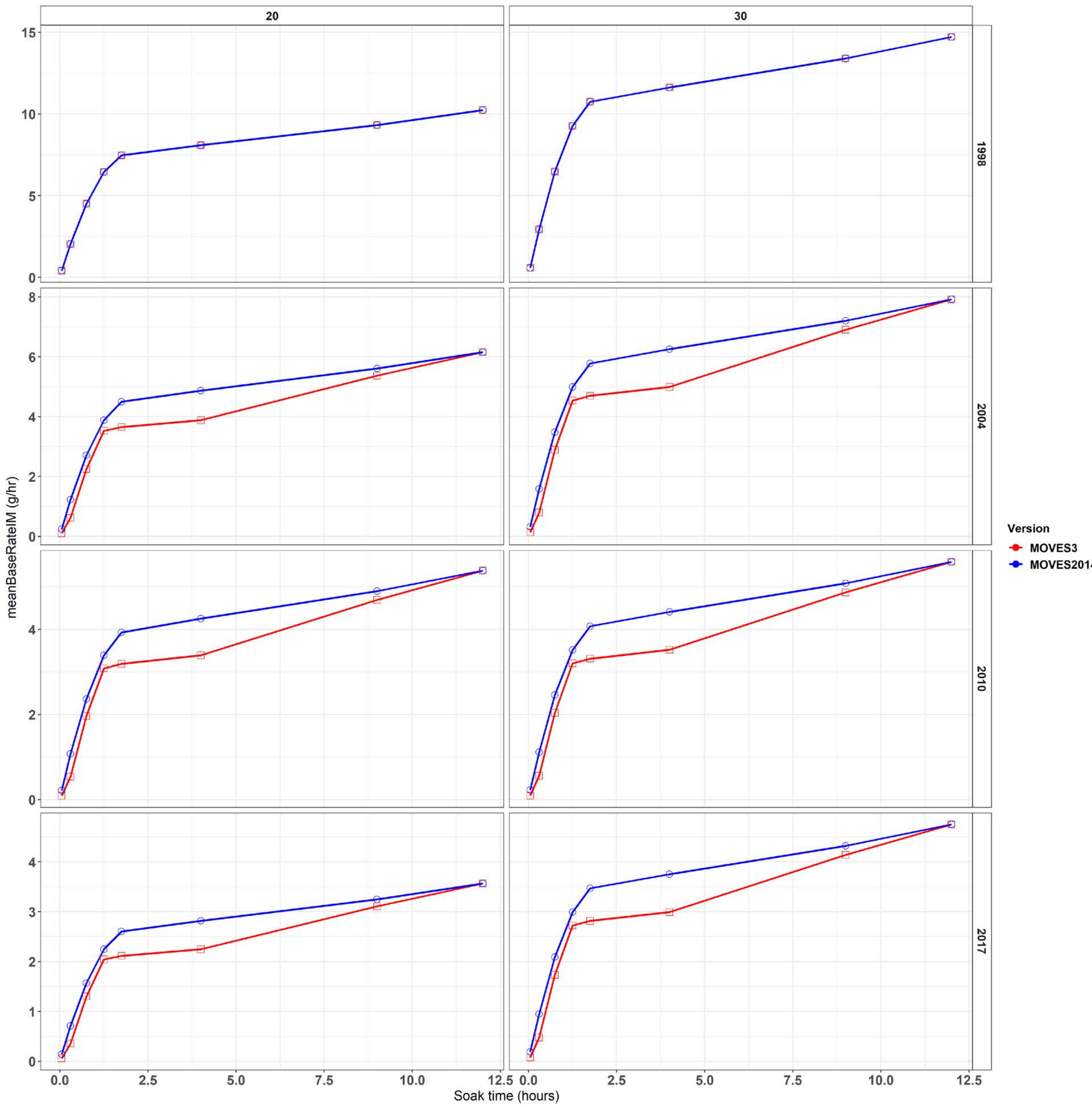

Figure 3-111 CO: Emission rate (meanBaseRateIM, g/start) vs. soak time for operating modes 101-108, for cars (20) and trucks (30) in four model years (1998, 2004, 2010, 2017), at ages 0-3 (Note that rows are scaled independently)

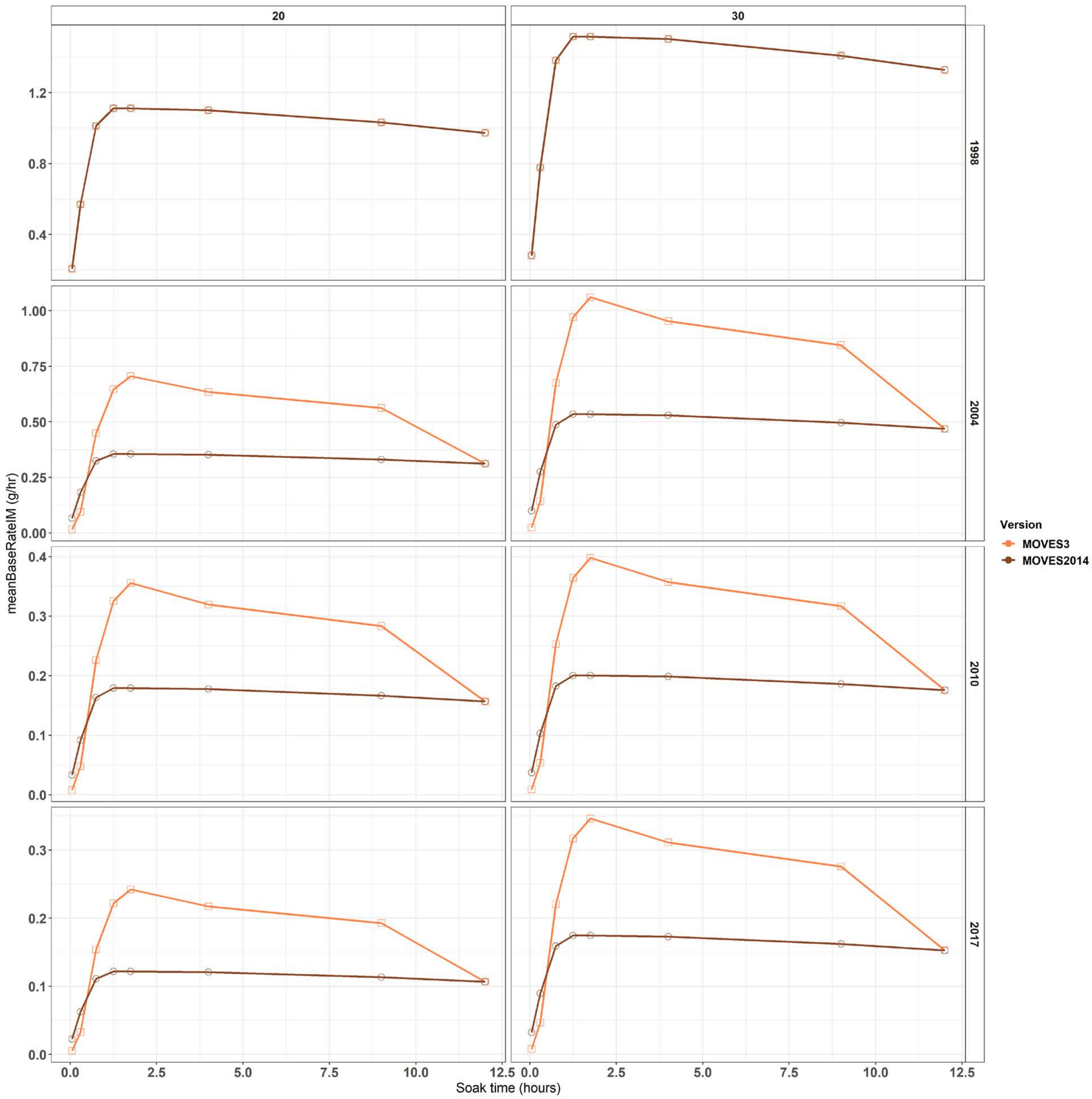

Figure 3-112. NO_x: Emission rate (meanBaseRateIM, g/start) vs. soak time for operating modes 101-108, for cars (20) and trucks (30) in four model years (1998, 2004, 2010, 2017), at ages 0-3 (Note that rows are scaled independently).

3.11.3 Trends with Age

Trends with age display the deterioration assumptions projected through the rates, reflecting a variety of data sources and analysis methods throughout the complete set. Comparing age trends is of particular interest because the reevaluation and revision of deterioration assumptions was one of the chief motivations in initiating the current update.

We present subsets of rates for the MOVES ageGroups, which show complete deterioration trends from 0-3 years through 20+ years. To give proper scaling, the midpoint values of age ranges for each ageGroup are used for plotting, as shown in Table 3-64.

Table 3-64 Midpoint ages for the MOVES ageGroups used for plotting

ageGroupID	Age range (yr)	Midpoint Age (yr)
3	0-3	2
405	4-5	5
607	6-7	7
809	8-9	9
1014	10-14	12.5
1519	15-19	17.5
2099	20+	23

The plots present the "I/M reference rate" (meanBaseRateIM) for cars (regClassID = 20, on left) or trucks (regClassID = 30, on right). As with previous plots, these plot shows four model years, although not always the same in all plots.

Unlike the previous two sets of plots, this set includes both rates for running and start operating modes. Each plot includes two running and two start modes, but with the specific modes varying by plot.

As before, each row in the plots is scaled independently of the others. In this set, however, the model years are arranged in rows, so that the decline in the rates with model year is clearly evident. In fact, for more recent model years, the age trends are difficult to see due to scaling effects.

Plots for THC, CO and NO_x are presented Figure 3-113, Figure 3-114 and Figure 3-115 below. The figure for THC presents rates for cars, whereas those for CO and NO_x present rates for trucks.

For the running rates the updated rate at age=2 is consistently higher than the previous rates, due to application of the "young-vehicle" adjustments. This point is particularly conspicuous for the THC rates.

For the start rates the updated rate at age 2 is always identical to that in the previous rates in model year 1998 and for operating mode 108 (cold start). In these cases, the lack of difference follows from not applying the "young-vehicle" adjustments. In model year 1998, the rates at age 2 are identical because the updated soak-time relationships were not applied. For model years following 1998, however, and for operating modes other than 108, the rates differ at all ages because the updated soak-time relationships apply, combined with updated deterioration.

For the updated rates, the shape of the age trends is always qualitatively the same, because these trends reflect the characteristic trends in the underlying three-piece spline deterioration models applied in the update. While these similarities always apply, they are not always obvious in the plots due to scaling effects.

In the MOVES2014 trends, however, the trends for MY1998 differ from those in the later model years, due to differences in methods applied in the development of the rates for MOVES2010.

That the deterioration in the update is substantially reduced is particularly evident in the start rates for THC and CO, and also to some degree in the start rates for NO_x. While not always as clear in the running rates, due to vertical offsets between the trends, Figure 3-69 (NO_x, page

148), Figure 3-72 (THC, page 150) and Figure 3-82 (CO, page 165) show clearly that relative or proportional deterioration is much lower in the updated rates.

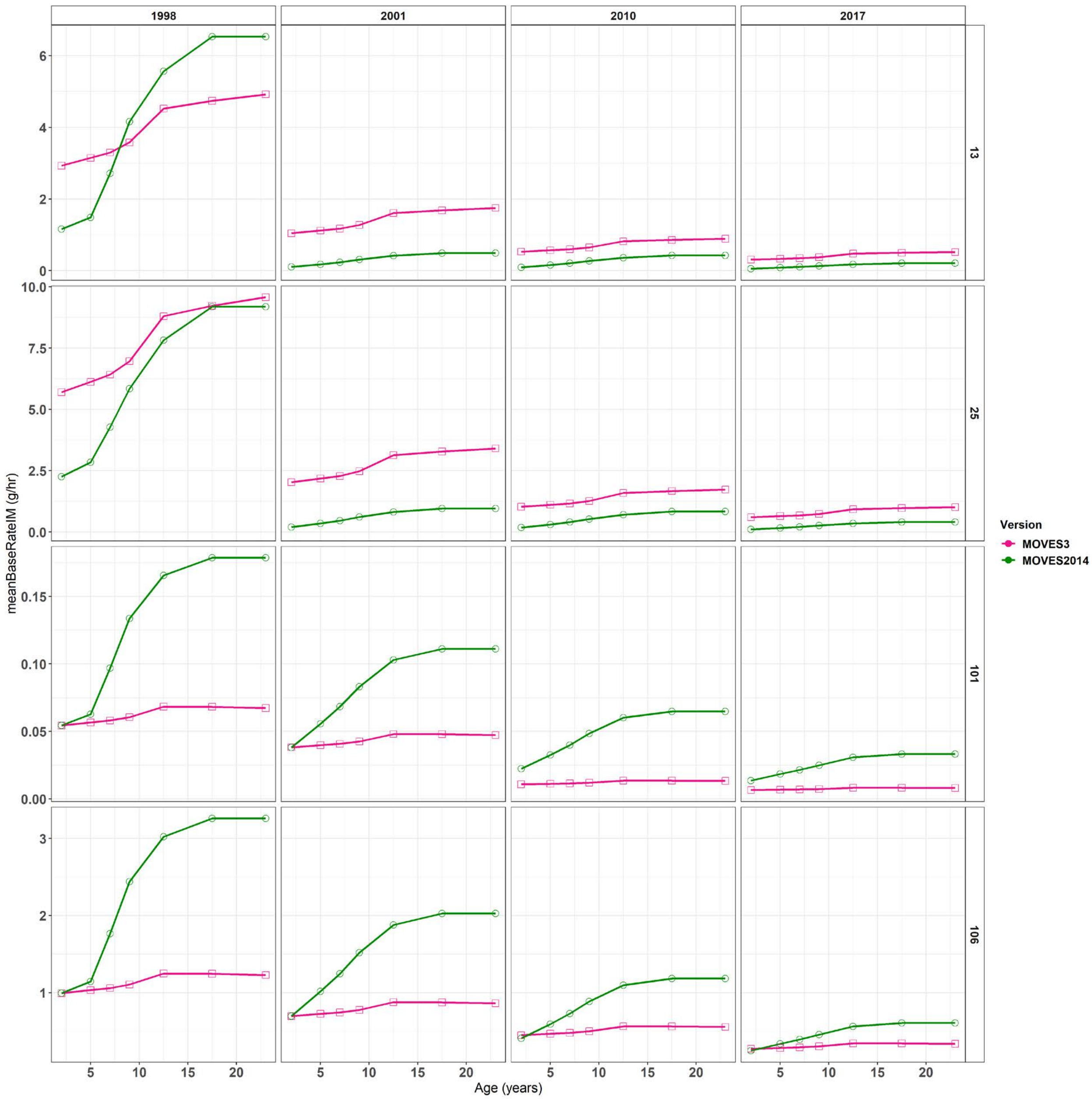

Figure 3-113 THC for Cars: Emission rate (meanBaseRateIM) vs. age for two running operating modes (13, 25, g/hr) and two start modes (101, 106. g/start), in four model years (1998, 2004, 2010, 2017), (Note that rows are scaled independently)

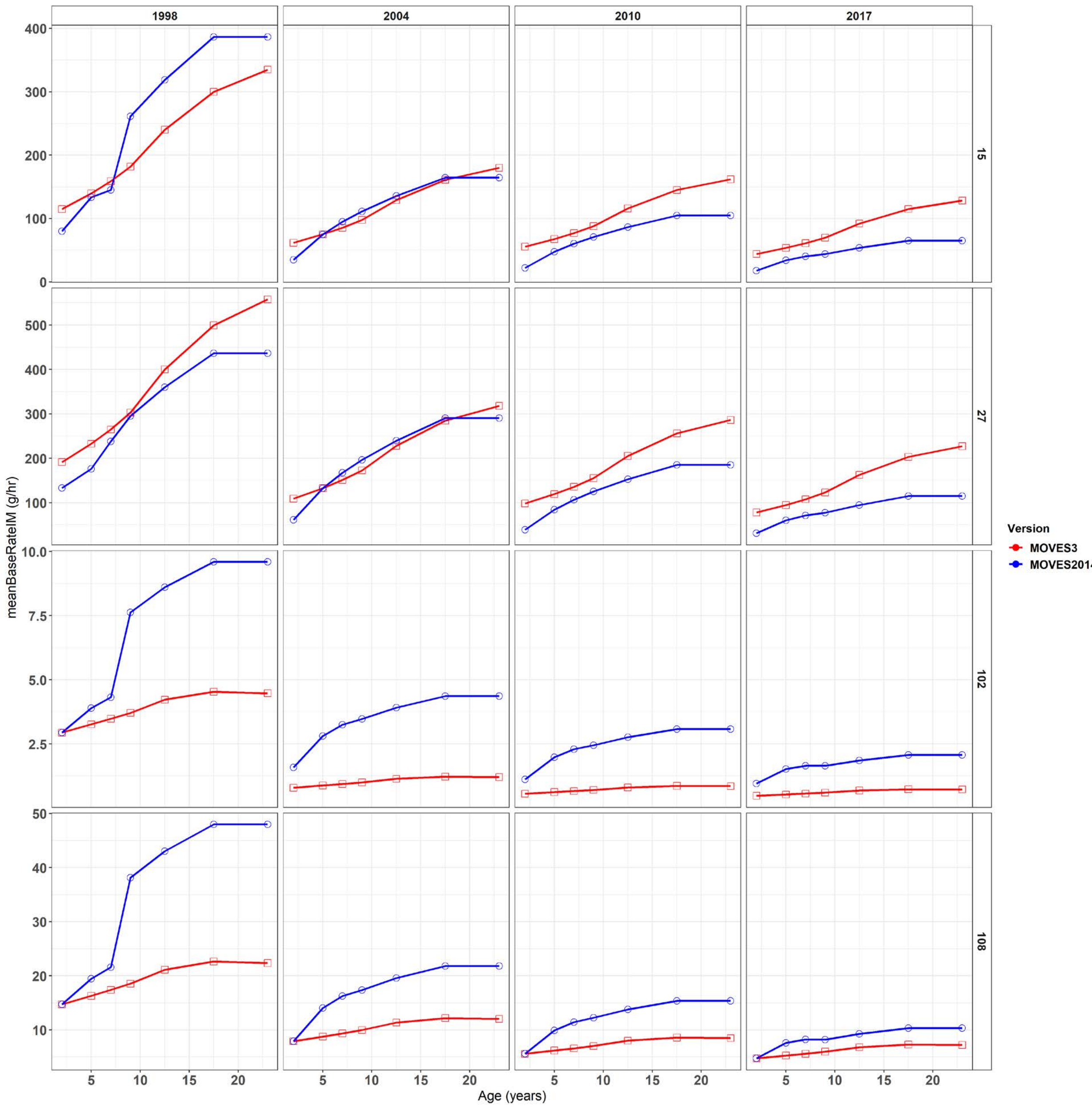

Figure 3-114 CO for Trucks: Emission rate (meanBaseRateIM) vs. age for two running operating modes (15, 27, g/hr) and two start modes (102, 108, g/start), in four model years (1998, 2004, 2010, 2017). (Note that rows are scaled independently)

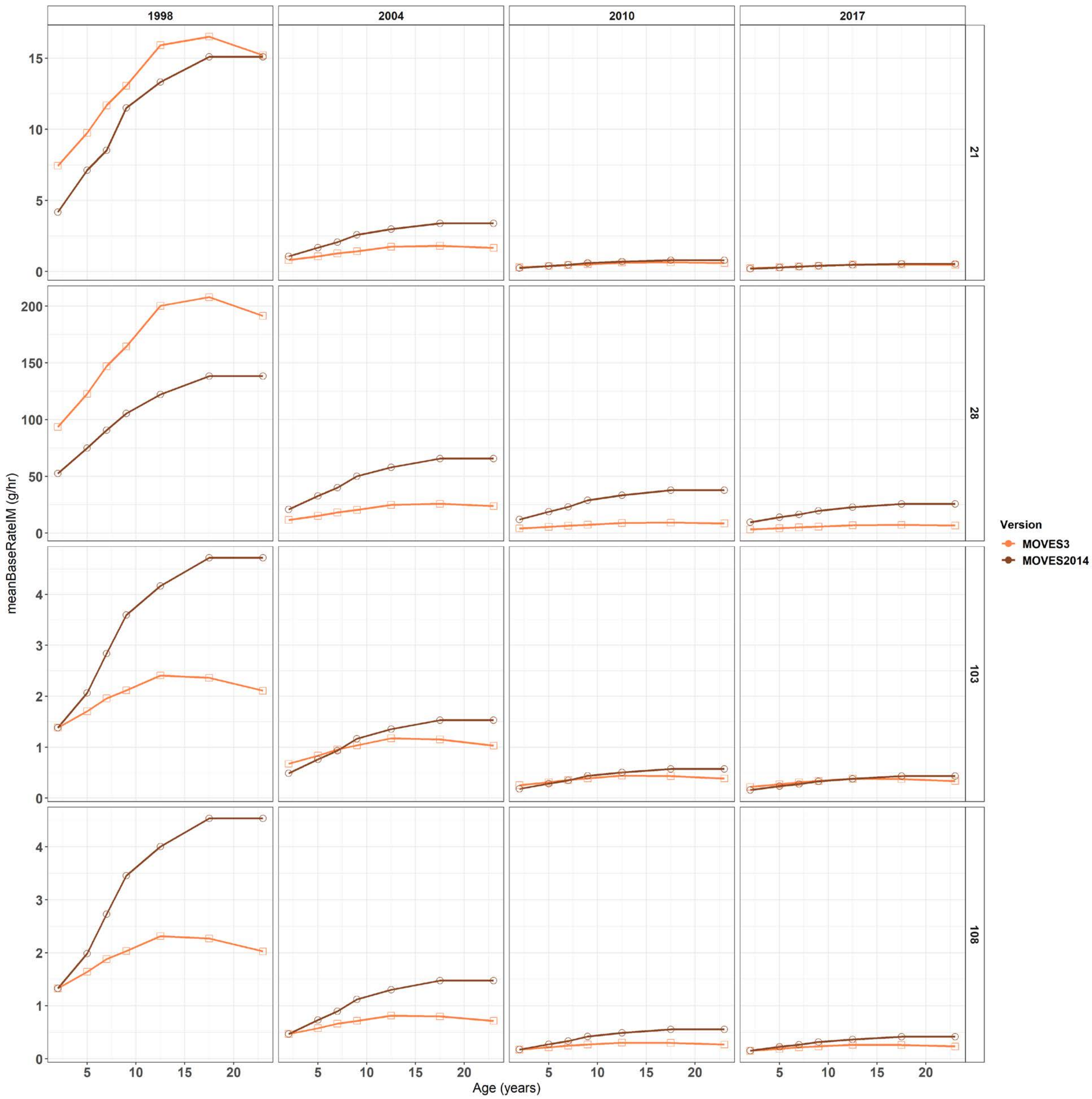

Figure 3-115 NO_x for Trucks: Emission rate (meanBaseRateIM) vs. age for two running operating modes (21, 28, g/hr) and two start modes (103, 108, g/start), in four model years (1998, 2004, 2010, 2017). (Note that rows are scaled independently)

3.11.4 Trends with I/M Status

The emissionRateByAge table contains two sets of rates, one representing a default "I/M reference" condition (meanBaseRateIM), and a second representing a default "non-I/M reference" condition (meanBaseRate).

In the current update, as well as in MOVES2010 and MOVES2014, the meanBaseRateIM was estimated first, as the datasets available to estimate deterioration are collected in I/M areas and in association with I/M programs. These datasets include the Phoenix I/M evaluation sample in MOVES2010 and MOVES2014. This dataset is still applicable in MOVES3 for model years prior to 1990. For MOVES3, newly available datasets include the Denver Evaluation Sample and the CDPHE remote-sensing data.

The non-I/M reference rates are estimated from the I/M references by applying ratios that vary by age (see 3.5, page 95). Thus, in the figures below, the I/M and non-I/M rates are presented as age trends. It is important to emphasize that the differences between the non-I/M and I/M defaults assume complete program compliance. This difference is discounted somewhat during model runs, based on the parameters that estimate compliance effectiveness (IMcomplianceFactor).

Examples are presented below for Figure 3-116, Figure 3-117 and Figure 3-118 for THC, CO and NO_x, respectively. In the plots, the rates represent cars or trucks in an individual model year, with panels for MOVES2014 and MOVES3. As with the trends with age, the plots include two operating modes for running operation, and two for start operation.

In the MOVES2014 trends, the non-I/M trend resembles the I/M trend, as it is derived from it by application of the ratios. Because the ratios are both multiplicative and increase with age, the implication is that deterioration emission rates are higher and deterioration somewhat steeper in non-I/M areas.

In the MOVES3 trends, as with the previous age trends, the characteristic shapes of the underlying deterioration models are evident in both the I/M and non-I/M rates. In the update, the two sets of rates are exactly proportional.

In the MOVES2014 rates, a difference between the two sets of rates is that the I/M rates tend to stabilize in the two oldest age groups whereas the non-I/M rates continue to increase, with the increase more marked in the start rates. These differences are based on assumptions regarding behavior of emissions trends in non-I/M areas (see 3.2.2.3.1, page 56).

In the updated rates, by contrast, aside from application of the ratios to estimate the non-I/M default rates, no additional assumptions were made regarding whether deterioration trends in non-I/M areas would differ from those in I/M areas. This differs from the approach in previous versions of MOVES as documented in Section 3.2.2.3.1. Deterioration in non-I/M areas is an important area of uncertainty, due to the lack of large datasets outside of I/M areas. Thus, this question remains difficult to evaluate.

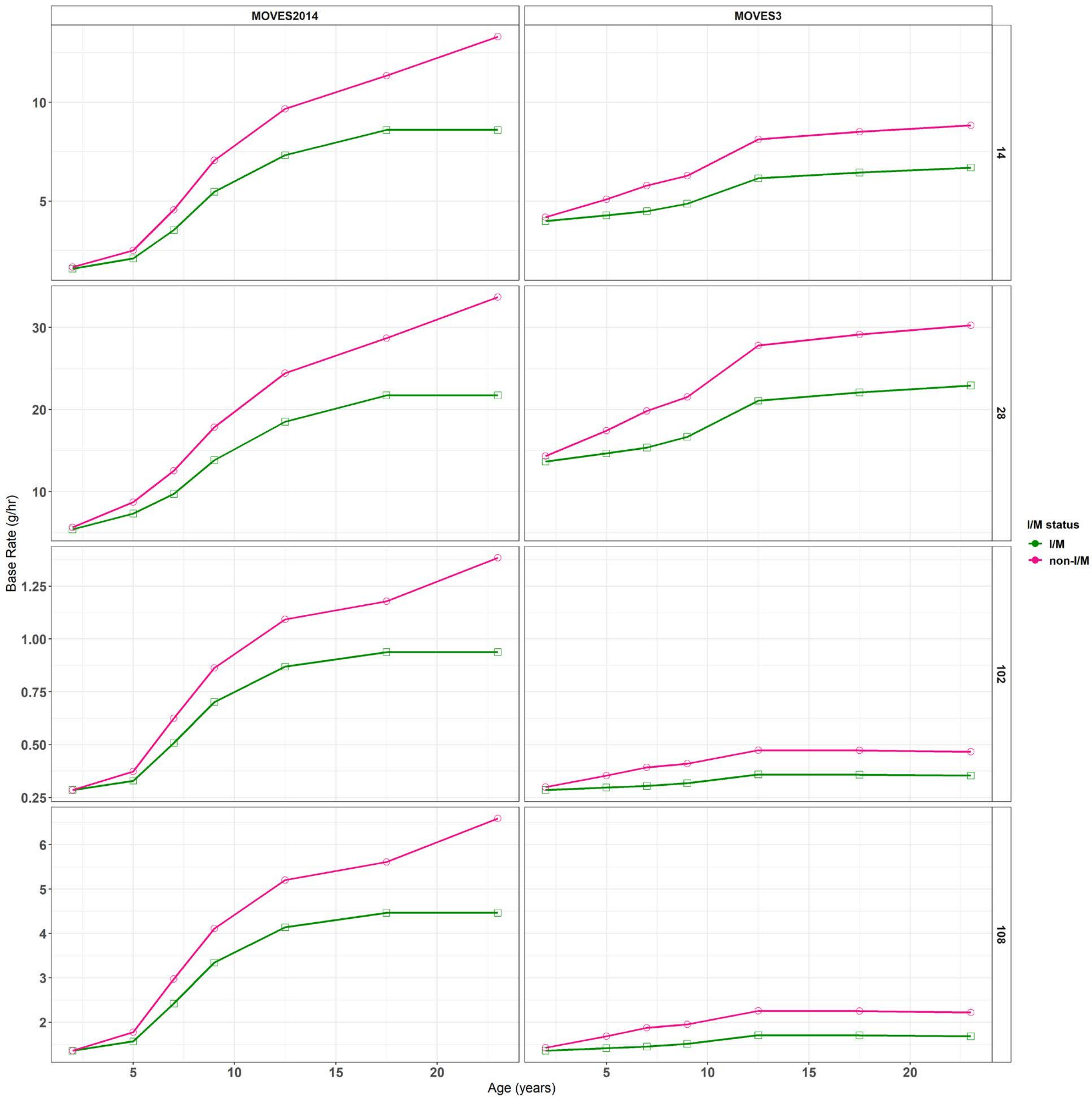

Figure 3-116 THC for Cars in MY1998: Emission rate (meanBaseRateIM, meanBaseRate) vs. age for two running operating modes (14, 28, g/hr) and two start modes (102, 108, g/start) (Note that rows are scaled independently)

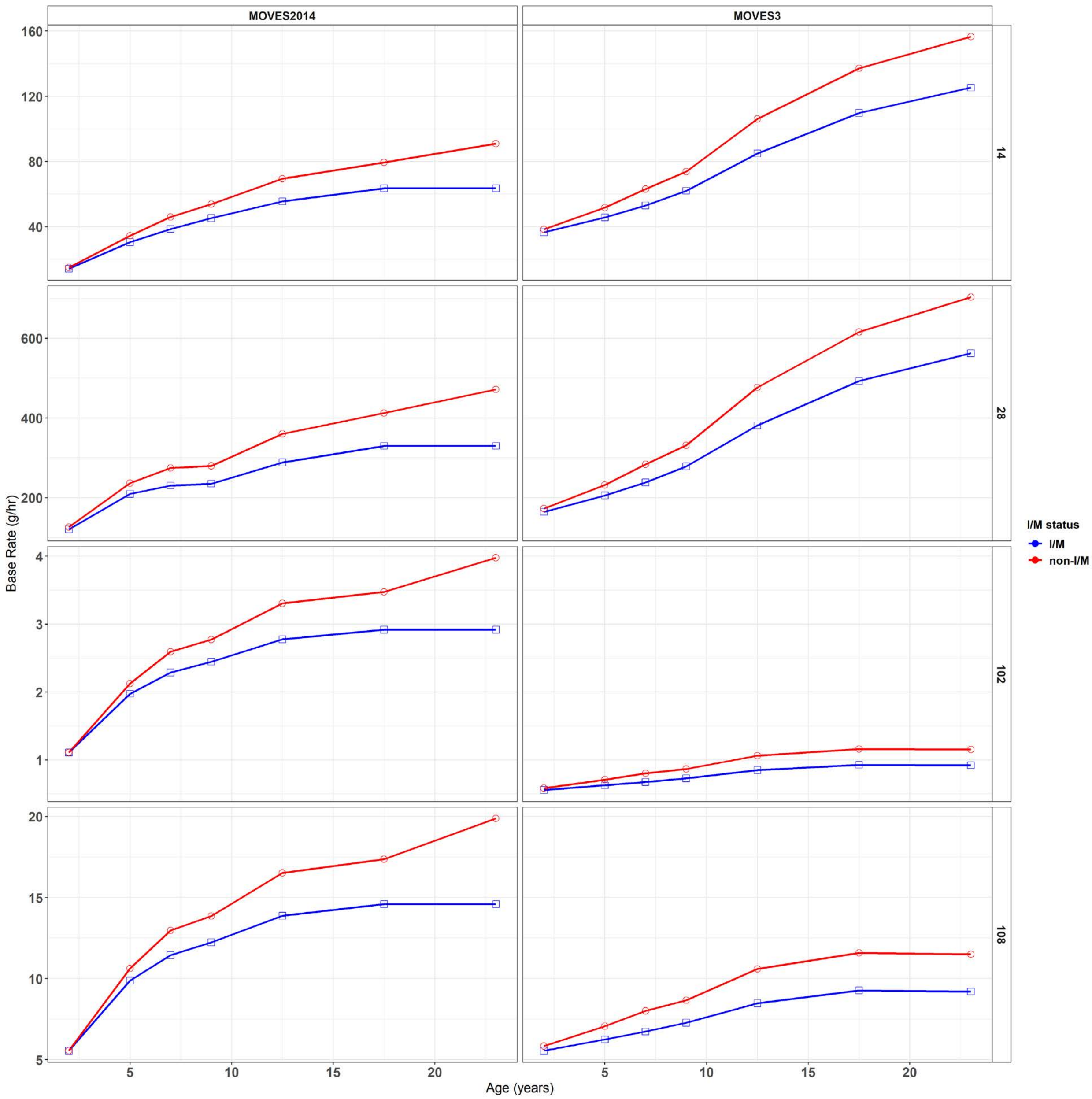

Figure 3-117 CO for Trucks in MY2008: Emission rate (meanBaseRateIM, meanBaseRate) vs. age for two running operating modes (14, 28, g/hr) and two start modes (102, 108, g/start) (Note that rows are scaled independently)

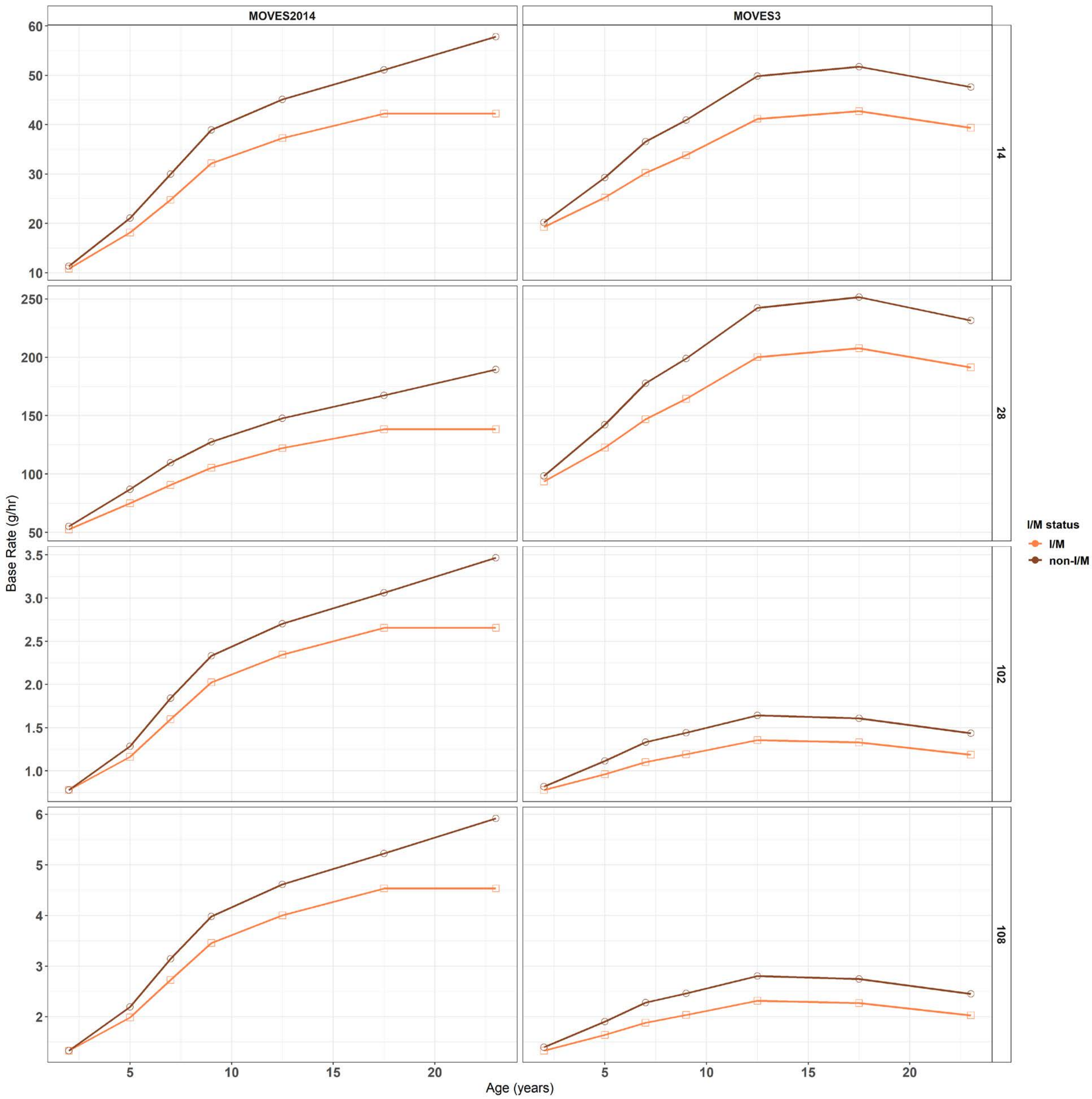

Figure 3-118 NO_x for Trucks in MY2008: Emission rate (meanBaseRateIM, meanBaseRate) vs. age for two running operating modes (14, 28, g/hr) and two start modes (102, 108, g/start) (Note that rows are scaled independently)

3.12 Development of Emission Rates representing California Standards

In general, the principle of pre-emption does not allow the states to promulgate or enact their own vehicle emission standards. However, due to the unique severity of the air pollution issues in Southern California, the Clean Air Act allows the state of California to seek waivers of preemption. When granted by EPA, such waivers allow California to enact and enforce its own emissions standards, under the condition that such standards are at least as stringent as applicable Federal standards.

California has enacted several such programs, beginning with Tier 0 (c. 1977-1992) and Tier 1 in 1993. These were followed by the "Low Emission Vehicle" programs, beginning with "LEV-I" in 1994[g] and continuing with "LEV-II" and "LEV-III" in 2001 and 2015, respectively. Under the LEV programs, multiple standard levels were assigned, designated as "Transitional Low Emission Vehicle" (TLEV), "Low Emission Vehicle" (LEV), "Ultra Low Emission Vehicle" (ULEV) and "Super Ultra Low Emission Vehicle" (SULEV).

Although assigned the same labels, each standard level can be assigned different numeric values for each vehicle class, i.e., LDV, LDT1, LDT2, LDT3 and LDT4. For simplicity, we have assumed that the California "Medium-Duty" classes, MDV2 and MDV3, can be treated as equivalent to Federal LDT3 and LDT4 classes, despite differences in loaded vehicle weights.

In addition, Section 177 of the Clean Air Act allows other states to adopt California emission standards, with the proviso that adopted standards are identical to standards for which waivers have been granted. States do not need approval from EPA to adopt California standards. As of 2019, 13 states had elected to adopt California LEV-II standards for emissions of criteria pollutants from varying classes of light-duty motor vehicles.[49] Collectively, these states will be called the "CA/S177" states.[h] In addition, these states have adopted the LEV-III standards.[50]

Effectively, then, two sets of emission standards are in place throughout the United States. One outcome of this situation is that many vehicles coming to market over the past 20 years have been certified to both CA and Federal standards. The analysis described in this section incorporates this reality by applying an assumption that the emissions behavior of vehicles with multiple certifications would be governed by the "most stringent" certification. For example, a vehicle certified to Tier 2/Bin-5 in the Federal sales regions but certified to LEV-II/SULEV in California, is assigned to "Bin-2" or "SULEV" for purposes of developing emission rates, rather than to Bin 5.

This section describes the process used to develop a set of emission rates representing the LEV programs, covering model years 1994-2031. The methods used are similar to those used to develop rates representing vehicles under the Federal standards (NLEV, Tier 2 and Tier 3) as described in 3.4 (page 79). In general, as the implementation of LEV standards involved higher fractions of vehicles at lower standard levels than under the corresponding Federal standards; rates for a LEV program in a given model year are equal to or lower than corresponding "Federal" rates.

To apply this assumption, we developed the CA/S177 rates by scaling down the Federal rates by appropriate margins. The calculations were performed in a series of steps, with the first three steps identical to those used to develop the Federal rates. The following discussion assumes that the reader is familiar with the relevant sections of this report (See 3.4.1 (page 80) to 3.4.3)). However, the final steps differ from that used to generate the default rates, as described below in 3.12.4 and 3.12.5.

[g] The "National LEV" (NLEV) program was a voluntary program modeled on the LEV-I program, and applicable to LDV, LDT1 and LDT2 vehicles.
[h] These states include Colorado, Connecticut, Delaware, Maryland, Maine, Massachusetts, New Jersey, New York, Oregon, Pennsylvania, Rhode Island, Washington and Vermont.

3.12.1 Averaging IUVP Results

The calculation of CA/S177 rates uses the same set of average IUVP results as the default rates. Equivalencies between Federal and corresponding LEV standards is shown in Table 3-65. Note that the equivalences listed in the table are not exhaustive; they are limited to the subset that were applied in developing emission rates.

Table 3-65 Selected equivalencies between Federal and corresponding CA/S177 standards

Program		Vehicle Class		Standard Level	
Fed.	**CA/S177**	**Fed.**	**CA/S177**	**Fed.**	**CA/S177**
Tier 1[1]	Tier 1[1]	LDV-T1	LDV-T1	LDV-T1	LDV-T1
		LDT2	LDT2	LDT2	LDT2
		LDT3	MDV2	LDT3	MDV2
		LDT4	MDV3	LDT4	MDV3
NLEV	LEV-I	LDV, LDT1	PC, LDT1	TLEV	TLEV
				LEV	LEV
				ULEV	ULEV
		LDT2	LDT2	TLEV	TLEV
				LEV	LEV
				ULEV	ULEV
Tier 2[2]	LEV-II[2]	LDV, LDT1, LDT2,3,4	PC, LDT1, LDT2,3,4	Bin 5	LEV
				Bin 3[3]	ULEV[3]
				Bin 2	SULEV

[1] Under Tier 1, each vehicle class was assigned a specific standard.
[2] Under this program, there was no assigned correspondence between vehicle class and standard level for the FTP standards, however, such an assignment remains in effect for the SFTP standards.
[3] This equivalence is exact for THC and CO only, for NO_x, LEV-II/ULEV is equivalent to Bin 5 (LEV-II/LEV).

3.12.2 Develop Phase-In assumptions

Differences between the CA/S177 and Federal programs are expressed primarily through the phase-in assumptions. For this step we developed phase-in assumptions representing the phase-in of California Tier-1, LEV-I and LEV-II programs. These assumptions cover model-years from 1994 through 2016. Starting in model year 2017 for cars, and 2018 for trucks, Federal rates are harmonized with CA rates during the Tier 3/LEV-III phase-in and thereafter.

The CA/S177 phase-in was based on fractions of sales, grouped by standard level and model year. The LEV phase-in, however, is simplified in that, as in the LEV-II standards, the three largest truck classes, LDT2, 3 and 4, were consolidated into a single class, which we will refer to as LDT234.

Phase-in assumptions for passenger cars (PC) and light trucks (LDT1) are shown in Figure 3-119. In model year 2009 and later, the CA/S177 fleet is dominated by ULEV, SULEV and LEV vehicles, in that order. The phase-in for trucks (LDT234) is shown in Figure 3-120

As a final step, a distinct "simplified" Federal phase-in was also developed. In this version, the truck classes LDT2, LDT3 and LDT4 were also pooled, to facilitate comparison to the CA/S177 version.

Figure 3-119 Phase-In assumptions for CA Tier-1, LEV-I and LEV-II standards for passenger cars and light-trucks (PC, LDV, LDT1)

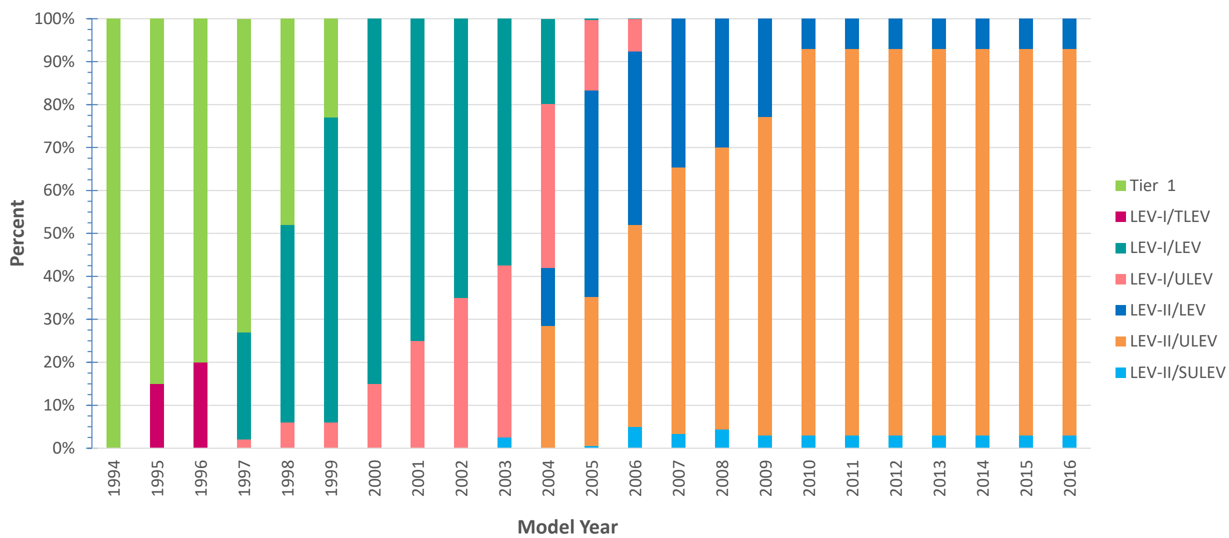

Figure 3-120 Phase-In assumptions for CA Tier-1, LEV-I and LEV-II standards for light trucks (LDT2, LDT3, LDT4)

3.12.3 Merge FTP Results and Phase-In Assumptions

In this step the FTP results and phase-in assumptions were merged so as to calculate weighted average results for composites, cold-start and hot-running emissions, as described in 3.3.2.3 (page 68). However, as the truck classes for the CA/S177 phase-in were pooled and assigned a uniform phase-in, calculating weighted averages by truck class did not play a role in these calculations as in the default calculations.

This step was repeated for the CA phase-in and for the Federal phase-in.[i]

Sets of weighted averages by model year are shown for FTP Composite Emissions (Figure 3-1, Figure 3-121), FTP cold-start emissions (Bag 1 – Bag 3) (Figure 3-122), and FTP hot-running emissions (Bag 2) (Figure 3-123).

[i] Note that the 'Federal' phase-in is identical to that used to develop the default rates.

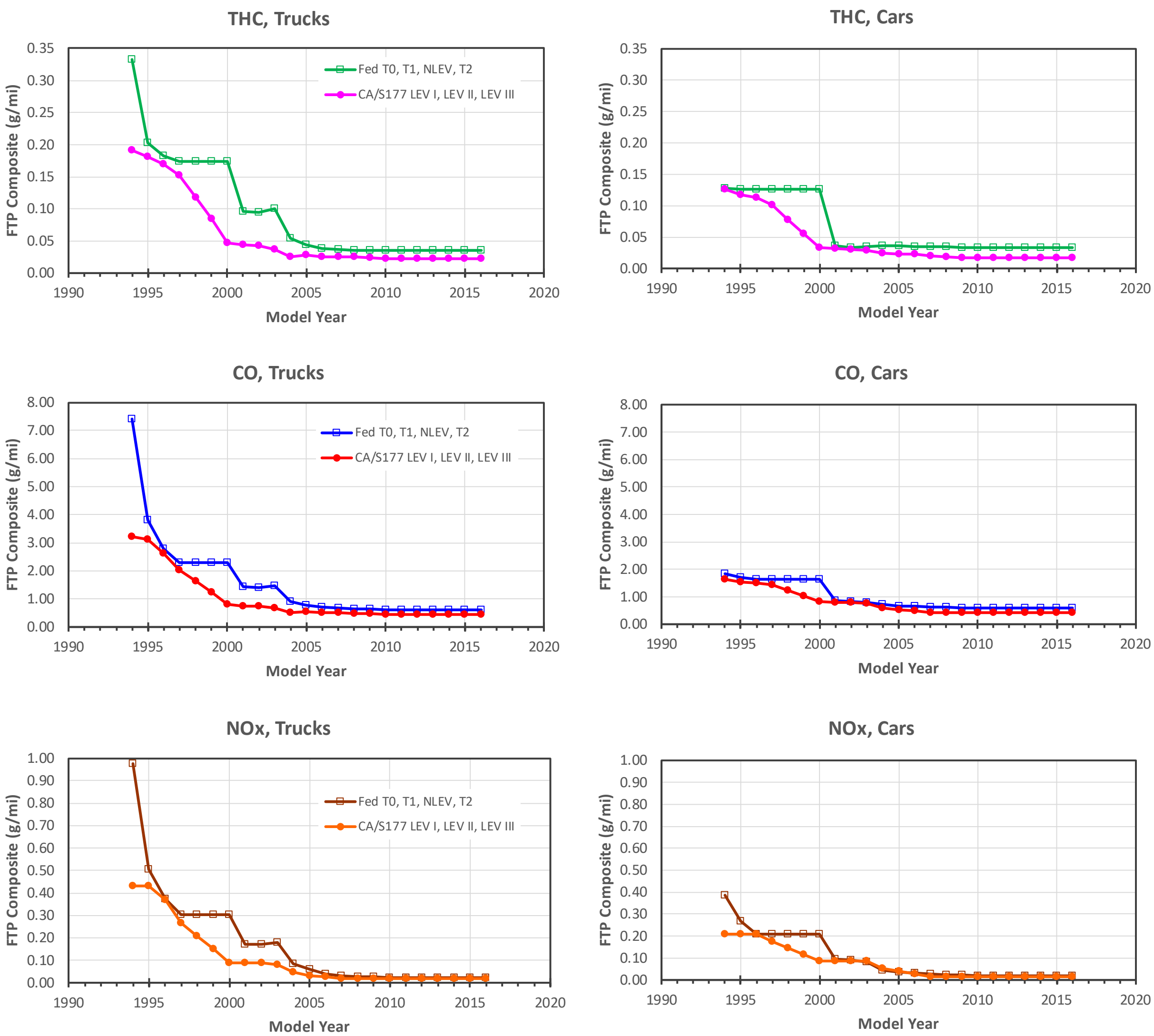

Figure 3-121 Weighted average FTP composite emissions for cars and trucks, for Federal and CA/S177 standards

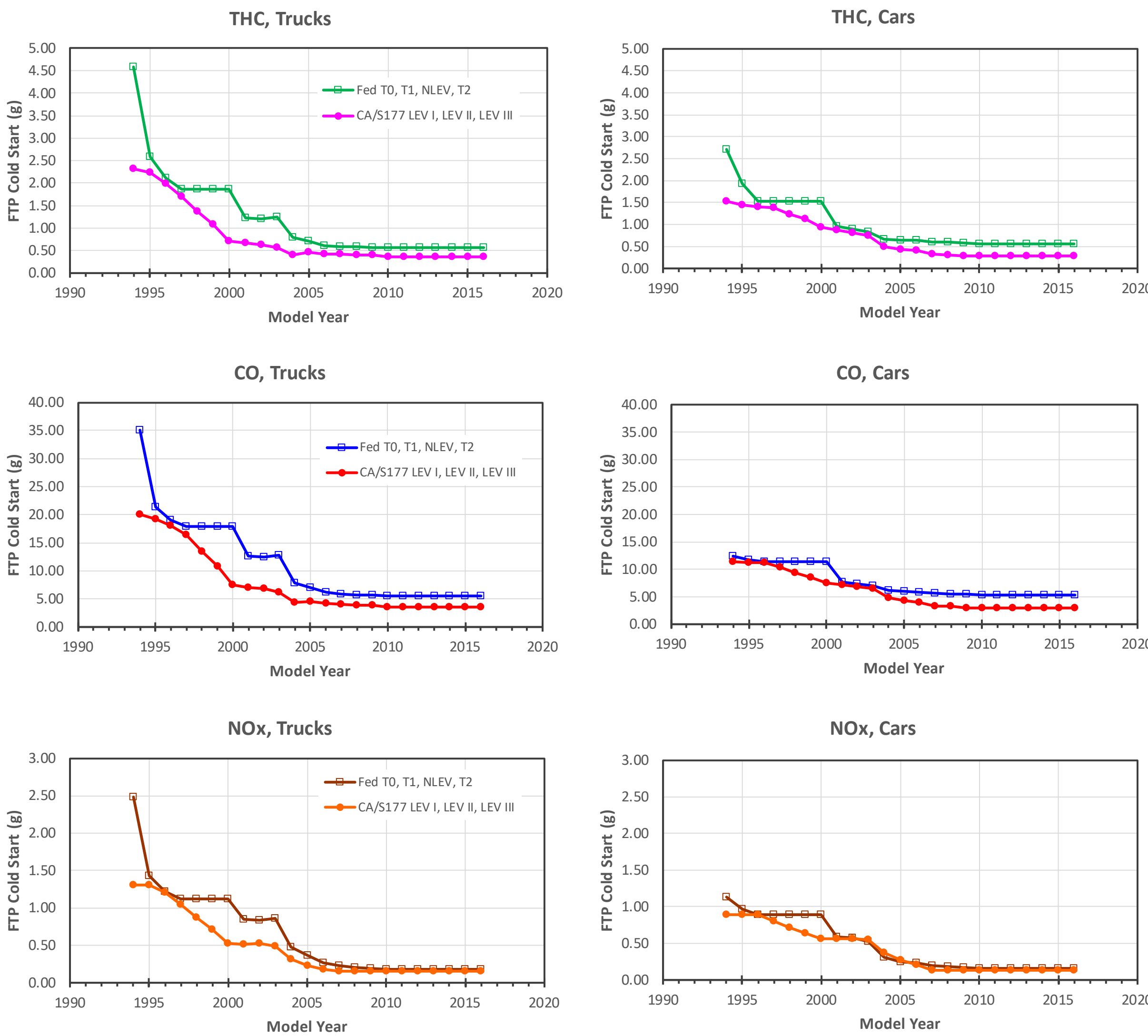

Figure 3-122 Weighted average FTP cold-start emissions, for Federal and CA/S177 standards

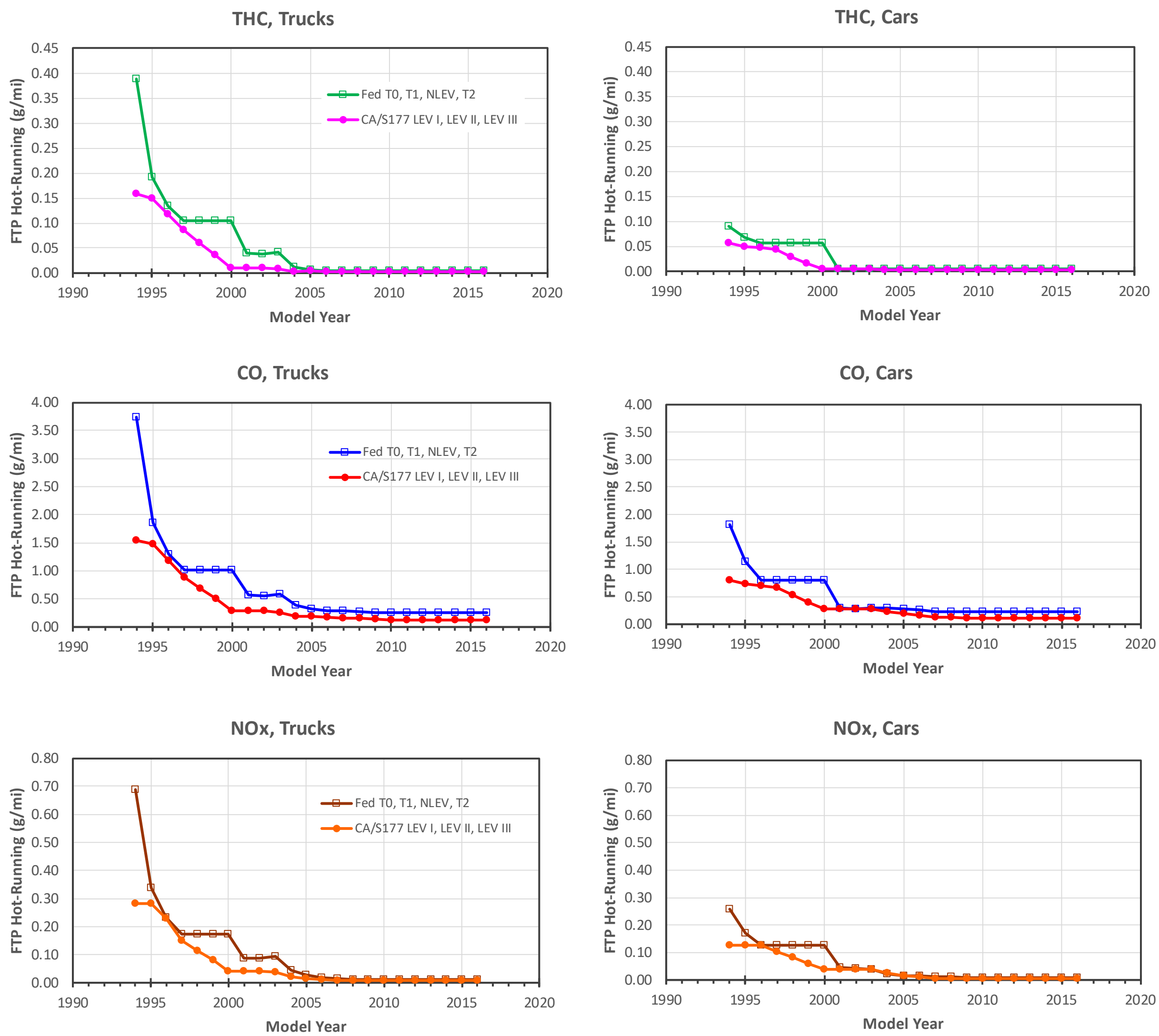

Figure 3-123 Weighted average FTP hot-running emissions (Bag 2), for trucks and cars, under Federal and CA/S177 standards

3.12.4 Scaling CA/177 Rates to Federal Rates

At this point the next step in the calculation differs from the approach used to generate the default Federal rates. As in the calculation of the default rates, we normalized hot-running emissions for both FTP and US06 to Federal T1 levels, represented by MY1998. However, in this calculation, we also performed this normalization for cold-start rates. The results were sets of ratios relative to Tier 1 for both running and start emissions.

Next, we calculated ratios of the weighted CA ratio to its Federal counterpart, by model year, as shown in Equation 3-54,

$$R_{\text{CA:Fed}} = \frac{R_{\text{CA}}}{R_{\text{Fed}}}$$ **Equation 3-54**

where $R_{\text{CA:Fed}}$ = the ratio of the CA/S177 weighted average to that for the Federal phase-in, and R_{Fed} and R_{CA} are ratios of respective weighted averages to that for MY1998, in the CA/S177 and Federal phase-ins, respectively. Note that if raw values of $R_{\text{CA:Fed}}$ were > 1.0, they were adjusted to 1.0, under than assumption that fleet averages under the LEV program(s) would be ≤ corresponding averages under the Federal program(s).

Values of $R_{\text{CA:Fed}}$ are presented below. Note that ratios were calculated and applied separately for each of the three gaseous pollutants (THC,CO,NO_x) and for start emissions (opmodeid = 101-108), "FTP Bag-2" running emissions (opmodeid = 0,1, 11-16, 21-27, 33-37) and "US06" running emissions (opmodeid = 28-30, 38-40).

In MY2017 and later, following the onset of the Tier 3/LEV-III phase-in, all ratios are set to 1.0, to reflect an assumption that under T3, the Federal program is targeting the same NMOG+NO_x fleet average requirements as LEV-III. See Section 3.4 for more information on these rates.

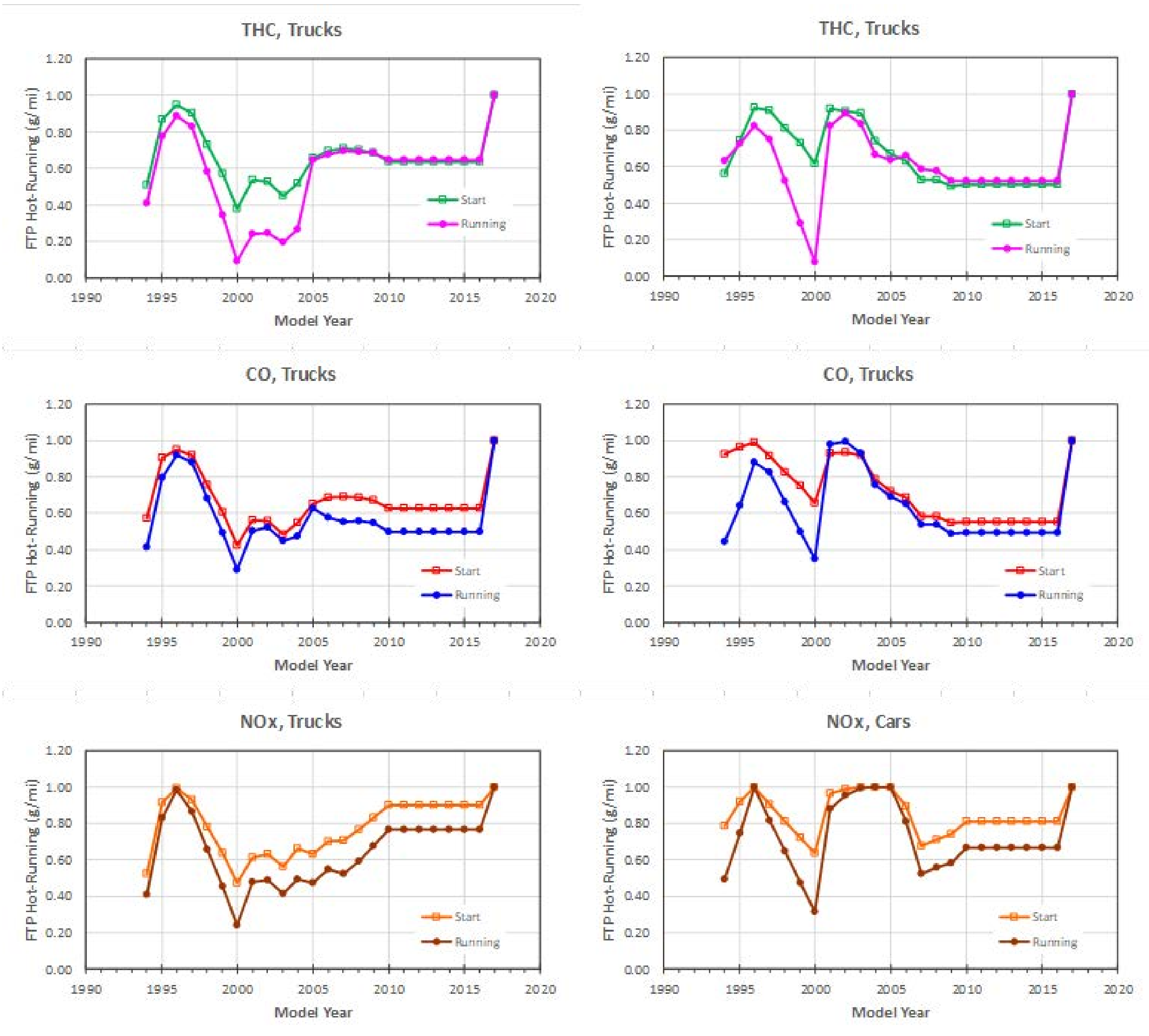

Figure 3-124 Ratios of relative emission levels by model year under CA/S177 and Federal standards, both individually normalized to "Tier-1" levels (See Equation 3-54)

The LEV rates derived by application of the ratios, as described above, are shown in the plots below. Each plot shows two panels, for cars and trucks, so that each are present in each comparison. Note that the rates developed in this step are "I/M reference rates" (meanBaseRateIM). The "non-I/M reference" rates were subsequently generated in relation to the reference rates.

For each pollutant, one operating mode is shown for running emissions, and one for start emissions. Due to the proportional scaling in the rates, single modes are sufficient to illustrate trends and patterns.

The plots show the default Federal rates (in blue), the initial LEV rates derived by ratio as previously described (in red). Plots are presented for THC, CO and NO_x, in that order, with the same colors used in all plots.

Trends for THC and CO, shown in Figures Figure 3-125 to Figure 3-128, are considered first as the patterns are very similar for these two pollutants. In addition, the qualitative patterns are similar for running process, represented by opMode 27, and for the start process, represented by opMode 108.

The plots show trends in rates vs MY in the first age group (0-3 years). As mentioned, the default Federal rates are shown in blue and the initial LEV rates in red. Note that the LEV trends for cars drop to a consistent level between MY ~2010 and 2016 but then increase from 2016 to 2017, at the beginning of the LEV-III phase-in. For trucks, this behavior is more pronounced, showing an actual "spike" between 2016 and 2018.

For NO_x, shown in Figure 3-129 and Figure 3-130, the pattern differs. The LEV rates, like the Federal rates, begin to decline at the onset of the Tier3/LEV-III phase-in, without showing any short-term increases.

Note that the plots also show an additional green trend, labelled 'extrap.' The derivation and significance of these trends is explained in 3.12.5 below.

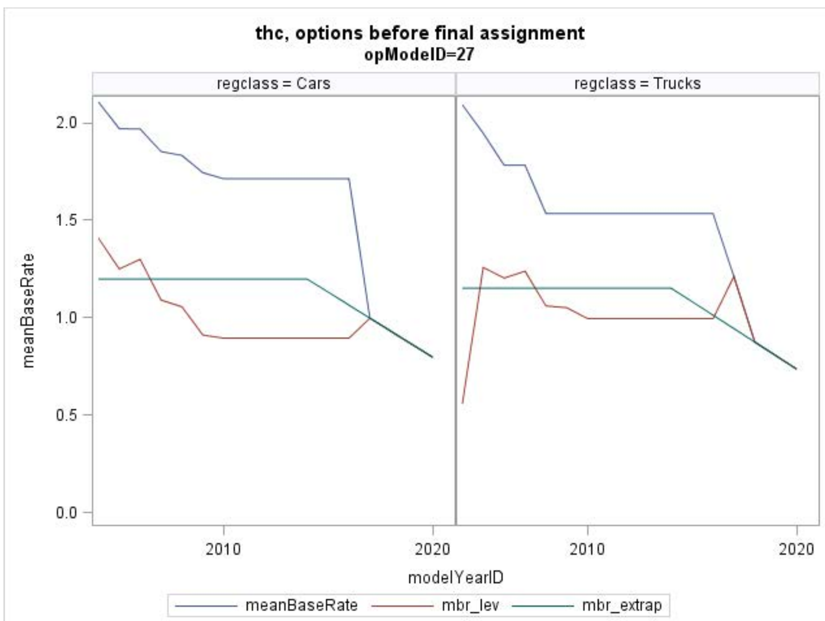

Figure 3-125 THC: Trends in Emissions for Federal and Estimated CA/S.177 rates, for cars and trucks at age 0-3 years, for the running emissions process (opModeID = 27)

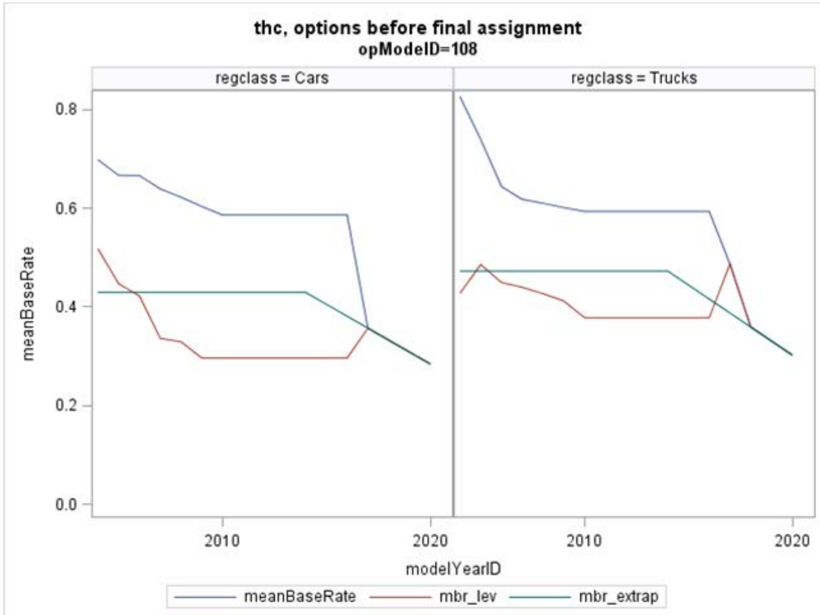

Figure 3-126 THC: Trends in Emissions for Federal and Estimated CA/S.177 rates, for cars and trucks at age 0-3 years, for the start emissions process (opModeID = 108)

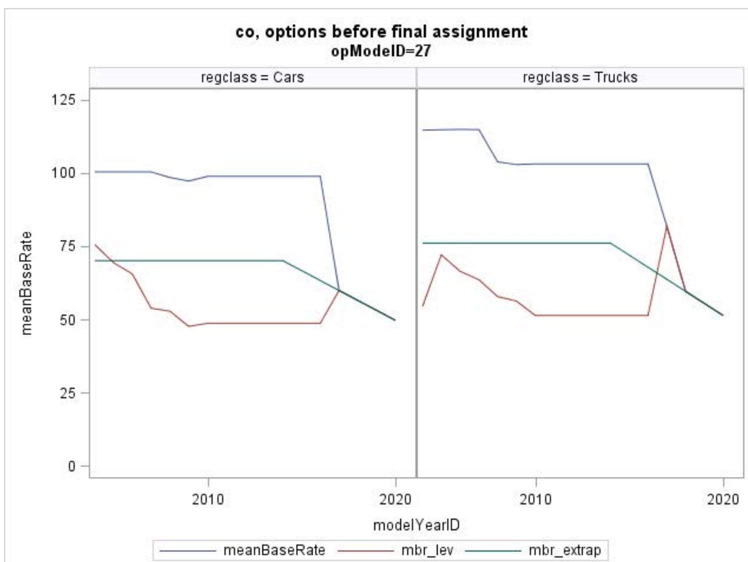

Figure 3-127 CO: Trends in Emissions for Federal and Estimated CA/S.177 rates, for cars and trucks at age 0-3 years, for the running emissions process (opModeID = 27)

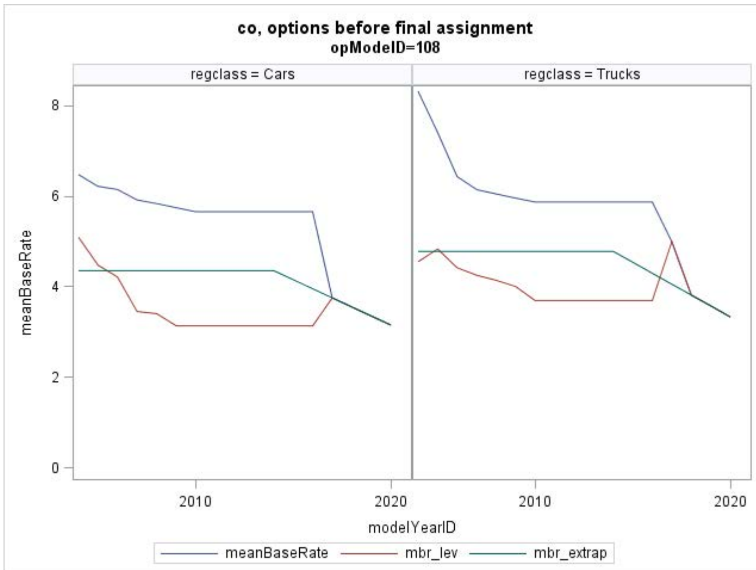

Figure 3-128 CO: Trends in Emissions for Federal and Estimated CA/S.177 rates, for cars and trucks at age 0-3 years, for the start emissions process (opModeID = 108)

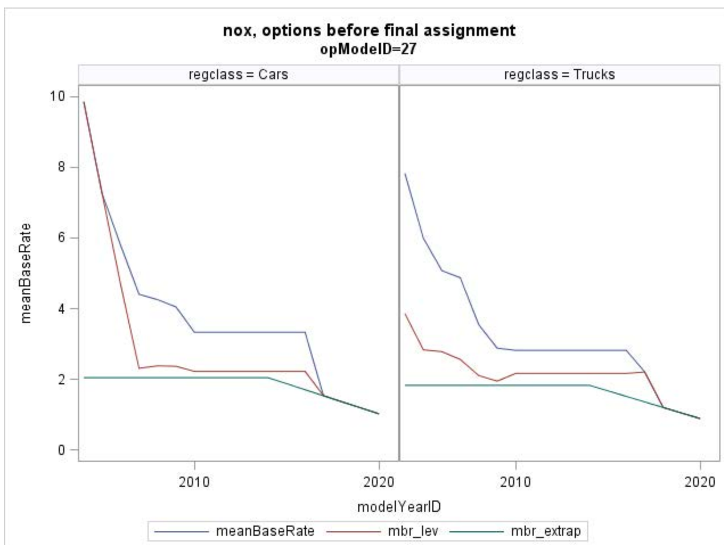

Figure 3-129 NO_x: Trends in Emissions for Federal and Estimated CA/S.177 rates, for cars and trucks at age 0-3 years, for the running emissions process (opModeID = 27)

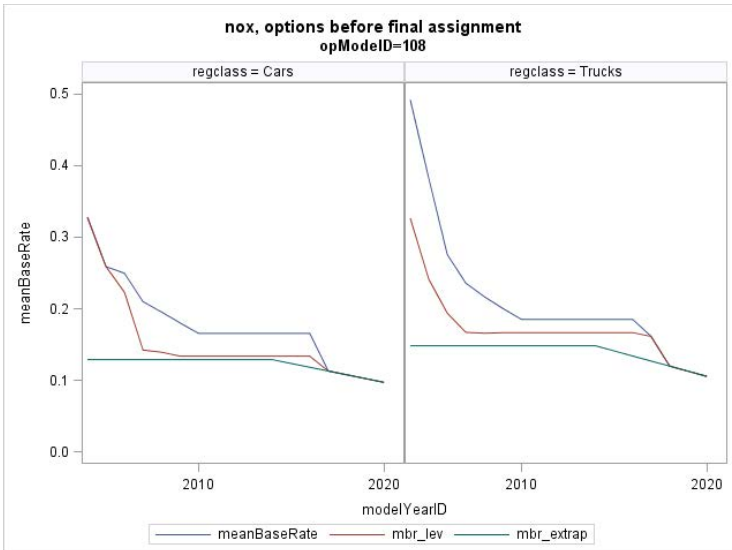

Figure 3-130 NO_x: Trends in Emissions for Federal and Estimated CA/S.177 rates, for cars and trucks at age 0-3 years, for the running emissions process (opModeID = 108)

3.12.5 Extrapolating Phase-in Trends

The charts above show that based simply on the phase-ins, disjuncts appear at the beginning of the Tier-3 phase-in (MY 2017-2018), in which the rates increase briefly before declining again. This behavior gives the impression that the rates during the phase-in would be higher than during Tier 2/LEV-II, e.g., 2010-2016.

In any case, the simple application of the ratios, as described above, led to the counterintuitive results shown in the charts above. We developed an approach to adjust and correct these rates.

In projecting the phase-in of the Tier 3 standards, we made specific assumptions. See 3.4.1, page 80 and 3.4.2, page 82. The foundational assumptions can be restated as follows:

- the Tier 3 rates would meet the same NMOG+NO_x fleet-average requirements projected for LEV-III,
- following the onset of the phase-in, the trends in emission rates in Tier 3 and LEV-III would follow declining linear trends, and
- Tier-3 rates would converge with the LEV-III rates starting in 2017 for cars, and 2018 for trucks. The LEV-III phase-in begins earlier, in 2015, giving LEV-III a "head start." The Federal rates start later but immediately 'catch up' at the onset of the Tier-3 phase-in.

As mentioned, the initial estimates assume that the LEV rates are meeting LEV-III fleet averages prior to the onset of the phase-in (2015), and then actually increase before starting to decline again.

To rectify the situation, we extrapolated the linear phase-in trends backwards to reconstruct their behavior between 2015 and 2018. Using subsets of rates at age = 0-3 years for MY 2017, 2018, 2020 and 2021, we calculated slopes in the phase-in trends. These slopes were calculated for each pollutant on the basis of process (running and start) and operating mode. The calculations were performed separately for cars and trucks.

For cars, we calculated the slopes from between 2020 and 2017 (m_{car}), the latter of which is the year when the Tier-3 phase-in began for cars.

$$m_{\text{car}} = \frac{R_{IM,2017} - R_{IM,2020}}{2020 - 2017}$$

where $R_{\text{IM},MY}$ is the emission rate (meanBaseRateIM) the given model year.

Similarly for trucks, we calculated the slopes between MY 2021 and 2018 (m_{truck}), the latter of which is the year when the Tier-3 phase-in began for trucks.

$$m_{\text{truck}} = \frac{R_{IM,2018} - R_{IM,2021}}{2021 - 2018}$$

Then for cars, we extrapolated this slope backwards from 2017 to earlier model years

$$R^{*}_{IM,MY} = R_{IM,2017} + (2017 - MY)m_{\text{car}}$$

where MY = 2016, 2015 and 2014, to obtain projected rates $R^{*}_{\text{IM},MY}$ lying on the linear phase-in trend.

And for trucks, we extrapolated the slope backwards from 2018 backwards to earlier model years

$$R^{*}_{IM,MY} = R_{IM,2018} + (2018 - MY)m_{\text{trucks}}$$

where MY = 2017, 2016, 2015 and 2014.

For both cars and trucks, the extrapolated value for 2014 was projected backwards for MY to MY 2005. As mentioned, the extrapolated trends are shown in green for HC, CO and NO_x start and running emissions in Figure 3-125 to Figure 3-130 in 3.12.4 above.

Having performed the extrapolation, modified rates were assigned by applying the following logic:

For cars:

IF MY ≥ 2005 AND < 2016, THEN

IF the initial rate ($R_{\text{IM,MY}}$) < the extrapolated rate ($R^{*}_{\text{IM,MY}}$), THEN

Reassign the rate to the extrapolated value ($R^{*}_{\text{IM,MY}}$),

ELSE retain the initial rate.

For trucks, the logic is identical except for the applicable model-year range:

IF MY ≥ 2005 AND < 2017, THEN

IF the initial rate ($R_{\text{IM,MY}}$) < the extrapolated rate ($R^{*}_{\text{IM,MY}}$), THEN

Reassign the rate to the extrapolated value ($R^{*}_{\text{IM,MY}}$),

ELSE retain the initial rate.

The plots with the final results are shown below, for the same set of operating modes, for THC, CO and NO_x. The plots show that the extrapolated trends are selected for THC and CO, both for start and running. For NO_x, the initial trends are retained.

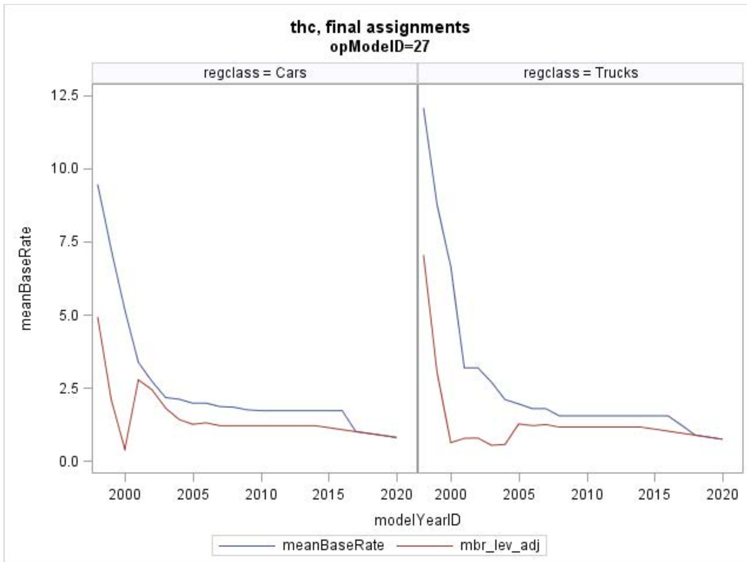

Figure 3-131 THC: Final assignments for Federal and Estimated CA/S.177 emission rates, for cars and trucks at age 0-3 years, for the running emissions process (opModeID = 27)

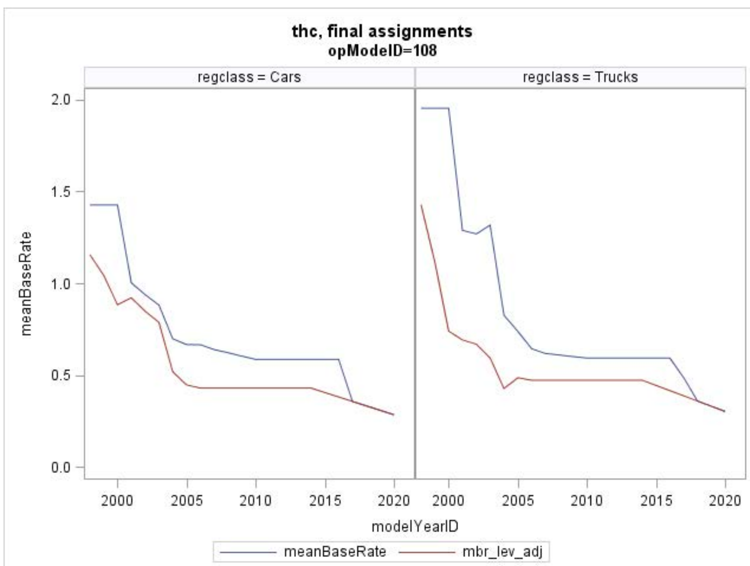

Figure 3-132 THC: Final assignments for Federal and Estimated CA/S.177 emission rates, for cars and trucks at age 0-3 years, for the start emissions process (opModeID = 108)

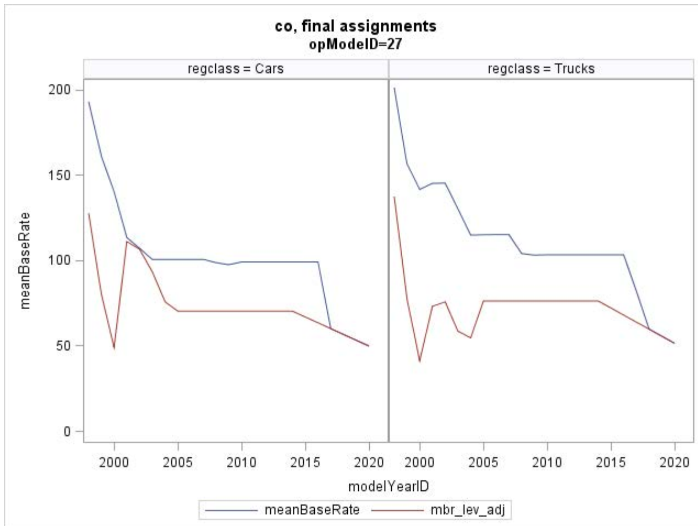

Figure 3-133 CO: Final assignments for Federal and Estimated CA/S.177 emission rates, for cars and trucks at age 0-3 years, for the running emissions process (opModeID = 27)

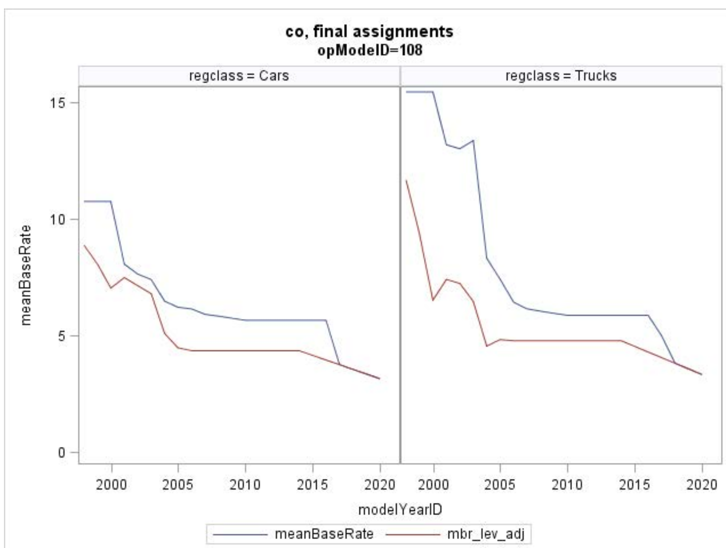

Figure 3-134 CO: Final assignments for Federal and Estimated CA/S.177 emission rates, for cars and trucks at age 0-3 years, for the start emissions process (opModeID = 108)

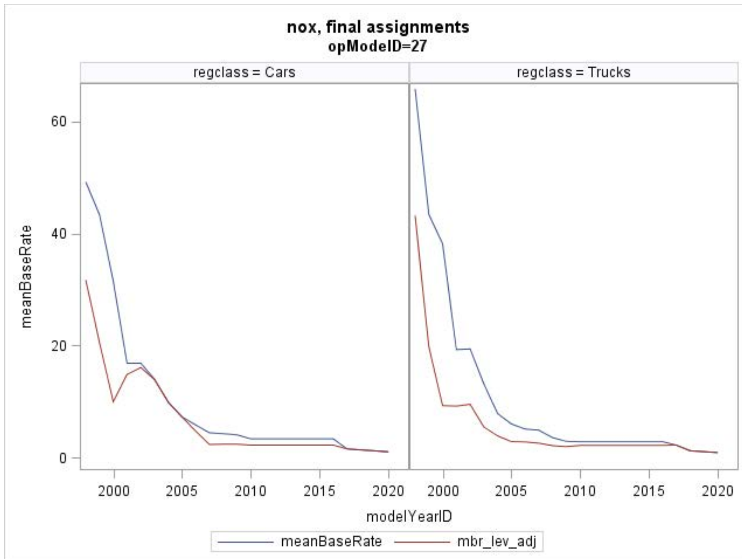

Figure 3-135 NO$_x$: Final assignments for Federal and Estimated CA/S.177 emission rates, for cars and trucks at age 0-3 years, for the running emissions process (opModeID = 27)

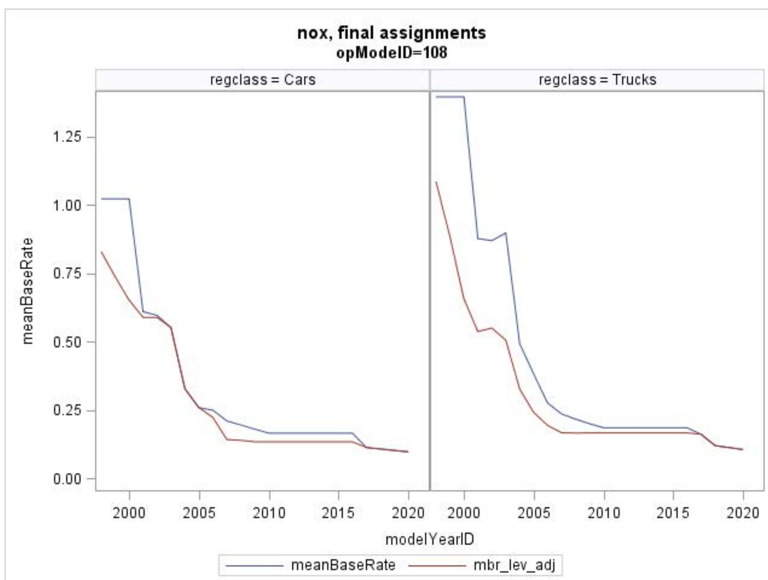

Figure 3-136 NO$_x$: Final assignments for Federal and Estimated CA/S.177 emission rates, for cars and trucks at age 0-3 years, for the start emissions process (opModeID = 108)

3.12.6 Additional Steps

As mentioned, the rates developed as described represent “I/M reference rates” at age = 0-3 years. Following completion of the steps described in 3.12.1 to 3.12.5, the following three steps were completed.

3.12.6.1 Apply Deterioration Adjustments

To project emission rates for the remaining six ageGroups, deterioration was projected by ratio as described for the Federal default rates in 3.10.3, page 202.

3.12.6.2 Apply Non-I/M ratios

Having projected deterioration for the "I/M reference rates" (meanBaseRateIM), we projected the "non-I/M reference rates" (meanBaseRate) representing default emission rates in non-I/M areas, as described for the Federal default rates in 3.10.4, page 202.

3.12.6.3 Replicate Rates for additional Fuels

Having generated I/M and non-I/M reference rates for gasoline (fuelTypeID = 1), we replicated the gasoline rates in their entirety to represent diesel (fuelTypeID = 2) and E85 (fuelTypeID = 5), as described in 3.10.5, page 202.

3.12.7 Availability

The emissionRateByAgeLEV table contain the subsets of CA/S177 rates and is incorporated into the default MOVES database. Instructions for using it are available in the MOVES graphical user interface.

3.12.8 Early Adoption of National LEV Standards

The National Low Emission Vehicle Standards program was adopted in 2001. However, a group of states in the "Northeast Trading Region" (NTR) adopted the standards early, in 1999. Using an approach identical to that used to develop the CA/S177 rates, we developed a supplemental table for the emissionRateByAge values representing the adoption of NLEV rates in model years 1999 and 2000. As with the national program, "early" NLEV applied only to the LDV, LDT1 and LDT2 vehicle classes.

As with the CA/S177 rates, we developed phase-in assumptions specific to "early" NLEV. Figure 3-137 shows that fractions of Tier-1 vehicles start declining markedly in MY1999, whereas in the default phase-in, the fractions for Tier 1 are 100 percent until MY2001 for LDV-T1 and LDT2. The fractions shown apply to LDT2, as well as to LDV-T1. Vehicle classes LDT3 and LDT4 remain in Tier 1 until the onset of Tier 2, in MY2004.

The NTR rates were developed by scaling default rates for start and running emissions down appropriately as implied by the differences in phase-in assumptions, as performed for the LEV rates and described in 3.12.1 through 3.12.4.

The supplemental table for early NLEV rates is stored in the MOVES default database. Instructions for using it are available in the MOVES graphical user interface.

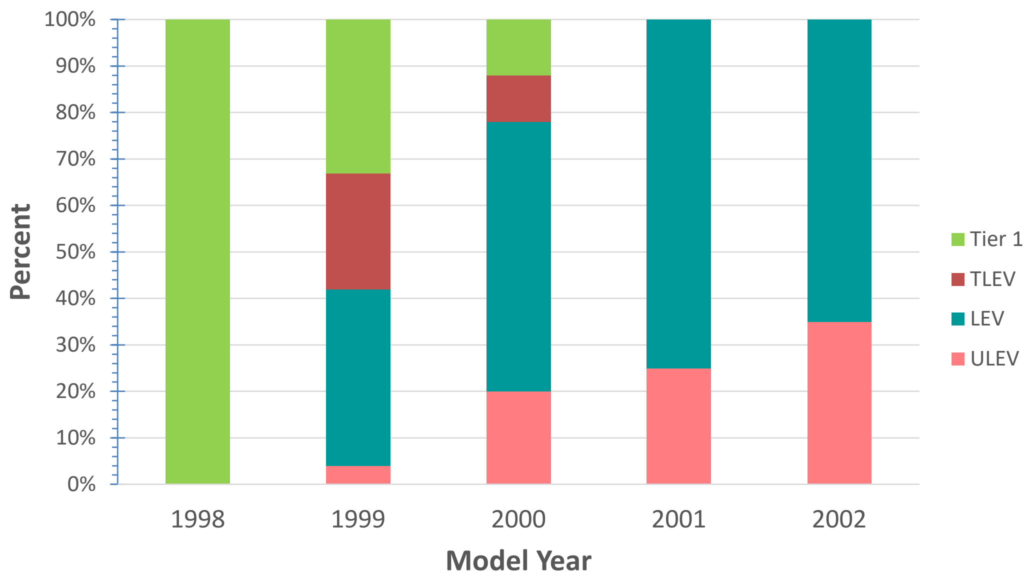

Figure 3-137 Phase-in assumptions for early NLEV adoption, for LDV, LDT1 and LDT2

3.13 Rates for E-85 Vehicles

The rates developed as described in Section 3 represent gasoline-fueled conventional-technology engines.

Because data on E-85 LD vehicles is lacking and they are required to meet the same emission standards as gasoline vehicles, we use the start and running rates developed for gasoline vehicles in modelling other fuels and technologies.

We replicated the entire set of gasoline rates for high-level ethanol blends, i.e., "E77" through "E85." However, for lower-level ethanol blends (i.e., 0 – 20 vol. percent), 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 report.[79]

4 Particulate-Matter Emissions from Light-Duty Vehicles

The emission rates for particulate matter described in this chapter are developed in two parts. The first part (Section 4.1) derives modal emission factors and deterioration rates for vehicles manufactured before 2004. The second part (Section 4.2) presents the updated rates in MOVES3 for vehicles manufactured since 2004, by scaling the base modal emission rates in MOVES2014 according to newer test data, and applies emission rate modifications for the phase-in of future standards.

4.1 Particulate-Matter Emission Rates for Model Year 2004 and Earlier Vehicles

The primary study that this chapter relies on is the Kansas City Light-duty Vehicle Emissions Study (KCVES) conducted in 2004-2005.[51] 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. 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.*"[52] This "analysis report" (which is the partner to this chapter) presented preliminary emission rates for PM, elemental carbon fraction (EC) and 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 backcast 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 KCVES. The rates from this deterioration model allow both forecasting and backcasting as required by MOVES.

In addition, the preliminary analyses[52] did not attempt to translate results measured on the LA92 cycle (used in KCVES) 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 2-5). 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 this program.

4.1.1 Particulate Measurement in the Kansas City Study

For measurements conducted on the dynamometer, vehicles were operated over the LA92 Unified Driving Cycle (see Figure 4-1). 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.

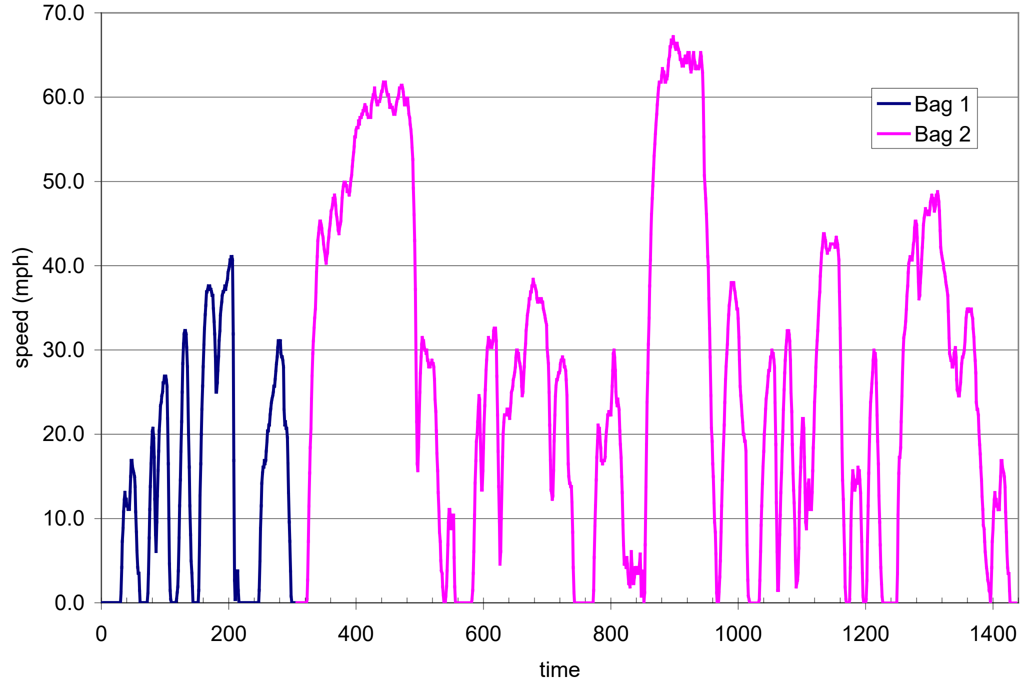

Figure 4-1 Phases 1 and 2 of the LA92 Cycle, representing "cold-start" and "hot-running" operation, respectively

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 a 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 4-2 and Figure 4-3.

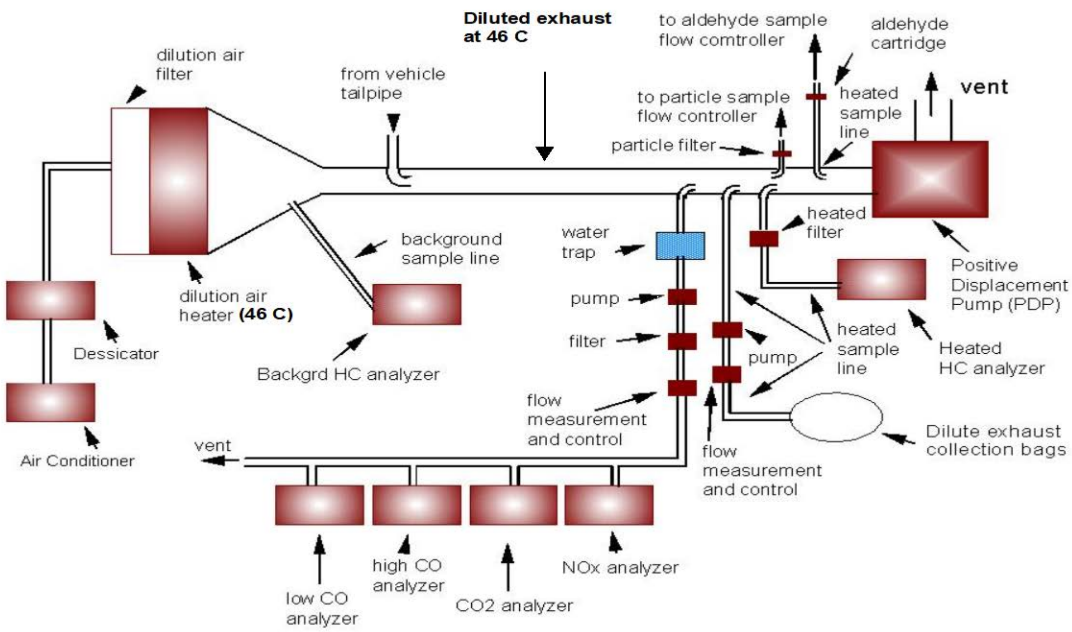

Figure 4-2 Schematic of the constant-volume sampling system used in the Kansas-City Study

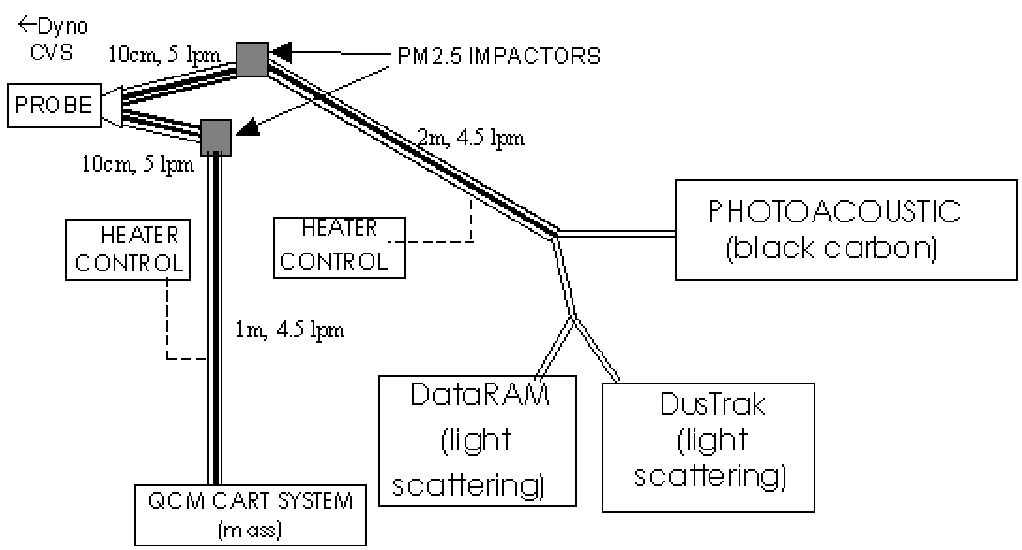

Figure 4-3 Continuous PM analyzers and their locations in the sample line

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.[51] 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 for MOVES, 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 most 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.[51] 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. 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 continuous PM at the time of the Kansas City study, these instruments were 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.

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

In this section, we develop an approach to extend the PM results from the KCVES 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 4-4), the greatest challenge is distinguishing between model-year and age effects. As with most datasets, this issue arises because the program was conducted over a two-year period. 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.

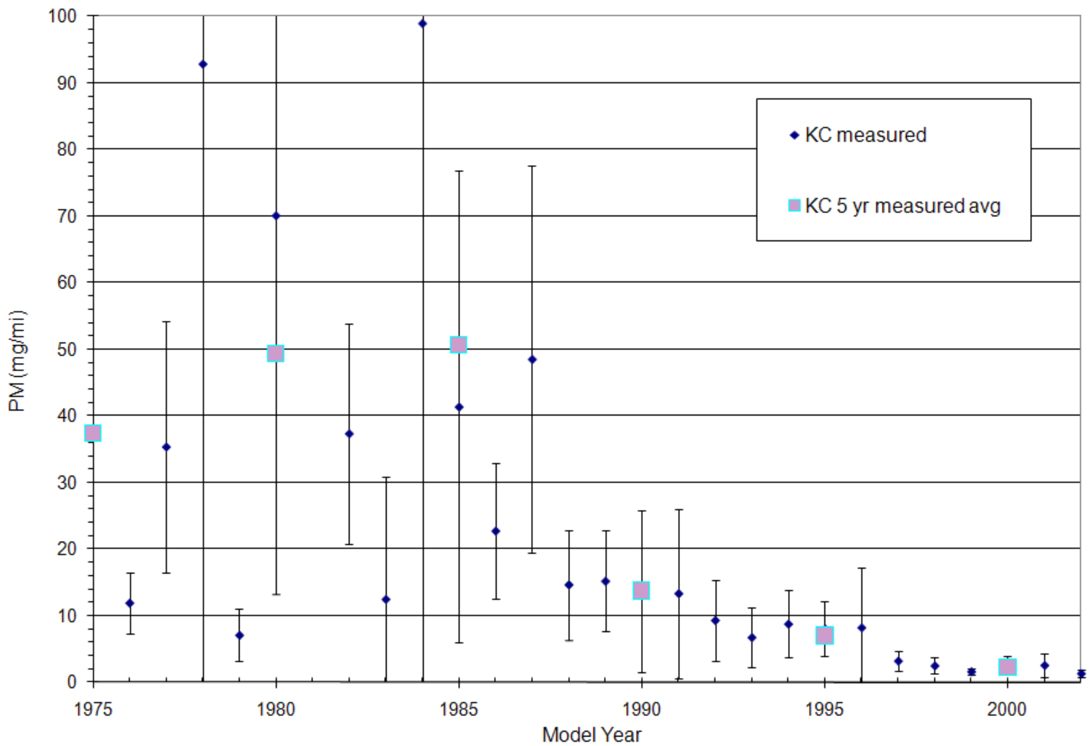

Figure 4-4 Average particulate emission rates from the Kansas City study, by model year, shown as cycle aggregates on the LA92 The five year averages (e.g. 1988-1991,1993-1997, 1998-2002) are also shown without error bar

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.

4.1.2.1 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 distinguish model-year effects 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.[53] 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 THC (Figure 4-5).

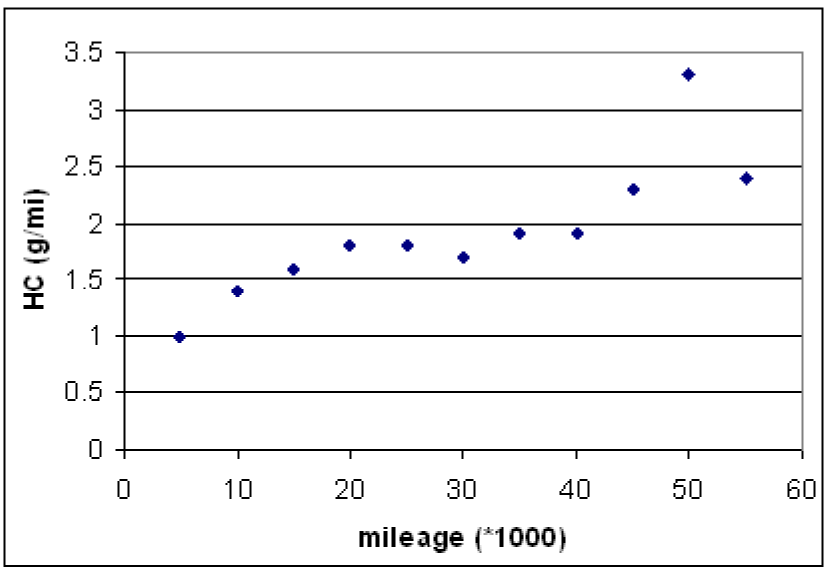

Figure 4-5 Hydrocarbon emissions as a function of mileage (Gibbs et al., 1979)

Hammerle *et al*. (1992) measured PM from two vehicles over 100,000 miles.[54] 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.

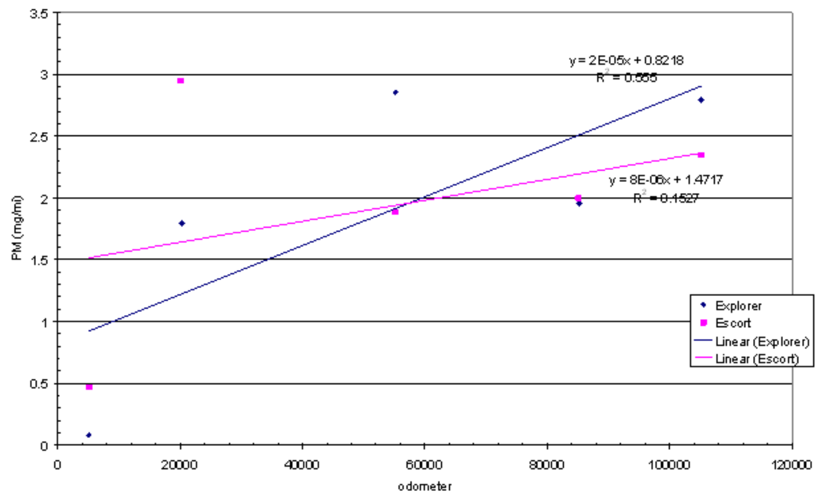

Figure 4-6 Particulate emissions as a function of odometer for two Ford vehicles (Hammerle et al., 1992)

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 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).[55] 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 percent 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.

4.1.2.2 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 goal can be achieved 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 THC 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 4-1 lists the 15 studies employed for this analysis.

Table 4-1 Historical gasoline PM studies including new vehicles at time of study

Program	**Year of study**	**No. vehicles**	**Drive cycle**
Gibbs *et al.*[53]	1979	27	FTP
Cadle *et al.*[56]	1979	3	FTP
Urban & Garbe[57,58]	1979, 1980	8	FTP
Lang *et al.*[59]	1981	8	FTP
Volkswagen[60]	1991	7	FTP
CARB[61]	1986	5	FTP
Hammerle *et al.*, 1992[54]	1992	2	FTP
CRC E24-1 (Denver)[62]	1996	11	FTP
CRC E24-2 (Riverside)[63]	1997	20	FTP
CRC E24-3 (San Antonio)[64]	1998	12	FTP
Chase *et al.*[65]	2000	19	FTP
Whitney (SwRI)[55]	1999		LA92
KC (summer)[51,52]	2004	13	LA92
EPA (MSAT)[66]	2006	4	FTP
Li *et al.*, 2006[67]	2006	3	FTP, LA92

Before we examine these emissions, we should convince ourselves that the LA92 driving cycle will not give substantially 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.[67] 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 in relation to other results, such as the one conducted by Whitney (2000).

Finally, the California Air Resources Board conducted an extensive program over several years comparing many different drive cycles. Unfortunately, PM was not measured in this program. However, Figure 4-7 shows the HC emissions compared for the two cycles. The trends indicate little difference on average between the LA92 and FTP cycles for HC.

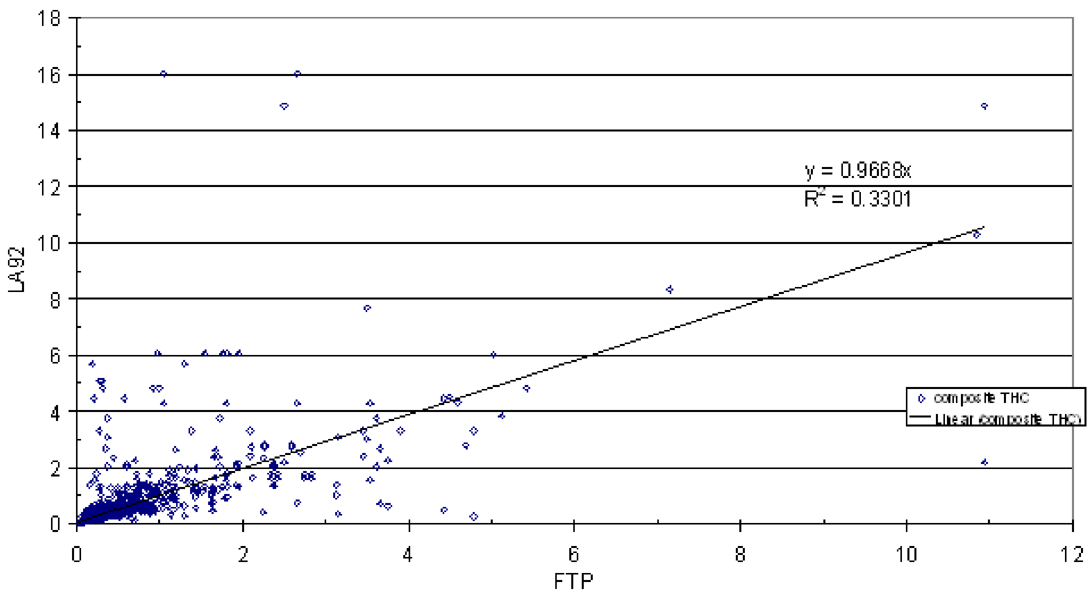

Figure 4-7 Hydrocarbon emissions on the LA92 versus corresponding results on the FTP cycle

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 overall results will be nearly identical even if we omit the LA92 data, thus minimizing the significance of this issue.

Figure 4-8 shows the new-vehicle emission rates from the studies listed in Table 4-1. 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 PM_{10} (for the plot), which is nearly identical (about 97 percent of total PM is PM_{10}). We also assume that 90 percent of PM_{10} is $PM_{2.5}$ (EPA, 1981).[68] 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 sulfur emission factors from MOBILE6 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.

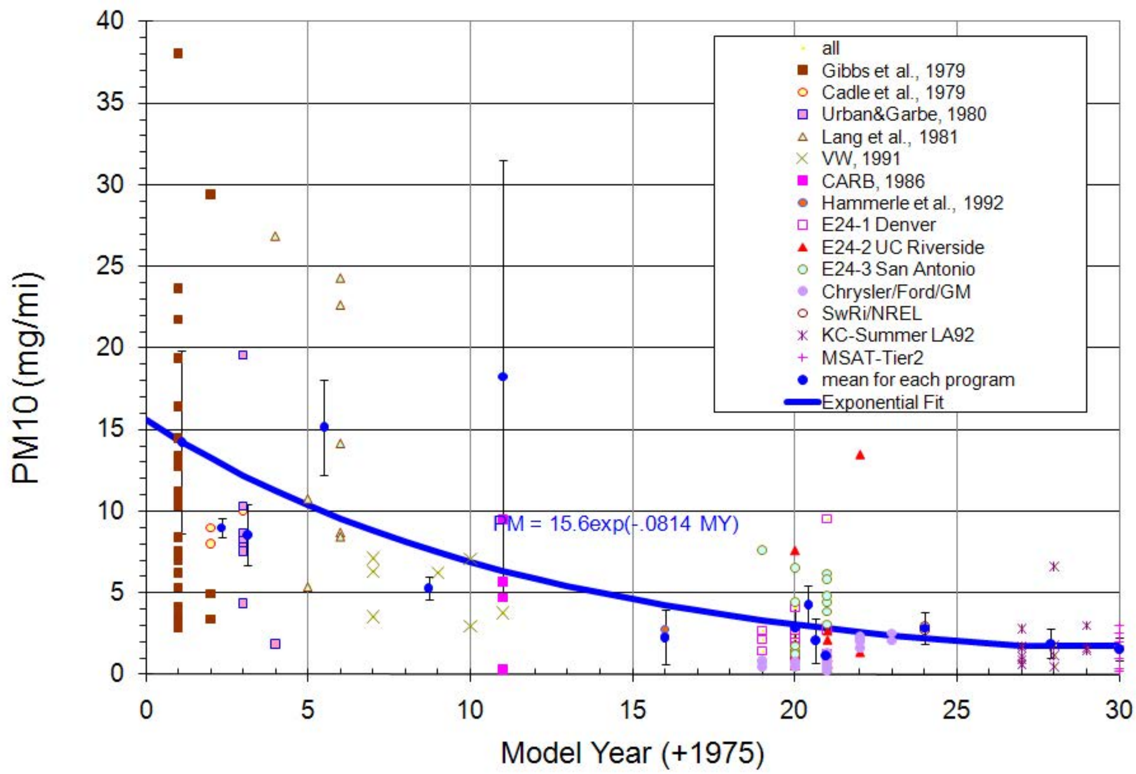

Figure 4-8 Particulate emission rates for new vehicles compiled from 14 independent studies

To estimate 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 calculated from the KCVES 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) ($E_{\mathrm{HR},y}$) is:

$$E_{\mathrm{HR},y} = E_{\mathrm{HR},2005}\mathrm{e}^{-0.814\,y}$$ **Equation 4-1**

where

y = model year – 1975, and

$E_{\mathrm{HR},2005}$ = 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 SPSS statistical software. The averages of these ratios by model year are shown in Figure 4-9, in which no clear trend is discernible. The parameters of the model are summarized in Table 4-2.

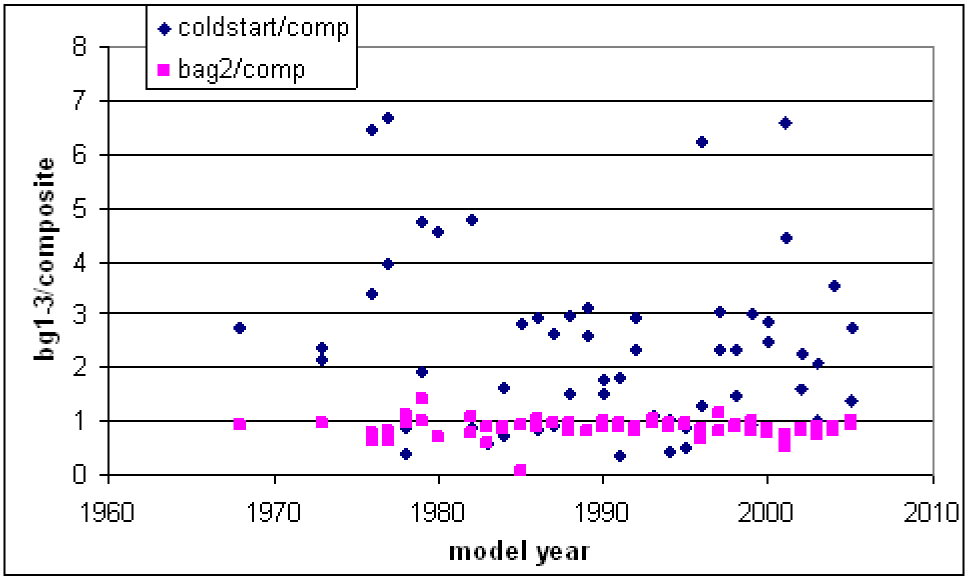

Figure 4-9 Ratios of hot-running/composite and cold-start/composite, Bag2 and Bag1-Bag3, respectively, averaged by model year

Table 4-2 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 4-10 shows the ZML emission rates. The rates are assumed to level off for model years before 1975.

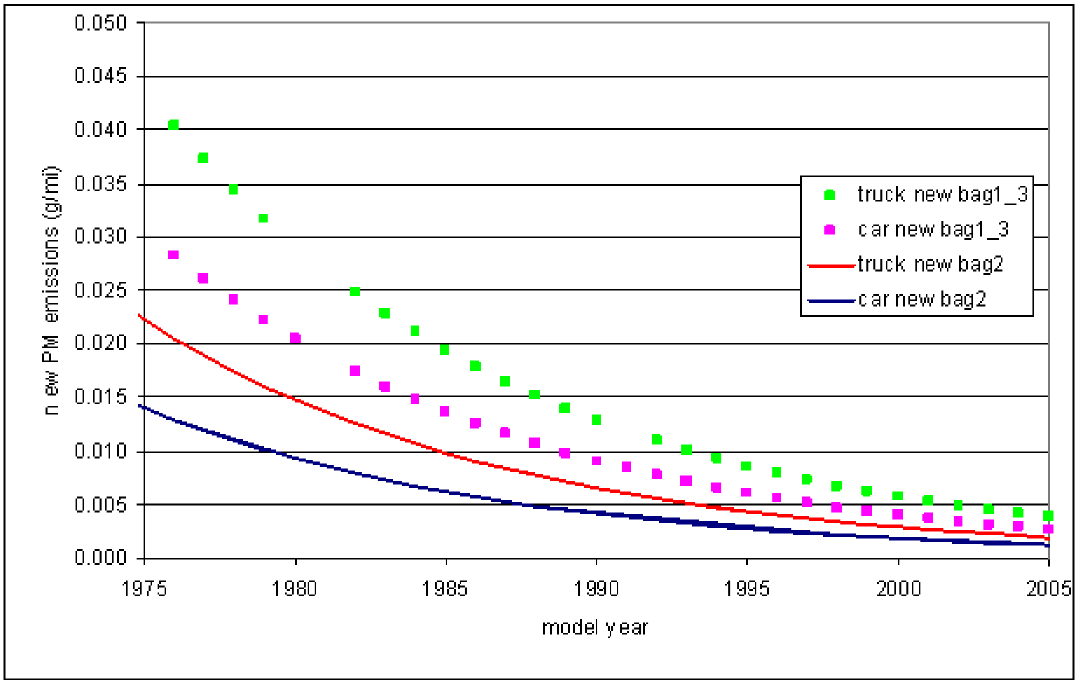

Figure 4-10 Particulate ZML emission rates (g/mi) for cold-start and hot-running emissions, for LDV and LDT

4.1.2.3 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 in 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 backcast the past as well as forecast the future, as required in MOVES

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 the 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 ageGroups. 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+.

As a first step, the bag measurements from all of the vehicles measured in Kansas City were adjusted for temperature using the equation derived in the analysis report.[52] The equation used is:

$$E_{\mathrm{PM},72} = E_{\mathrm{PM},T} e^{-0.03344\,(72-T)}$$ **Equation 4-2**

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 (Section 3.6 and 3.7).

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 4-11 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 log-linear scale, the deterioration trends appear approximately linear over this time period, suggesting that the deterioration rates are exponential. 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 4-12. The lines fan out exponentially on a linear scale as shown in Figure 4-13. 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.

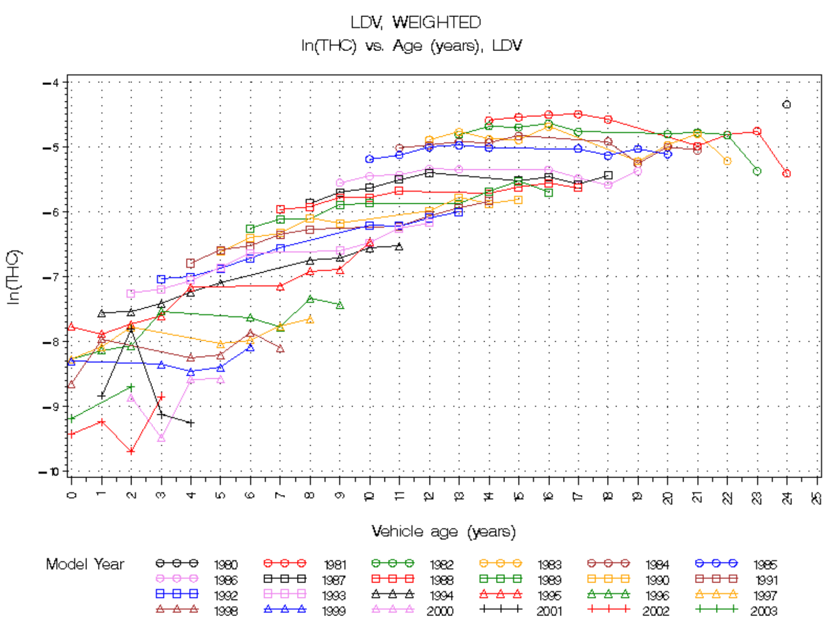

Figure 4-11 The natural logarithm of THC emissions vs. Age for LDV in the Phoenix (AZ) Inspection and Maintenance program over a ten-year period (1995-2005)

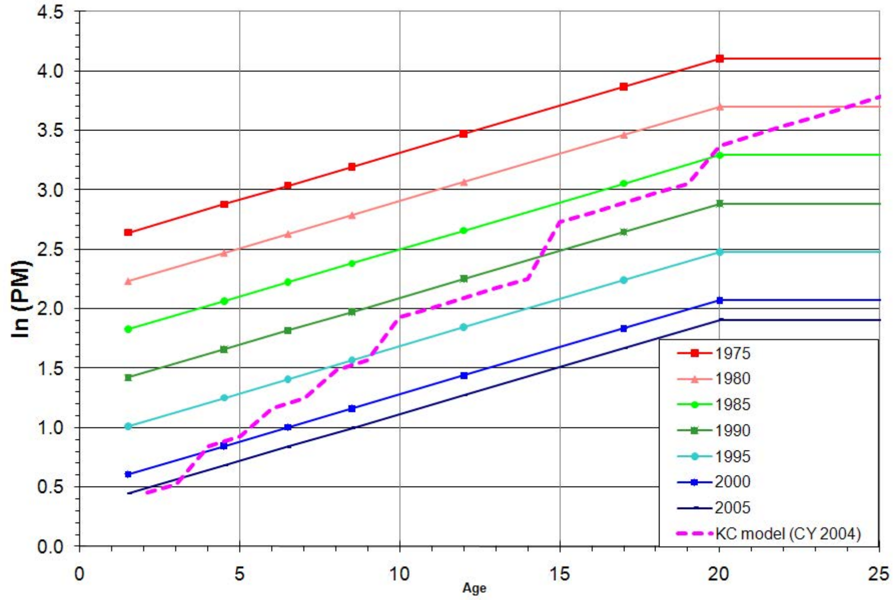

Figure 4-12 The multiplicative deterioration model applied to PM results from Kansas City. The y-axis offsets represent ZML rates. The dotted line represents the Kansas-City Data

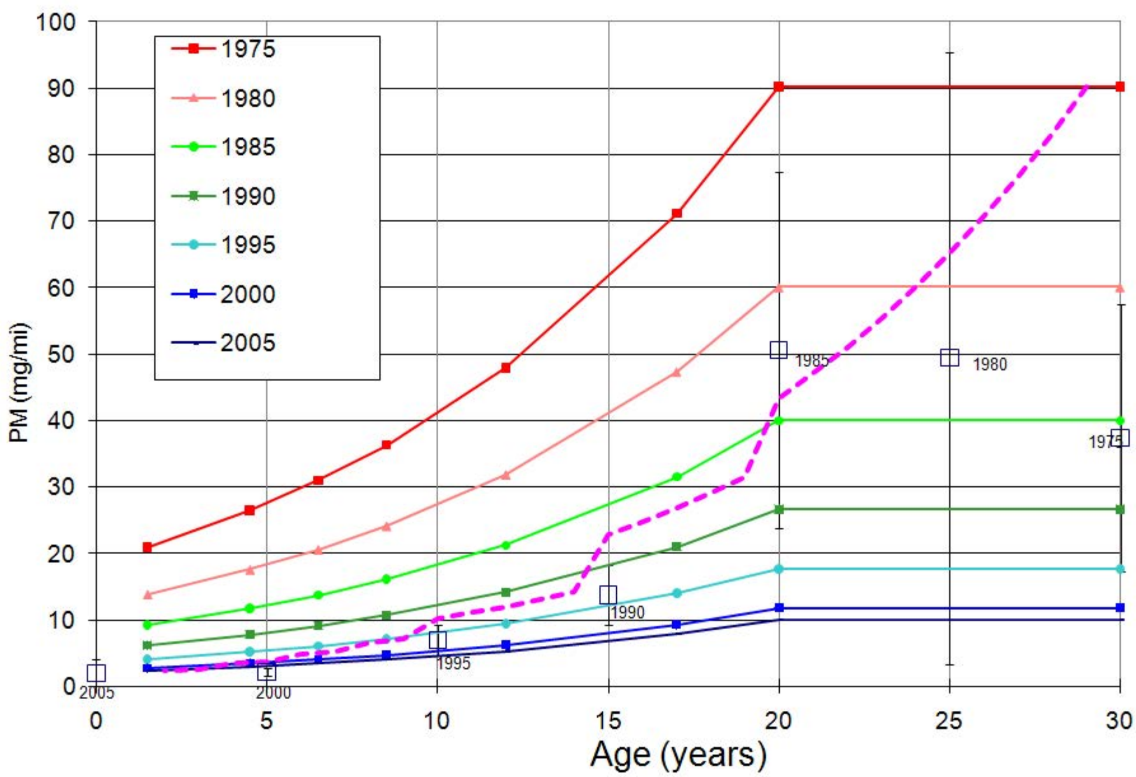

Figure 4-13 The multiplicative deterioration model shown on a linear scale. The y-axis offsets capture the new-vehicle ZML rates. The dotted lines and points with error bars represents the Kansas-City results (with 95 percent confidence intervals)

We applied the multiplicative deterioration factors directly to both cars and trucks, cold start, hot-running, EC, and OC emissions, assuming that the deterioration factors are independent of these effects. The estimation of the elemental carbon fractions, modal emission rates, and modal start rates are discussed in the next sections.

4.1.3 Estimating Elemental Carbon Fractions

After performing the analyses described above to estimate total particulate ($PM_{2.5}$), we partitioned the total into components representing elemental carbon (EC) and non-elemental carbon (nonECPM), respectively. Following this step, the values for EC and nonECPM were loaded into the emissionRateByAge table, using the pollutant and process codes shown in Table 2-1 (page 16). Non-elemental carbon particulate matter (NonECPM, or pollutantID 118), represents particulate species other than elemental carbon. For light-duty exhaust, NonECPM is primarily composed of organic carbon (pollutantID 112), and small amounts of inorganic ions and elements. Background and further detail on the speciation of $PM_{2.5}$ is discussed in greater detail in the MOVES TOG and PM Speciation Report.[19]

The initial analysis of the EC composition of the light-duty exhaust is documented in the Kansas City analysis report.[52] 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 using 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[69] and Fujita et al. (2006).[70] The former reference indicates that the photoacoustic 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 4-14 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 there is relatively more variability (in log-space) between the two measurements.

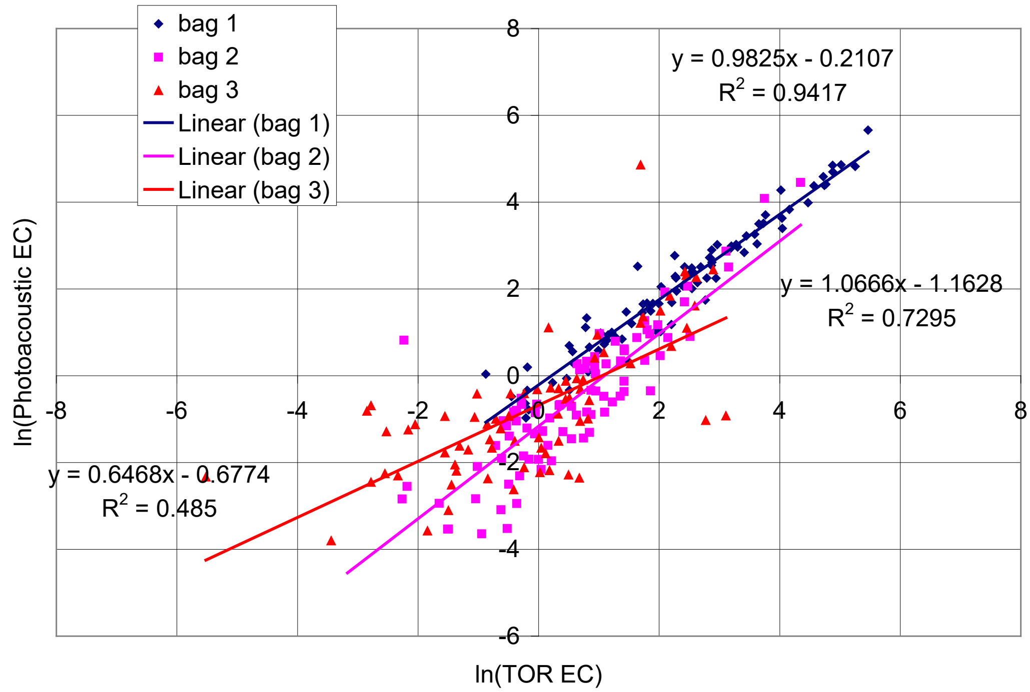

Figure 4-14 Comparison of photoacoustic to TOR EC measurements on a logarithmic scale

We explored the EC/PM fraction for the four measurement techniques employed in the Kansas-City 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 4-3 shows the comparison of the 3 different fractions using results from these instruments. The values were calculated as fractions of average values in the numerator and denominator. The TOR fractions have two major limitations: the ratios are unexpectedly high and, after eliminating bad data points, only 75 valid measurements remain. Due to the latter condition (primarily), the TOR fractions will not be used in subsequent analysis. The photoacoustic to Dustrak ratios present a reasonable approach, however, since the Dustrak and PM are not strongly correlated[51], we elected to use the photo-acoustic to gravimetric filter ratios for EC/PM fraction estimation.

Table 4-3 Elemental to total PM ratio for 4 different measurement techniques

Instruments	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 MOVES, the EC/PM fractions for light-duty gasoline vehicles are consistent with detailed $PM_{2.5}$ speciation profiles developed for all the measured PM species in the Kansas City Study.[71] The EC/PM fractions are estimated using the photoacoustic analyzer to filter-based PM emissions. The MOVES speciation analysis confirmed our previous analysis[52] that the EC/PM fraction is relatively consistent across the range temperatures measured in Kansas City study, and across the ranges of model years in the study. For this reason, no differentiation in the EC/PM fraction is modeled in relation to temperature or model year of vehicles in MOVES.

In developing speciation profiles for light-duty gasoline vehicles from the KCVES,[71] we discovered high concentrations of silicon in the particulate matter samples. Upon further investigation, we determined that the silicone rubber couplers used in the sampling system probably contributed to the filter-measured mass. The resulting contamination of filter masses with silicon substantially impacted the Bag 2 $PM_{2.5}$ emission rates, which had the highest exhaust temperatures. No significant contribution of silicon was found in the $PM_{2.5}$ start emissions. The adjustment to the MOVES running $PM_{2.5}$ emission rates based on the silicon measurements is discussed in Appendix A. Revisions to the Pre-2004 Model Year $PM_{2.5}$ Emission Rates between MOVES2010b and MOVES2014.

The silicon contamination in these measurements resulted in a positive bias in the values for OC. In consequence, the EC and nonECPM emission rates in MOVES were revised to account for the updated data analyses used to derive the $PM_{2.5}$ profile (e.g. VMT-weighted means), and to compensate for the silicon contamination in the $PM_{2.5}$ emission rates. Upon removal of the silicon contamination, the EC/PM fractions are not significantly different between light-duty cars and trucks. The data from cars and trucks were pooled as documented in the speciation analysis.[71] The EC/$PM_{2.5}$ fractions in MOVES are presented in Table 4-4. The EC/$PM_{2.5}$ ratio is constant across all operating modes for start and running processes.

Table 4-4 EC/$PM_{2.5}$ fractions by start and running emissions processes for pre-2004 light-duty gasoline vehicles

Emission Process	EC/$PM_{2.5}$
Running	14.0%
Start	44.4%

4.1.4 Modal Running Emission Rates

As mentioned in section 4.1.1, the Dustrak instruments was selected as the most reliable second-by-second PM time-series data measurement from the Kansas City Study. The Dustrak $PM_{2.5}$ measurements were used to develop the $PM_{2.5}$ emission rates by operating mode. The following two figures show Dustrak PM emissions binned by VSP and classified by model year Groups. Figure 4-15 shows this relationship on a linear scale and Figure 4-16 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.

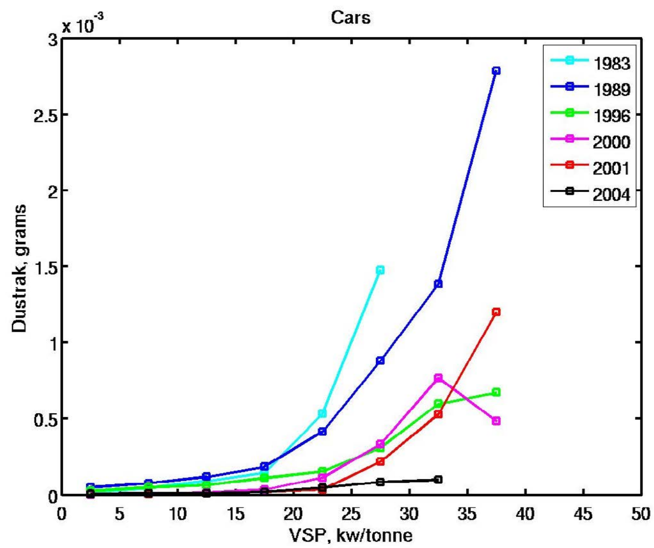

Figure 4-15 Particulate emissions, as measured by the Dustrak, averaged by VSP and model-year group (LINEAR SCALE)

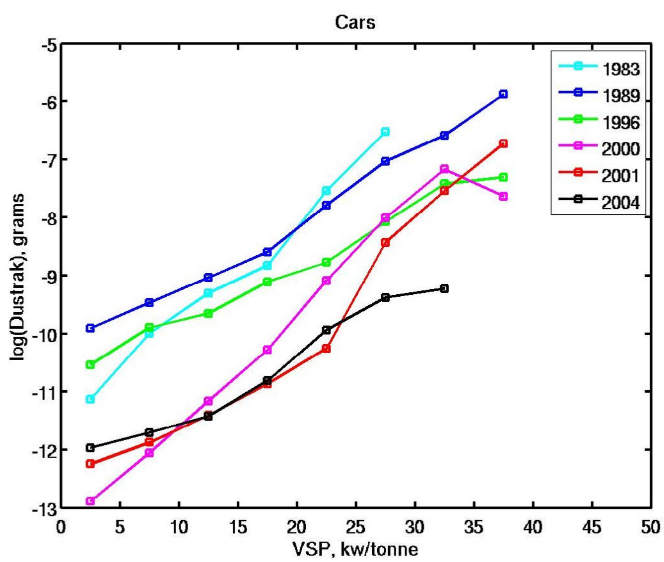

Figure 4-16 Particulate emissions, as measured by the Dustrak, averaged by VSP and model-year group (LOGARITHMIC SCALE)

In order to calculate VSP-based modal rates, we followed seven steps:

1. The LA92 equivalent hot-running emission rate (g/mi) is calculated for each age group within each model-year group, using the deterioration model described in section 4.1.2.3.
2. Continuous emission rates (g/sec) are calculated from the Dustrak measurements for cars and trucks. These trends are then extrapolated to higher VSP 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 set of continuous measurements (Step 2) are then classified into the operating-mode distribution and summed to give an aggregate emission rate representing Bag 2 of the LA92.
5. The results from Step 4 are divided by those from Step 1 to calculate a ratio for each combination of the model-year and age groups. The ratios are used to normalize the modal emission rates to the aggregate filter measurements.
6. The rates from step 5 are then apportioned into EC and nonEC components to give final rates for the hot-running process. These rates are stored in the emissionRateByAge table under polProcessID 11201 and 11801, respectively.

The output from step 3 (operating-mode distribution) for cars and light trucks is shown in Figure 4-17. For operating-mode definitions, see Table 2-5.

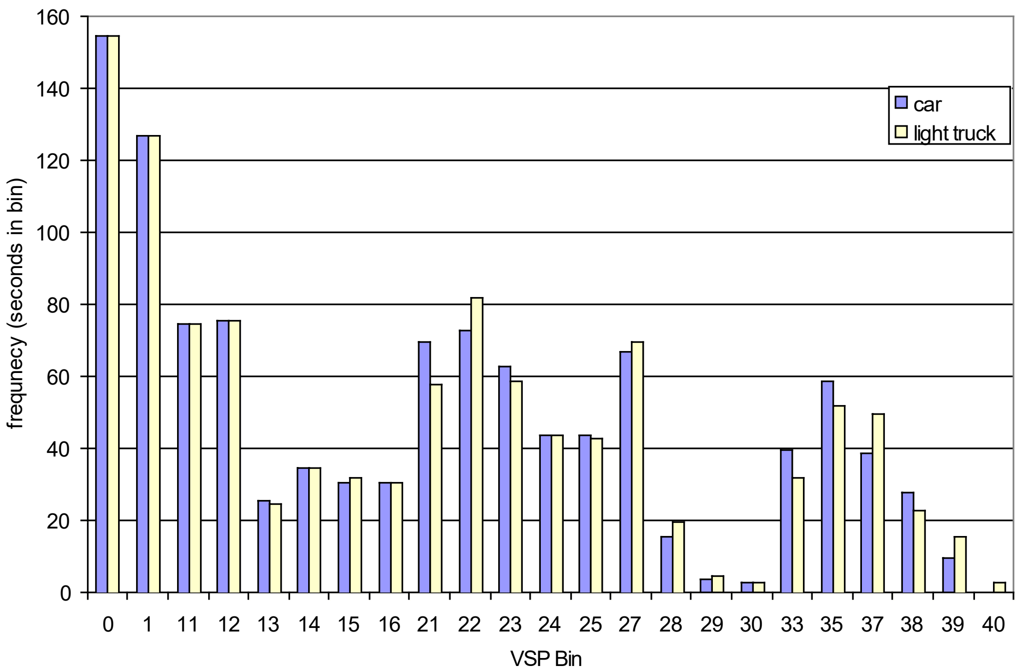

Figure 4-17 Operating-mode distribution for cars and light trucks representing the hot-running phase (Bag 2) of the LA92 cycle

The output of step 5 for the ZML (0-3 year age Group) in each model year is shown in Figure 4-18.

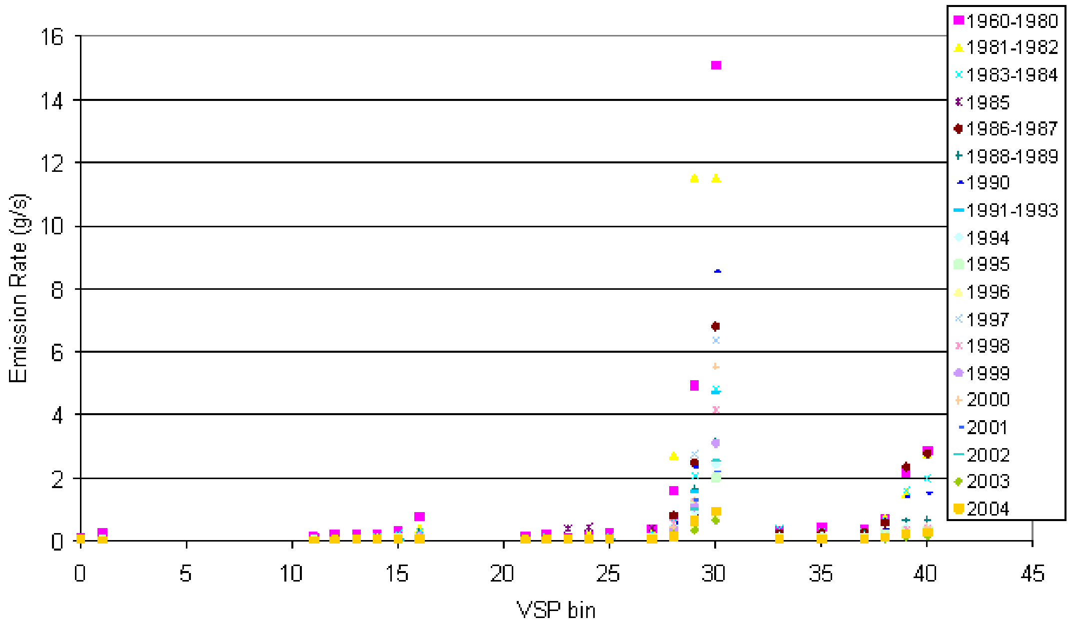

Figure 4-18 Particulate emissions for passenger cars (LDV) from Kansas City results, by model year Group, normalized to filter mass measurements

After the rates were calculated, a quality check was performed to ensure that the aged rates in any particular mode 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 for cars and trucks in the 1975 model-year group in operating mode bin 30. In these cases, the value from operating mode 29 was replicated for operating mode 30.

4.1.5 Modal Start Emission Rates

The development of the cold start emission rates (opMode 108; soak time > 12 hours), is discussed in Section 4.1.2.2. The cold start emission rates (g/start), as estimated using Bag1 – Bag3 of the LA92, were estimated to be a factor of 1.972 times the reported LA92 composite g/mile emission rate from the Kansas City study. This factor was then used to estimate cold start emissions from the zero mile level emission rates. Subsequently, the impact of deterioration on starts was incorporated as discussed in detail in Section 4.1.2.3.

In MOVES, the start rates by operating mode account for the different soak times preceding the start as shown in Table 2-6. Section 3.9.1.1 discusses how the start emission rates for hot starts (opModeID 101-107; soak times < 12 hours) are estimated as a fraction of the cold start emission rates (opModeID 108). Due to limited data on PM emissions at different soak lengths, we apply the same ratios between start operating modes for hydrocarbon start emissions as for PM emissions presented in Table 3-51.

4.2 Particulate-Matter Emission Rates for Model Year 2004 and Later Vehicles

4.2.1 Introduction

This section addresses PM running emission rates for gasoline light-duty vehicles for model years 2004 through 2060. Previously, MOVES2014 used the same PM emission rates for model years 2003 through 2016 and then applied phase-in assumptions to account for Tier 3 standards. This section, therefore, represents an update to the MOVES emission rates for vehicles subject to Tier 2 and Tier 3 standards. Since 2004, gasoline direct injection (GDI) vehicles have entered the market. In 2016, GDI vehicles represented roughly half of new vehicles sold in the United States.[72] Additionally, several studies of vehicle emissions have been conducted since the Kansas City study[51] using vehicles newer than MY 2004 vehicles. The emission rates derived in this section are based on the data from six such studies, including studies of GDI vehicles. The adoption of GDI engines has been taken into account by separately calculating PM emission rates for PFI (port fuel injection) and GDI vehicles, and then combining them to form population-weighted average rates by model year. However, the datasets used in these analyses do not contain enough information to derive completely new modal emission rates or deterioration rates for these model years. Therefore, to determine the new modal rates, we rescaled the existing modal rates used for model year 2003 in MOVES using the new data, and retained the deterioration behavior described in Section 4.1.2.3. Finally, we applied the phase-in of Tier 3 standards to the newly derived rates.

4.2.1.1 Dataset Description

Data from six studies was used to develop the 2004 and later PM emission rates. The dataset for each study includes PM filter weight measurements collected on FTP or LA-92 three-phase or "bag" test cycles. Phase 1 (bag 1) is a cold start where the vehicle has been "soaking" at a controlled temperature for 12 or more hours with the engine turned off. Typically, vehicles are soaked at room temperature (~72°F). Phase 2 follows Phase 1 and is used to characterize temperature-stabilized or "hot running" conditions. At the end of Phase 2, the engine is shut off, and the vehicle is allowed to soak for 10 minutes under the ambient test cell conditions. Finally, the engine is restarted and Phase 3 follows the same driving cycles as Phase 1. For the LA92 cycle, Phases 1 and 3 last for 310 seconds, and Phase 2 lasts for 1,135 seconds. Phases 1 and 3 of the FTP cycle are longer than for the LA92, taking 505 seconds. Phase 2 of the FTP cycle is shorter at 867 seconds. PM filters were collected and weighed for each phase of the test cycles providing a measure of the total PM mass emitted during each phase. The studies selected for analysis are summarized in Table 4-5.

Table 4-5 Summary of PM studies analyzed for model year 2004 and later vehicles

Study name	Engine Type	Number of vehicle models	Number of unique vehicles
EPA Tier 2 Fuel Sulfur Study[73]	PFI	17	72
EPAct Phase 1 FTP[74]	PFI	6	6
EPAct Phase 3[75]	PFI	15	15
EPAct Phase 4[76]	PFI	6	6
CARB LEV III PM Emissions Study[77]	GDI	6	6
EPA Tier 3 Certification Fuel Impacts Study[78]	GDI	7	8

Altogether, the dataset for PFI vehicles consists of measurements from 99 vehicles representing 19 different models. Unlike the KCVES, these studies were designed to capture properly functioning vehicles. We assume that the vehicles in the study represent age zero emission rates in MOVES, with no effects of emissions deterioration due to age. The dataset for GDI vehicles is composed of measurements from 14 vehicles, and 13 models. Because of the limited number of GDI vehicles, there was not enough data for both wall-guided and spray-guided injection architectures to differentiate between them for this study. Only the tests conducted at room temperature were included in this analysis in order to eliminate influences from hot or cold temperature tests. Measurements conducted with greater than 20 percent ethanol fuels were omitted from analysis because MOVES only handles fuel with ethanol content less than or equal to 15 percent for gasoline vehicles.

4.2.1.2 Fuel Considerations

The four studies used to generate PM emission rates for PFI vehicles used a combined total of 27 different fuels with ethanol content less than 20 percent. In order to minimize the effects of these fuels on the emission rate calculations, the measured rates were corrected to the equivalent rates for Tier 2 certification fuel. The corrected rates were calculated using the EPAct fuel effects calculator, which uses the same method used by MOVES to calculate fuel-effect adjustments.[79] The EPAct calculator applies the set of statistical models developed using the EPAct Phase 3 dataset, also used for developing the particulate matter emission rates in the current analysis. Additionally, the EPA Tier 2 sulfur study used Tier 2 based fuels and as such required negligible correction.[73] The corrections were applied to all three phases of the FTP and LA92 PM mass measurements. The effects on the distribution of measured start and running emissions for each test program are summarized in Figure 4-19.

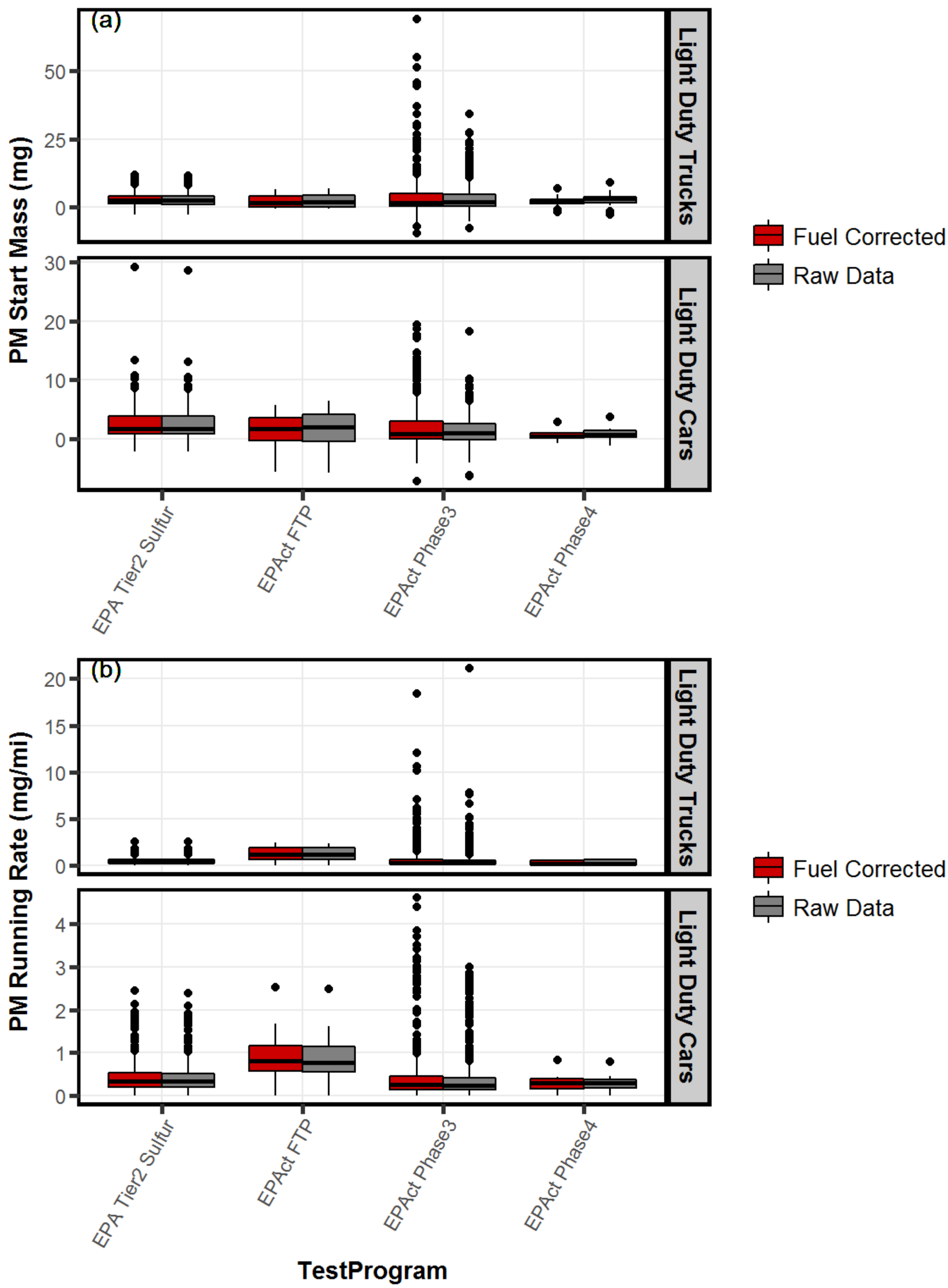

Figure 4-19 Boxplots of start (a) and running (b) emissions measurements with and without fuel corrections applied

4.2.2 Calculating FTP and LA92 Cycle Rates Using MOVES Emission Rates

The six datasets used for this analysis are not adequate to develop revised running modal emission rates *de novo* for vehicles with model years 2004 and later. Therefore, the modal rates for model year 2003 vehicles are rescaled to generate the emission rates for 2004 and later model years. In order to develop the appropriate rescaling factors, Bag 2 emission rates are calculated for both the FTP and LA92 drive cycles using MOVES model year 2003 emission rates.

The Bag 2 rates of both the FTP and LA92 cycles for both MOVES light-duty regulatory classes (light-duty cars, and trucks) are calculated using the MOVES operating mode distribution calculated for the hot running phase of each test cycle, and multiplying the time in each operating mode with its associated emission rate. To generate an emission rate, the emission masses calculated for each operating mode are summed, and the total is divided by the distance driven. The MOVES operating mode distribution for Bag 2 of both the FTP and the LA92 cycles are shown in Figure 4-20.

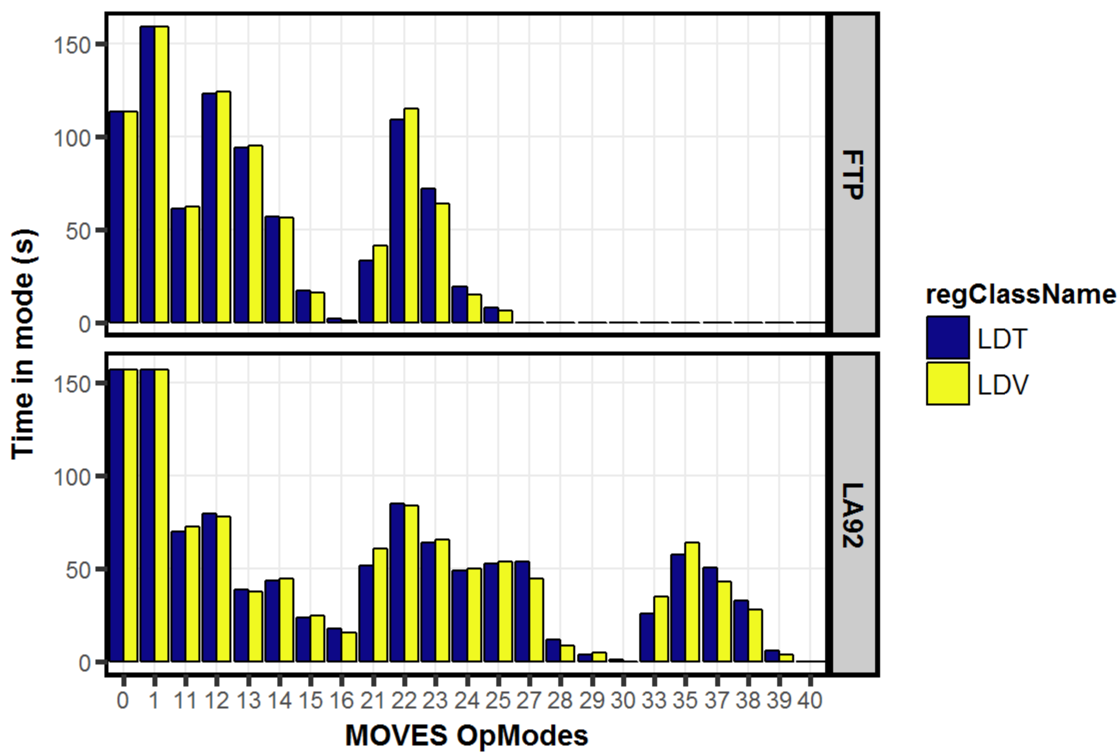

Figure 4-20 MOVES operating mode distributions for the hot-running phase (Bag 2) of the FTP and LA92 drive cycles

As the figure illustrates, Bag 2 of the LA92 cycle is more aggressive than Bag 2 of the FTP cycle. As a result, different average running emission rates result from each cycle. For cold starts, based on the analysis presented in Section 4.1.2.2, it is assumed that both the LA92 and FTP cycles will have the same PM mass emitted for each vehicle type. The cold-start masses and Bag 2 hot running rates calculated using MOVES model year 2003 emission rates are summarized in Table 4-6. These calculated cycle rates are used as a basis for comparison to the measured rates in the datasets that are analyzed in Sections 4.2.3 and 4.2.4. Additionally, these calculated cycle rates are used in Section 4.2.5 to determine the rescale factors used to develop the model year 2004 and later PM emission rates used in MOVES.

Table 4-6 Modeled FTP and LA92 start and bag 2 running rates for model year 2003 light-duty vehicles

Test cycle	regClassID	Cold-start mass (mg)	Hot-running rate (mg/mi)
FTP	LDT	8.781	1.444
FTP	LDV	6.158	2.090
LA92	LDT	8.781	2.133
LA92	LDV	6.158	1.924

4.2.3 Estimating Start Emissions for Particulate Matter

Start emissions from three-phase test cycles are calculated by comparing the measured masses of the Phase 1 and Phase 3 PM filters. For both the LA92 and FTP drive cycles, the speed trace for Phases 1 and 3 are identical. The difference in measured PM masses between the two phases is attributed to the change in engine condition from cold start to hot stabilized running. Typically, this transition results in higher Phase 1 PM mass. If the value of the Phase 1 minus the Phase 3 mass is negative, it suggests that the hot stabilized engine emitted more particulate matter than it did when it was warming up. We observed this behavior in some of the test results. Because we found no technical reason to exclude these points, they are included in the averaged rates. For this analysis, we assume that cold-start PM emissions are independent of the test cycle. The average rates from the data discussed in this section are used in Section 4.2.5 to develop the scaling factors for constructing the PM start rates.

4.2.3.1 Start Emissions for Vehicles with Port Fuel Injection (PFI)

Figure 4-21 summarizes the cold-start results from the PFI vehicles used in this analysis, which are drawn primarily from the EPAct Phase-3 study. The solid horizontal lines show the average cold-start mass for light-duty cars and trucks, as averaged by vehicle model. The dashed horizontal line shows the cold start mass for new vehicles with model year 2003 in MOVES. For PFI light-duty cars, the average cold start mass is 2.06 mg and for PFI light-duty trucks, it is 3.75 mg. On average, the measured PM cold start emission masses for the analyzed data were substantially lower than modeled for model year 2003 vehicles in MOVES.

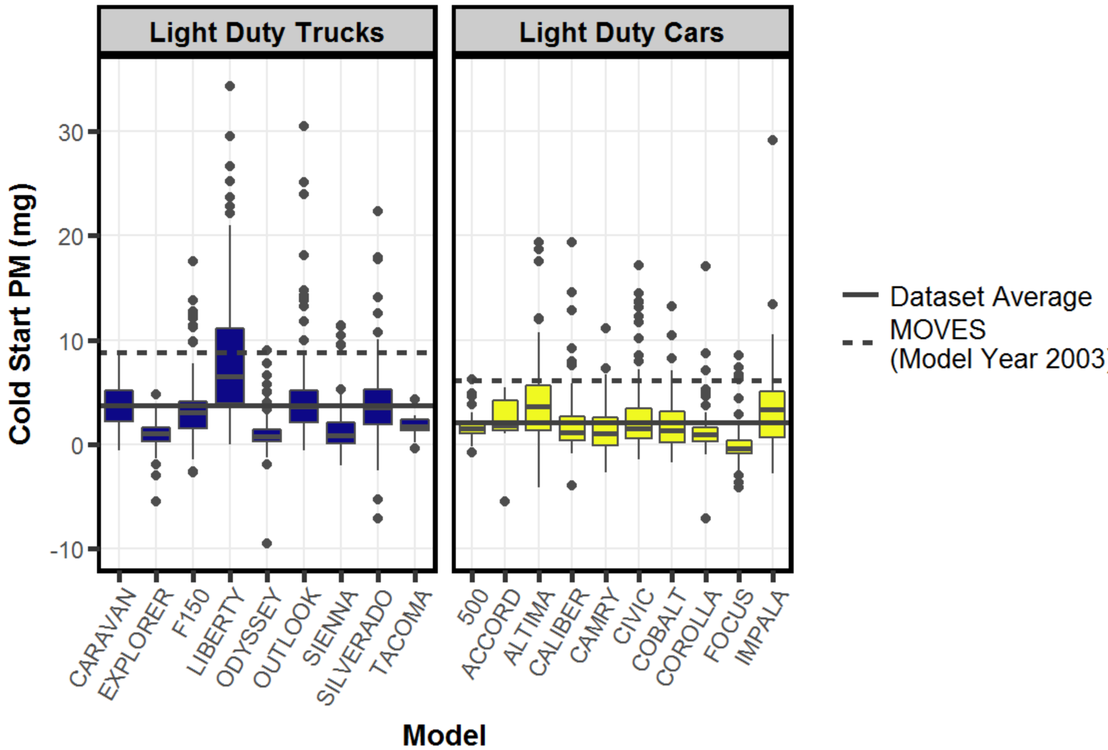

Figure 4-21 Measured PFI PM start emission masses

4.2.3.2 Start Emissions for Vehicles with Gasoline Direct Injection (GDI)

Figure 4-22 summarizes the cold-start results from all of the GDI vehicles used in this analysis. The solid horizontal lines show the cold-start mass for light-duty cars and trucks, as averaged by each unique vehicle. The dashed horizontal line shows the cold start mass for new vehicles with model year 2003 in MOVES. For GDI light-duty cars, the average cold start mass is 20.92 mg. While only data from two GDI trucks is available in these studies, the average cold start mass for these two vehicles is 38.34 mg. Generally, the measured PM start emission masses for GDI vehicles in the analyzed dataset were significantly higher than modeled for model year 2003 vehicles in MOVES.

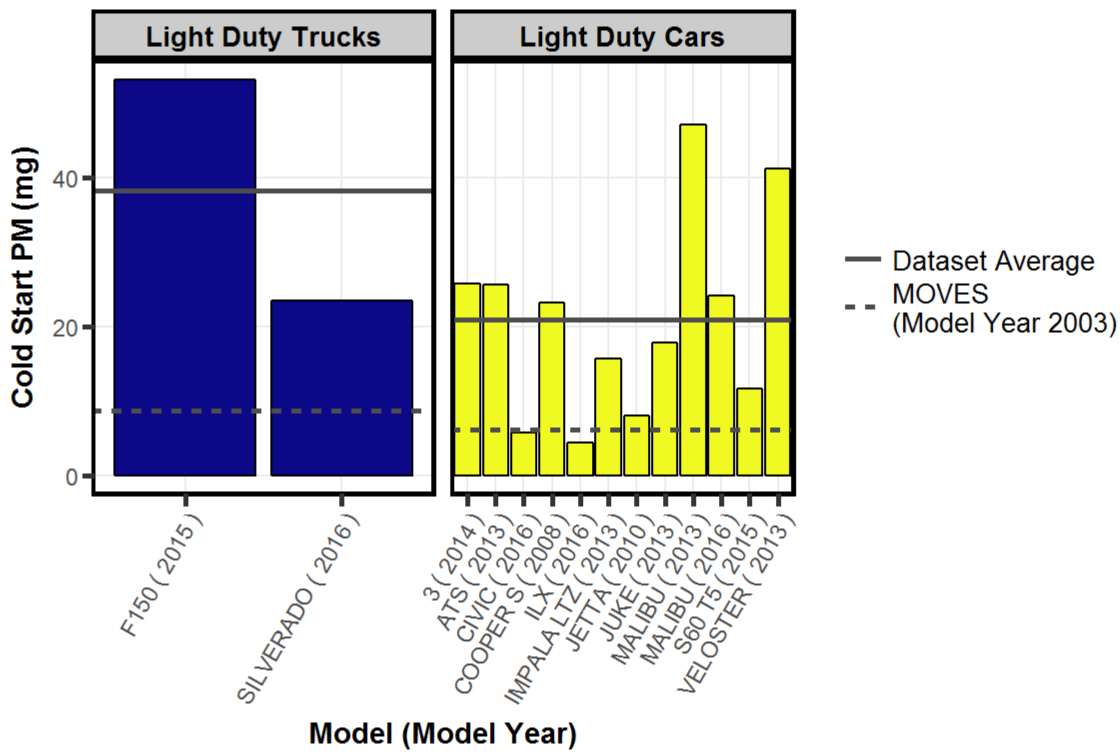

Figure 4-22 Measured GDI PM start emissions

4.2.4 Estimating Running Emissions for Particulate Matter (PM)

Running emission rates were calculated for each test in units of milligrams per mile. Because the FTP and LA92 cycles cover different engine power ranges as shown in Figure 4-20, the average emission rate for each vehicle model was calculated separately for each test cycle. In general, the results for both PFI and GDI vehicles show substantially lower running PM rates than modeled for model year 2003 in MOVES. The average rates from the data discussed in this section are used in Section 4.2.5 to develop rescale factors for constructing the MOVES PM running rates.

4.2.4.1 Running Emissions for Vehicles with Port Fuel Injection (PFI)

For the four test programs used in the PFI analysis (Table 4-5), the running PM rates are grouped by vehicle model. Figure 4-23 summarizes the results. The solid horizontal lines show the average Phase 2 running mass for light-duty cars and trucks, as averaged by vehicle model. The dashed horizontal line shows the Phase 2 running mass for new vehicles with model year 2003 in MOVES. As Figure 4-20 demonstrates, the LA92 drive cycle has a more aggressive Phase 2 than the FTP cycle. This difference results in a higher average emission rate for the LA92 cycle than for the FTP cycle. This difference is reflected in both the measured datasets and the cycle average rates calculated by combining model year 2003 emission rates and operating-mode distributions for the two cycles.

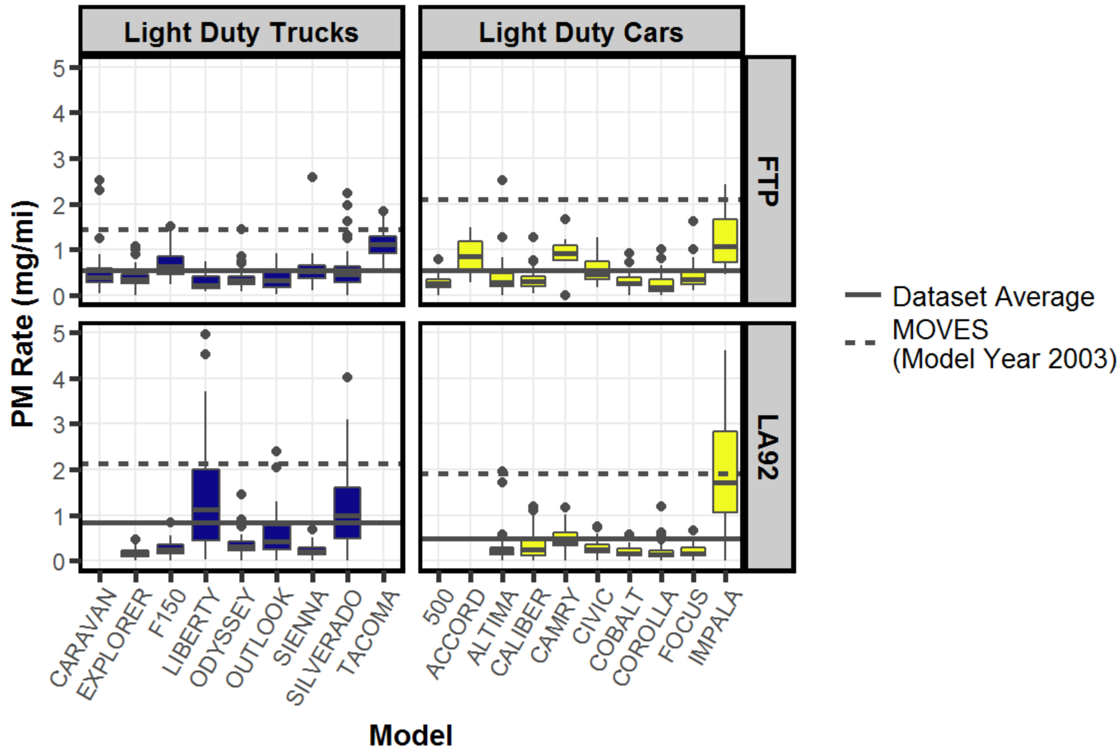

Figure 4-23 Measured PFI PM running emission rates

4.2.4.2 Running Emissions for Vehicles with Gasoline Direct Injection (GDI)

The summary of running emission rate results for the GDI vehicles used in this analysis are shown in Figure 4-24. Because the GDI vehicles were tested only using the FTP drive cycle, the results are not split by test procedure. As with the GDI start emissions, the averages rates are calculated weighted by test vehicle. While there is significant variation in the PM rates for the GDI vehicles, the average running emission rates fall below the model year 2003 MOVES average.

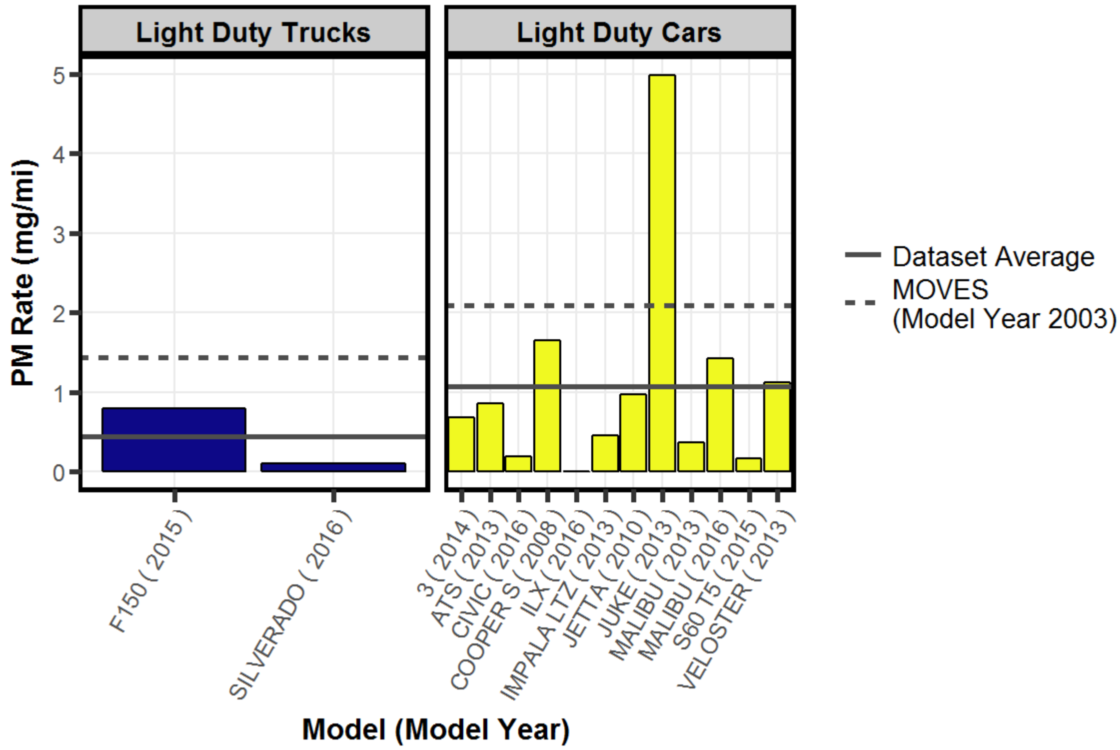

Figure 4-24 Measured GDI PM running emission rates

4.2.5 Developing Base Emission Rates for Model Year 2004 and Later

As mentioned previously, the six datasets, used to develop light-duty PM rates for 2004 and later vehicles, do not contain the data necessary to assemble new modal running emission rates. Therefore, the modal running emission rates for model year 2003 are scaled to represent the observed emission rates from these studies. The scaling factors are calculated by taking the ratio of the running emissions rate for each measurement to the rate for the same drive cycle calculated using the model year 2003 MOVES emission rates (Section 4.2.2). For PFI vehicles, these ratios are calculated as an average weighted by model. For GDI vehicles, the averages are weighted by unique test vehicle. Table 4-7 summarizes the average scaling factors for both start and running emissions.

Table 4-7 Cold-start and hot-running scaling factors for PFI and GDI vehicles

Engine type	regClassID	Cold-start scaling factor	Hot-running scaling factor
PFI	LDT	0.427	0.382
PFI	LDV	0.335	0.260
GDI	LDT	4.367[a]	0.312[a]
GDI	LDV	3.398	0.515

Note: [a] See Section 4.2.5.1for the final scaling factors for GDI LDT.

4.2.5.1 Additional Assumptions Used to Determine GDI Truck Scaling Factors

The data for the two GDI trucks included in the six datasets is not sufficient to form the basis for revised emission rates in MOVES3. To compensate, we developed an approximation of start and running emission rates for GDI trucks using the data analyzed for PFI vehicles, and for the GDI light-duty cars. We assume that the apparent difference in PM emissions between GDI and PFI vehicles are due to the change in injection technology. Additionally, we assume that the change in injection technology will have a similar proportional emissions effect on engines in light-duty trucks as in light-duty cars. To calculate GDI truck start emissions, we use the following equation:

$$Start_{LDT}(GDI) = Start_{LDT}(PFI)\frac{Start_{LDV}(GDI)}{Start_{LDV}(PFI)} \qquad \textbf{Equation 4-3}$$

where LDV indicates light-duty cars, and LDT indicates light-duty trucks.

For running emissions, we used a slightly different approach. Because the datasets only contain results for GDI vehicles on the FTP cycle, it was difficult to directly compare them to the PFI results where a significant proportion were measured on the LA92 test cycle. Therefore, we made the assumption that the scaling of the 2003 model year MOVES rates for GDI light-duty trucks would be the same as the scaling for light-duty cars, i.e.:

$$Running_{LDT}(GDI) = Running_{LDT}(MOVES)\frac{Running_{LDV}(GDI)}{Running_{LDV}(MOVES)} \qquad \textbf{Equation 4-4}$$

Table 4-8 contains the calculated start and running rescale factors using these assumptions as well as the average measured values from the two trucks in the studies. For start emissions, the rates calculated from these assumptions are very similar to the measured rates from the two trucks. The calculated running rates on the other hand show a more modest reduction relative to the 2003 model year rate than suggested by the test results from the two trucks. The rescale factors derived from these assumptions are the ones used to derive the final MOVES3 light-duty truck emission rates.

Table 4-8 Scaling factors for light-duty trucks calculated from measured data and from modeling assumptions

	Cold-start	Hot-running
Unadjusted scaling factor (Table 4-7)	4.367	0.312
scaling factor calculated from Equation 4-3 and Equation 4-4	4.330	0.515

4.2.5.2 EC/NonECPM Fractions

In the MOVES EmissionRateByAge table, total PM emission rates are partitioned into elemental carbon (EC) and non-elemental carbon (nonECPM). Section 4.1.3 describes the method for using photo-acoustic to gravimetric filter mass ratio to determine the fraction of EC to total PM. Because the datasets used for PFI vehicles did not have additional EC information, we retain the EC/$PM_{2.5}$ fractions calculated from the Kansas City study to represent light-duty PFI vehicles with model years 2004 and later. The CARB LEVIII PM study used as part of the GDI rates analysis, also included photo-acoustic PM mass measurements. As such, we used the same method to calculate EC/$PM_{2.5}$ fractions for light-duty GDI vehicles. The resulting fractions show a significantly higher EC fraction for both start and running emissions from GDI vehicles as compared to PFI vehicles. The start and running EC/$PM_{2.5}$ fractions for both PFI and GDI vehicles are summarized inTable 4-9.

Table 4-9 Start and running EC/$PM_{2.5}$ fractions for PFI and GDI vehicles

Engine type	Start EC/$PM_{2.5}$	Running EC/$PM_{2.5}$
PFI	0.44	0.14
GDI	0.70	0.67

4.2.6 Calculation of Fleet-Average PM Emission Rates by Model Year, Vehicle Age, and PM component

This section describes how the cold-start and hot-running rescale factors and the EC/$PM_{2.5}$ fraction determined in Section 4.2.5 are combined to create the PM emission factors used in MOVES for model years 2004 and later. Here, the emission rates are derived without accounting for the implementation of new emission standards. Sections 4.2.7 and 4.2.8, describe how the Tier 3 and LEV-III standards are applied to the PM emission rates.

Thus far, the discussion of PM rates for light-duty vehicles for model years 2004 and later has divided these vehicles by fuel injection technology, however, MOVES does not currently accommodate partitioning emission rates for a given regClass by engine technology. Rather, fleet-average rates must be entered into the emissionRateByAge table. Therefore, average PM emission rates were calculated for each model year using weights for the PFI and GDI emission factors determined from vehicle production volumes.

4.2.6.1 Vehicle Population Data for Model Years 2004 – 2016

For model years 2004 through 2016, the annual EPA *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends Report* provides data on the relative production volumes of vehicles with different engine technologies.[80] Tables 5.3.2 and 5.3.3 of the report include the proportions of the light-duty car and truck populations that have PFI and GDI engines. This data is shown by the symbols plotted Figure 4-25. These proportions were used directly to weight the fleet-average PM emission rates from PFI and GDI vehicles.

4.2.6.2 Modeling Vehicle Populations for Model Years After 2016

The rapid adoption, and expected continued growth of the GDI portion of the light-duty vehicle population make it inappropriate to use the 2016 population fractions to represent the light-duty vehicle population into the future. Therefore, the relative PFI and GDI vehicle populations were extrapolated for model years 2017 and later. To make this projection, a simple sigmoidal function was fit to the data for years 2004 through 2016. A sigmoidal function was used because it reasonably reproduced the trend of GDI adoption, and created a smooth transition from one technology to the other. The functions used for this fit are:

$$GDI(MY) = \frac{1}{1 + e^{-K(MY - MY_0)}} \qquad \textbf{Equation 4-5}$$

$$PFI(MY) = 1 - GDI(MY) \qquad \textbf{Equation 4-6}$$

Where GDI(MY) and PFI(MY) are the fractions of the light-duty vehicle population with GDI and PFI engines respectively, and MY is the vehicle model year. The fitted terms of the functions are K, which represents the rate of change of the populations, and MY_0 indicates when the modeled PFI and GDI populations are equal. The fitted values of K and MY_0 are given in Table 4-10.

Table 4-10 Fitting parameters for future GDI and PFI populations

regClassName	K	MY_0
LDT	0.421	2016.27
LDV	0.375	2015.17

The fit values of MY_0 have the populations of light-duty GDI and PFI vehicles becoming equal in 2017 for trucks, and in 2016 for cars. The symbols in Figure 4-25 show the population fractions of GDI and PFI vehicles from the trends report.[80] The fitted sigmoidal curves are shown as dashed lines. The solid lines show the combined curves of the 2004 to 2016 population data, with the modeled post 2016 population fractions.

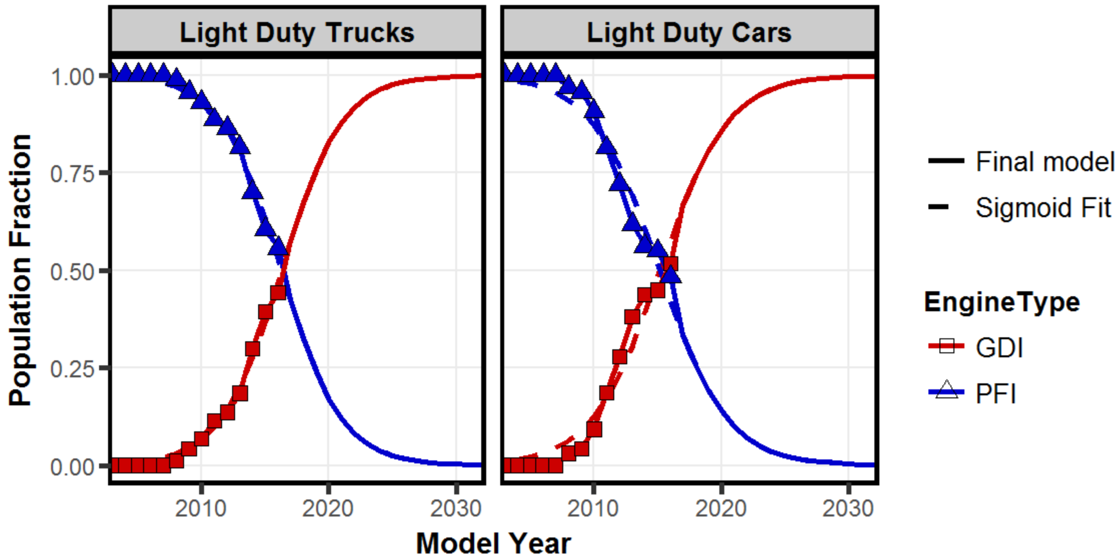

Figure 4-25 Population fractions of GDI and PFI vehicles by model year

4.2.6.3 Calculating Rates by Model Year, Vehicle Age, and PM Component

The MOVES EmissionRateByAge table was populated for model year 2004 and later light-duty vehicles (regClassID 20,30) using the start and running average rates, EC/$PM_{2.5}$ fractions, and population fractions determined above for GDI and PFI vehicles. The rates were determined by scaling the model year 2003 modal emission rates in MOVES using these factors. As noted in Section 4.2.1, these scaling factors derived below are based on age zero emissions rates and are applied across the vehicle age range in MOVES. Thus, the deterioration behavior described in Section 4.1.2.3 developed for the pre-2004 MY vehicles is retained for the MY 2004+ vehicles.

First, for each regClass, the scaling factors for the start and running total PM emission rates for each model year were calculated using the scaling factors developed in Section 4.2.5 combined with the GDI and PFI population fractions for that year as described in Equation 4-7.

$$RS_{Fleet}(MY) = S_{GDI} * P_{GDI}(MY) + S_{PFI} * P_{PFI}(MY) \qquad \textbf{Equation 4-7}$$

Where S is the scaling factor for the fleet of the given engine type, and P is the population fraction of PFI or GDI engines for each model year (MY).

Next, the EC/$PM_{2.5}$ fractions for each model year were calculated as a population and emission rate weighted sum of the EC/$PM_{2.5}$ fractions for PFI and GDI vehicles using the following equation:

$$EC/PM_{2.5\,Fleet} = \frac{EC/PM_{2.5\,GDI}(P_{GDI} * S_{GDI})}{(P_{GDI} * S_{GDI}) + (P_{PFI} * S_{PFI})} + \frac{EC/PM_{2.5\,PFI}(P_{PFI} * S_{PFI})}{(P_{GDI} * S_{GDI}) + (P_{PFI} * S_{PFI})} \qquad \textbf{Equation 4-8}$$

Where $EC/PM_{2.5}$ is the EC fraction, P is the population fraction. The subscripts indicate the values associated with the combined fleet, and for GDI and PFI vehicles. The $EC/PM_{2.5}$ values are used to estimate emission rates are portioned into two PM components (EC and nonECPM) as discussed in Section 4.2.5.2. Finally, the scale factors and new $EC/PM_{2.5}$ fractions were applied to the start and running modal emission rates from MOVES model year 2003 light-duty cars and light-duty trucks to generate a complete set of revised EC and nonECPM emission rates in MOVES3 for model year 2004 through 2060. This method thus preserves the modal rate structure as well as the deterioration effects modeled for earlier model years. Figure 4-26 through Figure 4-28 illustrate how these emission rates change with model year. Note that these rates do not yet account for the phase-in of the Tier 3 standards, which is handled in Section 4.2.7. Figure 4-26 shows how the PM cold start mass for light-duty cars and trucks changes with model year, showing increases in both EC and nonECPM as the percentage of GDI vehicles increases.

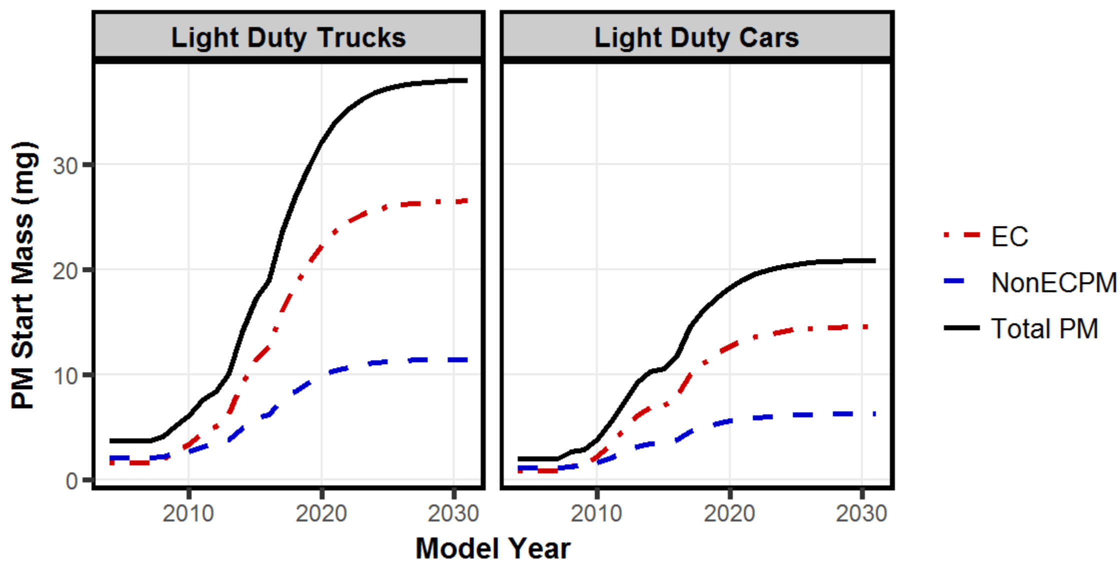

Figure 4-26 Modeled cold start PM emissions by model year for age 0 vehicles- not adjusted for phase-in of Tier 3 standards

Figure 4-27 shows calculated FTP Bag 2 running rates to illustrate how the MOVES rates for light-duty cars and trucks change with model year. For these rates, the nonECPM portion of the emissions decrease with GDI phase in while the EC portion increases. Together, the changes in EC and nonECPM rates result in a net increase in Total PM with increasing model year.

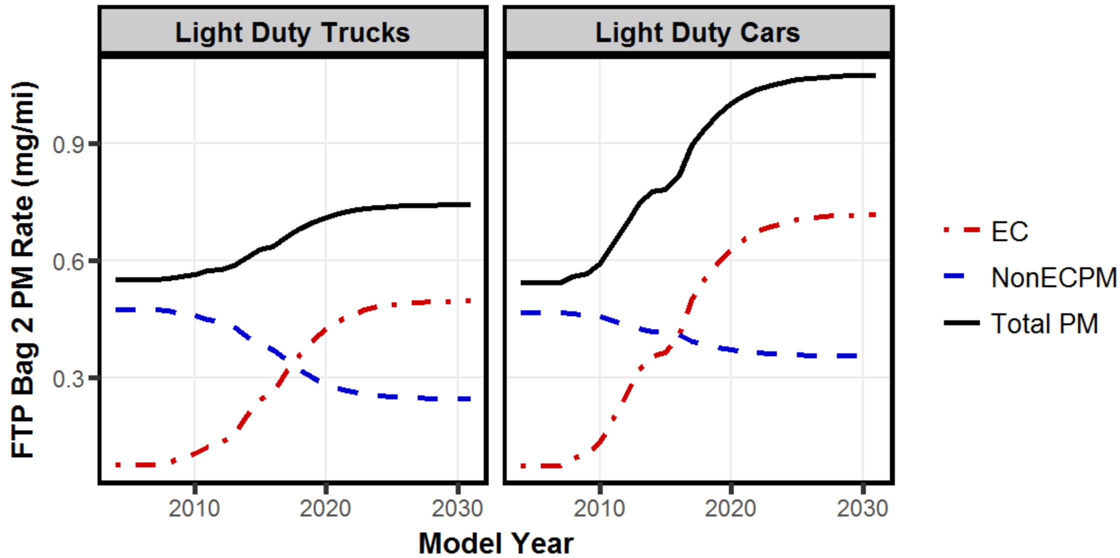

Figure 4-27 Modeled FTP bag 2 PM emission rate by model year for age 0 vehicles - not adjusted for phase-in of Tier 3 standards

Finally, Figure 4-28 shows the calculated combined FTP cycle average PM rates. For the FTP cycle, the overall PM rates increase with model year largely due to an increase in the EC rates, while the nonECPM rates only increase slightly.

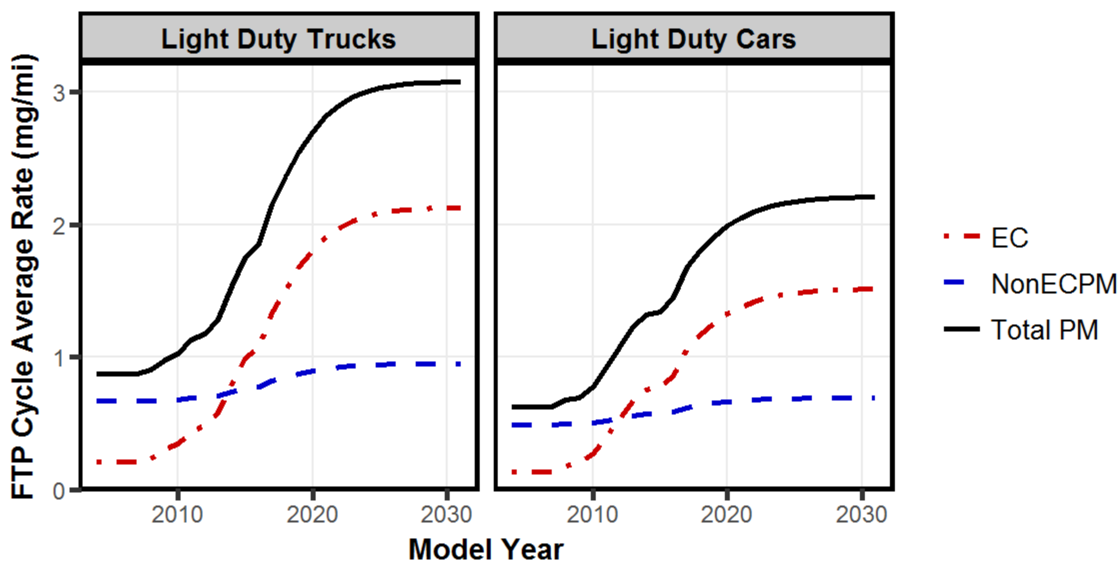

Figure 4-28 Modeled FTP cycle average PM emissions by model year for age 0 vehicles - not adjusted for phase-in of Tier 3 standards

4.2.7 Incorporating Tier 3 Emissions Standards for Particulate Emissions

Under the Tier 3 exhaust emissions standards, finalized in April, 2014, the FTP standard for particulate emissions was reduced from its level under the Tier 2 standard (10.0 mg/mi) to a new value of 3.0 mg/mi.[81]

Developing rates to represent particulate emissions from gasoline-fueled vehicles under the Tier 3 standards involved scaling down rates representing vehicles under the Tier 2 standard to a level that assumes a reasonable compliance margin with respect to the lower standard. More specifically, we assumed that average FTP emissions for new light-duty vehicles (age 0-3 years) would be 1.5 mg/mi in MY 2025, corresponding to a compliance margin of 50 percent, when the new standard was fully phased in. This assumption is independent of engine and fuel-injection technology. The reduced rates assume that additional controls are needed to meet the new standard for vehicles employing gasoline direct-injection technologies, but not for the declining fraction of vehicles in the market employing port-fuel-injection. The analysis above shows that new PFI vehicles start at about this level, and thus can virtually meet the new standard without modification.

Additionally, as with the gaseous emissions, the regulatory useful life was increased from 120,000 to 150,000 miles. The concomitant assumption of increased durability was expressed through a reduction in the assumed deterioration rate.

We applied these modifications to the MOVES EmissionRateByAge table in a series of three steps.

4.2.7.1 Apply Phase-in Assumptions

The first step was to apply the phase-in assumptions applicable to PM. The phase-in begins with model year 2017 and ends with model year 2021 for cars (LDV) and trucks (LDT). Fractions of new vehicles meeting the new standard during the phase-in are shown in Table 4-11. The table also shows simulated FTP composites during the phase-in. These projections were simply calculated as averages of the Tier 2 and Tier 3 baselines, with the phase-in fractions used as weights. Figure 4-29 shows how the simulated Tier 3 FTP composite rates compare against the base rates derived in Section 4.2.6.2, and to the rates used in MOVES2014.

Table 4-11 Phase-in Fractions and simulated FTP composites projected for the introduction of the Tier 3 exhaust particulate-matter standard

Model year	Fraction meeting Tier 3 standard	Simulated FTP composite (mg/mi)	
		Cars (LDV)	Trucks (LDT)
2016	0.0	1.56	2.03
2017	0.10	1.78	2.28
2018	0.20	1.86	2.39
2019	0.40	1.84	2.30
2020	0.70	1.70	1.95
2021+	1.00	1.50	1.50

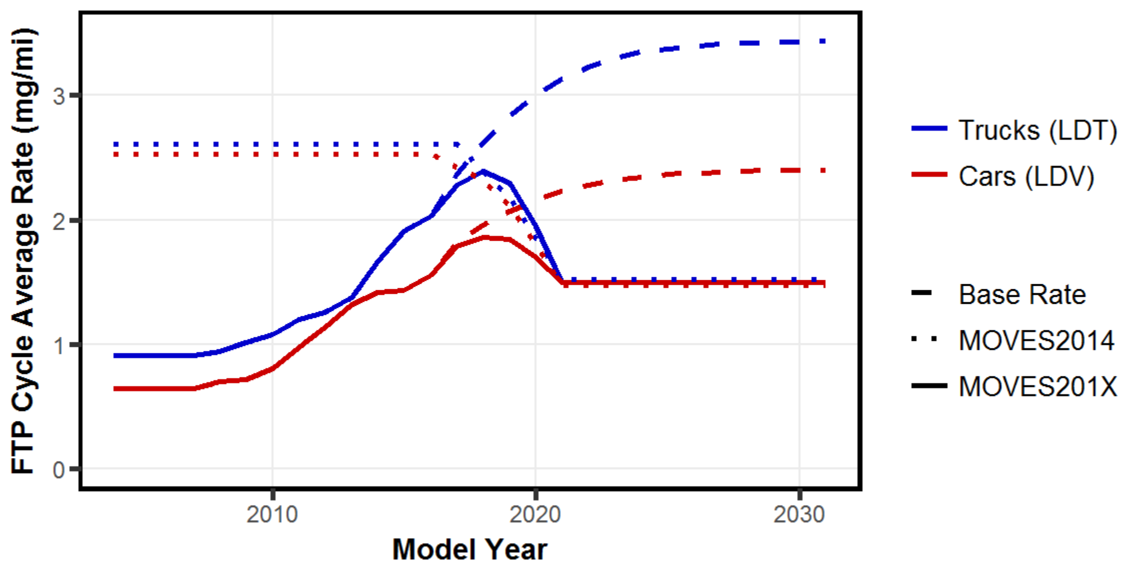

Figure 4-29 Simulated FTP composite rates for Tier 2 base line and Tier 3 phase-in. Base Rate represents age zero emissions prior to adjustment for phase-in of Tier 3 standards (MOVES201X refers to MOVES3).

4.2.7.2 Apply Scaling Fractions

The second step was to apply the fractions to the emission rates for running and start emissions in the EC and nonECPM pollutant processes (11201, 11202, 11801, 11802). The fractions were applied uniformly to rates in all operating modes, for both cars and trucks.

Figure 4-30 shows an example of scaling, for a subset of non-elemental-carbon (nonECPM, 11801) rates for three model years, 2016, 2019 and 2021. Model year 2016 represents Tier 2 standards prior to the onset of the phase-in, 2021 shows fully phased-in Tier 3 standards, and 2019 shows an intermediate year during the phase-in period. In (a), the rates are shown on a linear scale to show the steepness and non-linearity of the trends against power, whereas in (b), rates are shown on a logarithmic scale to make clear that the multiplicative scaling is uniform across the power range. Although not pictured, note that rates for elemental-carbon (ECPM, 11201) show an identical scaling pattern. Note also, that for convenience, emissions in the plot are presented in mg/hr, whereas rates in the emissionRateByAge table are provided in g/hr.

The uniformity of the multiplicative scaling is also clear if the rates for a single model year are viewed against age for a set of operating modes, as shown in Figure 4-31. The plot shows rates for six modes of running operation, including idle (mode 1), with the remaining five modes spanning a range from low to moderate power. As previously described in 4.1.2.3, the deterioration trends are exponential (or log-linear).

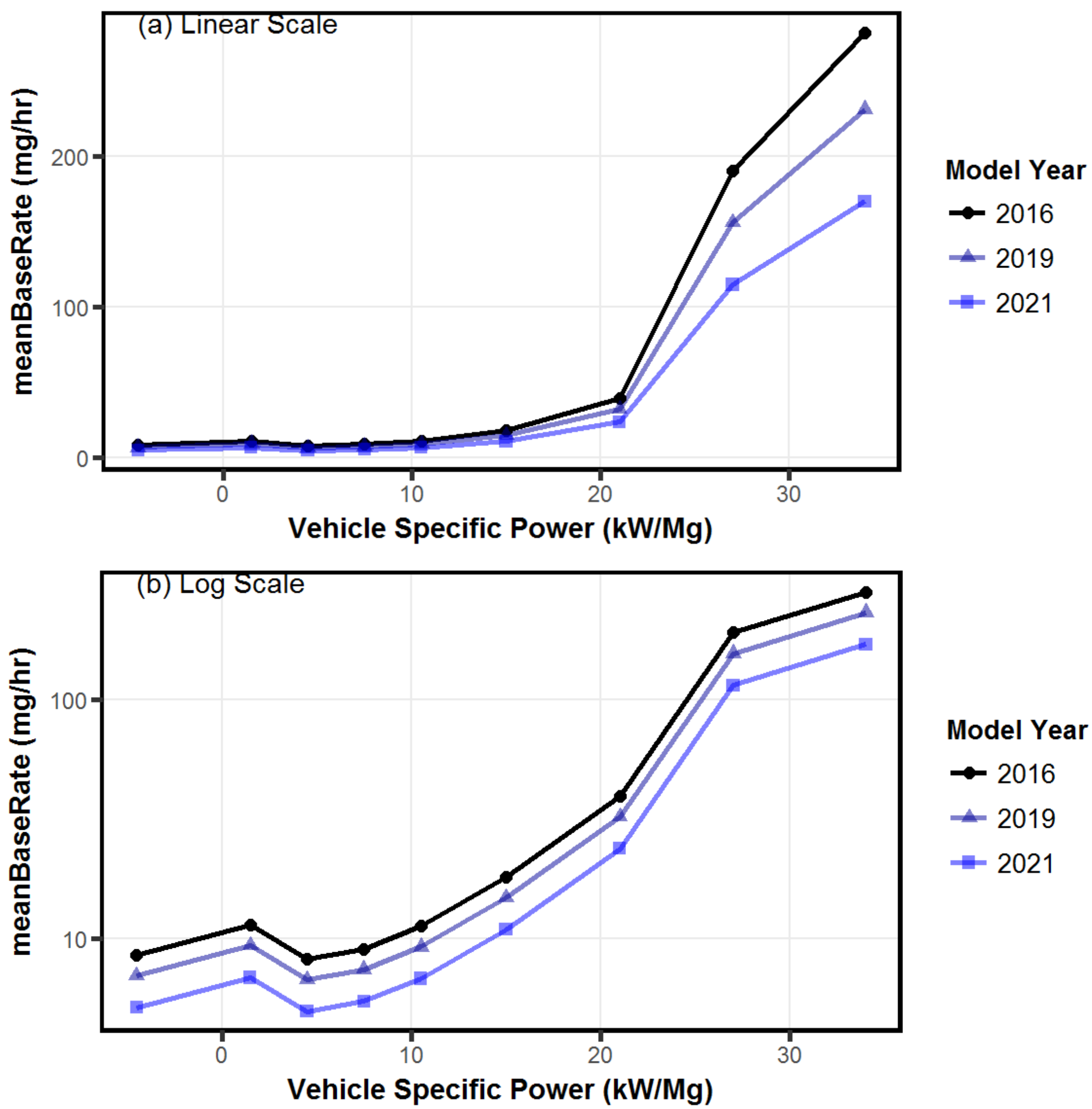

Figure 4-30 Non-elemental-carbon (nonECPM) running rates for cars vs. vehicle-specific power for three model years on (a) linear, and (b) logarithmic scales (NOTE: rates are presented for operating Modes 21-30, with each mode represented by VSP at its respective midpoint)

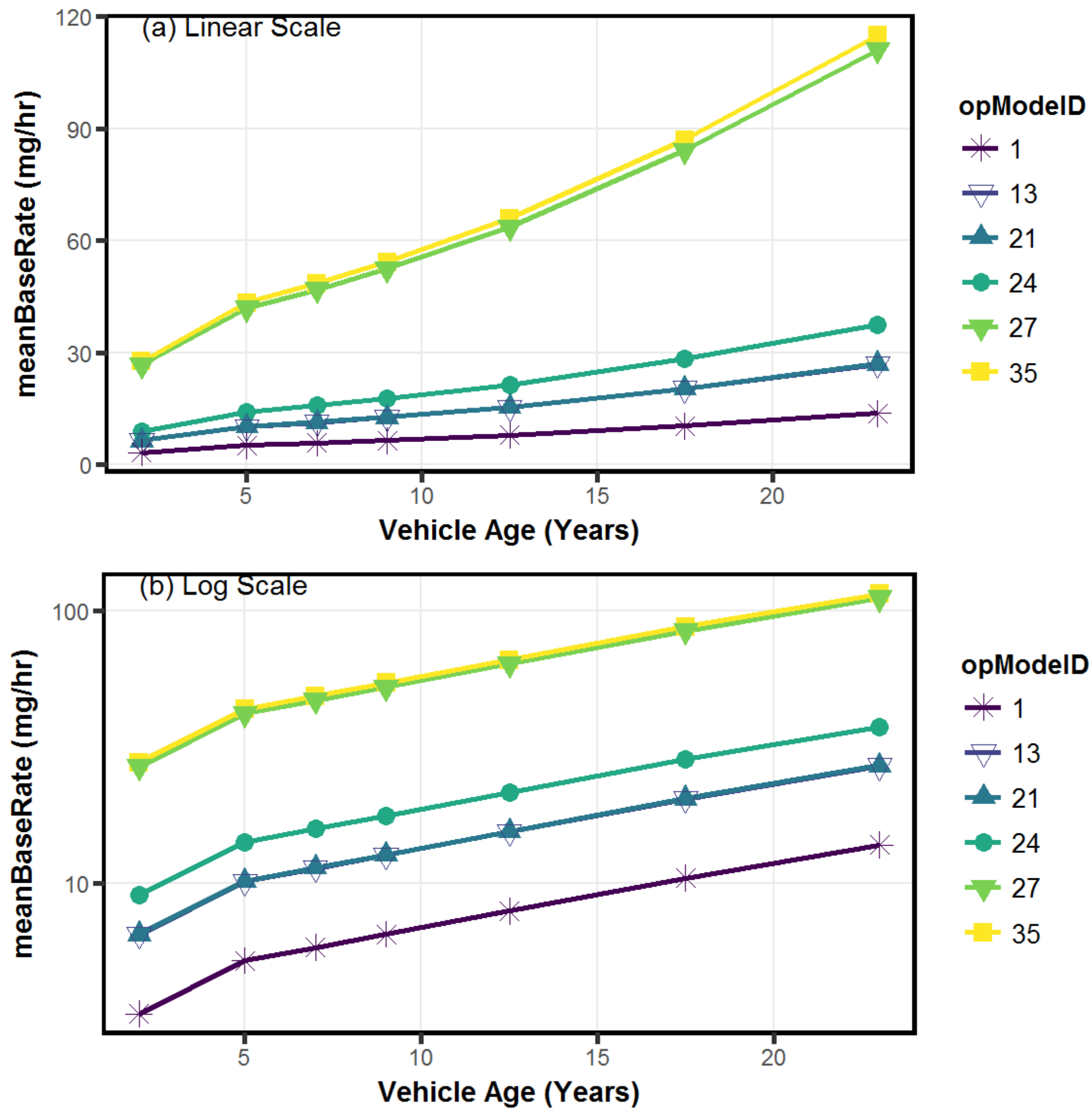

Figure 4-31 Non-elemental-carbon rates for trucks vs. Age for selected running operating modes in model year 2016, presented on (a) linear and (b) logarithmic scales

4.2.7.3 Simulate the Extended Useful Life

The third and final step was to reduce deterioration for vehicles under Tier 3, relative to those for Tier 2. The deterioration trends were scaled down such that the fleet is 1.25 times as old when a given emissions level is reached under the extended useful life as under the original useful life. The value of the fraction, 1.25, was calculated as 150,000 mi/120,000 mi, or 15/12.

The reduction in the deterioration trend is illustrated in Figure 4-32, which shows age trends for cold-start non-elemental-carbon before and during the phase-in period. The upper pane (a) shows the moderation of the exponential trend, whereas the lower pane (b) shows the reduction in the logarithmic slope starting in model year 2017. As before, these rates are presented in mg/start, as opposed to g/start in the database table. Note again that a similar chart for elemental carbon would show an identical pattern.

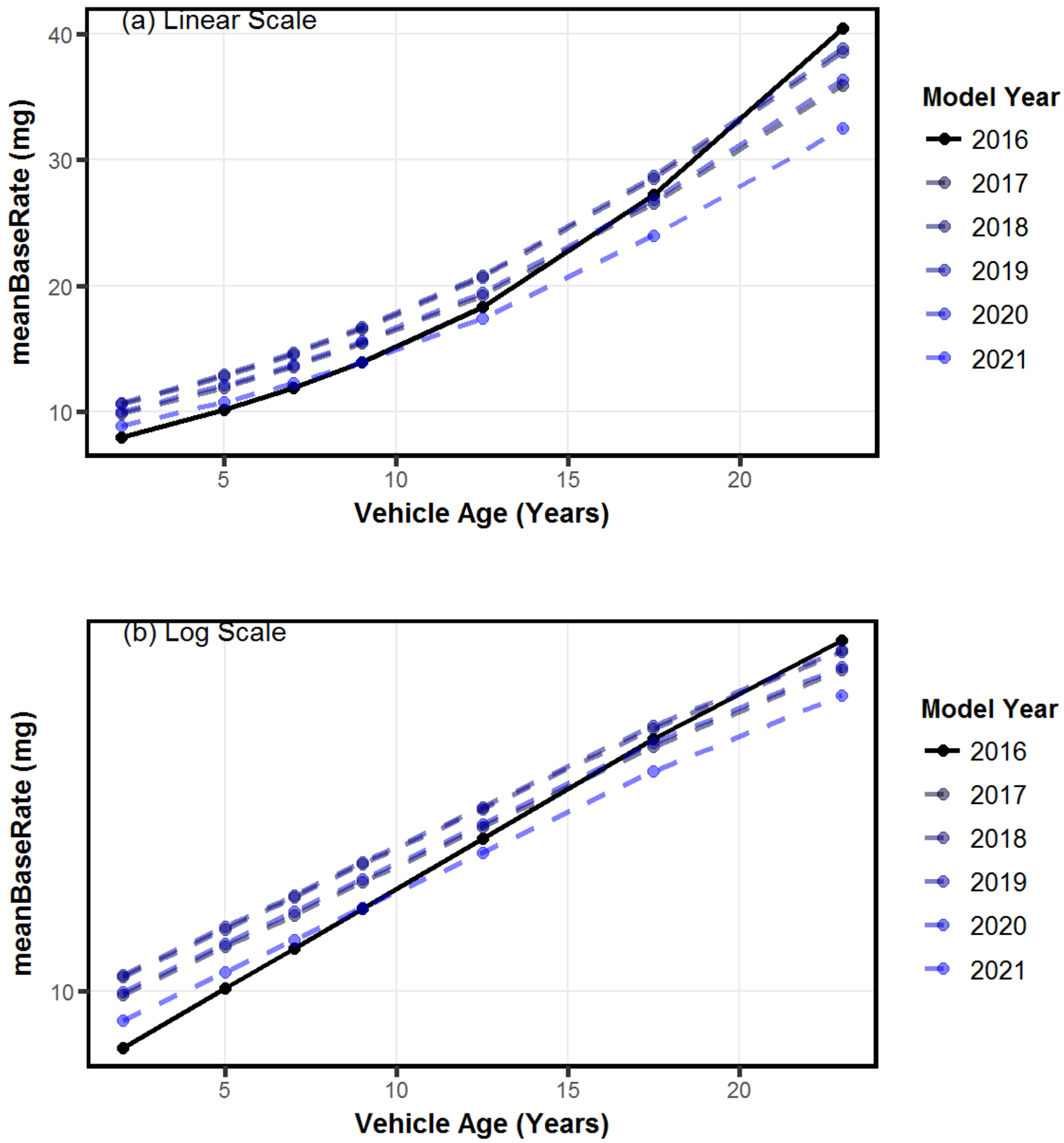

Figure 4-32 Elemental-carbon rates for cars vs. Age for cold-start emissions in six model years, presented on (a) linear, and (b) logarithmic scales

4.2.8 Incorporating the LEV-III Standard for Particulate Matter

The Tier 3 and LEV-III standards are harmonized with respect to the light-duty standard for particulate matter through MY 2024, at which point, a 3.0 mg/mi FTP standard will be fully phased in. However, after MY 2025, the LEV-III program goes further, enacting a further phased-in reduction to a 1.0 mg/mi FTP standard. This reduction is incorporated into the emissionRateByAgeLEV table applicable to California and Section 177 states.

The assumptions used to express the transition from rates at the 3.0 mg/mi level to the 1.0 mg/mi level are shown in Table 4-12. We assume a linear phase-in over the three years. The calculations assume a 50 percent compliance margin with respect to the 3.0 mg/mi standard in MY 2024, transitioning to a 25 percent compliance margin in MY 2028.

These assumptions were modeled in MOVES by applying the reduction fractions shown in the right-most column in Table 4-12 to default MOVES rates for the LEV-III phase-in model years. These fractions were applied uniformly to start and running emissions of EC and nonECPM, for cars and trucks, across all operating modes.

The emissionRateByAgeLEV table including these rates is incorporated into the default MOVES database. Instructions for use of the applicable portions of this table in a MOVES run are available at https://www.epa.gov/moves/tools-develop-or-convert-moves-inputs. Section 3.12 details how the emission rates representing California standards were developed for criteria pollutants.

Table 4-12 Phase-in assumptions and reduction fractions used to represent a transition to the 1.0 mg/mi PM standard under LEV-III

Model year	Phase-in fraction		FTP composite (mg/mi)	Reduction fraction[1]
	At 3.0 mg/mi	At 1.0 mg/mi		
2024	1.00	0.00	1.50	1.000
2025	0.75	0.25	1.31	0.873
2026	0.50	0.50	1.13	0.753
2027	0.25	0.75	0.94	0.627
2028+	0.00	1.00	0.75	0.500

[1] Applied to default rates in listed model years.

4.3 Comparing Light-Duty PM Emission Rates Between Pre-2004 and 2004-and-later model years

As demonstrated in Figure 4-21 and Figure 4-23, the MOVES PM emission rates developed from the MY 2004 and later PFI vehicles are significantly lower than those developed for MY 2003 PFI vehicles from the studies and analysis discussed in Section 4.1. There are several differences in the vehicle samples, measurement methods, and data analysis methods that are likely contributing to the difference in PM emission rates as described below:

- **Vehicle samples:** The most recent studies (KCVES, MSAT, and Li *et al.*, 2006[67]) included in the pre-2004 emission rates included MY vehicles between 2002-2005. The studies used in the MY 2004 and later emission rate update included later model year vehicles between (2007 and 2014). The decrease in PM emissions could be partially attributed to lower PM emission rates from the newer technology vehicles.

- **Measurement methods**: Particulate matter emissions measurements were not conducted with consistent methods across the studies. Uncorrected sampling artifacts could be the cause of the large differences between the pre-2004 and the 2004+ PM emission rates. As documented in Appendix A of this report, we corrected for a sampling issue in the KCVES that would have caused the PM emission rates to be significantly overestimated. Additionally, several years had passed from the last study used in to derive the pre-2004 rates (2006) and the earlier study conducted for the MY 2004+ rates (2013). In this time there were significant improvements in particulate sampling methods, including filter handling and filter weighing techniques. These differences in particulate matter sampling methods could be the cause for much of the differences observed between the pre-2004 and the 2004+ model year rates.
- **Data analysis methods**: Different data analysis methods were used to estimate the zero-mile emission rates for the two model year ranges. For example, we fit an exponential curve to age 0-3 vehicles from 15 different studies (including both FTP and LA-92 cycles) by model year to estimate the pre-2004 zero-mile emission rates. For the MY 2004+ rate update, we assumed that the measured vehicles did not include deterioration and simply averaged all the measured data according to sample size to represent the zero-mile emission rates. In addition, we accounted for differences in the MOVES operating modes between the LA-92 and FTP cycle for the recent update. These different data analysis methods could contribute to the observed differences.

In general, we have higher confidence in the more recent PM emission rates because they are based on more recent studies and updated sampling procedures. Additionally, the data analysis methods for the most recent rates are more straightforward than the analysis conducted for the pre-2004 MY rates. Despite our higher confidence in the more recent PM rates, we have decided to leave the pre-2004 MY PM rates unchanged in MOVES3 for at least these three reasons:

- Some of the differences in the pre-2004 and 2004+ emission rates may be due to the actual differences in engine and aftertreatment differences in MY vehicles
- In a calendar year 2018 MOVES run using a draft version of MOVES, the pre-2004 model year vehicles contribute just over 50% of $PM_{2.5}$ emissions[j] from all light-duty vehicles (regulatory class LDV and LDT). In current and future years, the contribution of these older model year vehicles to the overall inventory will decrease, and no longer be the majority of emissions from light-duty vehicles.
- Revisiting the pre-2004 model years emission rates would be a substantial effort. As documented in this report, the pre-2004 were based on an analysis of many different studies which measured PM emissions. The analysis of these different studies provided data to estimate light-duty deterioration, which continues to serve the basis of the modal VSP-trends, EC/PM ratios for PFI vehicles, and the deterioration of light-duty PM deterioration for all model year vehicles. Additional scientific evidence is likely needed

[j] From a draft MOVES run conducted at national aggregation, using January and July to represent the entire year, pre-2004 model years contributed 51.5% of PM2.5 exhaust emissions from regulatory class LDV and LDT vehicles.

for us to revisiting the emission rates of these older model year vehicles, which continue to be used as a basis for the emission rates for the 2004+ model year emission rates.

5 Gaseous and Particulate Emissions from Light-Duty Diesel and Electric Vehicles (THC, CO, NO_x, PM)

This section explains the gaseous and particulate emissions from light-duty diesel vehicles and provides some important notes on how MOVES models light-duty electric and hybrid vehicles.

Table 5-1 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 (E77, E85, etc.)
Engine Technology	engTechID	01	Conventional internal combustion (CIC)
		30	Electric

5.1 Light Duty Diesel

In MOVES, emission rates 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 for running emissions in relation to vehicle-specific power.

Upon additional review, we concluded that the diesel rates developed for draft MOVES and retained in MOVES2010 were not plausible in relation to corresponding rates for gasoline vehicles. We concluded that these rates were not adequate to retain in MOVES2014. However, we also did not consider it a tenable option to release MOVES2014 without rates representing diesel vehicles.

Consequently, we decided to allow rates for light-duty gasoline vehicles to represent those for light-duty diesel vehicles. While not an exact parallel and not desirable from a technical standpoint, we considered it an acceptable solution, as vehicles running on both fuels would be certified to similar standards. Also, as there are very few light-duty diesel vehicles in the U.S. fleet, their contribution to the inventory is very small.

However, in contrast to the gasoline rates, we did not incorporate a difference in the base rates attributable to Inspection and Maintenance. That is to say, values for meanBaseRate (non-I/M condition) were substituted for both the meanBaseRate and meanBaseRateIM. Note, however, that for rates representing diesel emissions, the model does not apply the fuel adjustments applied to gasoline emissions.[79]

For MOVES3, we used the same approach as in MOVES2014, taking the light-duty gasoline values for meanBaseRate and using them to populate both the meanBaseRate and meanBaseRateIM values for light-duty diesel.

The level of detail for the rate substitution is shown in Table 5-2.

Table 5-2 Level of detail for substitution of light-duty gasoline Rates onto light-duty diesel rates

Parameter	Description	Identifier
Pollutant	THC CO NO_x EC-PM NonECPM	1 2 3 112 118
Process	Running Exhaust Start Exhaust	1 2
Regulatory Class	Passenger Car (LDV) Light Truck (LDT)	20 30
Model-year Group	All	1960-2031
Data Source	Replicated from corresponding Rates for light-duty gasoline	4910

5.2 Light Duty Electric Vehicles

MOVES can also model electric vehicles. While electric vehicles are associated with upstream and life-cycle emissions not modelled by MOVES, and with energy consumption[1] and brake and tire wear emissions[82] as described in other MOVES reports, they do not generate direct exhaust emissions of HC, CO, NO_x or PM, and thus these emissions are modelled as zero in MOVES.

Note, EPA is aware that manufacturers can include electric vehicles and hybrid electric vehicles in their computation of average emissions for compliance with Tier 3 standards. Thus, if a manufacturer sells a large number of zero or low-emitting vehicles, the manufacturer would be allowed to increase the average emissions of other vehicles.

In the case of hybrid vehicles, MOVES accounts for this by not modelling hybrids explicitly--instead, their emissions are combined with all other fleet average vehicles.

MOVES takes a different approach for electric vehicles. While the MOVES3 default fleet includes no electric vehicles,[83] MOVES3 allows users to input an appropriate fraction of electric vehicles. However, we must caution that MOVES does not account for potential associated increases in emissions from conventional light-duty vehicles. If the future fraction of electric vehicles is large, and manufacturers take advantage of the flexibility allowed by the Tier 3 regulations, this could lead to underestimation of light-duty NMOG and NO_x emissions from conventional (i.e. gasoline, diesel and E85) vehicles.

6 Crankcase Emissions

6.1 Background

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, since model year 1969.

6.2 Modeling Crankcase Emissions in MOVES

Crankcase emissions are calculated by chaining a crankcase emissions ratio to the calculators for start, running, and extended-idle processes. 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 elemental-carbon and non-elemental-carbon particulate fractions of $PM_{2.5}$. For each of these pollutants, ratios are stored in the CrankcaseEmissionRatio table.

For vehicles with working PCV valves, we assume that emissions are zero. Based on EPA tampering surveys, MOVES assumes a failure rate of 4 percent for PCV valves.[84] 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 percent of the emission fractions assumed for uncontrolled emissions. While this 4 percent 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.

6.3 Light-duty Gasoline Crankcase Emissions

Very little information is available on crankcase emissions, especially those for gasoline vehicles. A literature review was conducted to identify available data sources for emission fractions for gasoline vehicles (Table 6-1).

Table 6-1 Selected Sources of published data on hydrocarbon crankcase emissions from gasoline vehicles

Authors	Year	Fuel	No. Vehicles	Estimate	Units
Heinen and Bennett[85]	1960	Gasoline	5	33	% of exhaust
Bowditch[86]	1968	Gasoline		70	% of exhaust
US EPA[87]	1985	Gasoline	9	*1.21-1.92*	g/mi

Based on these sources, we estimated emission fractions for model years without mandated PCV valves. 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 are largely heavy duty, and that most gasoline vehicles are light-duty, there is a potential mismatch between the data sources, which is unavoidable due to the paucity of data. As noted previously, model years with PCV valves were assigned emission fractions calculated as 4 percent of the fractions shown in Table 6-2.

Table 6-2 Emission fractions for vehicles without PCV systems (percent of exhaust emissions)

Pollutant	Gasoline (uncontrolled, pre-1969)	Gasoline (1969 and later)
THC	0.33	0.013
CO	0.013	0.00052
NO_x	0.001	0.00004
PM (all species)	0.20	0.008

The crankcase emission fractions for THC, CO and NO_x may underestimate emissions. These percentages of exhaust emissions are generally based on engine- out, uncontrolled exhaust, which is not estimated 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.

6.4 Light-duty Diesel Crankcase Emissions

After 2001, all light-duty vehicles, including diesels, are required to avoid venting crankcase emissions into the atmosphere.[88] This requirement differs from turbocharged and supercharged heavy-duty diesel engines, which are allowed to vent crankcase emissions, as long as the crankcase emissions are included in the certification tests. As such, we modeled crankcase emissions from light-duty diesel emissions with two model-year groups, pre-2001, and post-2001. The values used for the pre-2001 are the same as the pre-2007 heavy-duty diesel fractions. For 2001 and later, we multiply the pre-2007 by 4 percent (our assumed PCV failure rate). These crankcase emission ratios are located in Table 6-3.

Table 6-3 Light-duty diesel crankcase emission fractions (percent of exhaust emissions)

Pollutant	Light-duty diesel 1960-2000)	Light-duty diesel (2001-2060)
THC	0.037	0.00148
CO	0.013	0.00052
NO_x	0.001	0.00004
$PM_{2.5}$ (all species)	0.2	0.008

7 Nitrogen Oxide Composition

Nitrogen oxides (NO_x) are defined as NO + NO_2. In MOVES, NO_x includes NO, NO_2, and a small amount of HONO. The rationale for including HONO in NO_x emissions is discussed in the heavy-duty report.[89] Currently, the HONO/NO_x ratio is estimated as 0.8 percent of NO_x emissions based a study that measured concentrations of NO_x and HONO from a highway tunnel in Europe.[90] The NO/NO_x and NO_2/NO_x fractions were developed from a report by Sierra Research.[8]

7.1 Light-Duty Gasoline Vehicles

The NO_x and HONO fractions for light-duty gasoline vehicles are presented in Table 7-1 The HONO fraction of NO_x, was subtracted from the original NO_2 fraction, because the HONO likely interferes with the estimated NO_2 fraction when measured with a chemiluminescent analyzer, as discussed in the heavy-duty report.

Table 7-1 NO_x and HONO fractions for light-duty gasoline vehicles

Model Year	Running			Start		
	NO	NO_2	HONO	NO	NO_2	HONO
1960-1980	0.975	0.017	0.008	0.975	0.017	0.008
1981-1990	0.932	0.06	0.008	0.961	0.031	0.008
1991-1995	0.954	0.038	0.008	0.987	0.005	0.008
1996-2050	0.836	0.156	0.008	0.951	0.041	0.008

7.2 Motorcycles

The NO/NO_2 fractions for motorcycles were also developed by Sierra Research.[8] The values are based on measurements on light-duty gasoline vehicles, but apply to different model year groups, to correspond to similar exhaust emission control technologies. The NO_2 fractions reported by Sierra Research were adjusted to account for the HONO measurements. Development of the NO_x, CO, THC, and PM, emission rates for motorcycles, is documented in the same report.[8]

Table 7-2 NO_x and HONO fractions for motorcycles

Model Year	Running			Start		
	NO	NO_2	HONO	NO	NO_2	HONO
1960-1980	0.975	0.017	0.008	0.975	0.017	0.008
1981-2000	0.932	0.06	0.008	0.961	0.031	0.008
2001-2005	0.939	0.053	0.008	0.97	0.022	0.008
2006-2009	0.947	0.045	0.008	0.978	0.014	0.008
2010-2060	0.954	0.038	0.008	0.987	0.005	0.008

7.3 Light-duty Diesel Vehicles

The NO_x and HONO fractions for light-duty diesel vehicles are the same as those for heavy-duty diesel. Discussion of the heavy-duty diesel fractions is presented in the corresponding report.[89] These values are presented in Table 7-3 for completeness.

Table 7-3 NO_x and HONO fractions for Light-duty Vehicles

Model Year	NO	NO_2	HONO
1960-2006	0.935	0.057	0.008
2007-2009	0.764	0.228	0.008
2010-2060	0.594	0.398	0.008

8 Appendix A. Revisions to the Pre-2004 Model Year $PM_{2.5}$ Emission Rates between MOVES2010b and MOVES2014

The $PM_{2.5}$ exhaust emission rates for pre-2004 model year light-duty vehicles are unchanged between MOVES2014 and the current version, MOVES3. As noted in Section 4.1.3, we corrected the $PM_{2.5}$ light-duty gasoline emission rates between MOVES2014 and MOVES2010 to account for the silicon contamination measured in the Kansas City study, using our best available estimates. The $PM_{2.5}$ emission rates in MOVES2010 were based on a meta-analysis of multiple studies and programs. The Kansas City study was used to estimate deterioration from the estimated zero-mileage emission rates, to estimate the modal $PM_{2.5}$ emission rates, and the $PM_{2.5}$ temperature dependency. In MOVES2014 we reduced the running $PM_{2.5}$ emission rates across all age groups and operating modes by the values shown in Table 8-1.

Table 8-1 contains the estimated contribution of silicon to the start (bag 1-bag 3) and the running (bag 2) $PM_{2.5}$ emissions measured in Kansas City. The silicone rubber contains silicon, oxygen, carbon, and hydrogen which contribute to the measured particulate and organic carbon mass. We estimated the contribution of the silicon to the $PM_{2.5}$ emission rates by using the elemental silicon emission rates from the set of 102 tests analyzed for elements. Additionally, we estimated that the silicone rubber contributed particulate mass equal to 4.075 times the measured silicon emission rates, as documented in the speciation profile analysis by Sonntag et al. (2013).[71] We applied these estimates to average silicon emission rates measured for each model year group, and for trucks and cars. The trucks have a higher silicon contribution which is expected due to higher exhaust temperatures and larger exhaust tailpipes which expose more silicone rubber to the hot exhaust. The updated emission rates reflect both the reduction in total PM from the silicon in Table 8-1 and the revised EC/PM ratios in Table 4-4.

Table 8-1 Reductions to $PM_{2.5}$ in MOVES2014 compared to MOVES2010b due to silicon contamination

Stratum	Vehicle type	Model group	Start	Running
1	Truck	pre-1981	0%	35.3%
2		1981-1990	0%	25.3%
3		1991-1995	0%	34.5%
4		1996-2005	0%	19.1%
5	Car	pre-1981	0%	14.6%
6		1981-1990	0%	3.5%
7		1991-1995	0%	6.1%
8		1996-2005	0%	8.5%

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