Evaluation of MOBILE Models: MOBILE6.1 (PM), MOBILE6.2 (Toxics), and MOBILE6/CNG

Requested by:

American Association of State Highway
and Transportation Officials (AASHTO)

Standing Committee on the Environment

Prepared by:

Philip L. Heirigs
Siona S. Delaney
Robert G. Dulla

Sierra Research, Inc.
1801 J Street
Sacramento, CA 95814

May, 2004

The information contained in this report was prepared as part of NCHRP Project 25-25, Task 7, National Cooperative Highway Research Program, Transportation Research Board.

Acknowledgements

This study was requested by the American Association of State Highway and Transportation Officials (AASHTO), and conducted as part of the National Cooperative Highway Research Program (NCHRP) Project 25-25 . The NCHRP is supported by annual voluntary contributions from the state Departments of Transportation. Project 25-25 is intended to fund quick response studies on behalf of the AASHTO Standing Committee on the Environment. The report was prepared by Philip L. Heirigs, Siona S. Delaney, and Robert G. Dulla of Sierra Research, Inc. The work was guided by a task group chaired by Brent Jensen which included Kevin Black, William Jordan, Behshad Norowzi, Howard Simons, and John Zamurs. The project was managed by Christopher Hedges, NCHRP Senior Program Officer.

FINAL REPORT

Evaluation of MOBILE Models:
MOBILE6.1 (PM), MOBILE6.2 (Toxics), and MOBILE6/CNG

Table of Contents

Page #

List of Tables

List of Figures

List of Figures (continued)

Page #

List of Figures (continued)

Page #

List of Abbreviations and Acronyms

AMFA - The Alternative Motor Fuels Act of 1988

AWMA - Air and Waste Management Association

CAFE - corporate average fuel economy

CARB - California Air Resources Board

CAWRSS - Clark and Washoe County Remote Sensing Study

CBD - Central Business District test cycle

CE-CERT - U.C. Riverside's College of Engineering - Center for Environmental Research and Technology

CIFER - Colorado Institute for Fuels and High Altitude Engine Research

CNG - compressed natural gas

CO - carbon monoxide

CO_2 - carbon dioxide

CRC - Coordinating Research Council

DDC - Detroit Diesel Corporation

DOT - Department of Transportation

DPF - Diesel particulate filter

DR - deterioration rate (typical units = g/mi per 10,000 miles)

ECARBON - elemental carbon and residual carbon portion of Diesel exhaust PM

EGR - exhaust gas recirculation

EPA - U.S. Environmental Protection Agency

EPACT - Energy Policy Act of 1992

FTP - Federal Test Procedure

g/bhp-hr - grams per brake-horsepower-hour g/gal - grams per gallon

g/mi - grams per mile

GVWR - gross vehicle weight rating

HAP - hazardous air pollutant

HC - hydrocarbon

HDDV - heavy-duty Diesel vehicle

HDDV8B - heavy-duty Diesel vehicle over 60,000 lbs. gross vehicle weight rating

HDGV2B - heavy-duty gasoline vehicle between 8,501 and 10,000 lbs. gross vehicle weight rating

HFET - Highway Fuel Economy Test

HHDDT - heavy-heavy-duty Diesel truck

I/M - inspection and maintenance

LDDT - light-duty Diesel truck

LDDT12 - light-duty Diesel truck, weight category 1 and 2 (i.e., trucks with a GVWR up to 6,000 lbs)

LDDT34 - light-duty Diesel truck, weight category 3 and 4 (i.e., trucks with a GVWR from 6,001 to 8,500 lbs)

LDDV - light-duty Diesel vehicle

LDGT2 - light-duty gasoline trucks between 3,751 and 5,750 lbs. loaded vehicle weight

LDGV - light-duty gasoline vehicle

LEV - low-emission vehicle

MC - motorcycle

mg/mi - milligrams per mile

mpg or mi/gal - miles per gallon

MSAT - mobile source air toxic

MVRATS - Motor Vehicle-Related Air Toxics Study

NCHRP - National Cooperative Highway Research Program

NFRAQS - Northern Front Range Air Quality Study

NGV - natural gas vehicle

NH_3 - ammonia

NLEV - national low emission vehicle

NMHC - non-methane hydrocarbon

NMOG - non-methane organic gas

NOx - oxides of nitrogen

NREL - National Renewable Energy Laboratory

NYSDEC - New York State Department of Environmental Conservation

NYSERDA - New York State Energy Research and Development Authority

OAQPS - EPA's Office of Air Quality Planning and Standards

OBD - on-board diagnostics

OCARBON - organic carbon portion of Diesel exhaust PM

OEM - original equipment manufacturer

PFI - port fuel injection

PM - particulate matter

PM2.5 - particulate matter ≤ 2.5 µm in diameter

PM10 - particulate matter ≤ 10 µm in diameter

PM30 - particulate matter ≤ 30 µm in diameter

ppm - parts per million

PSC - particle size cutoff

RCP - remaining carbon portion

RFG - reformulated gasoline

RSD - remote sensing device

SAE - Society of Automotive Engineers

SFTP - Supplemental Federal Test Procedure

SIP - State Implementation Plan

SO_2 - sulfur dioxide

SO4 - sulfate particulate emissions

SOF - soluble organic fraction

TBI - throttle-body injection

TIUS - Truck Inventory and Use Survey

TNRCC - Texas Natural Resource Conservation Commission

TOG - total organic gas

TWC - three-way catalyst

UC - Unified Cycle

UDDS - Urban Dynamometer Driving Schedule

ULEV - ultra-low-emission vehicle

µm - micron (i.e., 10^{-6} meter)

VIUS - Vehicle Inventory and Use Survey

VMT - vehicle miles traveled

VOC - volatile organic carbon

vol% - volume percent

WVU - West Virginia University

ZML - zero-mile level (typical units = g/mi)

1. SUMMARY

In January 2002, the U.S. Environmental Protection Agency (EPA) released its latest on-road motor vehicle emissions model, MOBILE6. After years of development in which nearly every aspect of the emissions model was reviewed and revised, MOBILE6 has replaced its predecessor model, MOBILE5, as the official tool for developing State Implementation Plan (SIP) inventories and for making conformity determinations. The version of MOBILE6 released in January 2002 is often referred to as MOBILE6.0, and it is used to estimate gram per mile (g/mi) emission rates of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) from the in-use motor vehicle fleet. One of the features included in MOBILE6.0 is the ability to model the emissions impacts of vehicles powered by compressed natural gas (CNG).

In May 2002, EPA released another version of MOBILE6, commonly referred to as MOBILE6.1/6.2. MOBILE6.1 calculates particulate matter (PM) emission rates, while MOBILE6.2 calculates emission rates of air toxics. Although referred to by different names, the PM and toxics calculations, as well as the HC, CO, and NOx calculations, are consolidated into a single computer program. In the May 2002 release, the MOBILE6.1 and MOBILE6.2 versions of the model were in draft form and were subject to a five-month review period. On November 12, 2002, EPA released an updated version of MOBILE6 that included changes to respond to comments on the draft versions of MOBILE6.1 and MOBILE6.2. EPA simply called that version of the model MOBILE6.2 and indicated that MOBILE6.2 is the "recommended and approved version" of the model for estimating emissions of HC, CO, and NOx. The PM and air toxics components of the model were recently finalized in a February 2004 release of MOBILE6.2.

Under contract to the National Cooperative Highway Research Program (NCHRP), Sierra Research, Inc. (Sierra) and Parsons-Brinkerhoff (PB) evaluated several components of MOBILE6. Specifically, this included:

- An evaluation of emission factors related to PM;
- An evaluation of emission factors related to air toxics; and
- An assessment of emission factors when compressed natural gas (CNG) is specified as the fuel.

Since the November 2002 release of MOBILE6.2, the model has also included a draft algorithm for estimating emissions of carbon dioxide (CO_2), and EPA has invited comments on the procedures used to calculate CO_2 emissions. As a result, this study also reviewed the methodology used in MOBILE6 to estimate CO_2.

Particulate Matter Emissions Estimates

Historically, PM emission rates were not calculated by the MOBILE series of models. Instead, PM was calculated with a separate model, the latest one being PART5 which was released in 1995. However, with the release of MOBILE6.2, the data and algorithms from PART5 (with updates where applicable) have been integrated into MOBILE so that a separate model is no longer needed to generate PM estimates.

MOBILE6.2 calculates g/mi emission factors for exhaust PM, brake and tire wear PM, gaseous sulfur dioxide (SO_2), and ammonia (NH_3). Emission rates for particle sizes ranging from 1 to 10 microns (μm) can be calculated by the model. EPA's objective was to produce a combined model that reflected EPA's particulate emissions modeling performed for recent rulemakings.

Included among the revisions incorporated into the PM component of MOBILE6.2 are the following:

- ***Base Emission Rates*** - The base emission rates are mostly unchanged from PART5, except that 2007 and newer model year heavy-duty Diesel vehicles reflect the more stringent PM standards promulgated in 2000. In addition, PM emission rates for light-duty vehicles were made consistent with the Tier 2 rule, and PM emission rates for 2005 and newer heavy-duty gasoline vehicles were made consistent with the requirements spelled out in the 2000 rulemaking above.

- ***Sulfate PM and Gaseous SO2 Calculations*** - PART5 contained hard-coded national default values for gasoline and Diesel sulfur level. MOBILE6.2 now allows users to enter local data for fuel sulfur content.

- ***Ammonia Emission Factors*** - PART5 did not calculate ammonia emissions. This is an entirely new feature with MOBILE6.2.

- ***Zero Emission Vehicles*** - MOBILE6.2 accounts for zero emission vehicles by assuming zero exhaust PM, while tire and brake wear are assumed to be the same as for gasoline vehicles.

- ***Natural Gas Vehicles*** - MOBILE6.2 assumes that natural gas vehicle PM emission rates are the same as for their gasoline vehicle counterparts operating on low-sulfur fuel. Tire and brake wear are assumed to be the same as for gasoline vehicles.

A number of constituents previously modeled by PART5 are no longer calculated by MOBILE6.2. This includes: (1) indirect sulfate, which PART5 calculated by assuming a certain fraction of gaseous SO_2 was converted to particulate sulfate in the atmosphere; and (2) fugitive dust (i.e., re-entrained road dust). Indirect sulfate was removed because secondary particulate formation can be highly area-specific, and MOBILE6 is not an atmospheric model. The fugitive dust calculation was removed because PART5 did not properly account for unpaved roads (which can be a significant source of fugitive dust), and a new tool for calculating road dust has been developed by EPA's Office of Air Quality Planning and Standards (OAQPS).

Most of the data upon which the MOBILE6.2 PM estimates are based were collected in the late-1970s and early-1980s. Thus, although MOBILE6.2 incorporated significant new data into the HC, CO, and NOx algorithms, the PM estimates are based on data that are somewhat out-of-date.

Gasoline Vehicle Exhaust Emissions - Figure 1-1 shows PM10 (i.e., particles that are less than or equal to 10 micrometers [µm] in diameter) emissions as a function of model year calculated by MOBILE6.2 for light-duty gasoline vehicles (LDGVs). As observed in the figure, estimates are shown for model years 1970 through 2010, and separate estimates are presented for exhaust PM and brake/tire wear. The large drop in exhaust emissions seen in the 1975 model year is a result of the introduction of catalysts and the use of unleaded fuel, while the gradual decline in emissions throughout the 1980s is a result of reductions in particulate sulfate as fewer vehicles in the fleet are equipped with air injection. Emissions continue to decline between 2001 and 2006 as the Tier 2 gasoline sulfur limits are implemented, resulting in a decrease in particulate sulfate emissions. It is interesting to note that the model estimates that brake wear and tire wear emissions are greater than exhaust emissions beyond the 1981 model year.

Over the past several years, a number of test programs have been conducted to investigate PM emissions from light-duty gasoline vehicles. Unfortunately, the results from that testing have been inconsistent -- some programs have higher emissions than MOBILE6.2, while others have lower emissions than MOBILE6.2. Further, the degree to which the test programs differ from MOBILE6.2 and one another is largely dependent upon the fraction of visibly smoking vehicles in the test fleet. As a result, EPA decided not to update emission factors for MOBILE6.2 and instead wait for the results of a comprehensive test program that is to be conducted in Kansas City during 2004.

Nonetheless, it is interesting to compare MOBILE6.2 exhaust PM10 results to newer data. This is done in Figure 1-2, which shows the results of several studies sponsored by the Coordinating Research Council (CRC) and a study conducted by U.C. Riverside's College of Engineering - Center for Environmental Research and Technology (CE-CERT) versus estimates prepared with MOBILE6.2 for calendar year 1997 (the approximate timeframe when the in-use data were collected). As seen in that figure, MOBILE6 appears to overestimate exhaust PM emissions from newer vehicles, as results from all recent programs fall below the MOBILE6 estimates. However, for pre-1990 model years, the MOBILE6 predictions fall within the range of values reported in the recent test programs. However, the results from CRC E-24-1 are based on testing performed at high altitude, and it is unclear how much this may impact PM emissions from gasoline-fueled vehicles.

It's worth noting that MOBILE6 appears to underestimate exhaust PM emissions under wintertime conditions. Part of the reason for that is because MOBILE6 does not apply any type of temperature correction to PM estimates. However, recent data suggest that exhaust PM emissions increase with decreasing temperature, particularly during cold start

Figure 1-1

MOBILE6 PM10 Emissions vs. Model Year for LDGVs

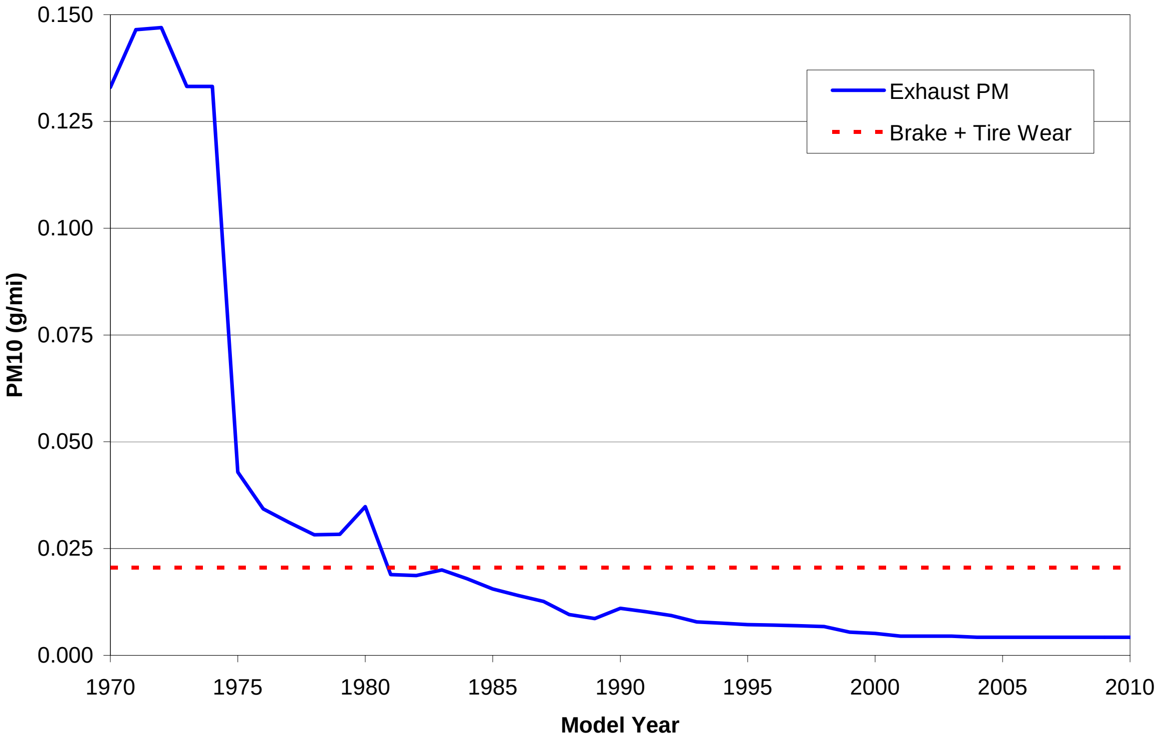
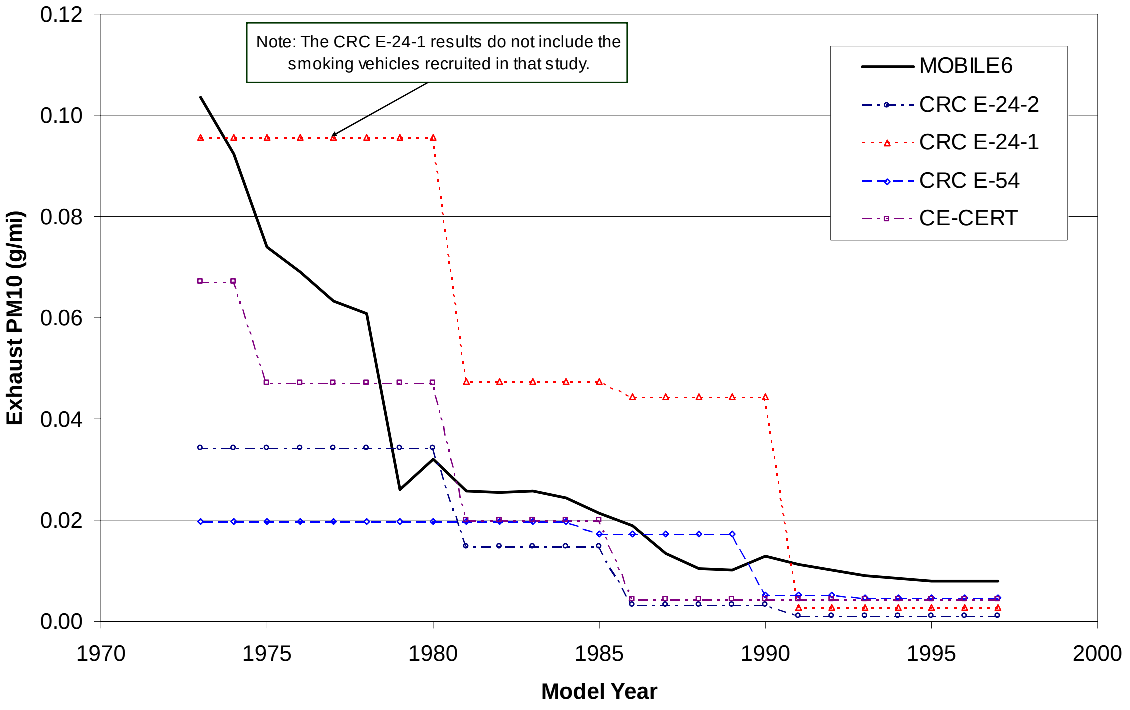


Figure 1-2

Comparison of MOBILE6 LDGV/T Exhaust PM10 Emissions to Results of Recent Test Programs

Calendar Year 1997 Summertime Basis



conditions. Recent data also suggest that oxygenated fuels help reduce PM emissions from light-duty gasoline vehicles. That is also not accounted for in the MOBILE6 model.

<u>Diesel Vehicle Exhaust Emissions</u> - Figure 1-3 shows the MOBILE6 PM10 emission rates versus model year for Class 8b heavy-duty Diesel vehicles (HDDVs), which would include 18-wheel tractor-trailer rigs. Prior to the 1988 model year, exhaust PM10 emissions averaged approximately 2.2 g/mi, which is about 100 times greater than exhaust PM from a catalyst-equipped gasoline light-duty vehicle. After 1987, however, exhaust PM is estimated to decrease substantially as a result of PM standards implemented by EPA and the California Air Resources Board (CARB). In addition, Diesel sulfur controls were implemented federally in 1993, which resulted in a decrease in sulfate particulate. PM emissions from 1995 to 2006 model year vehicles are about 90% lower than pre-control levels, and the 2007 standards will result in another 90% reduction from 2006 levels.

With the implementation of the 2007 standards, MOBILE6 estimates that exhaust PM from HDDV8B vehicles will be lower than brake wear and tire wear emissions. As discussed in more detail below, however, the brake wear estimates in MOBILE6 for all vehicle classes are based on <u>passenger car testing</u> and do not account for the increased mass carried by Class 8B HDDVs. Assuming a loaded vehicle weight of 80,000 lbs and an unloaded weight of 30,000 lbs, the average vehicle weight would be 55,000 lbs, or 10 times that of a passenger car or light-duty truck. Thus, the brake wear emissions for HDDV8B trucks could be low by as much as an order of magnitude, at least in urban driving. If that is in fact the case, brake and tire wear emissions would be 0.16 g/mi, which is only about 25% lower than exhaust PM emissions for the 1995 through 2006 model year vehicles.

In 2000, CARB updated the heavy-duty Diesel vehicle exhaust PM estimates in its on-road motor vehicle emissions model, EMFAC2000. As part of that update, CARB staff compiled emissions data from several test programs in which heavy-duty vehicles had been tested on a chassis dynamometer. These data are attractive for use in emissions modeling because they have been collected on the same driving schedule (within weight categories) and they have been extensively peer-reviewed. In addition, because they were collected on a chassis dynamometer, there is no need to apply conversion factors to obtain g/mi results.

The data compiled by CARB for EMFAC2000 were analyzed by Sierra to generate mean PM emissions estimates as a function of model year group. Figure 1-4 compares those results to MOBILE6 output for heavy-heavy-duty Diesel vehicles (MOBILE6 Class 8B HDDVs). That figure indicates that MOBILE6 may be underestimating PM10 emissions from this vehicle class. However, both MOBILE6 and the available emissions data track changes in certification standards.

<u>Tire and Brake Wear Emissions</u> - In addition to exhaust PM emissions, MOBILE6 calculates PM emissions from tire wear and from brake wear. The data upon which the MOBILE6 estimates are based are very dated; however, there have been few recent studies of tire wear emission rates. Although research related to brake wear has been

Figure 1-3

MOBILE6 PM10 Emissions vs. Model Year for Class 8B HDDVs

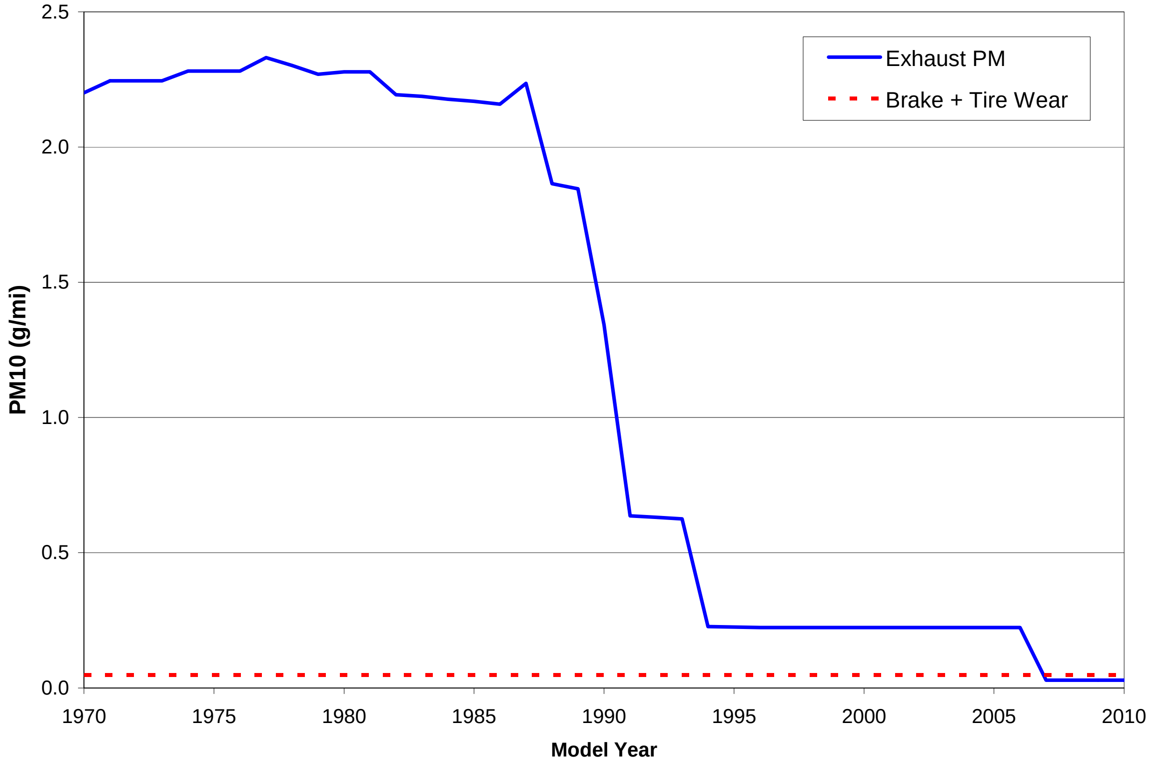
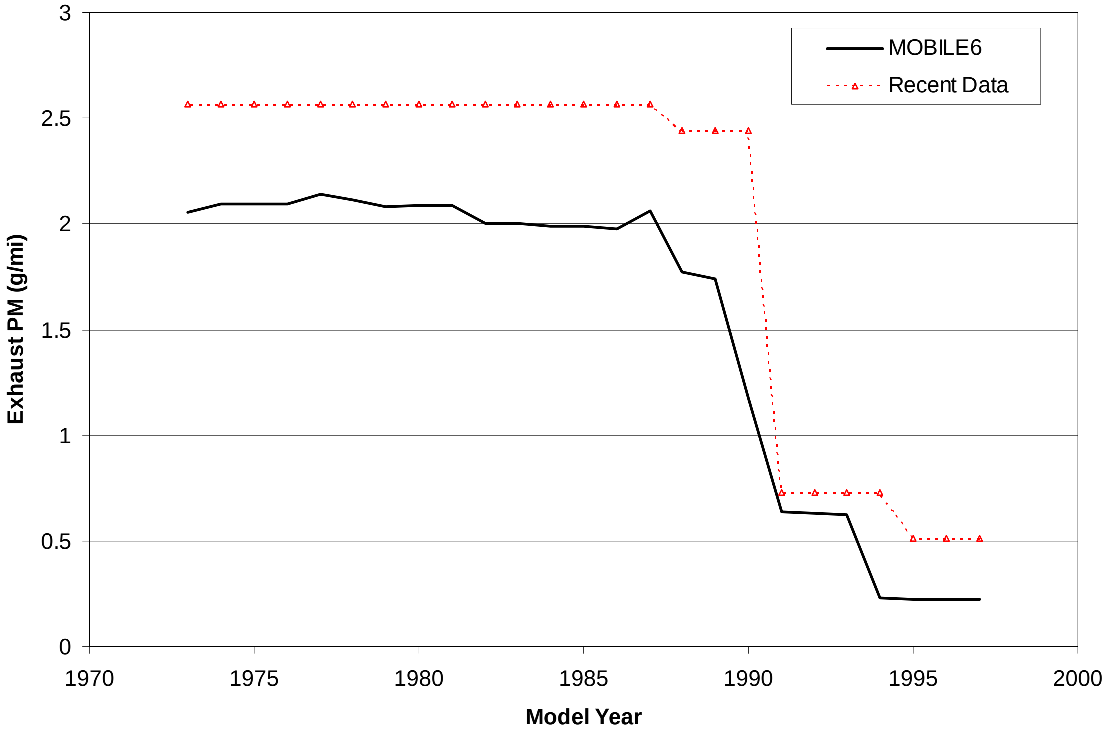


Figure 1-4

Comparison of MOBILE6 HDDV8B Exhaust PM Emissions to Results of Recent Test Programs



more common in the past several years, the results are not dramatically different than MOBILE6 estimates for passenger cars.

As noted above, a significant shortcoming in the MOBILE6 brake wear estimates is that the same g/mi value, which was developed from passenger car data, is applied to all vehicle classes. This likely results in a substantial underestimate of brake wear emissions for the heavier vehicle classes, as brake wear should be proportional to the energy required to stop the vehicle (which is a function of vehicle speed and weight).

Gaseous SO_2 and Ammonia Estimates - Gaseous SO_2 emissions are calculated in MOBILE6.2 using the same methodology as in PART5. This is a very straightforward procedure in which the sulfur in the fuel is assumed to be exhausted as either gaseous SO_2 or particulate sulfate. Once the fraction of sulfur converted to SO_2 is determined (e.g., for heavy-duty Diesel vehicles, it is assumed that 2% of the sulfur is converted to particulate sulfate and 98% is converted to gaseous SO_2), it is a simple matter of performing a mass balance on sulfur in the fuel to determine the SO_2 emission rate.

Ammonia estimates are new to MOBILE6; however, the data upon which these estimates are based were collected in the late-1970s and early-1980s. A review of more recent data on ammonia from motor vehicles indicates that MOBILE6 likely overestimates ammonia from late-model vehicles.

Particle Size Distributions - MOBILE6 adjusts the total PM emission rates downward to calculate emissions of PM10 and PM2.5 (or any other particle size cutoff selected by the user between 1 and 10 μm) using particle size distributions that are specific to emission type (i.e., exhaust, brake wear, and tire wear), fuel type (gasoline versus Diesel), and technology type (catalyst versus non-catalyst). Because the particle size distributions used in the model to make this adjustment are dated, a limited review of alternative data sources was conducted, and the results of that review are presented in Table 1-1. In general, it was found that the default particle size distributions for gasoline and Diesel vehicle exhaust in MOBILE6 are similar to more recent data on particle size distributions. The one exception was for non-catalyst gasoline vehicles; however, this is not a critical input to MOBILE6 as non-catalyst vehicles make up a very small fraction of the fleet. The tire wear and brake wear particle size distributions showed more variability, but the availability of newer data is limited, particularly for tire wear emissions.

Air Toxics Emissions Estimates

The MOBILE6.2 model is capable of calculating emission rates for the following air toxics: benzene, 1,3-butadiene, formaldehyde, acetaldehyde, MTBE, and acrolein. The methodology used in MOBILE6.2 follows very closely a toxics model based on MOBILE5b that was prepared to support a number of EPA rulemakings developed in the late-1990s and early-2000s (e.g., Tier 2 emission standards and gasoline sulfur regulations, the 2007 Diesel-sulfur rule, and the mobile source air toxics rule).

Table 1-1
Comparison of MOBILE6 Particle Size Distributions to Other Published Sources

Emission Type	Source of Estimate	Fraction ≤ 10 µm	Fraction ≤ 2.5 µm
Gasoline Exhaust (Non-Catalyst)	MOBILE6	0.90	0.68
	CE-CERT	0.96	0.90
	CE-CERT	0.96	0.93
Gasoline Exhaust (Catalyst-Equipped)	MOBILE6	0.97	0.90
	CE-CERT	0.96	0.91
	CE-CERT	0.97	0.94
Diesel Exhaust	MOBILE6	1.00	0.92
	TNRCC	1.00	0.98
	CE-CERT	0.99	0.95
Tire Wear	MOBILE6	1.00	0.25
	Fauser	92% < 1 µm	
	Fishman and Turner	PM2.5/PM10 Ratio = 0.2	
Brake Wear	MOBILE6	0.98	0.42
	General Motors	0.86	0.63
	Ford Motor Co.	0.80	0.15

In brief, the model generates toxics emissions estimates by applying a "toxics fraction" to the gram per mile (g/mi) total organic gas (TOG) emission rate generated by the model. For example, if the TOG exhaust emission rate is calculated to be 1 g/mi, and benzene makes up 4% of TOG exhaust, the benzene emission rate is calculated to be 0.04 g/mi. These toxics fractions vary by technology type (e.g., non-catalyst versus oxidation catalyst versus three-way catalyst), vehicle type (e.g., light-duty versus heavy-duty vehicles), emitter category (normal versus high emitters), fuel type (gasoline versus Diesel), and fuel characteristics (e.g., oxygenated versus non-oxygenated fuels). The toxics ratios for gasoline-fueled vehicles are based on a series of algorithms that calculate ratios based on fuel parameter inputs; thus, the user must supply the model with local-level fuel specification data.

Figures 1-5 and 1-6 show the trends in benzene and 1,3-butadiene emission rates, respectively, between 1990 and 2020 using gasoline specifications reflective of the Northeastern U.S. Two sets of estimates were prepared -- one based on the implementation of reformulated gasoline (RFG) and the other without RFG in place. The following comments can be made with respect to these figures:

- Significant reductions in mg/mi air toxics are expected between 1990 and 2020 for benzene and 1,3-butadiene (as well as all other toxics modeled by MOBILE6.2). This is primarily related to the implementation of more stringent emissions standards that will result in substantial fleet-average hydrocarbon reductions over this time period.

Figure 1-5

Northeast States Fleet-Average Benzene Emissions Calculated with MOBILE6.2 Using Summertime Fuels

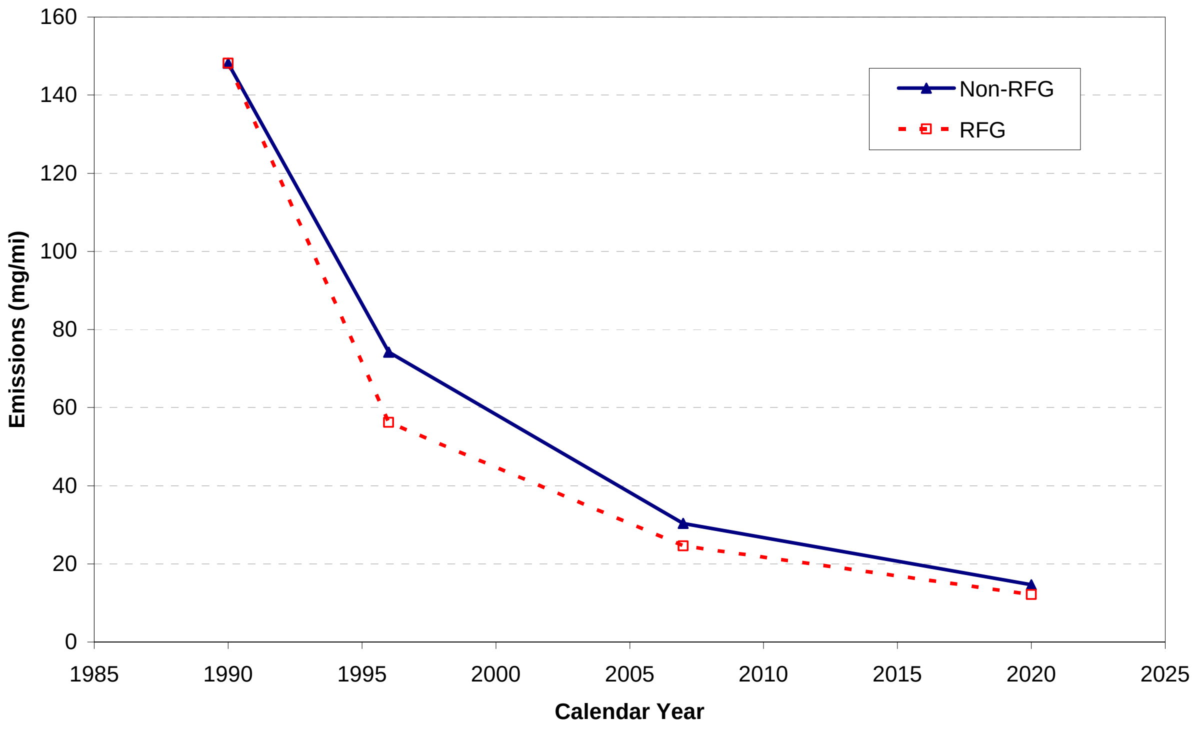
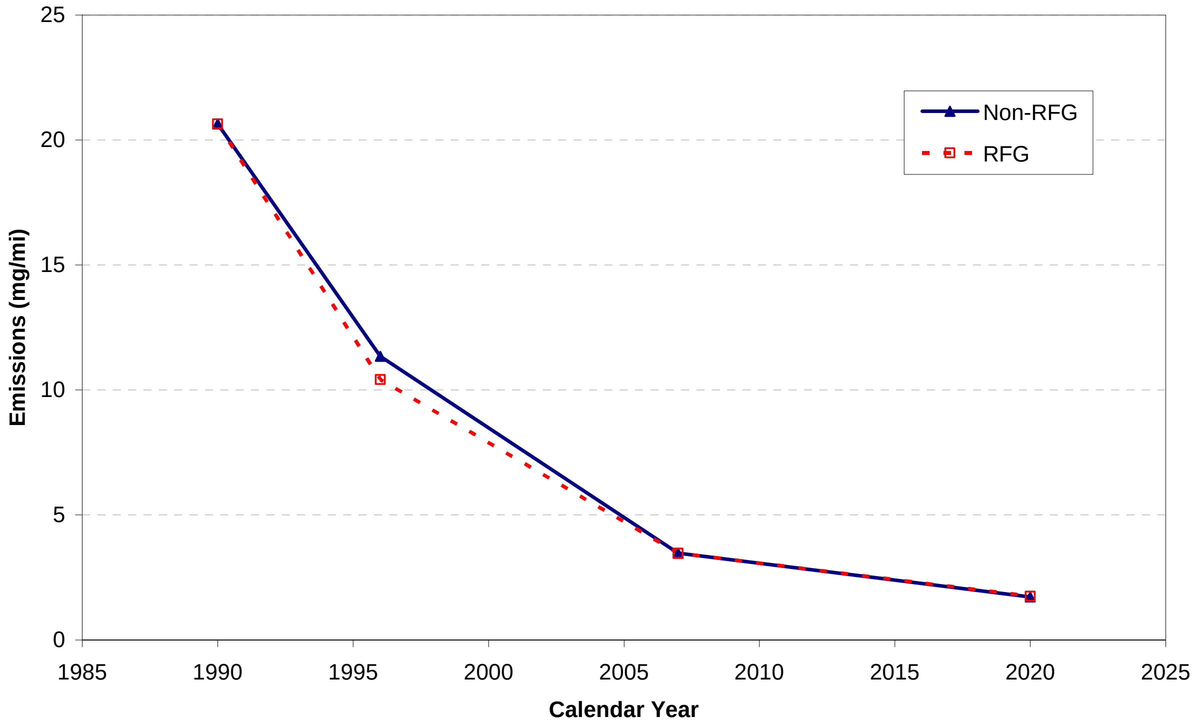


Figure 1-6

Northeast States Fleet-Average 1,3-Butadiene Emissions Calculated with MOBILE6.2 Using Summertime Fuels



- The RFG runs show lower emissions of benzene and 1,3-butadiene relative to the non-RFG runs for the 1996, 2007, and 2020 runs (federal RFG requirements were first implemented in 1995). This is not unexpected, as the RFG rule requires a minimum level of HC and toxics reductions. Although not shown in this summary (see Section 4 of this report), it is interesting to note that emissions of formaldehyde are noticeably greater under the RFG case and acetaldehyde is marginally greater under the RFG case. That is because the RFG rule requires 2% oxygen by weight which was assumed to be met with the addition of MTBE for the Northeast RFG scenario, and MTBE-containing fuels typically have a higher fraction of formaldehyde and acetaldehyde in exhaust than non-oxygenated fuels.

The impacts of gasoline parameter changes on toxics emissions was also investigated in this effort. That evaluation revealed that benzene emissions can vary by three to four times based on the minimum and maximum gasoline benzene and aromatic levels observed in fuels produced in 2003. Emissions of 1,3-butadiene can vary by up to three times based on the minimum and maximum gasoline olefin content observed in gasolines produced in 2003.

A summary of the strengths and weaknesses associated with toxics modeling in MOBILE6.2 is presented in this report. One of the greatest strengths of the model is that with MOBILE6.2, EPA has developed a framework for calculating air toxics that is easy to use and easy to modify (with a user-defined air toxics feature) as more data become available on mobile source air toxics. In addition, benzene, 1,3-butadiene, formaldehyde, and acetaldehyde emissions from early-1980 through mid-1990 light-duty gasoline cars and trucks are very well characterized. That is because those estimates are based on the Complex model for reformulated gasoline, which was developed from a very large number of tests and was extensively peer reviewed.

The primary weakness of the MOBILE6.2 toxics estimates is related to the lack of data on some key vehicle and technology types. In particular, newer technology gasoline vehicle toxics fractions are based on test results from Tier 0 vehicles (i.e., 1981 to 1993 model year), and it is unclear how well those results reflect Tier 1 vehicles, low-emission vehicles (LEVs), and Tier 2 vehicles. Additionally, toxics data on heavy-duty Diesel vehicles are very sparse, and the toxics fractions used in MOBILE6.2 are based on few data points. This will become more of an issue as the 2007 Diesel standards are implemented. Those standards will likely require catalyzed particulate traps, which will most certainly change the exhaust characteristics from those vehicles.

Modeling of Natural Gas Vehicles in MOBILE6

A new feature added to the MOBILE model with the release of MOBILE6 is the capability to model the emissions impacts of natural gas vehicles (NGVs). The basic methodology used in MOBILE6 to model the emissions impacts of NGVs is to apply an implementation schedule of NGVs by vehicle type and model year (supplied by the user) to the emission rates of NGVs that are hard-coded into the model (but can be modified by the user). The non-NGV vehicles are then assigned emission rates equivalent to the gasoline or Diesel vehicle class being modeled, and the model reports a weighted average emission rate of NGVs and non-NGVs. In general, most areas will have a very low fraction of NGVs, and users will often enter a value of 100% to obtain emissions estimates that reflect only emissions from NGVs.

Sierra reviewed the basis of the default NGV emission factors contained in MOBILE6. The light-duty NGV exhaust emission rates were based on gasoline vehicle emission rates for vehicles certified to ultra-low-emission vehicle (ULEV) standards, with some modifications to "high emitter" emission rates to better reflect available test data on NGVs. The heavy-duty NGV exhaust emission rates were based primarily on test data from NGVs. The exception to this approach was for NOx emissions for medium-heavy duty vehicles (14,001 to 33,000 lbs. gross vehicle weight rating, GVWR) and heavy-heavy duty vehicles (above 33,000 lbs. GVWR). For those vehicle types, it was assumed that NGVs would have emissions equivalent to Diesel vehicles certified to the 2004 emission standard of 2.5 g/bhp-hr NMHC+NOx. For all NGVs, evaporative emissions were assumed to be zero.

In general, the volatile organic carbon (VOC) and CO emission rates of NGVs contained in MOBILE6 are lower than emissions from their gasoline and Diesel counterparts. (VOC emissions from NGVs are much lower than comparable gasoline vehicles.) However, the default NGV emission rates contained in MOBILE6 do not account for the light-duty Tier 2 standards, nor do they account for the heavy-duty 2007 standards. As a result, NOx emissions from NGVs are predicted by the model to be higher than corresponding gasoline and Diesel vehicles beyond 2004 for light-duty vehicles and beyond 2006 for heavy-duty vehicles. This is observed in Figures 1-7 and 1-8, which compare NOx emissions for passenger cars and Class 8B trucks, respectively. As a result, users must be very careful when using this feature of the model to forecast emissions to future years, as NGVs would be subject to the Tier 2 and 2007 heavy-duty standards but are not modeled as such in MOBILE6.

A limited literature review was also conducted to determine the availability of emissions data from natural gas vehicles. As observed in Section 5 of this report, there is a fairly extensive literature of emissions from natural gas vehicles and comparisons to similar gasoline and Diesel vehicles. However, the emission results from the various programs are often mixed, with some programs showing lower emissions from NGVs and other programs showing higher emissions from NGVs relative to gasoline or Diesel vehicles. This is sometimes related to making comparisons between vehicles in different states of development (e.g., it is not fair to compare emissions from a NGV certified to ULEV emission standards to emissions from a 1990-technology Tier 0 gasoline vehicle), or not accounting for emission control system durability in customer service.

Figure 1-7

MOBILE6 Light-Duty Vehicle (Passenger Car) NOx Emission Rates
Natural Gas vs. Gasoline Vehicles

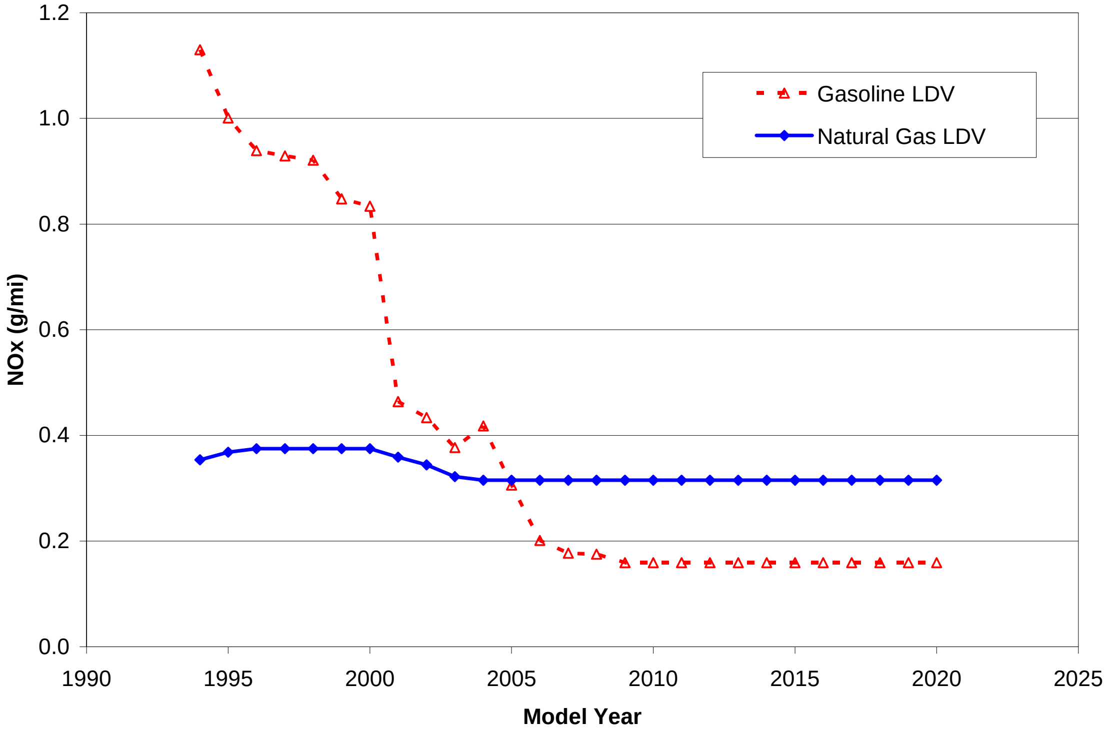
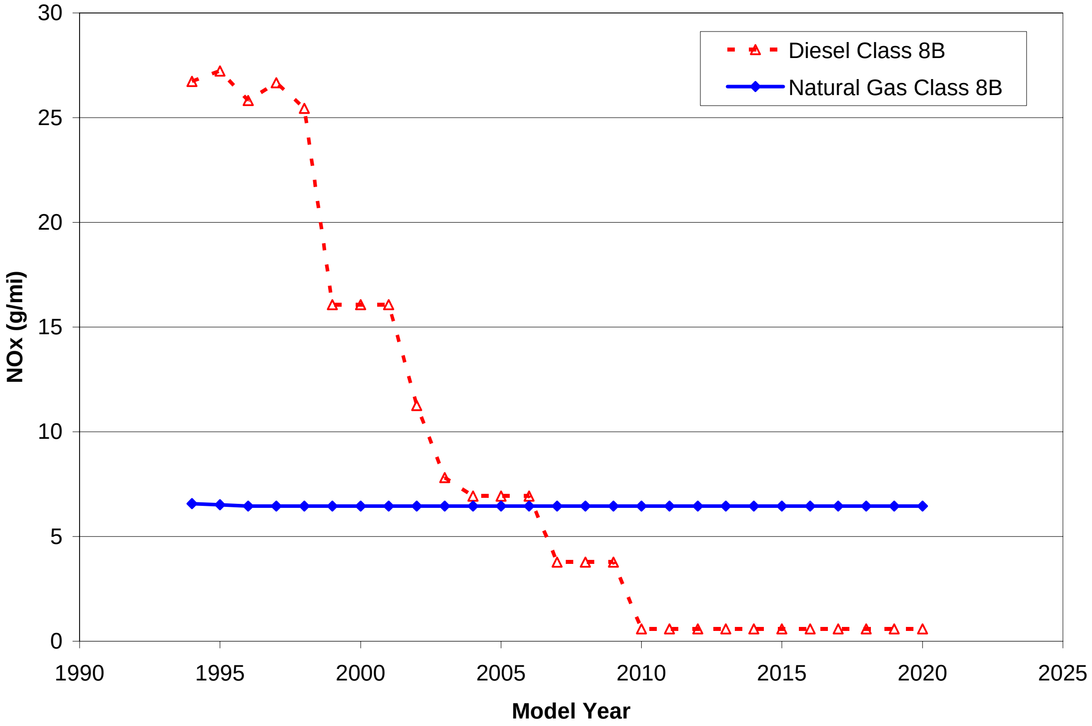


Figure 1-8

MOBILE6 Class 8B Heavy-Duty Vehicle NOx Emission Rates
Natural Gas vs. Diesel Vehicles



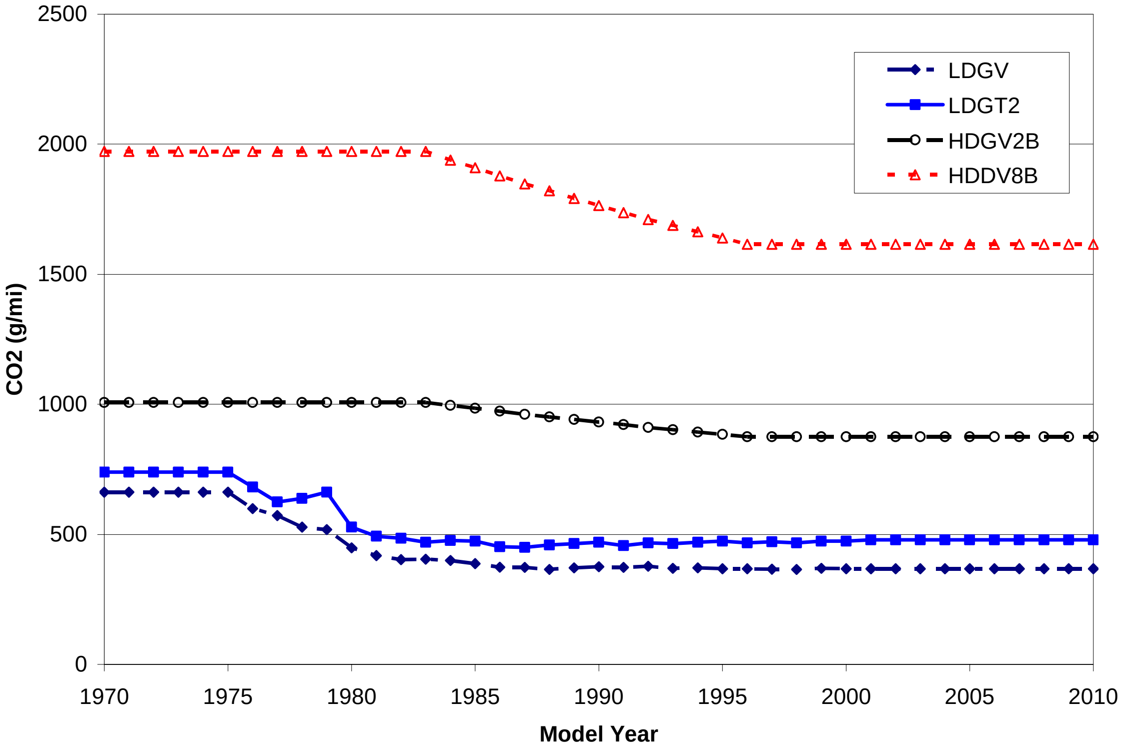
Carbon Dioxide (CO_2) Emissions Estimates

The CO_2 emissions estimates in MOBILE6 are based on a mass balance over carbon in the fuel consumed, i.e., fuel economy (in miles per gallon) is used to determine the amount of fuel consumed for each mile driven, and all of the carbon in the fuel is assumed to be converted to CO_2. Therefore, CO_2 emissions are inversely proportional to the fuel economy of a particular vehicle class, i.e., better fuel economy translates to lower CO_2 emissions.

Figure 1-9 shows the CO_2 emissions versus model year estimated by MOBILE6 for four classes of vehicles: light-duty gasoline vehicles (LDGVs), light-duty gasoline trucks between 3,751 and 5,750 lbs. loaded vehicle weight (LDGT2), heavy-duty gasoline vehicles between 8,501 and 10,000 lbs. gross vehicle weight rating (HDGV2B), and heavy-duty Diesel vehicles over 60,000 lbs. gross vehicle weight rating (HDDV8B). The reduction in CO_2 emissions for light-duty vehicles between the mid-1970s and the mid-1980s is a result of improvements in fuel economy mandated by the Corporate Average Fuel Economy (CAFE) standards that were phased in beginning with the 1978 model year. The CO_2 reductions observed between the mid-1980s and mid-1990s for heavy-duty vehicles are a result of economically induced changes in technology leading to improved fuel economy that occurred during this time period (e.g., lower rolling resistance tires, more aerodynamic truck designs, etc.).

Figure 1-9

MOBILE6 Carbon Dioxide Estimates by Vehicle Class and Model Year



MOBILE6 Validation Studies

A final task in this project was to review available studies on the validation of MOBILE6, with an emphasis on PM and toxics. In general, there have been few validation studies focused on MOBILE6 PM and toxics estimates. However, a Coordinating Research Council study (CRC Project E-64) was recently released that compares HC, CO, and NOx emissions estimates from MOBILE6 to various "real-world" data sources, and that was also reviewed in this effort. Our review of model validation studies is summarized below. The reader should keep in mind, however, that alternative methods of estimating vehicle emission rates are subject to their own limitations and uncertainties.

PM - A recent remote sensing study conducted in Las Vegas included measurement of PM emissions and compared those results to predictions from PART5. This study found that PART5 over-predicted PM emissions from light-duty gasoline and Diesel vehicles, and it under-predicted heavy-duty Diesel PM emissions relative to the RSD results. A comparison of recent chassis dynamometer based PM test data to MOBILE6 PM estimates for heavy-duty Diesel vehicles (shown in Figure 1-4 above) shows that MOBILE6 may be under-predicting PM emissions from heavy-duty Diesel vehicles.

Toxics - We were unable to identify any validation studies focused at MOBILE6 air toxics estimates. However, the 1999 mobile source air toxics assessment prepared for EPA included a comparison of motor vehicle related toxics exposure to ambient levels of air toxics for several cities. That evaluation showed that the exposure estimates (based on emission rates calculated with MOBTOX5b) generally agreed relatively well with the ambient concentration data.

Fuel Consumption - EPA included a comparison of fuel consumption calculated by dividing national level VMT by the MOBILE6 fuel economy estimates to fuel consumption developed by the Department of Transportation based on fuel sales data provided by the states. Overall fuel consumption generated with both methods agreed to within 1%, although vehicle class specific estimates differed between the two methods.

HC, CO, and NOx - The CRC E-64 project compared MOBILE6 HC, CO, and NOx emissions estimates to various "real-world" data sources including: (1) tunnel studies, (2) ambient pollutant concentration ratios (i.e., HC/NOx and CO/NOx ratios), (3) emission ratios from remote sensing devices (RSDs), and (4) heavy-duty vehicle emissions data based on chassis dynamometer testing. In addition, the CRC study also presented a comparison of MOBILE6 Diesel fuel consumption estimates with data on fuel sales.

Compared to tunnel studies, the CRC study found that MOBILE6 over-predicts fleet-average emissions, with the over-prediction being most pronounced for CO; NOx emissions estimates from MOBILE6 most closely matched the tunnel data. The RSD data also revealed that MOBILE6 likely over-predicts CO emissions, particularly from newer vehicles. Compared to ambient data, the HC/NOx ratios developed from MOBILE6 appear to be reasonably accurate, and the RSD data generally supported the HC deterioration rates built into MOBILE6.

2. INTRODUCTION

Background

In January 2002, the U.S. Environmental Protection Agency (EPA) released a revised version of its on-road motor vehicle emissions model, MOBILE6. That model, which had been under development for over five years and included significant changes relative to its predecessor, MOBILE5b, calculates gram per mile (g/mi) emission factors for hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx). In May 2002, EPA released another version of MOBILE6, commonly referred to as MOBILE6.1/6.2. MOBILE6.1 calculates particulate matter (PM) emission rates, while MOBILE6.2 calculates emission rates of air toxics. Although referred to by different names, the PM and toxics calculations, as well as the HC, CO, and NOx calculations, have been consolidated into a single model.

In the May 2002 release, the MOBILE6.1 and MOBILE6.2 versions of the model were in draft form and were subject to a five-month review period. On November 12, 2002, EPA released an updated version of MOBILE6 that included changes to respond to comments on the draft versions of MOBILE6.1 and MOBILE6.2. EPA is simply calling this latest version of the model MOBILE6.2 and has indicated that MOBILE6.2 is the "recommended and approved version" of the model for estimating emissions of HC, CO, and NOx. On November 12, 2002, EPA released an updated version of MOBILE6 that included changes to respond to comments on the draft versions of MOBILE6.1 and MOBILE6.2. EPA simply called that version of the model MOBILE6.2 and indicated that MOBILE6.2 is the "recommended and approved version" of the model for estimating emissions of HC, CO, and NOx. The PM and air toxics components of the model were recently finalized in a February 2004 release of MOBILE6.2.[1][1][2]

Under contract to the National Cooperative Highway Research Program (NCHRP), Sierra Research, Inc. (Sierra) and Parsons-Brinkerhoff (PB) evaluated several components of MOBILE6. Specifically, this included:

- An evaluation of emission factors related to PM;
- An evaluation of emission factors related to air toxics; and
- An assessment of emission factors when compressed natural gas (CNG) is specified as the fuel.

---

[1] Superscripts denote references provided in Section 8.

[2] Note that the February 2004 release of MOBILE6.2 has an internal date stamp of September 24, 2003. Thus, it is sometimes referred to as the 24-Sep-2003 version of the model.

Since the November 2002 release of MOBILE6.2, the model has also included a draft algorithm for estimating emissions of carbon dioxide (CO_2), and EPA has invited comments on the procedures used to calculate CO_2 emissions. As a result, this study reviewed the methodology used in MOBILE6 to estimate CO_2. Finally, a review of MOBILE6 validation studies conducted by EPA and others was also performed for this study.

Structure of the Report

Following this introduction, Section 3 presents a review of the algorithms and data used in MOBILE6 to calculate PM emissions. This includes a review of exhaust, brake wear, and tire wear PM. In addition, the algorithms used to estimate gaseous sulfur dioxide and ammonia emissions are also reviewed. Section 4 presents an evaluation of the toxics algorithms used in MOBILE6 as well as the results of model runs showing toxics emissions trends by calendar year and the impacts fuel parameters on toxics emission rates. A review of the methods used in MOBILE6 to estimate emissions of natural gas vehicles is presented in Section 5. That section also presents a summary of a limited literature review performed to identify sources of emissions data for natural gas vehicles. Section 6 briefly summarizes the methodology used in MOBILE6 to calculate carbon dioxide emissions and presents CO_2 estimates for a number of different vehicle classes. Finally, Section 7 reviews and summarizes studies that have been performed to validate MOBILE6 emissions estimates, and Section 8 provides a list of references cited in the report.

3. PARTICULATE MATTER EMISSIONS ESTIMATES (MOBILE6.1)

This section of the report presents our review of the PM emissions estimates calculated by the MOBILE6.1 model. MOBILE6.1 is intended as a replacement for EPA's PART5 model, which was originally released in 1995. MOBILE6.1 includes emissions estimates for exhaust PM, brake and tire wear PM, gaseous SO_2, and ammonia. Emission rates for particle sizes ranging from 1 to 10 microns (μm) can be calculated by the model. The data and algorithms in PART5 (with updates where applicable) have been integrated into MOBILE6.1 so that a separate model is no longer needed to generate PM estimates. EPA's objective was to produce a combined model that reflected EPA's particulate emissions modeling performed for recent rulemakings. Technical details of the MOBILE6.1 model were published by EPA in report number M6.PM.001.[2]

Included among the revisions incorporated into MOBILE6.1 are the following:

- ***Base Emission Rates*** - The base emission rates are mostly unchanged from PART5, except that 2007 and newer model year heavy-duty Diesel vehicles reflect the more stringent PM standards promulgated in 2000.[3] In addition, PM emission rates for light-duty vehicles were made consistent with the Tier 2 rule, and PM emission rates for 2005 and newer heavy-duty gasoline vehicles were made consistent with the requirements spelled out in the 2000 rulemaking cited above.

- ***Sulfate PM and Gaseous SO2 Calculations*** - PART5 contained hard-coded national default values for gasoline and Diesel sulfur level. MOBILE6.1 now allows users to enter local data for fuel sulfur content.

- ***Ammonia Emission Factors*** - PART5 did not calculate ammonia emissions. This is an entirely new feature with MOBILE6.1.

- ***Zero Emission Vehicles*** - MOBILE6.1 accounts for zero emission vehicles by assuming zero exhaust PM, while tire and brake wear are assumed to be the same as for gasoline vehicles.

- ***Natural Gas Vehicles*** - MOBILE6.1 assumes that natural gas vehicle PM emission rates are the same as for their gasoline vehicle counterparts operating on low-sulfur fuel. Tire and brake wear are assumed to be the same as for gasoline vehicles.

In addition to the above, MOBILE6.1 also contains revised estimates of vehicle age distributions (i.e., registrations) and technology distributions that were updated for the release of MOBILE6.

It is worth noting that a number of constituents previously modeled by PART5 are no longer calculated by MOBILE6.1. This includes (1) indirect sulfate, which PART5 calculated by assuming a certain fraction of gaseous SO_2 was converted to sulfate in the atmosphere; and (2) fugitive dust (i.e., re-entrained road dust). Indirect sulfate was removed because secondary particulate formation can be highly area-specific, and MOBILE6 is not an atmospheric model. The fugitive dust calculation was removed because MOBILE6 cannot properly account for unpaved roads (which can be a significant source of fugitive dust), and a new tool for calculating road dust is being developed by EPA's Office of Air Quality Planning and Standards (OAQPS).

For the remainder of this section of the report, we have simply referred to the model as MOBILE6, although all calculations were performed with the November 2002 release of MOBILE6.2.

MOBILE6 Exhaust PM Methodology

The exhaust PM emission rates reported by MOBILE6 are summed from the individual components making up the exhaust particulate. These components are defined differently for gasoline versus Diesel vehicles, and therefore are discussed separately below.

Gasoline Vehicle Exhaust PM - There are three primary components comprising gasoline vehicle exhaust PM emissions that are modeled by MOBILE6:

- GAS PM: the sum of the organic and elemental carbon portion of gasoline vehicle exhaust particulate (sometimes simply referred to as carbon emissions).
- SO4: sulfate particulate emissions, which are based directly on the sulfur content of the fuel.
- LEAD: lead PM emissions, which are based directly on the lead level in gasoline.

MOBILE6 sums these individual components to calculate total exhaust PM from gasoline-fueled vehicles, i.e.,

Total Gasoline Exhaust PM = GAS PM + SO4 + LEAD

MOBILE6 calculates each of these components separately, as described below.

GAS PM Estimates - The GAS PM emission factors are stored in three separate external files read by MOBILE6:

- PMGZML.CSV - zero-mile level (ZML) in grams per mile (g/mi);
- PMGDR1.CSV - deterioration rate 1 (DR1) in g/mi per 10,000 miles; and
- PMGDR2.CSV - deterioration rate 2 (DR2) in g/mi per 10,000 miles.

The zero-mile levels reflect the carbon PM emission rate when the vehicle is new, while the deterioration rates reflect an increase in emissions as vehicles age. The model is configured to accept two sets of deterioration rates, and the user can identify the vehicle age at which the second deterioration rate becomes effective. Thus, carbon PM emissions from gasoline vehicles are calculated as a function of vehicle age and mileage as follows:

$$\text{GAS PM} = \text{ZML} + \text{DR1}*\text{M1} + \text{DR2}*(\text{M} - \text{M1})$$

where M is the mileage of the vehicle (divided by 10,000 miles) and M1 is the mileage at which the second DR becomes effective (also divided by 10,000 miles). For cases in which the vehicle mileage (M) is less than the mileage at which DR2 becomes effective (M1), the value of M1 is set to M. It is important to note, however, that the MOBILE6 model currently assumes that both DR1 and DR2 are zero for gasoline vehicles. Thus, no deterioration is assumed for PM emissions from gasoline vehicles unless the vehicle has been tampered with (i.e., catalyst removed) or misfueled (i.e., use of leaded gasoline in a vehicle with a catalyst). These conditions are discussed in more detail below.

The carbon emission factors (ZML) used in MOBILE6 were taken directly from the PART5 model[4] and are summarized in Table 3-1. Those factors were in turn derived from a July 1983 EPA report,[5] and are therefore quite dated. As observed in Table 3-1, the gasoline vehicle carbon emission factors are a function of vehicle type, model year, fuel type (i.e., leaded versus unleaded gasoline[*]), and emission control technology (i.e., catalyst versus non-catalyst and air injection versus no air injection). For 1981 and newer light-duty gasoline vehicles (LDGVs), all of which have catalysts, MOBILE6 assumes a carbon emission rate of 0.0043 g/mi. The same emission rate is also applied to 1987 and newer light-duty gasoline trucks equipped with a catalyst and operated on unleaded fuel (essentially 100% of these vehicles), while heavy-duty gasoline vehicles operated on unleaded fuel are assumed to have a carbon emission rate of 0.054 g/mi regardless of whether they are equipped with a catalyst.

---

[*] Note that leaded gasoline for use in on-highway vehicles was largely phased-out by 1992, with a complete ban on its use in 1996. MOBILE6.2 assumes that by 1992 the lead content of both leaded and unleaded fuel is so small that lead emissions are in the 5-10 µg/mi range and are not reported in the model output.

Table 3-1
Carbon Emission Factors for Gasoline Vehicles
"GAS PM" in MOBILE6
(g/mi)

Vehicle Type	Model Year Group	Leaded Gasoline	Unleaded Gasoline		
			Non-Cat[a]	Cat/No Air[b]	Cat/Air[c]
Light-Duty Gasoline Vehicle (LDGV)	pre-1970	0.193	0.030	--	--
	1970-1974	0.068	0.030	--	--
	1975-1980	0.030	0.030	0.0060	0.0250
	1981+	0.017	0.017	0.0043	0.0043
Light-Duty Gasoline Truck 1/2 (LDGT12)	pre-1970	0.193	0.030	--	--
	1970-1974	0.068	0.030	--	--
	1975-1986	0.030	0.030	0.0060	0.0250
	1987+	0.017	0.017	0.0043	0.0043
Light-Duty Gasoline Truck 3/4 (LDGT34)	pre-1979	0.370	0.054	--	--
	1979-1986	0.068	0.030	0.0060	0.0250
	1987+	0.030	0.017	0.0043	0.0043
Heavy-Duty Gasoline Vehicle (HDGV)	pre-1987	0.370	0.054	0.054	0.054
	1987+	0.163	0.054	0.054	0.054
Motorcycle (MC)	pre-1979	0.129	0.129	--	--
	1979+	0.032	0.032	--	--

[a] Non-catalyst vehicles.
[b] Catalyst-equipped vehicles without air injection.
[c] Catalyst-equipped vehicles with air injection.

Although MOBILE6 assumes no deterioration in the default GAS PM emission rates, there is an adjustment for vehicles that have had the catalyst removed (i.e., tampered). The catalyst removal rates used in MOBILE6 are based on the tampering rates used in PART5, except that there is no distinction between vehicles subject to I/M and those not subject to I/M. (MOBILE6 uses the non-I/M rates, regardless of whether or not an I/M program is in place.) In addition, the MOBILE6 model assumes a catalyst removal rate of zero for 1996 and newer model year vehicles. This is to account for the presence of on-board diagnostic (OBD) systems, which would identify vehicles with missing catalysts in an I/M program.

As an example of the above calculation, 1987 and newer vehicles in the LDGT4 category have a GAS PM emission rate of 0.0043 g/mi if equipped with a catalyst and a GAS PM emission rate of 0.017 g/mi if the catalyst has been removed. For five-year old vehicles (e.g., 1995 model year in calendar year 2000) operated on unleaded gasoline, MOBILE6 estimates that 8.5% of the LDGT4 vehicles would have had the catalyst removed. Thus, the GAS PM emission rate in this case would be:

$$\begin{aligned} \text{GAS PM}_{\text{MY1995 in CY2000}} &= 0.017\ \text{g/mi} * 0.085 + 0.0043\ \text{g/mi} * (1 - 0.085) \\ &= 0.0054\ \text{g/mi} \end{aligned}$$

Particle Size Adjustment to GAS PM Estimates - The GAS PM estimates outlined above reflect the mass of particles that are less than 30 micrometers (μm) in diameter (PM30). This is based on the sampling protocol and filters used in the Federal Test Procedure. However, the MOBILE6 model reports PM only in the size range from 1 μm to 10 μm. Thus, the PM30 values are scaled downward to reflect the size specified by the user. These particle size distributions, which were based on those used in PART5, are summarized in Table 3-2. As observed in that table, the particle size distributions are a function of fuel type (leaded gasoline, unleaded gasoline, Diesel) and technology (catalyst versus non-catalyst).

Using catalyst-equipped gasoline vehicles as an example, the particle size distributions in Table 3-2 show that:

- 97% of the PM30 is ≤ 10 μm;
- 89% of the PM30 is ≤ 2.0 μm; and
- 87% of the PM30 is ≤ 0.2 μm.

Thus, if the GAS PM (PM30) emission rate is 0.0043 g/mi, the emission rate for particles ≤ 10 μm (i.e., PM10) is 0.0043 g/m * 0.97 = 0.00417 g/mi. For particle sizes that fall between the particle size cutoffs (PSC) in Table 3-2, the model simply interpolates.

The values in Table 3-2 show that for Diesel vehicles and gasoline vehicles operating on unleaded fuel, most of the exhaust PM is ≤ 10 μm (PM10). This is very typical for combustion sources. The particle size distribution for gasoline vehicles operating on leaded fuel shows a much larger fraction of larger particles. (However, as noted above, model runs for calendar years 1990 and beyond assume leaded fuel has been phased out.)

Table 3-2
Particle Size Distributions Used in MOBILE6 for Exhaust Components

Vehicle/Technology Type and Particulate Component	Particle Size Cutoff (PSC, μm)	Mass of Particles ≤ PSC
Gasoline Vehicles Leaded Fuel Exhaust Carbon/Lead	10.0	0.64
	2.0	0.43
	0.2	0.23
Gasoline Vehicles with Catalyst Unleaded Fuel Exhaust Carbon/Lead	10.0	0.97
	2.0	0.89
	0.2	0.87
Gasoline Vehicles without Catalyst Unleaded Fuel Exhaust Carbon/Lead	10.0	0.90
	2.0	0.66
	0.2	0.42
Diesel Vehicles Exhaust PM	10.0	1.00
	2.5	0.92
	2.0	0.90
	1.0	0.86

SO4 Estimates - As summarized above, sulfate is another component of gasoline exhaust PM that is calculated separately by MOBILE6. For gasoline vehicles, MOBILE6 assigns sulfate emission factors on the basis of technology type, speed, and sulfur level. These emission factors, which have also been carried over from PART5, are listed in Table 3-3. As observed in that table, vehicles equipped with catalysts and air injection are estimated to have the highest sulfate emission rates. Consistent with the gasoline vehicle carbon emission factors, the sulfate emission factors are based on data that were collected in the late 1970s. Thus, it is uncertain how well those factors reflect newer technology vehicles.

The sulfate emission factors in Table 3-3 were based on testing conducted with gasoline containing 340 ppm sulfur. Therefore, corrections are made to account for sulfur levels below 340 ppm, as will be the case when Tier 2 sulfur regulations are in place. The sulfur correction simply assumes a linear decrease (or increase) in sulfate with decreasing (or increasing) gasoline sulfur level. Table 3-3 presents emission factors for two speed bins: <19.6 mph and >34.8 mph. At speeds between these two points, the emission factors are determined by linear interpolation.

Table 3-3 **Sulfate Emission Factors for Gasoline Vehicles** **(at 340 ppm Gasoline Sulfur Level)**		
Speed	Technology Type	Sulfate Emissions (g/mi)
< 19.6 mph	Non-Catalyst	0.002
	Oxidation Catalyst/No Air	0.005
	3-Way Catalyst/No Air	0.005
	Oxidation Catalyst/Air	0.016
	3-Way Catalyst/Air	0.016
> 34.8 mph	Non-Catalyst	0.001
	Oxidation Catalyst/No Air	0.005
	3-Way Catalyst/No Air	0.001
	Oxidation Catalyst/Air	0.020
	3-Way Catalyst/Air	0.025

LEAD Estimates - The final component of gasoline vehicle PM emissions calculated by MOBILE6 is particulate lead. This calculation is only pertinent for calendar years in which leaded gasoline was available (i.e., prior to 1992), and therefore is not very relevant for most current inventory work. Nonetheless, a short description of the methodology is summarized below.

The methodology used to estimate lead emissions from gasoline vehicles is based on a mass balance on lead in the fuel. For example, if a vehicle that has a fuel economy of 20 mpg burns gasoline that contains 1 gram of lead per gallon (g/gal), the amount of lead that is combusted is simply (1 g/gal)/(20 mi/gal) = 0.05 g/mi Pb. The model assumes that lead combines with chlorine and bromine to form a lead salt (PbClBr) particulate, thus the mass of lead in the above calculation is multiplied by 1.557 (the molecular weight of PbClBr divided by the atomic weight of lead) to obtain 0.078 g/mi PbClBr. Next, the model assumes that 75% of the lead combusted is emitted from the tailpipe for non-catalyst and catalyst vehicles operating on leaded fuel. (The rest is assumed to be deposited in the exhaust system and muffler.) For catalyst vehicles using unleaded fuel,[*] it is assumed that 40% of the lead combusted is emitted for 1975 to 1980 calendar years, and that 44% of the lead combusted is emitted for 1981 and later calendar years. Finally, particle size distributions are applied to the calculated LEAD emission factor; those distributions are the same used for carbon emissions that are summarized in Table 3-2.

---

[*] The model assumes that unleaded fuel contains a very small amount of lead (0.0002 g/gal for 1992 and later calendar years) that is combusted and emitted by catalyst-equipped vehicles. As a point of comparison, the lead content of leaded fuel in the mid-1970s was about 2 g/gal.

Adjustments for New Standards - The heavy-duty gasoline vehicle exhaust PM estimates are adjusted to account for new emission standards that will be implemented as part of EPA's 2007 heavy-duty rule.[6] Although those standards were focused at control of PM from Diesel engines, they are stringent enough such that the standards are lower than the baseline PM level assigned to heavy-duty gasoline vehicles. For example, Table 3-1 shows a GAS PM emission rate of 0.054 g/mi for HDGVs operated on unleaded fuel. However, the PM emission standard for 2007 and newer class 2B HDGVs (i.e., vehicles with a gross vehicle weight rating between 8,501 and 10,000 lbs) is approximately 0.011 g/mi,[*] and the model assumes an emission rate of 0.010 g/mi for this vehicle class. Thus, exhaust PM emissions for 2007 and newer class 2B HDGVs are assumed to be about 80% lower than pre-2007 model year vehicles. It is unclear that this is a "real" reduction in PM emissions, rather, it is more likely that the pre-2007 model year emission factors are outdated.

<u>Diesel Vehicle Exhaust PM</u> - There are three primary components that make up Diesel vehicle exhaust PM in MOBILE6:

- OCARBON: organic carbon portion of Diesel exhaust PM; this was denoted as soluble organic fraction (SOF) in PART5.
- ECARBON: elemental carbon and residual carbon portion of Diesel exhaust PM; this was denoted as remaining carbon portion (RCP) in PART5.
- SO4: sulfate particulate emissions, which are based directly on the sulfur content of the fuel.

The sum of these components comprise total exhaust PM from Diesel-fueled vehicles, i.e.,

Total Diesel Exhaust PM = OCARBON + ECARBON + SO4

Total Diesel Exhaust PM Estimates - Similar to the GAS PM emission factors, the total Diesel PM emission factors are stored in the following external data files that are read by MOBILE6:

- PMDZML.CSV - zero-mile level (ZML) in grams per mile (g/mi);
- PMDDR1.CSV - deterioration rate 1 (DR1) in g/mi per 10,000 miles; and
- PMDDR2.CSV - deterioration rate 2 (DR2) in g/mi per 10,000 miles.

---

[*] The value of 0.011 g/mi is based on the PM emission standard established in the 2007 rule (0.01 grams per brake horsepower-hour [g/bhp-hr]) multiplied by the HDGV class 2B conversion factor of 1.096. The application of conversion factors to g/bhp-hr emission factors is discussed later in this section when the basis for the heavy-duty Diesel vehicle emission factors is presented.

The zero-mile levels reflect the total PM emission rate when the vehicle is new, while the deterioration rates reflect an increase in emissions as vehicles age. Unlike the GAS PM emission factors, which reflect only carbon emissions, the Diesel PM emission factors stored in these files reflect total exhaust PM, including organic carbon, elemental carbon, and sulfate. Included in the PMDZML.CSV file is the sulfur level of the fuel used to collect the emissions data upon which the emission factors are based. For MOBILE6, the default emission factor fuel sulfur level is 500 ppm for all model years. As explained below, this is corrected in the model to account for the in-use Diesel fuel sulfur level specified by the user.

Using 1996 model year class 8B HDDVs (i.e., Diesel trucks over 60,000 lbs GVWR) as an example, the ZML contained in the PMDZML.CSV file is 0.2375 g/mi, while the DR1 and DR2 values are zero (i.e., no deterioration is assumed). Thus, the 0.2375 g/mi value reflects the total exhaust PM30 emission rate for this vehicle class and model year assuming a fuel sulfur level of 500 ppm.

SO4 Estimates - Particulate sulfate is calculated as a separate component of Diesel vehicle exhaust PM emissions. For Diesel vehicles, the sulfate PM component is calculated based on a mass balance of sulfur in Diesel fuel (similar to the LEAD calculations for gasoline vehicles). Consistent with PART5, MOBILE6 assumes that 2% of the fuel sulfur is exhausted as sulfate PM, and the remaining 98% is exhausted as gaseous SO_2.[*]

Continuing with the 1996 model year class 8B HDDV example, sulfate emissions are first calculated in MOBILE6 at the sulfur level used for emission factors development, which, as noted above, is 500 ppm. MOBILE6 assumes that the fuel economy of this vehicle is 6.30 mpg (or 1/6.3 = 0.159 gal/mi) and that the density of Diesel fuel is 7.11 lb/gal. Thus, the amount of sulfur exhausted per mile is:

$$\begin{aligned}\text{Sulfur}_{\text{Total g/mi}} &= (0.159 \text{ gal/mi}) * (7.11 \text{ lb/mi}) * (500 \text{ S}/1{,}000{,}000 \text{ fuel}) * 453.6 \text{ g/lb} \\ &= 0.256 \text{ g/mi}\end{aligned}$$

However, as noted above, the model assumes that only 2% of the sulfur is exhausted as particulate:

$$\begin{aligned}\text{Sulfur}_{\text{PM g/mi}} &= 0.256 \text{ g/mi} * 0.02 \\ &= 0.0051 \text{ g/mi}\end{aligned}$$

Finally, the model assumes that particulate sulfur is exhausted as $H_2SO_4 \bullet 7H_2O$ (i.e., sulfuric acid with 7 associated water molecules). Thus, the sulfur emission rate above must be scaled upward by the ratio of the molecular weight of $H_2SO_4 \bullet 7H_2O$ to the atomic weight of sulfur (i.e., 224/32 = 7), and the particulate sulfate emission factor in this example becomes:

---

[*] Although the documentation for MOBILE6.2 and PART5 indicates that 2% of the sulfur in Diesel fuel is converted to particulate sulfate, a review of the source code reveals that a value of 1.5% is used for light-duty Diesel vehicles and light-duty Diesel trucks and 2% is used for heavy-duty Diesel vehicles.

$SO4_{500ppm}$ = 0.0051 g/mi * 7
= 0.0357 g/mi

This value reflects the particulate sulfate emission rate using 500 ppm fuel, while current in-use Diesel fuel is typically below this value. (Note that the current limit on Diesel fuel used for on-highway applications is 500 ppm, but refiners typically distribute fuel with lower sulfur level to ensure compliance with the standard.) Thus, assuming an in-use sulfur level of 300 ppm, the particulate sulfate emission rate is:[*]

$SO4_{300ppm}$ = 0.0357 g/mi * (300/500)
= 0.0214 g/mi

OCARBON and ECARBON Estimates - The first step used in MOBILE6 to calculate OCARBON and ECARBON components of Diesel PM emissions is to subtract the particulate sulfate from the total PM at the fuel sulfur level upon which the emission factors were based (i.e., 500 ppm). In MOBILE6, this parameter is called "RCPSOF" (i.e., Remaining Carbon Portion/Soluble Organic Fraction), which is a carry-over from the PART5 nomenclature. Using the example above, this calculation is performed as follows:

RCPSOF = Total Diesel Exhaust $PM_{500ppm\ S}$ - $SO4_{500ppm\ S}$
= 0.2375 g/mi - 0.0357 g/mi
= 0.2018 g/mi

Once the sulfate is subtracted, the remainder is multiplied by the organic carbon fraction (OCFRAC) to arrive at the value of OCARBON. The organic carbon fractions are a function of vehicle type and were copied directly from the PART5 model. For class 8B HDDVs, the OCFRAC is 0.24, and OCARBON is calculated as summarized below.

OCARBON = RCPSOF * OCFRAC
= 0.2018 g/mi * 0.24
= 0.0484 g/mi

Finally, ECARBON is calculated by subtracting OCARBON from RCPSOF:

ECARBON = RCPSOF - OCARBON
= 0.2018 g/mi - 0.0484 g/mi
= 0.1534 g/mi

---

[*] Note that the sulfate calculation performed within MOBILE6 utilizes a single equation in which the separate steps outlined above are combined. During the process of combining these steps, it appears that a slight error was made in which the weight ratio of SO_4 to S was used (96/32 = 3.0) rather than the weight ratio of H_2SO_4 to S (98/32 = 3.063). Thus, the results of the SO4 calculation above are slightly higher (by about 2%) than the results reported by the model.

As noted above, the total Diesel exhaust PM is the sum of OCARBON, ECARBON, and SO4. However, the SO4 value is based on the in-use sulfur level as calculated above. Thus, for this example (1996 model year class 8B HDDVs), the total Diesel exhaust PM is:

$$\begin{aligned}\text{Total Diesel Exhaust PM} &= \text{OCARBON} + \text{ECARBON} + \text{SO4}_{300\text{ppm}} \\ &= 0.0484 \text{ g/mi} + 0.1534 \text{ g/mi} + 0.0214 \text{ g/mi} \\ &= 0.2232 \text{ g/mi}\end{aligned}$$

Adjustments to the Diesel Exhaust PM Estimates - The Diesel exhaust PM estimates outlined above are adjusted to account for the particle size cutoff specified by the user. The methodology for this adjustment is the same as that described above for gasoline vehicle PM estimates, and the particle size distributions for Diesel exhaust are summarized in Table 3-2. The particle size adjustment is applied to the RCPSOF value prior to separating it into the OCARBON and ECARBON fractions. Note that no particle size adjustment is made to the SO4 estimates, as it is assumed that this component of Diesel PM is in the smaller particle size ranges.

Another adjustment that is performed to the heavy-duty Diesel exhaust PM estimates is for the EPA 2007 HDDV rule that requires (1) implementation of low sulfur Diesel fuel (15 ppm limit) by the fall of 2006; and (2) a 90% reduction in exhaust PM emission standards for HDDVs. The MOBILE6 model accounts for the emissions impacts of this regulation by specifying alternative total Diesel exhaust PM emission rates in place of the values contained in the PMDZML.CSV file. (No deterioration rates are assumed for vehicles subject to the 2007 PM standards.) For class 8B HDDVs, the revised emission factor is 0.0279 g/mi (at 8 ppm sulfur).[*] This value is then used in the calculation methodology described above to generate total exhaust PM, ECARBON, OCARBON, and SO4 estimates for vehicles subject to the 2007 rule.

The light-duty Diesel vehicle (LDDV) and light-duty Diesel truck (LDDT) exhaust PM emission factors are adjusted for EPA's Tier 2 emissions standards, which are implemented in 2004 and establish PM standards of either 0.02 g/mi or 0.01 g/mi, depending on certification "bin."[**] As a practical matter, light-duty Diesel vehicles will most certainly be certified to the 0.02 g/mi PM level. This reflects a 80% reduction in PM relative to the Tier 1 (i.e., 1994 and newer model year) PM standard of 0.10 g/mi for light-duty Diesel vehicles and trucks.

---

[*] 8 ppm sulfur is assumed in the model to incorporate the effects of a "compliance cushion" that refiners typically incorporate into their fuel specifications.

[**] The Tier 2 rule establishes 10 different certification "bins" that have different levels of stringency. Manufacturers must meet a fleet-average NOx emission rate of 0.07 g/mi across their product line. Thus, vehicles certified to higher emissions levels can be offset by vehicles certified to lower emissions levels.

Basis of MOBILE6 Exhaust PM Base Emission Rates

The base emission rates (i.e., ZML and DR) described above are the most critical inputs to the exhaust PM calculations in MOBILE6. These are typically based on test data, and the values can be significantly impacted by the introduction of new technologies (e.g., catalysts). A discussion of the basis of the exhaust PM emission rates used in MOBILE6 is presented below separately for gasoline and Diesel vehicles.

Gasoline Vehicle PM Emission Rates - As noted above, the gasoline vehicle exhaust PM emission factors used in MOBILE6 are extremely dated, having been based on FTP data collected in the late 1970s and early 1980s. These are clearly in need of revision, and the results of several test programs have been published in recent years. However, EPA has indicated that it will not update the gasoline vehicle PM estimates until a study planned for the Kansas City area this coming summer has been completed and the results analyzed. Based on preliminary plans, the intent is to test 480 vehicles using EPA's portable dynamometer running the California Unified Cycle.[7] That test cycle, which was based on on-road speed data collected in Los Angeles in 1990, is thought to better represent in-use PM emissions than the traditional FTP test.

Diesel Vehicle PM Emission Rates - Because the methodology used to develop light-duty Diesel vehicle emission rates is much different than that used for heavy-duty Diesel vehicles, these two vehicle classes are discussed separately below.

Light-Duty Diesel Vehicles: MOBILE6 considers three separate classes of light-duty Diesel vehicles:

- LDDV - light-duty Diesel vehicles (i.e., passenger cars);
- LDDT12 - light-duty Diesel trucks, weight category 1 and 2 (i.e., trucks with a GVWR up to 6,000 lbs); and
- LDDT34 - light-duty Diesel trucks, weight category 3 and 4 (i.e., trucks with a GVWR from 6,001 to 8,500 lbs).

The base emission rates used in MOBILE6 for these vehicles are the same as those used in PART5, which were based on an analysis performed by EPA in 1990 to support the rulemaking that required on-highway Diesel fuel to have a maximum sulfur limit of 500 ppm beginning in 1993.[8] Those factors for pre-1987 model year vehicles were based directly on certification data, while the 1987 and newer model year factors used 1987 certification data to establish the non-sulfate particulate emissions, and expected reductions in fuel sulfur were used to estimate reductions in particulate sulfate and therefore total PM. An additional adjustment appears to have been made to account for more stringent PM emission standards as a result of the Tier 1 particulate standards, which were phased-in beginning with the 1994 model year.[*] Finally, as noted above, the model also internally adjusts the PM emission factors to account for the more stringent requirements of the Tier 2 rule that is phased-in beginning with the 2004 model year.

Heavy-Duty Diesel Vehicles: Because of the large number of applications for which heavy-duty engines are utilized, emissions testing is normally engine-specific and is performed on an engine dynamometer. Additionally, the heavier GVW rating of heavy-duty vehicles precludes testing on most chassis dynamometers. Therefore, engine dynamometer test cycles have been developed that simulate average urban driving for gasoline and Diesel heavy-duty engines. These engine test cycles specify RPM and torque by second and are roughly 20 minutes long. The test results are reported in units of grams per brake-horsepower-hour (g/bhp-hr).

Because the exhaust emission test procedure results in emissions reported in units of g/bhp-hr, it is necessary to convert the results into g/mi units to be consistent with available travel information. Therefore, conversion factors (in bhp-hr/mi) are developed to convert the emission results obtained from engine dynamometer testing to units appropriate for inventory purposes. The derivation of heavy-duty conversion factors is described in a 1984 EPA technical report,[9] and those conversion factors were updated for MOBILE6.[10]

For MOBILE6, the HDDV emission factors (in g/bhp-hr) were updated based on a review of certification data.[11] In general, the certification data show that manufacturers comply with the exhaust PM emissions standard with about a 10% to 20% “cushion.” Thus, for 1996 model year HDDVs, MOBILE6 assigns an emission rate of 0.08 g/bhp-hr to the heavier HDDVs (i.e., over 33,000 lbs GVWR), while those vehicles were certified to a standard of 0.10 g/bhp-hr.

Using 1996 model year HDDV class 8B trucks as an example, the exhaust PM emission rate is 0.08 g/bhp-hr and the conversion factor is 3.031 bhp-hr/mi. Thus, the g/mi emission rate for this vehicle class is:

$$\begin{aligned} PM_{\text{Class 8b}} &= 0.08 \text{ g/bhp-hr} * 3.031 \text{ bhp-hr/mi} \\ &= 0.242 \text{ g/mi} \end{aligned}$$

The emission rate above is slightly higher than the value of 0.2375 g/mi assigned to class 8b HDDVs in the PMDZML.CSV file. That appears to be a result of EPA combining both class 8a and class 8b HDDVs in the emission factor calculations that were used to generate the values in the PMDZML.CSV file—both class 8a and class 8b trucks are assigned the same g/mi emission rate, even though the conversion factor for the lighter truck class (8a) is slightly smaller than the conversion factor for class 8b.

---

[*] Note that the light-duty Diesel PM emission factors do not follow the phase-in schedule outlined in the Tier 1 rule. Instead, 100% compliance is assumed for LDDVs in 1996 and for LDDTs in 1997. This is a minor point, however, as very few light-duty Diesel vehicles were sold throughout the 1990s.

As noted above, the HDDV exhaust PM emission factors are modified within MOBILE6 to reflect the 2007 Diesel rule that implements a 90% reduction in the exhaust PM emission standard (from 0.10 g/bhp-hr to 0.01 g/bhp-hr).

Other Constituents Modeled by MOBILE6

In addition to exhaust PM emissions, MOBILE6 calculates PM emissions from tire wear and from brake wear. Two gaseous pollutants that contribute to particulate formation in the atmosphere are sulfur dioxide (SO_2) and ammonia (NH3), and those are also modeled by MOBILE6. Below is a discussion of issues related to modeling these constituents by MOBILE6.

Tire Wear PM Estimates - As a vehicle is operated on a roadway, its tires are gradually worn away by the pavement (if this did not occur, we would never have to replace the tires on our vehicles), and a certain fraction (about 1% to 10%) of this tire wear is emitted into the ambient air. MOBILE6 assumes that the tire wear emission rate is 0.002 g/mi for each tire, resulting in an emission rate of 0.008 g/mi for an average passenger car or light-duty truck. For heavy-duty vehicles with more than four wheels, the tire wear emission rate is increased in proportion to the number of wheels on the vehicle.

The value of 0.002 g/mi per tire was based on research published in the 1970s.[12,13] Although there has been little research conducted on tire wear emission rates since that time, Fishman and Turner[14] recently estimated a tire wear PM10 emission factor of 0.0016 ± 0.0008 g/mi per tire, which corresponds very well with the MOBILE6 estimate. This was based on ambient measurements of PM emissions in conjunction with a highway dispersion model.

Particle size distributions are applied to the MOBILE6 tire wear emission factors to generate estimates at different particle size cutoffs. MOBILE6 assumes that 100% of the 0.002 g/mi per tire emission rate is PM10 and that 1% is from particles less than or equal to 0.1 μm. Particle size cutoffs between these values are interpolated. Thus, PM2.5 is estimated to be 25% of the 0.002 g/mi emission rate. This value corresponds well with the PM2.5/PM10 ratio of 20% recently reported by Fishman and Turner. Other researchers, however, have reported tire wear PM2.5/PM10 ratios ranging from <10%[15] to as high as 70%.[16] Thus, there remains some uncertainty associated with the size distribution of tire wear PM emissions.

Brake Wear PM Estimates - Another non-exhaust PM component modeled by MOBILE6 is brake wear. During the braking process, the frictional force that stops the vehicle also generates break wear debris, primarily from the brake pads. This is emitted in the form of small particles and gaseous components. It has been estimated that about 30% of the brake pad wear is emitted as airborne PM.[17]

MOBILE6 uses a PM30 value of 0.0128 g/mi to reflect brake wear for all vehicle classes in the model. This estimate is based on PART5 and was derived from research published in 1983.[18] This work consisted of first measuring speed-time profiles, brake pressure, and brake temperature during urban driving with an instrumented vehicle (passenger car), from which “representative braking cycles” were developed. A total of 358 miles were driven in this effort, with an average of 5.05 stops per mile. These cycles were then replicated in a laboratory using an engine dynamometer coupled to a full-scale brake system, and particulate emissions were measured. This same study measured particle size distributions, and those are also used in MOBILE6. Based on that study, MOBILE6 estimates that 98% of the brake wear PM is PM10 and 42% is PM2.5.

In 2000, researchers from General Motors published results of a study in which mass emission rates from seven brake pads used on high production volume vehicles were determined.[19] In addition, particle size and composition were investigated in this effort. The following emission rates were estimated for airborne PM emissions as a function of vehicle type:

- Small car = 0.0054 g/mi
- Large car = 0.0084 g/mi
- Large pickup truck = 0.0141 g/mi

It should be noted, however, that the values above were not based on direct measurement. Rather, it was assumed that front brakes would last 35,000 miles and rear brakes would last 70,000 miles. It was then assumed that 80% of the friction material would be worn off. On this basis, the total brake wear for small cars was estimated to be 18 mg/mi; for large cars, 28 mg/mi; and for a large pickup truck, 47 mg/mi. Based on the data collected in this program, about 30% of the brake wear is emitted as airborne PM; thus, multiplying the total brake wear estimates by a 0.3 airborne fraction results in the g/mi values summarized above.

This study also reported airborne brake wear mass in terms of mg/stop based on a braking event of 50 to 0 km/hr at a deceleration rate of 2.94 m/s^2 (i.e., 31 to 0 mi/hr at a deceleration rate of 6.6 mi/hr per second). Results were reported as a function of brake type and temperature (100, 200, 300, and 400ºC). For the large pickup, the approximate airborne mass per stop (at 150ºC, typical average braking temperature) is estimated to be 2.94 mg/stop. Applying an average of 5.05 stops per mile to this result gives an estimate of 0.0148 g/mi, which compares exceptionally well with the estimate of 0.0141 g/mi outlined above.

The GM study also reported particle size distributions for brake wear emissions. Based on that work, it was found that 86% of the brake wear is PM10 and 63% is PM2.5. Relative to MOBILE6, this reflects a slight decrease in the PM10 fraction and an increase in the PM2.5 fraction.

A distinct shortcoming of the MOBILE6 brake wear estimates is that the same estimate (0.0128 g/mi) is used for all vehicle classes, even though that estimate was based on testing of passenger car brake systems. It is clear that heavier vehicles will have higher brake wear emissions, as the kinetic energy that must be dissipated in a stop is directly proportional to the mass of the vehicle (i.e., $KE = 1/2mv^2$). Thus, a fully loaded class 8B truck (80,000 lb. GVW) could have brake wear emissions an order of magnitude higher than light-duty cars and trucks.

<u>Gaseous SO_2 Estimates</u> - In addition to particulate sulfate, the MOBILE6 model also calculates emissions of gaseous SO_2. SO_2 estimates are often used in air quality models to account for the formation of particulate sulfate in the atmosphere (i.e., secondary particulate). The basic approach used by MOBILE6 to estimate SO_2 is with a simple mass balance on the sulfur in the fuel.

Continuing with the 1996 model year class 8B HDDV example used in the sulfate discussion above, recall that the amount of sulfur exhausted per mile is calculated as follows (assuming a sulfur level of 500 ppm for the base emission rates):

$$\begin{aligned} \text{Sulfur}_{\text{Total g/mi}} &= (0.159 \text{ gal/mi}) * (7.11 \text{ lb/mi}) * (500 \text{ S}/1{,}000{,}000 \text{ fuel}) * 453.6 \text{ g/lb} \\ &= 0.256 \text{ g/mi} \end{aligned}$$

MOBILE6 then assumes that 98% of the sulfur is exhausted as gaseous SO_2 for Diesel vehicles:

$$\begin{aligned} \text{Sulfur}_{\text{SO2 g/mi}} &= 0.256 \text{ g/mi} * 0.98 \\ &= 0.251 \text{ g/mi} \end{aligned}$$

This value is then converted to an SO_2 basis by multiplying the result by the ratio of the molecular weight of SO_2 to the atomic weight of sulfur (i.e., 64/32 = 2), and it is adjusted to reflect the sulfur content of in-use Diesel fuel (300 ppm in the example above) by applying the ratio of in-use sulfur to the 500 ppm sulfur level of the base emission rates:

$$\begin{aligned} SO_2 &= 0.251 \text{ g/mi} * (64/32) * (300 \text{ ppm}/500 \text{ ppm}) \\ &= 0.301 \text{ g/mi} \end{aligned}$$

SO_2 emission rates for gasoline vehicles are calculated in a similar fashion, i.e., the calculation is based on a mass balance of sulfur in the fuel. Particulate sulfate is first calculated as described above, and the remaining sulfur in the fuel (i.e., that not accounted for in the particulate sulfate emissions estimates) is assumed to be emitted as gaseous SO_2.

<u>Ammonia Estimates</u> - Ammonia is another gaseous compound that contributes to secondary aerosol formation in the atmosphere, typically in the form of ammonium nitrate (NH_4NO_3) and ammonium sulfates (NH_4SO_4, $NH_4(SO_4)_2$). As a result, emissions estimates of ammonia from on-highway vehicles are often needed as input to air quality models, and MOBILE6 now calculates ammonia emissions. This is a new feature with MOBILE6, as PART5 did not include ammonia estimates.

Ammonia (NH_3) is generated directly in an engine as a combustion product and additional quantities are formed as the exhaust gases pass over the catalyst. In general, catalyst-equipped vehicles (particularly three-way catalyst systems) that are malfunctioning rich tend to have much higher ammonia emissions than those vehicles that are able to maintain a stoichiometric air-fuel ratio.[*] The ammonia emission factors used in MOBILE6 are based on those historically used to develop EPA's National Trends Inventory estimates. These were developed from test data collected in the late 1970s and early 1980s,[20] and therefore are quite dated. The ammonia emission factors used in MOBILE6 are summarized in Table 3-4. For these estimates, EPA assumed that 75% of the fleet was functioning normally and that 25% of the fleet was malfunctioning.

Table 3-4
Ammonia Emission Factors Used in MOBILE6
(mg/mi)

Vehicle Type	Technology Type			
	Non-Cat	Ox Cat	3-Way Cat	All
LDGV and LDGT	11.3	15.1	102	--
Motorcycle	--	--	--	11.3
HDGV	--	--	--	45.1
LDDV and LDDT	--	--	--	6.8
HDDV	--	--	--	27.0

In the documentation for MOBILE6, EPA acknowledges that the ammonia emission factors used in the model are very dated and may not reflect emissions from newer technology vehicles. As a result, EPA conducted a literature search for more recent ammonia data to validate those used in MOBILE6. In general, few reports have been published on directly measured ammonia emissions from on-road motor vehicles,[**] although a fairly extensive research program on ammonia emissions from on-road motor vehicles has been on-going at U.C. Riverside's College of Engineering - Center for Environmental Research and Technology (CE-CERT) over the past several years. According to EPA, the ammonia emission factors used in MOBILE6 are in the same general range as the FTP test results that were available at the time the literature search

---

[*] Stoichiometric operation occurs when fuel and air enter the combustion chamber in a ratio that allows for all of the fuel and air to combust with no excess air and no excess fuel. For gasoline-fueled vehicles, stoichiometric operation occurs at an air-fuel ratio of about 14.6-to-1. Rich operation means that there is more fuel entering the combustion chamber than can be fully burned by the available oxygen (usually resulting in high HC and CO emissions), and lean operation means that there is more air than needed to fully combust the fuel (usually resulting in high NOx emissions).

[**] Several tunnel studies have been conducted in recent years that estimated emission rates of ammonia from the in-use fleet. However, EPA tends not to use such indirect measurements in its emission factors models because they can be subject to considerable uncertainty and reflect only a snapshot in time. Nonetheless, tunnel studies can be useful in helping to validate model predictions.

was conducted. However, EPA stated that there were substantial variations in ammonia emissions measurements, and ammonia emission rates are a function of fuel sulfur level, test cycle, catalyst technology, and other factors. EPA concluded by noting that additional research is recommended on this topic.

Table 3-5 summarizes FTP-based ammonia test results from two recent studies published by CE-CERT: (1) a 2001 paper presented at the 10th International Emission Inventory Conference,[21] and (2) a 2003 report prepared for the Coordinating Research Council (CRC).[22] As observed in that table, more recent data seem to indicate that MOBILE6 ammonia emission factors overstate ammonia emissions from newer technology vehicles, all of which use three-way catalyst technology. For example, the 2003 CRC study reported an average NH_3 emission rate for 2000-2001 model year LEV-category vehicles of 14-21 mg/mi, whereas MOBILE6 assigns an emission rate of 102 mg/mi to these vehicles. Although the 2001 CE-CERT paper stated that initial studies showed an increase in ammonia emissions with decreasing fuel sulfur level, the 2003 CRC work found a slight decrease in ammonia emissions with 30 ppm sulfur fuel relative to 150 ppm sulfur fuel on the FTP, although this was not a statistically significant difference. This result was somewhat counter-intuitive, as sulfur acts as a catalyst poison, and concern has been raised that the decreased gasoline sulfur levels required by the Tier 2 rule may result in an increase in ammonia emissions from the in-use fleet. Based on the 2003 CE-CERT data, this does not appear to be a problem for LEV-category vehicles during FTP operation. However, there was a statistically significant difference in emissions results as a function of sulfur level when the vehicles were operated on the US06 test cycle (an aggressive driving cycle developed for the Supplemental Federal Test Procedure rulemaking). Finally, CE-CERT found that ammonia emissions increase substantially during aggressive driving behavior, which is thought to be a result of rich operation. However, it is unclear to what extent this will continue for vehicles that are subject to off-cycle controls through the Supplemental Federal Test Procedure regulations.

Table 3-5
FTP-Based Ammonia Emission Rates from Recent CE-CERT Test Programs (mg/mi)

Source	Certification Category	Number of Vehicles	NH_3 Emissions
2001 Emission Inventory Conference	Tier 0	13	54
	Tier 1	11	79
	TLEV	8	49
	LEV/ULEV	6	23
2003 CRC Study	LEV/ULEV/SULEV	12	14 - 21

Review of Particle Size Distributions

MOBILE6 adjusts the total PM emission rates downward to calculate emissions of PM10 and PM2.5 (or any other particle size cutoff selected by the user). Because the particle size distributions used in the model to make this adjustment are dated, a limited review of alternative data sources was conducted. Table 3-6 summarizes the fractions used in MOBILE6 to generate PM10 and PM2.5 emissions estimates and compares those values to more recent data from the literature. For gasoline vehicles operating on unleaded fuel, data from two studies published in 1998 by U.C. Riverside CE-CERT[23,24] are compared to the MOBILE6 estimates. The CE-CERT and MOBILE6 estimates are very close except for the fraction of PM ≤ 2.5 µm from non-catalyst vehicles. However, because non-catalyst vehicles make up a very small fraction of the fleet, this is not a critical input to MOBILE6. The estimates shown in Table 3-6 for catalyst-equipped gasoline vehicles are weighted averages from the data presented in the CE-CERT report.[23] It is interesting to note that the newer model year vehicles tested in that study had a larger fraction of large particles than the older model year vehicles. Diesel vehicle exhaust particle size distributions from a study performed for the Texas Natural Resource Conservation Commission[25] (based on heavy-duty vehicles) and U.C. Riverside CE-CERT[23] (based on light-duty vehicles) are compared to MOBILE6 in Table 3-6. There is a relatively good agreement among these estimates.

Tire wear and brake wear particle size distributions are also presented in Table 3-6, which shows greater variability in these particle size distributions when MOBILE6 is compared to other available data. This is particularly true of tire wear estimates, for which few data sources exist. The particle size distributions for brake wear suggest that MOBILE6 may overestimate the fraction of total PM that is PM10, while the MOBILE6 PM2.5 fraction falls between estimates reported in 2000 by researchers at General Motors[18] and in 2003 by researchers at Ford Motor Company.[26]

Table 3-6
Comparison of MOBILE6 Particle Size Distributions to Other Published Sources

Emission Type	Source of Estimate	Fraction ≤ 10 µm	Fraction ≤ 2.5 µm
Gasoline Exhaust (Non-Catalyst)	MOBILE6	0.90	0.68
	CE-CERT[23]	0.96	0.90
	CE-CERT[24]	0.96	0.93
Gasoline Exhaust (Catalyst-Equipped)	MOBILE6	0.97	0.90
	CE-CERT[23]	0.96	0.91
	CE-CERT[24]	0.97	0.94
Diesel Exhaust	MOBILE6	1.00	0.92
	TNRCC[25]	1.00	0.98
	CE-CERT[24]	0.99	0.95
Tire Wear	MOBILE6	1.00	0.25
	Fauser[27]	92% < 1 µm	
	Fishman and Turner[14]	PM2.5/PM10 Ratio = 0.2	
Brake Wear	MOBILE6	0.98	0.42
	General Motors[19]	0.86	0.63
	Ford Motor Co.	0.80	0.15

MOBILE6 Output

MOBILE6 was run in its default configuration to generate estimates of PM10, SO_2, and ammonia. These estimates were prepared for different vehicle classes as a function of model year as well as calendar year. The model year estimates provide a good illustration of how changes in technology and emission standards impact tailpipe emissions, while the calendar year results show the impact of fleet-turnover on fleetwide emissions (i.e., the calendar year results reflect the average emission rate of the whole fleet of vehicles on the road, which is assumed by MOBILE6 to be made up of 25 model years; thus, a calendar year 2000 run consists of vehicles from the 1976 through 2020 model years).

Gasoline Vehicle PM10 Estimates - Figure 3-1 shows PM10 emissions as a function of model year for the LDGV vehicle class. As observed in the figure, estimates are shown for model years 1970 through 2010, and separate estimates are presented for exhaust PM and brake/tire wear. The large drop in exhaust emissions seen in the 1975 model year is a result of the introduction of catalysts and the use of unleaded fuel, while the gradual decline in emissions throughout the 1980s is a result of reductions in particulate sulfate as fewer vehicles in the fleet are equipped with air injection (see Table 3-3). Emissions continue to decline between 2001 and 2006 as the Tier 2 gasoline sulfur limits are implemented, resulting in a decrease in particulate sulfate emissions. It is interesting to note that the model estimates that brake wear and tire wear emissions are greater than exhaust emissions beyond the 1981 model year.

Figure 3-1

MOBILE6 PM10 Emissions vs. Model Year for LDGVs

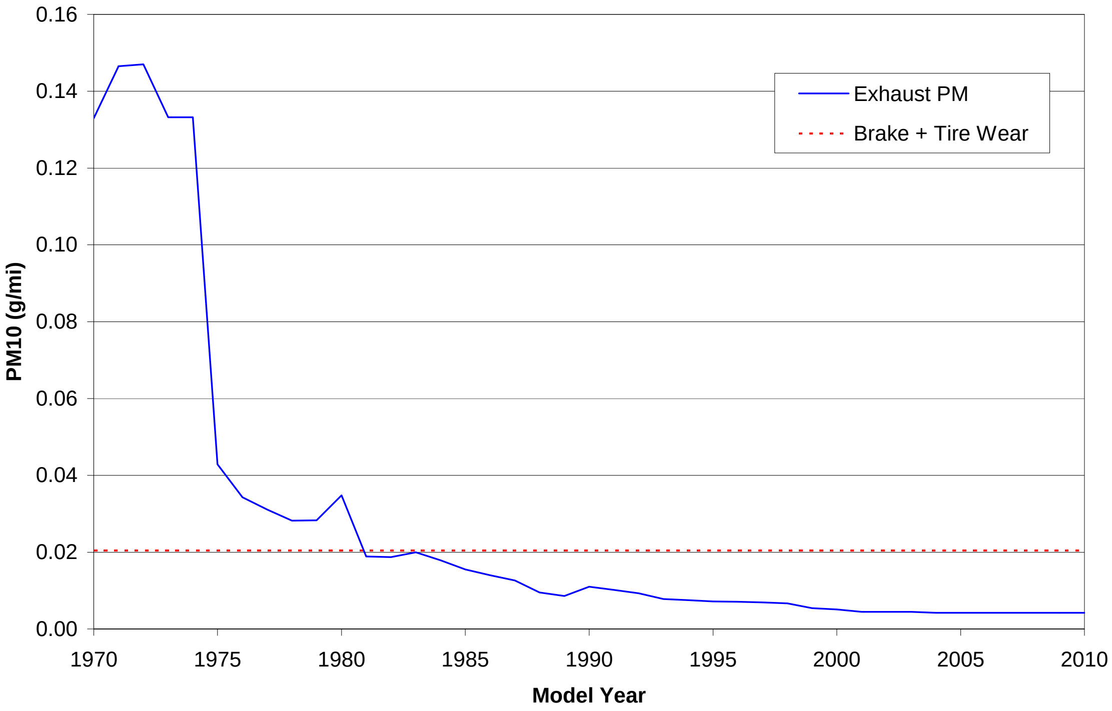


Figure 3-2 shows PM10 emissions for LDGVs as a function of calendar year for 1975 through 2020. The steep decline in emissions between 1975 and 1990 is a result of fleet turnover, i.e., older non-catalyst vehicles (with high emissions) are being replaced by newer catalyst-equipped vehicles. For this vehicle class, exhaust PM emissions are estimated to fall below brake and tire wear emissions by 1989.

Figure 3-2

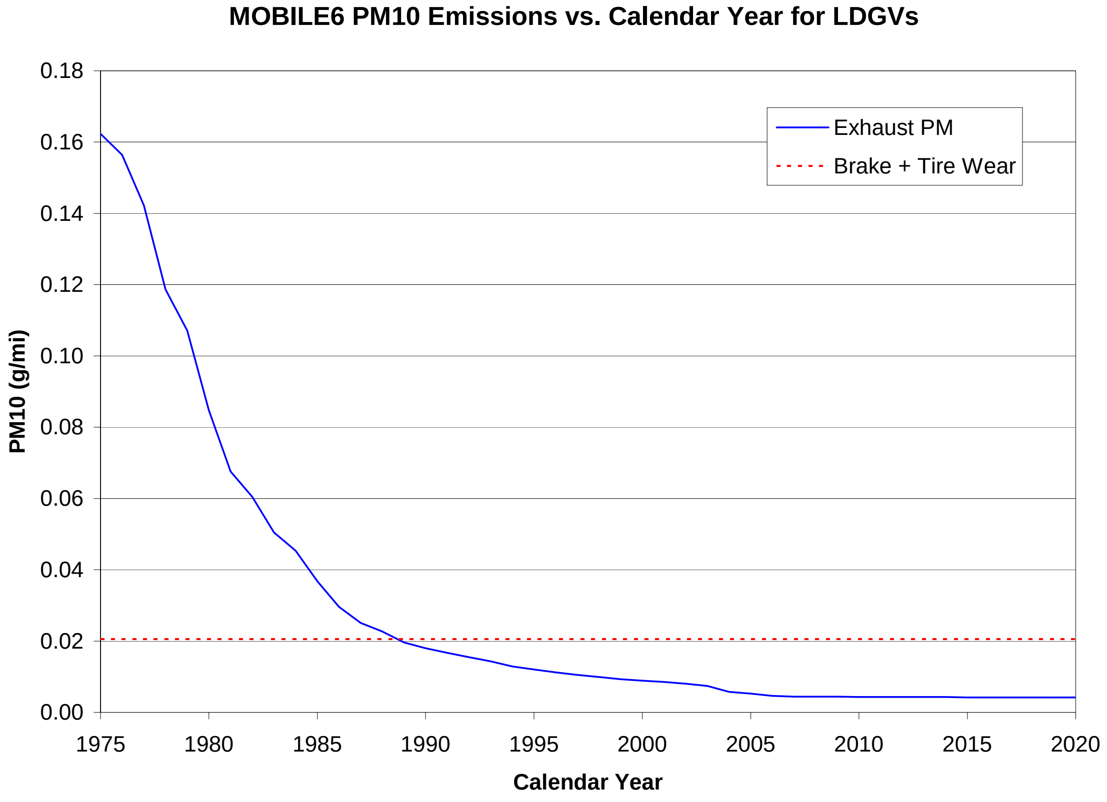


Figure 3-3 shows PM10 emissions for the lightest class of heavy-duty gasoline vehicles, class 2B HDGVs, which have a GVWR of 8,501 to 10,000 lbs This class was selected to be illustrative of heavy-duty gasoline vehicles because it has the largest sales and VMT fraction of all HDGV classes. The HDGV2B vehicles have exhaust PM emission rates that are about three times greater than LDGVs. Figure 3-3 shows a steady decline in exhaust PM10 emissions between 1970 and 1986, with a sharp drop in 1987. The steady decline between 1970 and 1986 is primarily a result of reductions in lead content of leaded fuel, while the sharp drop in 1987 is a result of hydrocarbon and carbon monoxide emissions standards that forced catalysts on this vehicle class. The sharp decline between 2006 and 2007 is a result of particulate standards that are to be implemented with the 2007 heavy-duty rule. As noted above, however, it is unclear that this level of reduction will be observed, or whether this is an artifact of the model. Emissions versus calendar year for this vehicle class are illustrated in Figure 3-4, which shows a similar trend as the calendar year emissions of LDGVs, except that the rate of emissions reductions is not as steep.

Figure 3-3

MOBILE6 PM10 Emissions vs. Model Year for Class 2B HDGVs

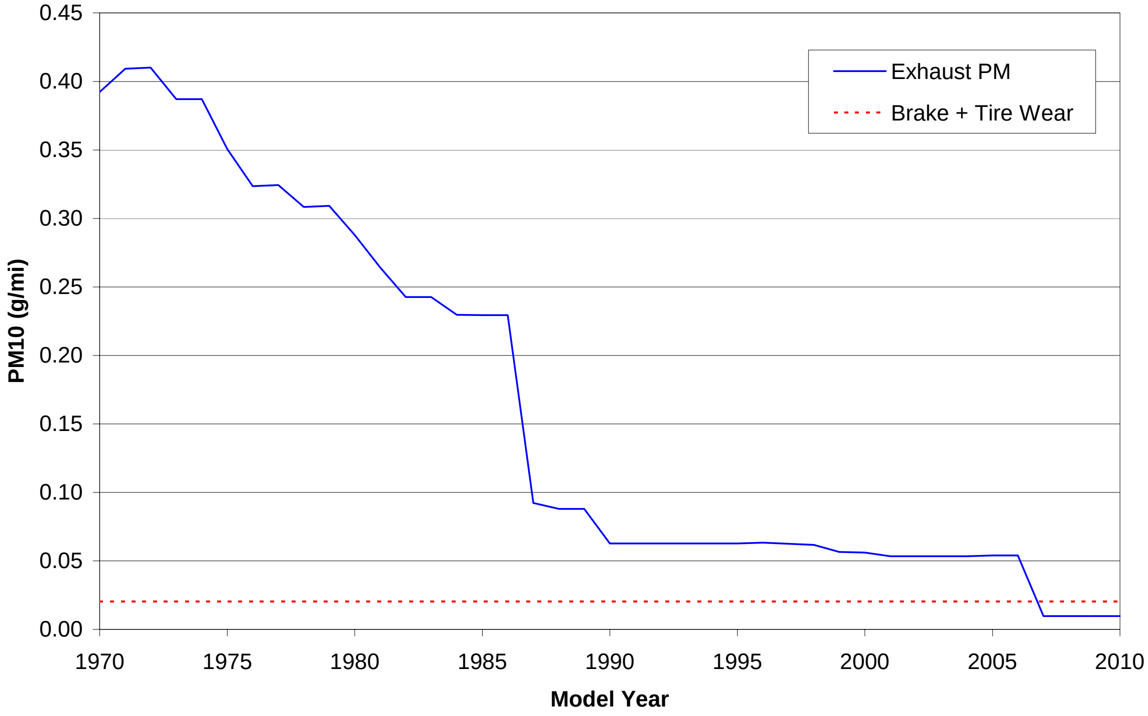
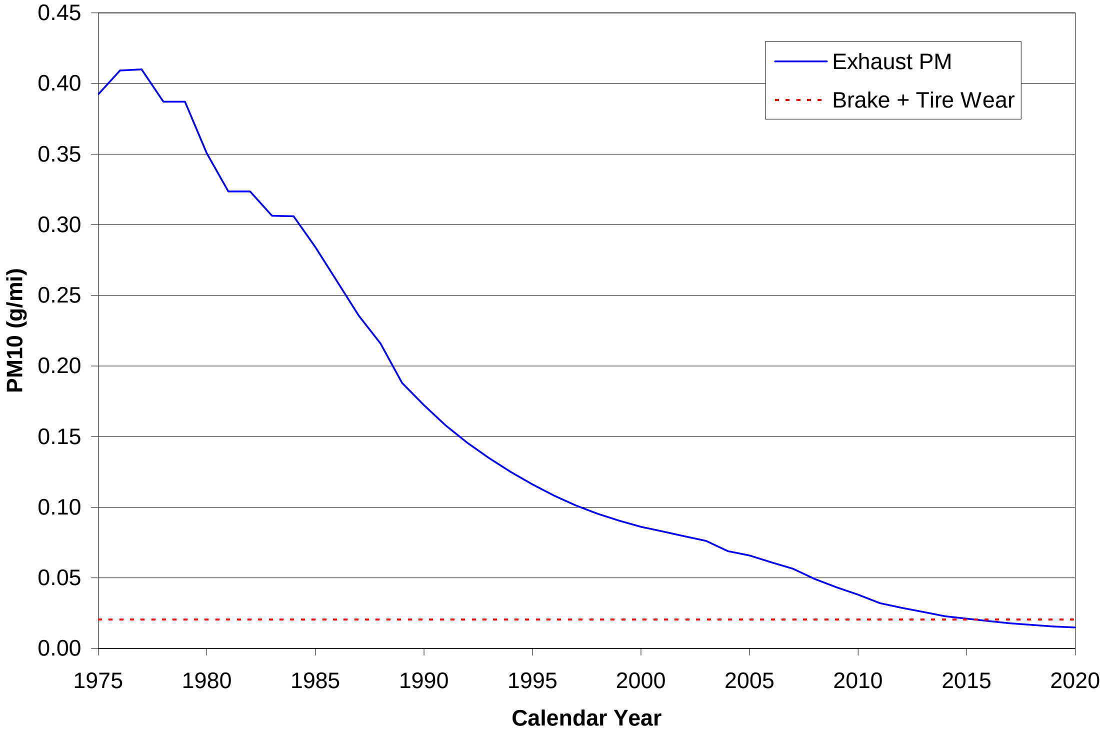


Figure 3-4

MOBILE6 PM10 Emissions vs. Calendar Year for Class 2B HDGVs



Diesel Vehicle PM10 Estimates - PM10 emissions estimates are presented in separate charts below for three Diesel vehicle classes: (1) light-duty Diesel trucks between 6,001 and 8,500 lbs GVWR (LDDT34); (2) class 2B heavy-duty Diesel vehicles (8,501 to 10,000 lbs GVWR); and (3) Class 8B heavy-duty Diesel vehicles (i.e., over 60,000 lbs GVWR). The LDDT34 and HDDV2B classes were selected for illustration because those are currently the most popular "light-duty" vehicle classes in which Diesel engines are used. Although technically the HDDV2B class is a heavy-duty vehicle, the vehicles in this size range are the larger pick-up trucks (e.g., Chevrolet Silverado 2500, Ford F250, etc.) and SUVs (e.g., Ford Excursion). In fact, the majority of "light-duty" trucks that offer a Diesel option are actually in the HDDV2B class because they are subject to less stringent NOx requirements relative to true light-duty trucks. Class 8b HDDVs (e.g., 18-wheel tractor-trailer rigs) were selected for illustration because they account for most of the VMT in the Diesel vehicle classes.

Figure 3-5 shows PM10 emissions versus model year for LDDT4 and HDDV2B vehicle classes. As with the gasoline vehicle PM emission rates, the Diesel vehicle PM emission rates are a strong function of model year. With the gasoline vehicles, however, PM emissions were reduced as a result of regulations aimed at controlling HC, CO, and NOx emissions (e.g., catalysts required to control HC and CO had a secondary benefit of controlling PM as did gasoline sulfur controls implemented as part of the Tier 2 rulemaking), while specific PM standards have been implemented to control exhaust PM from Diesel vehicles. As observed in Figure 3-5, implementation of more stringent PM standards for HDDV2B vehicles has generally lagged implementation for the LDDT34 class.

Figure 3-5

MOBILE6 PM10 Emissions vs. Model Year for LDDT34s and Class 2B HDDVs

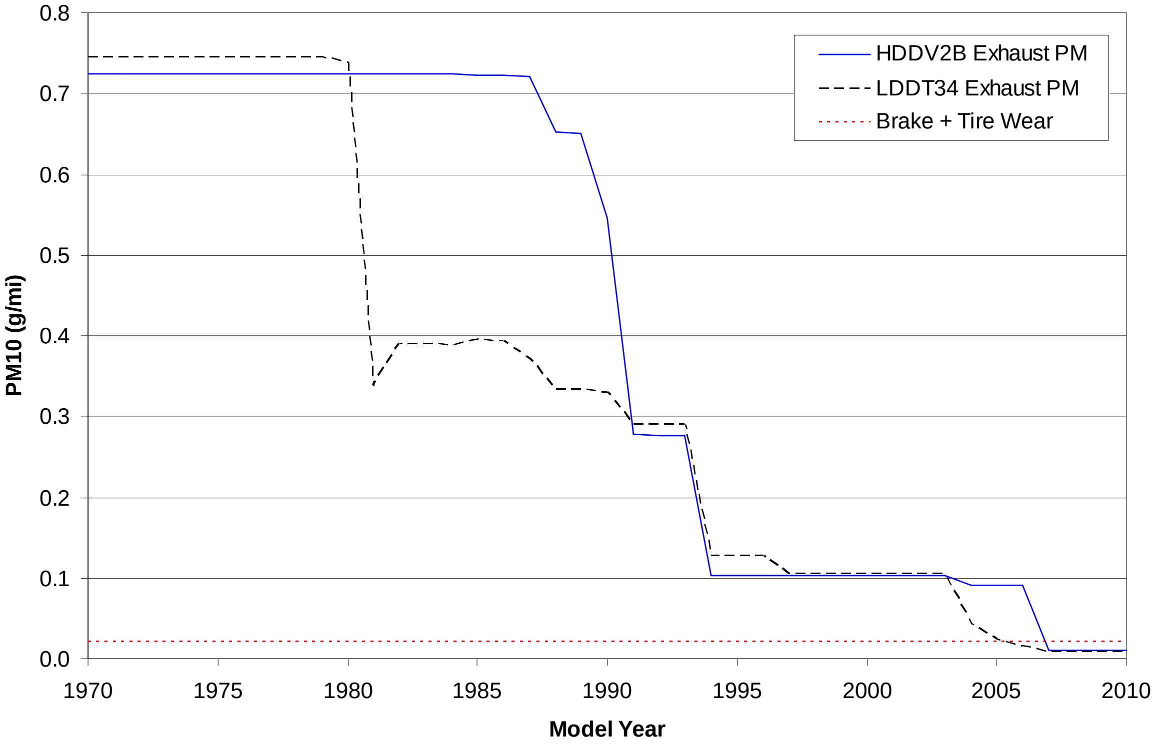


Figure 3-6 shows the MOBILE6 PM10 emission rates versus model year for class 8B HDDVs. Prior to the 1988 model year, exhaust PM10 emissions averaged approximately 2.2 g/mi, which is about 100 times greater than exhaust PM from a catalyst-equipped gasoline light-duty vehicle. After 1987, however, exhaust PM is estimated to decrease substantially as a result of PM standards implemented by EPA and the California Air Resources Board (CARB). In addition, Diesel sulfur controls were implemented federally in 1993, which resulted in a decrease in sulfate particulate. PM emissions from 1995 to 2006 model year vehicles are about 90% lower than pre-control levels, and the 2007 standards will result in another 90% reduction from 2006 levels.

With the implementation of the 2007 standards, MOBILE6 estimates that exhaust PM from HDDV8B vehicles will be lower than brake wear and tire wear emissions. As noted above, however, the brake wear estimates in MOBILE6 for all vehicle classes are based on <u>passenger car testing</u> and do not account for the increased mass carried by Class 8B HDDVs. Assuming a loaded vehicle weight of 80,000 lbs and an unloaded weight of 30,000 lbs, the average vehicle weight would be 55,000 lbs, or 10 times that of a passenger car or light-duty truck. Thus, the brake wear emissions for HDDV8B trucks could be low by as much as an order of magnitude, at least in urban driving. If that is, in fact, the case, brake and tire wear emissions would be 0.16 g/mi, which is only about 25% lower than exhaust PM emissions for the 1995 through 2006 model year vehicles.

Figure 3-6

MOBILE6 PM10 Emissions vs. Model Year for Class 8B HDDVs

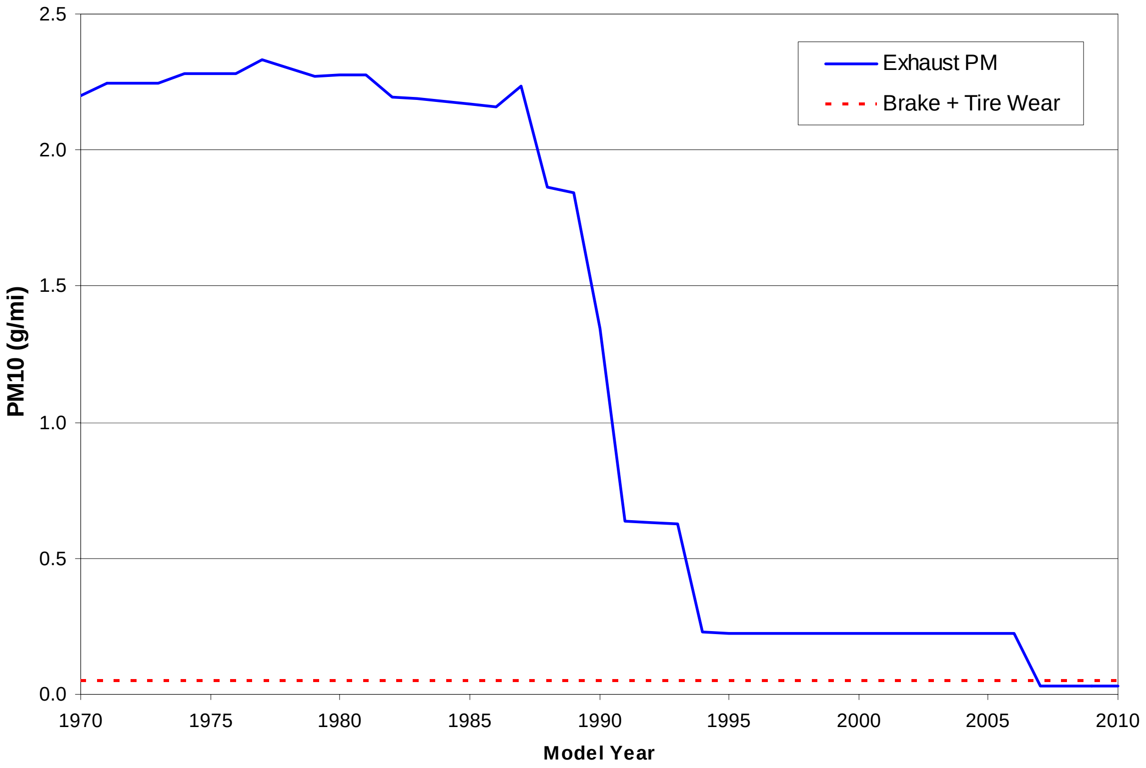
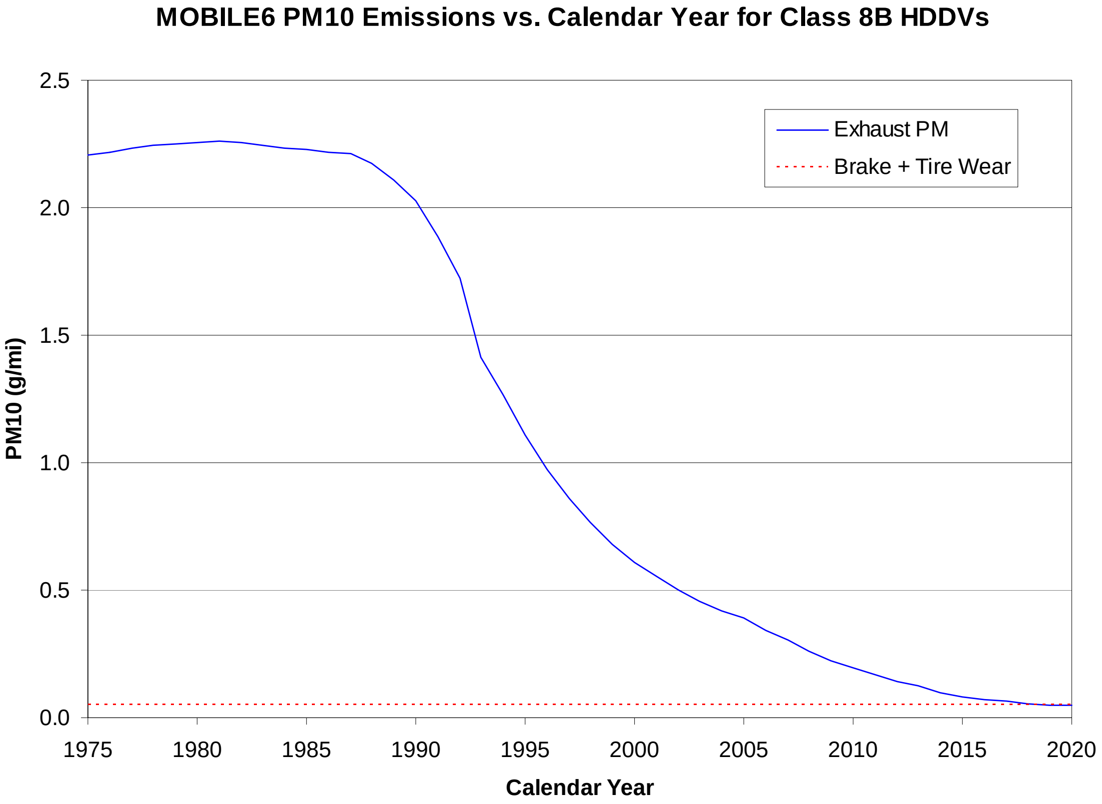


Figure 3-7 shows the MOBILE6-based fleet-average HDDV8B PM emission rates for calendar years 1975 through 2020. On a fleet basis, the uncontrolled emission rate of 2.2 g/mi is reduced by 50% by about 1995. By 2010, exhaust PM emissions are reduced by over 90% relative to uncontrolled levels, and additional reductions occur through 2020 as the 2007 heavy-duty rule is phased in.

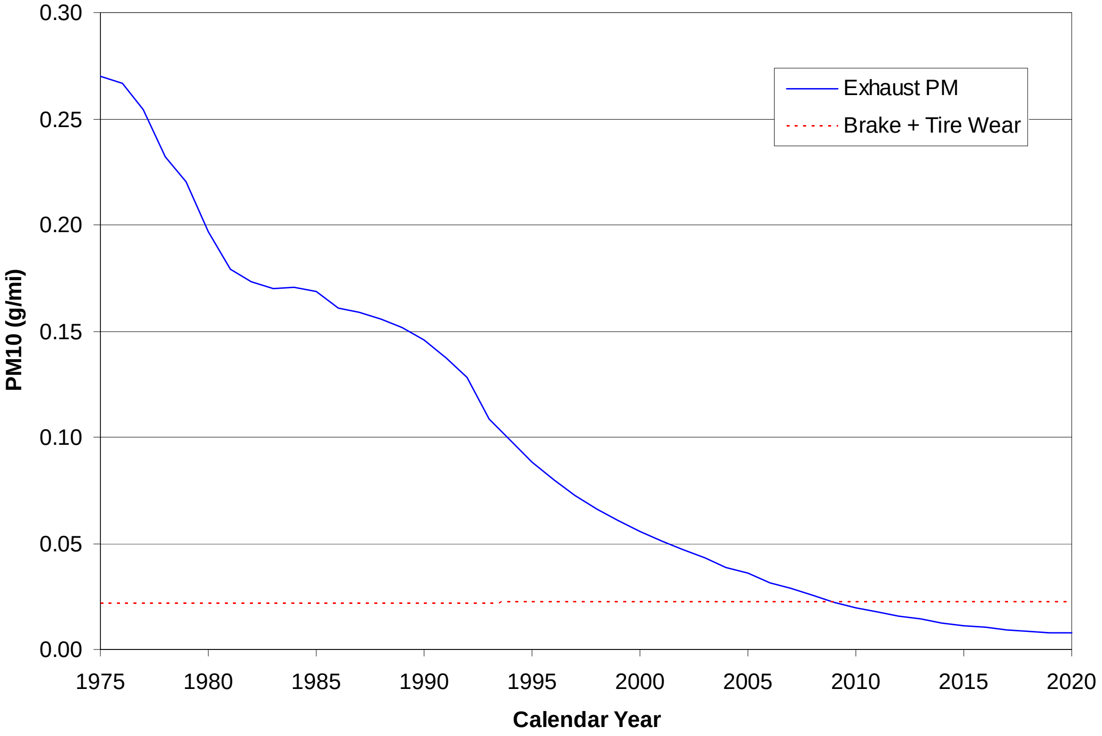
Figure 3-7



Fleet-average PM10 emissions calculated by MOBILE6 for the entire vehicle fleet are illustrated in Figure 3-8 for calendar years 1975 through 2020. Significant reductions in exhaust PM10 are modeled, resulting in a decrease of 80% between 1975 and 2000, and another 85% decrease between 2000 and 2020. As alluded to above, these reductions are a result of technology improvements (e.g., catalysts) as well as fuel modifications (e.g., removal of lead from gasoline and reduction in sulfur from both gasoline and Diesel fuel). It is important to note, however, that the reductions shown in Figure 3-8 (as well as the previous figures) do not reflect the growth in vehicle travel that has occurred since 1975 (and is expected to continue to occur) that somewhat mitigates the gains made in per-mile emissions reductions.

Figure 3-8

MOBILE6 PM10 Emissions vs. Calendar Year for All Vehicles



It is also interesting to investigate the contribution of individual vehicle types to the total on-road motor vehicle exhaust PM10 emission rate. For this analysis, four different vehicle categories were considered:

- Light-duty gasoline vehicles, trucks, and motorcycles (LDGV/T);
- Heavy-duty gasoline vehicles (all classes over 8,500 lbs GVWR);
- Light-duty Diesel vehicles and trucks (LDDV/T); and
- Heavy-duty Diesel vehicles (all classes over 8,500 lbs GVWR).

The results are presented in Figure 3-9 on an absolute g/mi basis (i.e., the vehicle-class specific g/mi values have been weighted by VMT such that the sum of the individual vehicle classes equals the fleet-average emission rate shown in Figure 3-8) and in Figure 3-10 on a relative contribution basis (i.e., the sum of the individual vehicle classes equals 100%). As observed in those figures, between 1981 and 2018, HDDVs are the largest contributors to on-road exhaust PM10, with light-duty vehicles being the largest contributors before and after that time period. Figure 3-10 shows that the contribution of HDDVs to exhaust PM10 increased steadily between 1975 and 1990, was relatively flat between 1991 and 2007, and decreased after 2007. The decrease in the HDDV contribution after 2007 is a direct result of the stringent PM emission standards adopted with the 2007 heavy-duty vehicle regulations.

Figure 3-9

MOBILE6 VMT-Weighted Exhaust PM Emissions Estimates by Vehicle Class for Calendar Years 1975 to 2020

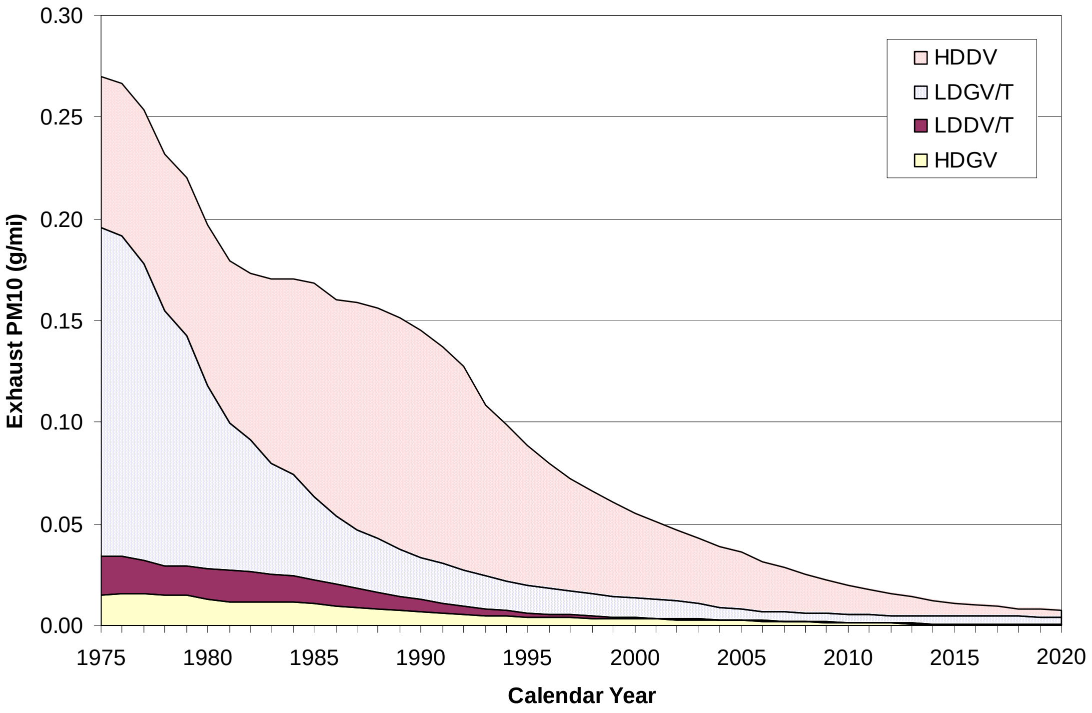
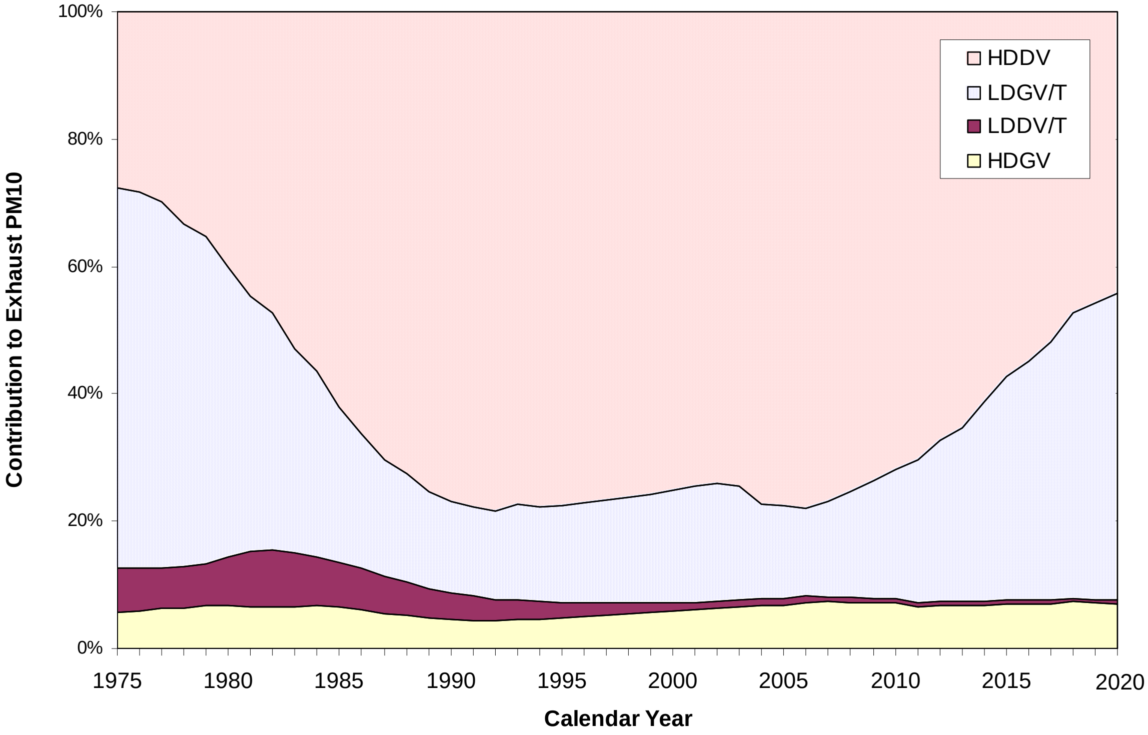


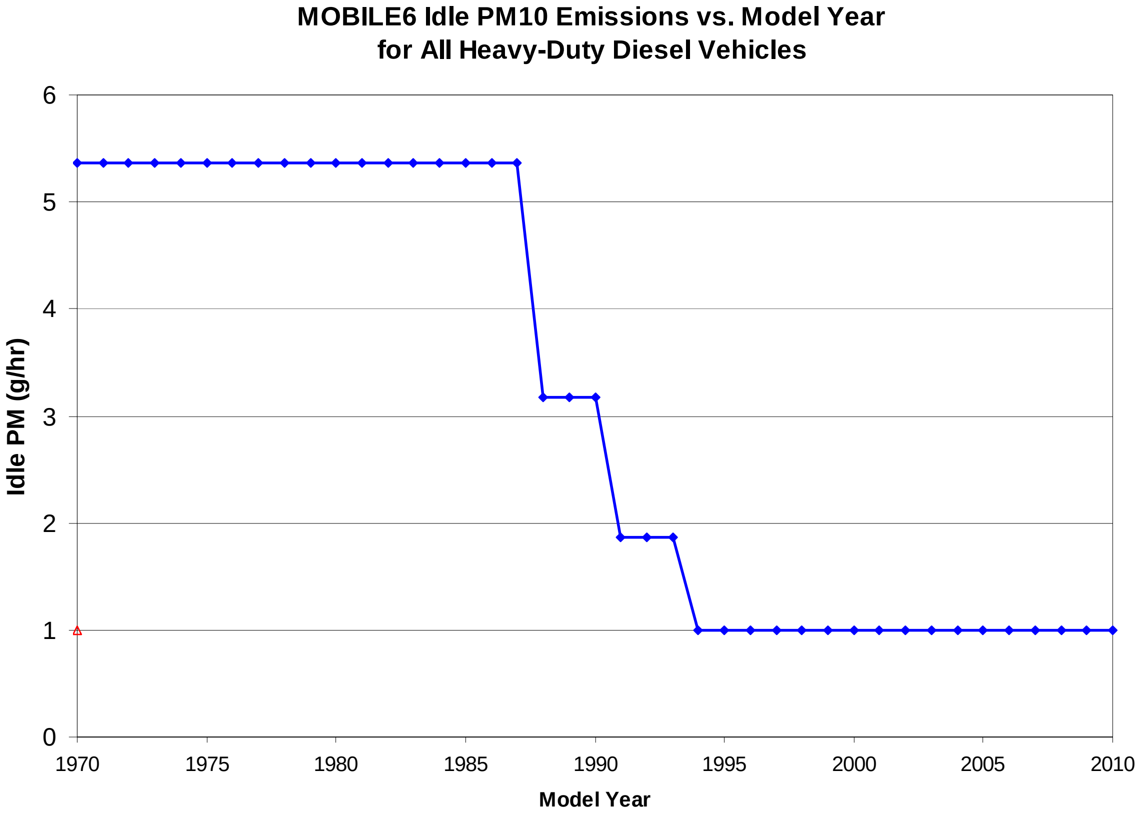
Figure 3-10

Contribution of Vehicle Classes to MOBILE6 Exhaust PM Emissions Estimates for Calendar Years 1975 to 2020



Idle Exhaust PM10 Estimates - In addition to generating estimates of exhaust PM during normal vehicle operation, MOBILE6 generates PM estimates during idle operation (reported in units of grams per hour). However, these estimates are prepared only for heavy-duty Diesel vehicles, and the same emission rates are applied to all heavy-duty Diesel vehicle classes. As a result, MOBILE6 likely overestimates idle PM from the lighter HDDVs, as the emission factors were based on testing of heavier HDDVs. Figure 3-11 illustrates the MOBILE6-based idle PM emission rates as a function of model year; those emission rates were copied over directly from PART5. Note that these estimates are not corrected for Diesel sulfur content, and they are not adjusted to account for the tighter PM standards required with the 2007 Diesel rule. However, the implementation of more stringent PM standards is accounted for through the 1994 model year.

Figure 3-11



SO$_2$ Estimates - As described above, gaseous SO$_2$ emissions are directly related to the quantity of sulfur in the fuel. For this analysis, the following Diesel fuel sulfur levels were assumed:

- Pre-1993 calendar years = 2500 ppm
- 1993 to 2006 calendar years = 300 ppm
- 2006 and later calendar years = 15 ppm

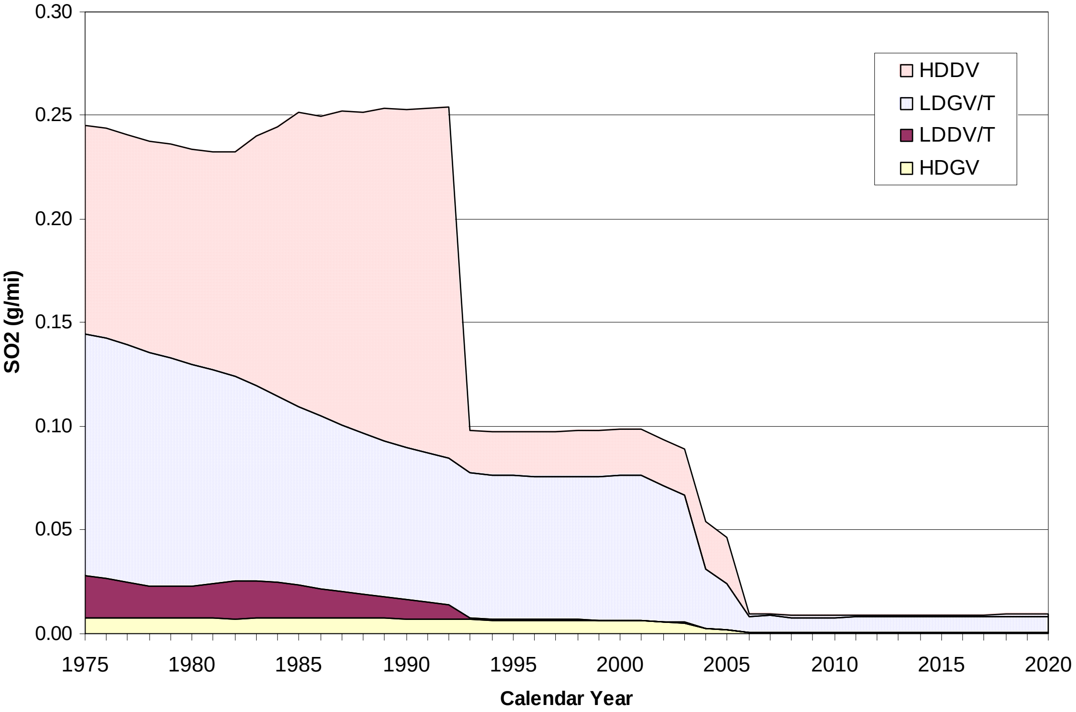
The change in 1993 reflects the federal requirement for a maximum sulfur level of 0.05% by weight (500 ppm) that took effect on October 1, 1993, with an added compliance cushion. (Fuel survey data show that most on-road Diesel fuel contains about 300 ppm sulfur.) The 15 ppm value modeled for 2006 and later calendar years reflects the 2007 low-sulfur Diesel rule that takes effect in the fall of 2006.

The default gasoline sulfur levels contained in MOBILE6 were used for this analysis, which assumes a 300 ppm sulfur level prior to calendar year 2001. Between calendar years 2001 and 2007, the model assumes a steady decline in gasoline sulfur content as the Tier 2 sulfur rules are phased-in. For 2008 and later calendar years, the model assumes an average gasoline sulfur content of 30 ppm.

The MOBILE6 SO_2 results are illustrated in Figure 3-12 as a function of vehicle class and calendar year. As observed in that figure, significant decreases in HDDV SO_2 emissions occurred in 1993 and will occur again in 2006 as a result of sulfur limits in Diesel fuel. Between 2001 and 2008, gasoline vehicle SO_2 emissions are estimated to decrease substantially as a result of Tier 2 sulfur control.

Figure 3-12

MOBILE6 VMT-Weighted Gaseous SO2 Emissions Estimates by Vehicle Class for Calendar Years 1975 to 2020



Ammonia Estimates - The ammonia (NH3) emission factors in MOBILE6 are a strong function of technology, and gasoline vehicles equipped with three-way catalysts are estimated to have higher emission rates than other vehicles in the fleet. MOBILE6 estimates of NH3 emission rates by vehicle class are shown in Figure 3-13 for model years ranging from 1970 to 2010. As seen in that figure, NH3 emission rates are constant for heavy-duty gasoline vehicles and for Diesel vehicles across all model years, but there is a significant increase in the per-mile NH3 emission rate for LDGVs between 1979 and 1984. That increase reflects the phase-in of three-way catalyst technology, which was implemented to meet the 1.0 g/mi federal NOx standard that took effect with the 1981 model year.

The calendar year specific NH3 emission rates calculated by MOBILE6 are presented in Figure 3-14 as a function of vehicle class. Because light-duty gasoline vehicles and trucks account for roughly 90% of the overall VMT, and because those vehicles have been equipped with three-way catalyst technology since the early 1980s, the LDGV/T class contributes the vast majority of NH3 from on-road motor vehicles. The increase in NH3 emissions throughout the 1980s and 1990s is a result of fleet turnover, with nearly all LDGV/T vehicles being equipped with three-way catalysts by calendar year 2000. Note, however, that recent NH3 test data on newer technology vehicles seem to indicate that NH3 emissions are overstated in MOBILE6, and fleet-average NH3 emissions may, in fact, trend downward beginning in the 1990s.

Figure 3-13

MOBILE6 Gaseous NH3 Emissions vs. Model Year and Vehicle Class

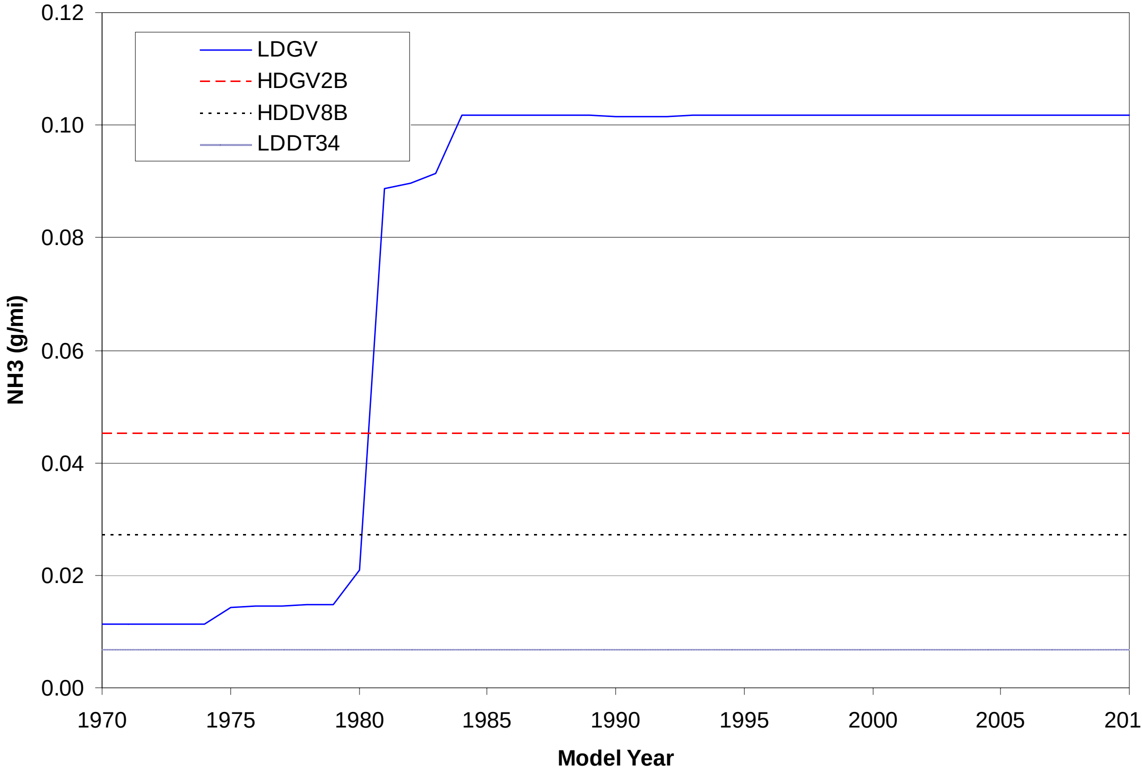
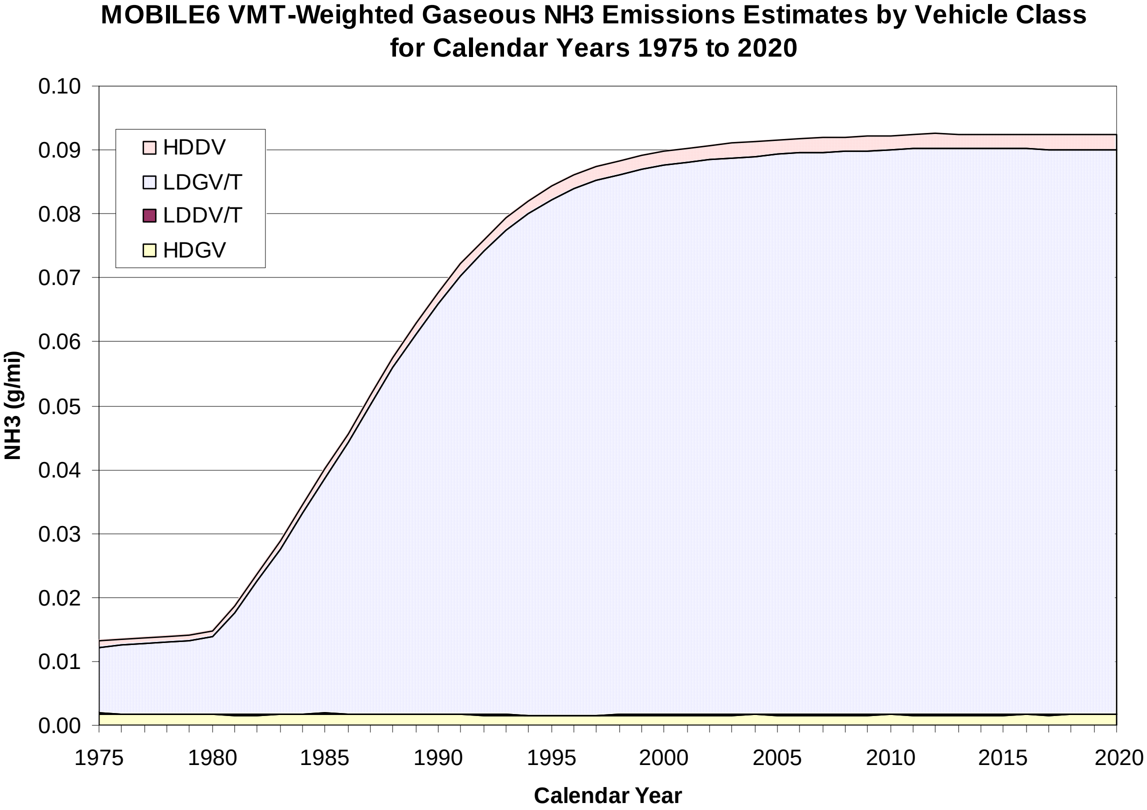


Figure 3-14



Comparison of MOBILE6 Exhaust PM Emission Estimates to Published Data

As noted above, the majority of inputs for the PM estimates in MOBILE6 have been carried over from PART5, and much of the data upon which PART5 was based were collected in the late 1970s and early 1980s. As such, the underlying data used in MOBILE6 are generally very dated. In the case of heavy-duty Diesel vehicles, EPA updated the emission factors based on engine test data submitted by manufacturers as part of the certification process (in units of g/bhp-hr), and used conversion factors to translate those results into g/mi values needed for the model. This method has been used for many years to generate emission factors for the MOBILE series of models; however, in recent years chassis dynamometer testing of heavy-duty vehicles has been conducted that measures emissions directly in terms of g/mi. This eliminates the need to convert the engine dynamometer-based emissions results to a g/mi basis, which is a potential source of error in the emission factors. In addition to recent PM testing conducted on heavy-duty vehicles, there have been a number of test projects conducted in the past seven years focused at measuring PM emissions from light-duty vehicles. This section of the report presents a comparison of exhaust PM emissions calculated with MOBILE6 to recently collected test data.

Light-Duty Gasoline Vehicles - Below is a summary of the more extensive PM test programs on light-duty gasoline vehicles that have been conducted over the past several years:

- CAWRSS (1997)[28] - As part of the Clark and Washoe County Remote Sensing Study (CAWRSS) conducted in 1994, 23 light-duty gasoline vehicles were tested over the IM240 test cycle. HC, CO, NOx, and PM10 emissions measurements were made on these vehicles. As vehicles were recruited on the basis of high HC or CO RSD readings, and 6 of the 23 vehicles tested were selected because they were smoking vehicles, this is not a randomly selected test group. Nonetheless, data from this program showed an extremely wide variability in PM10 emissions, ranging from 0.0056 g/mi to 1.3 g/mi, and were useful in spawning interest in additional PM testing of light-duty gasoline vehicles.

- CE-CERT (1998)[29] - Under contract to the California Air Resources Board, the College of Engineering Center for Environmental Research and Technology (CE-CERT) at U.C. Riverside tested 27 gasoline-fueled light-duty vehicles over the "Unified Cycle."[*] Vehicles in this program were randomly selected from a vehicle test matrix that was designed to be representative of the California vehicle fleet.

- CRC E-24-1 (1998)[30] - As part of CRC Project No. E-24-1, 111 light-duty vehicles (101 gasoline, 10 Diesel) were tested over the FTP and the IM240 in the summer portion of the test, and 84 vehicles (72 gasoline, 12 Diesel) were tested during the winter portion of the test, which was conducted in the Denver, Colorado area. Summer testing was conducted at a nominal temperature of 75ºF, while two sets of winter tests were performed on each vehicle: one outdoors at ambient temperature (averaging about 35ºF) and one indoors at 60ºF. Vehicles were randomly selected to fill a test matrix consisting of (1) 1991-1997 gasoline vehicles; (2) 1986-1990 gasoline vehicles; (3) 1981-1985 gasoline vehicles; (4) 1971-1980 gasoline vehicles; (5) 1971 or newer smoking vehicles; and (6) 1971 or newer Diesel vehicles. Because of concerns that a completely random recruitment effort would not capture enough vehicles in categories (5) and (6), special efforts were made to obtain these vehicles for testing. Note that the testing performed for this study was done at high altitude, and it is unclear how much PM emissions from gasoline vehicles are impacted by altitude.

- CRC E-24-2 (1998)[31] - The Coordinating Research Council and the South Coast Air Quality Management District sponsored PM testing of light-duty vehicles in the Los Angeles area in 1996 and 1997. A total of 129 light-duty gasoline vehicles were tested over the FTP in this effort, and 19 Diesel vehicles were also tested. Vehicles were primarily recruited randomly, but a subset of vehicles with high gaseous emissions were recruited based on RSD readings and other techniques (e.g., the use of a high emitter profile).

---

[*] The Unified Cycle, also known as the LA92, was developed from on-road measurements of speed using a chase car equipped with a laser range finder. The data were collected in Los Angeles in 1992, and the resulting test cycle was constructed to accurately represent the range of in-use driving observed in that program.

- CRC E-46 (1999)[32] - This project, also sponsored by the Coordinating Research Council, investigated the impact of driving cycles on PM emissions from light-duty gasoline vehicles. Thirty vehicles were tested in this program over the following three test cycles: FTP, UC, and REP05.[*] Testing was conducted at 35ºF with 24 properly functioning vehicles and 6 high CO emitters. Of the properly functioning vehicles, 12 were certified to Tier 0 emission standards from model years 1990-1995, and 12 were Tier 1 vehicles from model years 1994-1997. Five of the high CO emitters were Tier 0 vehicles and one was a Tier 1 vehicle. All vehicles were tested on oxygenated and non-oxygenated fuel.

- Environment Canada (1999)[33] - This study, prepared by Environment Canada, tested 75 light-duty gasoline vehicles over duplicate "Hot-505" test cycles.[**] The vehicles were recruited at random to represent the top 70% of the on-road fleet in British Columbia and included 1978 to 1998 model year vehicles. PM2.5 emissions were measured in this project, and emissions levels ranged from 0.0003 to 0.1 g/mi.

- CRC E-54 (2000)[34] - This CRC project, known as the Central Carolina Vehicle Particulate Emission Study, was conducted during the winter of 1999 and summer of 1999 by EPA in the Research Triangle Park area of North Carolina. A total of 120 light-duty gasoline and 4 light-duty Diesel vehicles were tested in each phase of the study over the IM240 cycle using EPA's transportable dynamometer. The average temperature during the winter testing was 63ºF and the summer testing averaged 78ºF. Vehicles were randomly selected to fill out a test matrix consisting of the following model year groups: (1) Pre-1982, (2) 1982-1986, (3) 1987-1991, and (4) 1992-1997.

- DOE Gasoline/Diesel Split Study (2003)[35] - This project is focused at quantifying the relative contribution of PM from gasoline and Diesel vehicles in the South Coast Air Basin. As part of this study, 57 light-duty gasoline vehicles were tested over the Unified Cycle.

- EPA Phoenix PM Test Program (2003)[36] - This test program was conducted in Phoenix, AZ, between December 2000 and April 2001. One hundred light-duty gasoline vehicles randomly recruited from the Mesa, Arizona, I/M test lane were tested in this effort. Vehicles were tested at a local emissions laboratory (ATL) using triplicate IM240s. The results were similar to those observed in the CRC E-54 program.

---

[*] The REP05 test cycle reflects very aggressive driving and was created during the development of the Supplemental Federal Test Procedure (SFTP) regulations.

[**] The Hot-505 uses the same speed-time trace as bags 1 and 3 of the FTP, but the vehicle is tested in a warmed-up condition.

Figure 3-15 compares MOBILE6 exhaust PM estimates for light-duty gasoline cars and trucks to the results from several of the test programs described above. This comparison is based on summertime conditions in calendar year 1997. (Note that 1997 was selected because it is roughly the timeframe in which the in-use data were collected.) As seen in that figure, MOBILE6 appears to overestimate exhaust PM emissions from newer vehicles, as results from all recent programs fall below the MOBILE6 estimates. However, for pre-1990 model years, the MOBILE6 predictions fall within the range of values reported in the recent test programs. As noted above, the results from CRC E-24-1 are based on testing performed at high altitude, and it is unclear how much this may impact PM emissions from gasoline-fueled vehicles.

Figure 3-16 shows MOBILE6 exhaust PM estimates compared to the wintertime testing that has been conducted in CRC E-24-1 and CRC E-54 projects. It is interesting to note that MOBILE6 appears to underestimate exhaust PM emissions under wintertime conditions. Part of the reason for that is because MOBILE6 does not apply any type of temperature correction to PM estimates. However, recent data suggest that exhaust PM emissions increase with decreasing temperature, particularly during cold start conditions. Although not shown in Figures 3-15 and 3-16, recent data also suggest that oxygenated fuels help reduce PM emissions from light-duty gasoline vehicles. That is also not accounted for in the MOBILE6 model.

Figure 3-15

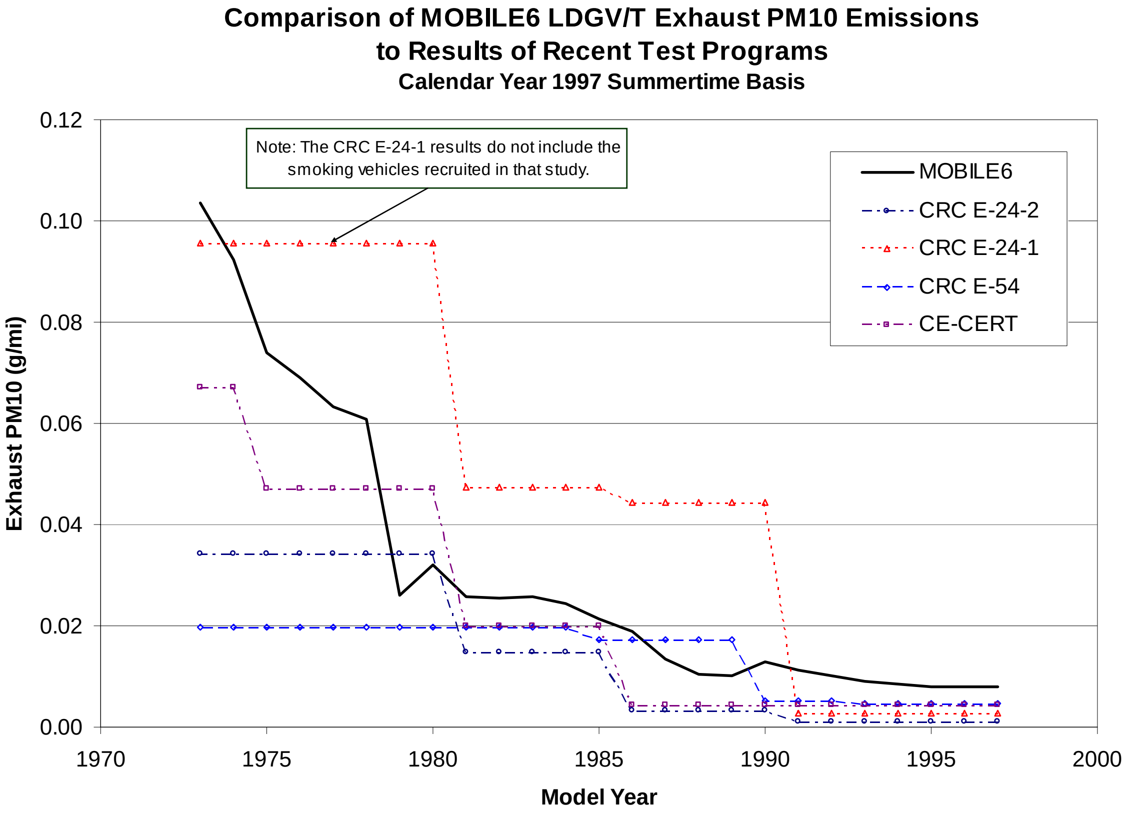
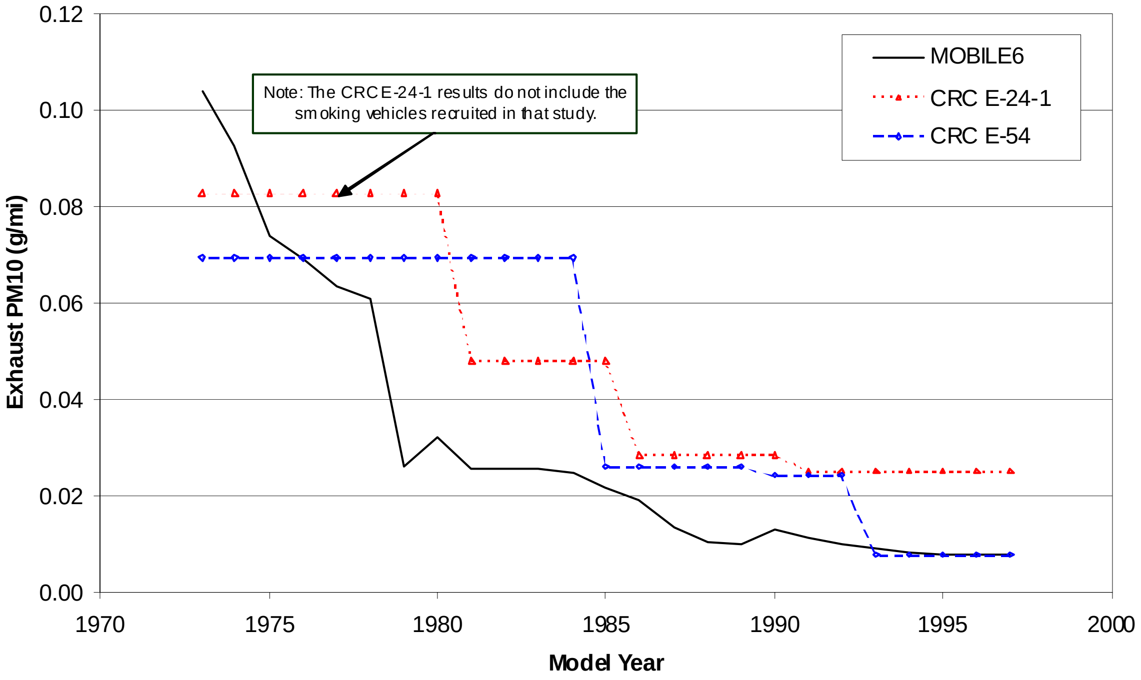


Figure 3-16

Comparison of MOBILE6 LDGV/T Exhaust PM10 Emissions to Results of Recent Test Programs

Calendar Year 1997 Wintertime Basis



As noted above, EPA has plans to conduct an extensive PM test program in Kansas City this summer to help answer remaining questions regarding PM from light-duty gasoline vehicles. In particular, it will be extremely important to obtain a better understanding of the frequency of visibly smoking vehicles in the fleet. As these vehicles can have PM emission rates over 100 times higher than a normal emitting vehicle, assumptions regarding the frequency of their occurrence in the fleet have a major impact on fleet-average emissions estimates.

<u>Heavy-Duty Diesel Vehicles</u> - In addition to recent PM testing of gasoline-fueled vehicles, there has been considerable activity related to testing heavy-duty Diesel vehicles in recent years. Much of this testing has been done by West Virginia University (WVU) with a portable chassis dynamometer. Thus, those data reflect a significant departure from historical data in that entire vehicles are tested on a chassis dynamometer rather than just the engine on an engine dynamometer.

In 2000, the California Air Resources Board updated the heavy-duty Diesel vehicle exhaust PM estimates in its on-road motor vehicle emissions model, EMFAC2000. As part of that update, CARB staff compiled emissions data from several test programs in which heavy-duty vehicles had been tested on a chassis dynamometer. As outlined in its technical support document describing the data and methodologies used to develop EMFAC2000,[37] the following data sources were available with which to update the HDDV emission rates:

- NYSDEC - The New York State Department of Environmental Conservation (NYSDEC) sponsored a test program conducted by WVU to collect emissions data on 35 heavy-duty Diesel vehicles on various chassis dynamometer test cycles. One of those cycles was the EPA's Urban Dynamometer Driving Schedule (UDDS), which can be used for vehicle certification and was developed from in-use vehicle activity data. As part of CARB's update of EMFAC2000, test data collected on the UDDS were included in their analysis.

- NFRAQS - As part of the larger Northern Front Range Air Quality Study (NFRAQS), emissions testing was conducted on heavy-duty Diesel vehicles by the Colorado School of Mines.[38] Eleven vehicles in this program were tested on the UDDS and were used in CARB's analysis. As these vehicles were tested at high altitude, however, CARB adjusted the results for low-altitude operation based on correction factors developed by EPA.[39] For PM, the ratio between high-altitude and low-altitude emissions was determined by EPA to be 1.47.

- WVU - According to the EMFAC2000 Technical Support Document, data on four additional heavy-duty Diesel vehicles were obtained directly from West Virginia University.

- CE-CERT - Two projects conducted by CE-CERT at U.C. Riverside included testing of light-heavy-duty Diesel vehicles that CARB included in its EMFAC2000 update. The first was sponsored by EPA and investigated the impacts of payload on emissions (five vehicles). The second was sponsored by the South Coast Air Quality Management District and included testing of 15 vehicles.[40] These vehicles, which ranged between 8,500 and 11,000 lbs GVWR, were tested over the light-duty vehicle FTP.

The data outlined above are attractive for use in emissions modeling because they have been collected on the same driving schedule (within weight categories) and they have been extensively peer-reviewed. In addition, because they were collected on a chassis dynamometer, there is no need to apply conversion factors to obtain g/mi results.

In addition to the above test programs, a number of other studies have recently been published on heavy-duty Diesel vehicle PM testing. This includes testing conducted as part of the DOE's Gasoline/Diesel PM Split Study (discussed above) in which 32 heavy-duty Diesel vehicles were tested over a number of different test cycles.

The data compiled by CARB for EMFAC2000 were analyzed by Sierra to generate mean PM emissions estimates as a function of model year group. Figure 3-17 compares those results to MOBILE6 output for light-heavy HDDVs (i.e., MOBILE6 Class 2B HDDVs), and Figure 3-18 presents the results for heavy-heavy HDDVs (MOBILE6 Class 8B HDDVs). For the lighter HDDVs, it appears that MOBILE6 is overestimating PM10 emissions, while for the heavy HDDVs, MOBILE6 may be underestimating PM10 emissions. In both cases, however, both MOBILE6 and the available emissions data track changes in certification standards.

Figure 3-17

Comparison of MOBILE6 HDDV2B Exhaust PM Emissions to Results of Recent Test Programs

Figure 3-18

Comparison of MOBILE6 HDDV8B Exhaust PM Emissions to Results of Recent Test Programs

Review of CARB's EMFAC Model Predictions and Comparison to MOBILE6

During the development of MOBILE6, EPA had stated that it would use PM emission factors from CARB's EMFAC2000 model to update the PART5 estimates for MOBILE6.[41] At that time, EPA indicated a desire to use those emission factors because they were based on recent test programs, many of which were discussed in the previous section of this report. However, EPA ultimately decided to continue using the exhaust PM emission rates used in PART5, with relatively little modification.

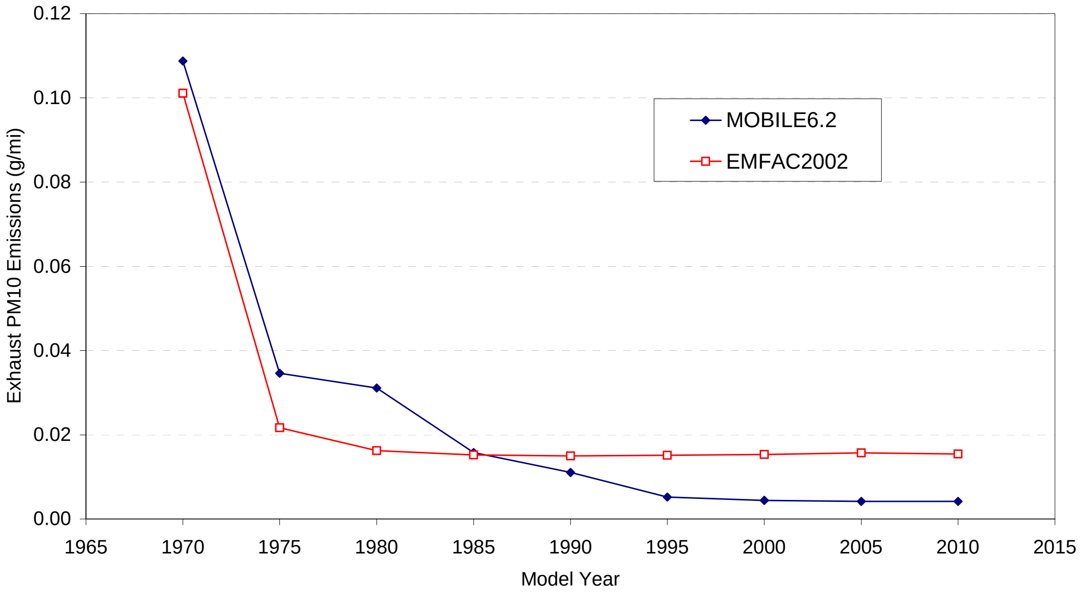
Similar to PART5 and MOBILE6, the EMFAC model generates estimates of exhaust PM, lead, and brake and tire wear PM. The evolution from its predecessor MVEI7G to EMFAC2000 included an update of most of the model's emission factors. The most recent version of the EMFAC model, EMFAC2002 (dated April 2003), uses the same PM emission rates developed for EMFAC2000. Detailed discussions of most of the PM emission rates used in EMFAC are described in various sections of CARB's EMFAC2002 Technical Support Document for the model.[42,43] Comparisons of exhaust PM10 emissions estimated by EMFAC2002 and MOBILE6 are presented below for several vehicle classes. Each vehicle class comparison is described separately.

Gasoline Passenger Cars - Exhaust PM results from EMFAC2002 and MOBILE6 runs as a function of model year are shown in Figure 3-19.[*] Because MOBILE includes lead (Pb) emissions when it reports total exhaust PM for gasoline vehicles, the lead emissions in EMFAC were added to the reported non-lead exhaust PM10 emissions of gasoline passenger cars. The large decrease in emissions between model years 1970 and 1975 reflects the shift from non-catalyst vehicles to mostly catalyzed vehicles. The continued decrease in exhaust PM10 over time results from improvements in fuel and further improvements in vehicle technology. As shown in Figure 3-19, EMFAC2002 predicts lower emissions for vehicles prior to model year 1985 and higher emissions for model years beyond 1985. This is primarily because of the use of much different data sets to develop emission factors between EMFAC2002 (which is based on more recent test data) and MOBILE6. Note, however, that the EMFAC predictions for gasoline-fueled light-duty vehicles are based on very rough estimates of the fraction of smoking vehicles in the fleet. Because smoking vehicles contribute significantly to the fleet-average emission rate, the emission rate is very sensitive to assumptions regarding how many of them there are in the fleet.

---

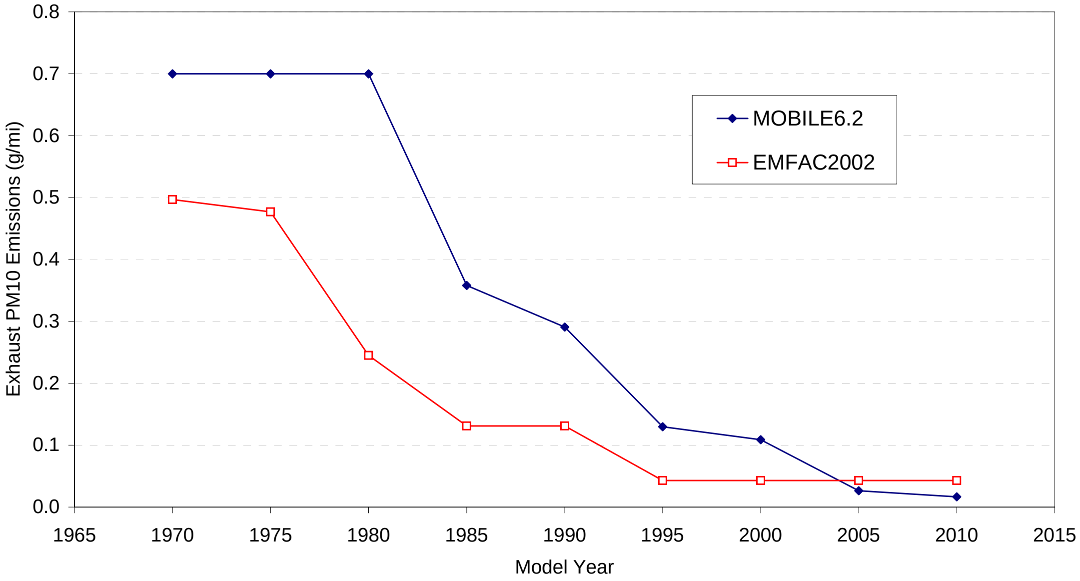
[*] Note that the model runs were prepared such that the vehicles were 10 years old, e.g., 1975 model year was evaluated in calendar year 1985. This was done so that emission control system deterioration is included in the estimates.

Figure 3-19
Gasoline Passenger Car PM10 Exhaust Emissions as a Function of Model Year
EMFAC2002 versus MOBILE6



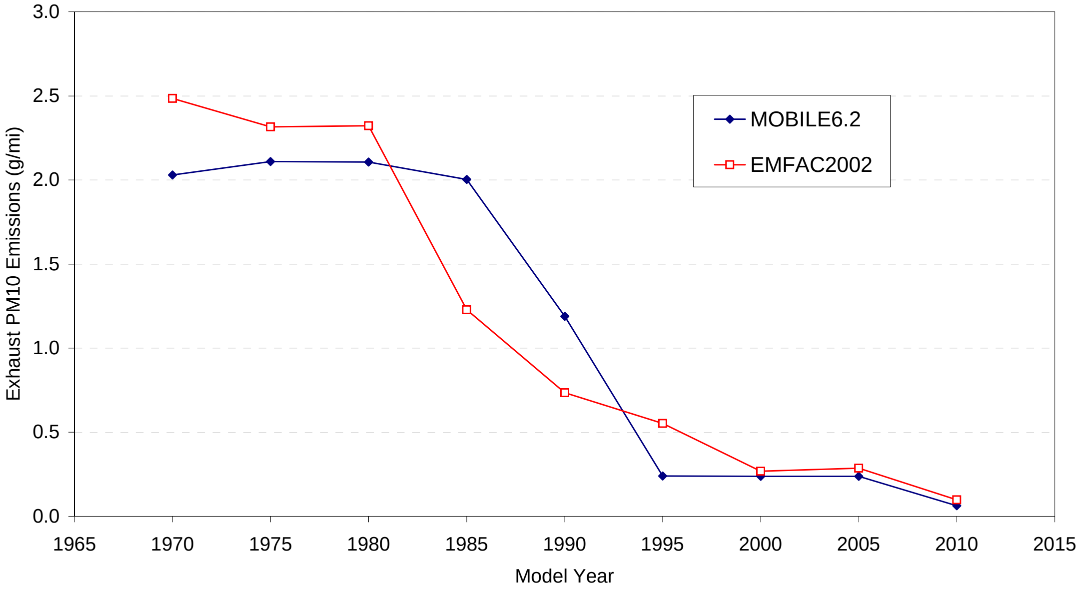
Light-Duty Diesel Trucks - Figure 3-20 presents a comparison of exhaust PM10 emissions versus model year for light-duty Diesel trucks (LDDTs). CARB assumed that there are no light-duty Diesel powered vehicles newer than model year 1995 in the in-use fleet in EMFAC. Consequently, no emission factors are reported by EMFAC for LDDTs after model year 1995. In Figure 3-20, the EMFAC PM emission rates for model years after 1995 were assumed to be equivalent to the 1995 level and therefore do not incorporate the impacts of the more stringent Tier 2 PM standards that become effective with the 2004 model year. As shown in the figure, exhaust PM10 emissions from both models continue to decrease in time as a result of improvements in both vehicle technology and fuel. However, MOBILE6 estimates much higher exhaust PM10 emissions compared to EMFAC2002 until model year 2005 when Tier 2 controls are assumed in the MOBILE6 estimates.

Figure 3-20
LDDT PM10 Exhaust Emissions as a Function of Model Year EMFAC2002 versus MOBILE6



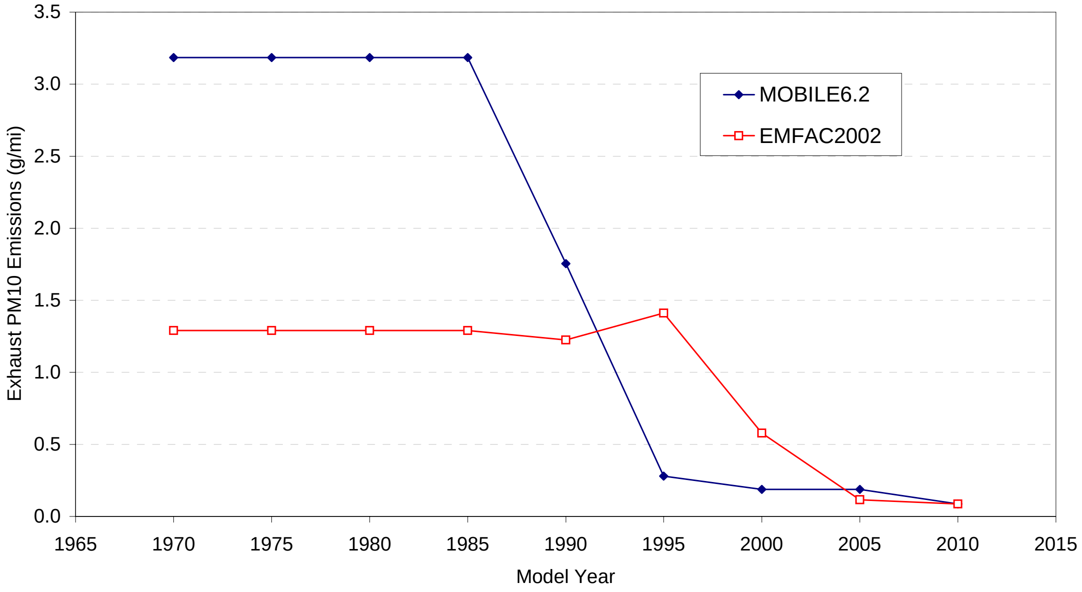
Heavy-Heavy-Duty Diesel Trucks - Results of the EMFAC2002 and MOBILE6 runs for heavy-heavy-duty Diesel trucks (HHDDTs, which are equivalent to MOBILE6 Class 8B and Class 8B trucks) are shown in Figure 3-21. The exhaust PM10 emission predictions from both models continue to decrease in time as a result of improvements in both vehicle technology and fuel. The EMFAC estimates are higher than MOBILE6 for 1980 and older model years and 1995 and newer model year vehicles. For 1985 and 1990 model years, the EMFAC predictions are lower than MOBILE6. This is not entirely consistent with the data used to develop the emission factors for EMFAC2002 (see Figure 3-18), and it is likely a result of various correction factors applied within the EMFAC2002 model (e.g., for low aromatic Diesel fuel required in California).

Figure 3-21
HHDDT PM10 Exhaust Emissions as a Function of Model Year
EMFAC2002 versus MOBILE6



Diesel Urban Buses – Figure 3-22 shows a comparison of PM10 exhaust emissions modeled by EMFAC2002 and MOBILE6 for Diesel urban buses. For older buses, MOBILE reports much higher emissions until model year 1990. Note, however, that the EMFAC-based emission rates were developed from chassis dynamometer test data collected over the Central Business District (CBD) test cycle, which was designed to simulate transit bus operation in a downtown business district. On the other hand, the MOBILE6 emission factors were based on engine dynamometer data collected from testing on the transient certification cycle that were then converted to a g/mi basis using conversion factors. Thus, the EMFAC results are likely a more realistic estimate of PM emissions from Diesel urban buses.

Figure 3-22
Diesel Urban Bus PM10 Exhaust Emissions as a Function of Model Year
EMFAC2002 versus MOBILE6



4. AIR TOXICS EMISSIONS ESTIMATES (MOBILE6.2)

This section of the report presents a review of the algorithms used in MOBILE6.2 to estimate emissions of air toxics. In addition, a number of model runs are performed to determine the impacts of changes in fuel formulations on air toxics emissions from motor vehicles.

Background

The 1990 Amendments to the Clean Air Act added requirements for hazardous air pollutants (HAPs), or air toxics. For the most part, those requirements are spelled out in Section 112, which focuses on stationary and area sources. In addition, other sections of the Act include provisions for air toxics. In particular, Section 202(l) contains two requirements specific to motor vehicles:

- By May 15, 1992, EPA was to complete a study of the need for, and feasibility of, controlling emissions of toxic air pollutants associated with motor vehicles and motor vehicle fuels. That study was to focus on the categories of emissions that pose the greatest risk to human health (or about which significant uncertainties remain), including benzene, formaldehyde, and 1,3-butadiene.
- By May 15, 1995, EPA was to promulgate regulations containing reasonable requirements to control HAPs from motor vehicles and motor vehicle fuels. At a minimum, those regulations were to apply to benzene and formaldehyde.

The result of the first directive was the “Motor Vehicle-Related Air Toxics Study,” (MVRATS) finalized by EPA in April 1993.[44] As part of that study, EPA developed a toxics routine for the MOBILE4.1 model and named that toxics model MOBTOX. MOBTOX was able to calculate emissions of benzene, 1,3-butadiene, formaldehyde, and acetaldehyde. Toxics emission rates were calculated by applying a “toxics fraction” to the gram per mile (g/mi) total organic gas (TOG) emission rate generated by the model. For example, if the TOG exhaust emission rate was calculated to be 1 g/mi, and benzene made up 4% of TOG exhaust, the benzene emission rate was calculated to be 0.04 g/mi.

The result of the second directive above was EPA’s final rule regarding the control of emissions of HAPs from mobile sources, which was published in March 2001.[45] As part of that rulemaking, EPA developed a list of 21 toxic compounds that are emitted by on-road and off-road motor vehicles. These mobile source air toxics (MSATs) are summarized in Table 4-1. To support the development of the MSAT rule, as well as other assessments prepared by EPA in the late-1990s and early-2000s,[*] an air toxics

---

[*] Estimates of air toxics were developed for the Tier 2/Gasoline Sulfur rule, the 2007 Diesel rule, and for the 1996 National Toxics Inventory and National Scale Air Toxics Assessment.

model was developed based on MOBILE5b. That model, known as MOBTOX5b, calculated emissions of benzene, 1,3-butadiene, formaldehyde, acetaldehyde, and MTBE.

Table 4-1
EPA's List of Mobile Source Air Toxics (MSATs)

Formaldehyde	Arsenic Compounds	Styrene
Acetaldehyde	Nickel Compounds	Chromium Compounds
MTBE	Benzene	Manganese Compounds
Acrolein	n-hexane	Toluene
Ethylbenzene	POM	Dioxins/Furans
Napthalene	1,3-Butadiene	Mercury Compounds
Diesel PM + Diesel Exhaust Organic Gases	Lead Compounds	Xylene

The MOBTOX5b model was developed during 1998[46] and 1999.[47] At that time, MOBILE6 was not yet complete, but many of the revisions that were planned for MOBILE6 had been identified, and work had begun to develop revised inputs and algorithms for the model. Thus, the MOBTOX5b model accounted for the emissions impacts of revised base emission rates, off-cycle operation (i.e., air conditioning and aggressive driving effects), gasoline sulfur impacts, and revised data on fleet characteristics (e.g., registration distributions). Air toxics were calculated in a similar fashion as the MOBILE4.1 version of the model -- a toxics fraction was applied to TOG emission rates generated by the model. However, the toxics fractions for the MOBTOX5b model accounted for the impacts of specific fuel formulations and were developed from the relationships contained in the Complex model for reformulated gasoline (RFG).[48] (Note that MTBE is not included in the official release of the Complex model. Therefore, a draft fuel effects model developed by EPA and patterned after the Complex model[49] was used to develop MTBE toxics fractions.)

Although MOBTOX5b reflected a substantial improvement over EPA's previous toxics model, MOBTOX, a significant shortcoming of MOBTOX5b is that it is complicated and difficult to use. That is because it consists of several different software tools that are not fully integrated into the MOBILE framework. For example, the toxics fractions are first developed with a spreadsheet model, those results are pre-processed with a Fortran routine, and the resulting files are then read by MOBTOX5b. Unless the user is very familiar with the procedure, it is quite easy to introduce errors into the calculations.

With the release of MOBILE6.2, the calculation of air toxics is fully integrated within the MOBILE6 framework. As with the MOBTOX5b model, MOBILE6.2 uses toxics emissions data and algorithms from EPA's Complex model, making gasoline specifications important inputs to the model. MOBILE6.2 calculates emission rates for the following toxic compounds: benzene, 1,3-butadiene, formaldehyde, acetaldehyde, MTBE, and acrolein. In addition, MOBILE6.2 can estimate emissions of other toxics based on user-supplied data.

MOBILE6.2 Toxics Emissions Calculation Methodology

Presented below is a summary of the methodology used in MOBILE6.2 to calculate emissions of air toxics. More detail can be found in the EPA technical report on the MOBILE6.2 toxics module[50] and in the previously cited technical reports on MOBTOX5b.

Exhaust Emissions - In general, exhaust emissions of air toxics are calculated in MOBILE6.2 by applying a toxics ratio (i.e., the toxics fractions described above) to the TOG or VOC emission rate calculated by the model, where:

$$\text{Ratio} = (\text{g/mi toxic}) / (\text{g/mi TOG})$$

and the toxic emission factor is therefore:

$$EF_{TOX}\ (\text{g/mi}) = \text{TOG (g/mi)} \times \text{Ratio}$$

Thus, the toxics emission rates are calculated in terms of g/mi but are reported in terms of milligrams per mile (mg/mi) by MOBILE6.2. In addition, an adjustment for off-cycle operation is applied to the light-duty vehicle toxics emission rates for exhaust emissions.

The toxic-TOG ratios vary by technology type (e.g., non-catalyst versus oxidation catalyst versus three-way catalyst), vehicle type (e.g., light-duty versus heavy-duty vehicles), emitter category (normal versus high emitters), fuel type (gasoline versus Diesel), and fuel characteristics (e.g., oxygenated versus non-oxygenated fuels). The toxics ratios for gasoline-fueled vehicles are based on a series of algorithms that calculate ratios based on fuel parameter inputs; thus, the user must supply the model with local-level fuel specification data. Note that fuel specification data are only required for gasoline; toxics emissions from Diesel vehicles are not tied to the Diesel fuel formulation in MOBILE6.2. However, that is not to say that Diesel vehicle toxics emission rates are unrelated to fuel parameters, rather, sufficient data did not exist with which to correlate toxics fractions and fuel parameters in the development of MOBILE6.2.

As an example of the toxic-TOG ratios, consider a gasoline reflective of summertime conditions in New York City (which is subject to RFG regulations). Based on the 2003 Alliance of Automobile Manufacturers fuel survey,[51] the average regular unleaded gasoline for that area had the following specifications:

Parameter	Description	Value
RVP	Reid Vapor Pressure	7.0 psi
Sulfur	Sulfur content by weight	100 ppm
Aromatics	Aromatic content (vol%)	23.0%
Olefins	Olefin content (vol%)	12.8%
Benzene	Benzene content (vol%)	0.5 %
E200	Percent evaporated at 200°F	48.0%
E300	Percent evaporated at 300°F	83.1%
Oxygenate	Oxygenate content (vol%) and type	10.5% MTBE

Applying these gasoline specifications in a MOBILE6.2 model run, the toxics fractions for exhaust emissions contained in Table 4-2 were obtained. (Note that these values are not output by the model; rather, the FORTRAN code was modified to report these fractions.) These fractions are presented by fuel type (gasoline versus Diesel), vehicle type (light-duty versus heavy-duty), and technology type. Several items are worth noting with respect to the estimates in Table 4-2:

- The benzene fractions range from 0.0207 to 0.0439 for gasoline vehicles and from 0.0105 to 0.0200 for Diesel vehicles. High emitting light-duty vehicles had the highest fraction of exhaust benzene.
- 1,3-butadiene emissions for gasoline vehicles are a strong function of whether a catalyst is present and how effective it is (i.e., non-catalyst vehicles and high emitters show the highest 1,3-butadiene fraction in TOG exhaust).
- Diesel vehicle TOG exhaust has a much higher fraction of formaldehyde and acetaldehyde than does gasoline vehicle TOG exhaust.
- MTBE only shows up in the gasoline vehicle exhaust, as it is not added to Diesel fuel.

Table 4-2
Exhaust Toxics Fractions Calculated by MOBILE6.2 for 2003 Summertime New York City Gasoline
(Not Accounting for Off-Cycle Adjustments)

Fuel Type	Vehicle Type	Technology Type[a]	Toxics Fractions				
			Benzene	1,3-Butadiene	Form-aldehyde	Acet-aldehyde	MTBE
Gasoline	LDV	Non-Catalyst	0.0207	0.0102	0.0291	0.0070	0.0231
		Oxidation Catalyst	0.0207	0.0037	0.0278	0.0055	0.0322
		TWC/Carb/Air/EGR (~1981-1984 MY)	0.0418	0.0069	0.0164	0.0061	0.0244
		TWC/TBI/NoAir/EGR (~1985-1987 MY)	0.0393	0.0070	0.0165	0.0061	0.0252
		TWC/PFI/NoAir/EGR (~1988+ MY)	0.0389	0.0071	0.0168	0.0058	0.0195
		High-Emitters	0.0439	0.0175	0.0119	0.0055	0.0264
	HDV	Non-Catalyst	0.0207	0.0063	0.0377	0.0067	0.0145
		Catalyst Equipped	0.0368	0.0022	0.0278	0.0055	0.0108
Diesel	LDV	All	0.0200	0.0090	0.0386	0.0123	0
	HDV	All	0.0105	0.0061	0.0782	0.0288	0

[a] TWC = three-way catalyst; Carb = carbureted; Air = air injection; EGR = exhaust gas recirculation; TBI = throttle-body injection; PFI = port fuel injection.

The third through seventh entries in Table 4-2 for light-duty vehicles (i.e., TWC/Carb/Air/EGR through High Emitters) reflect values that are calculated from relationships contained in the Complex model. There are actually 10 technology combinations calculated by the Complex model and used in MOBILE6.2; however, only technologies with the highest sales volumes are presented in the table.

Note that acrolein is not included in Table 4-2. Toxics fractions for this compound were not calculated by the Complex model, and it was not included in the MOBTOX5b model. However, as on-road motor vehicles are large contributors to the overall acrolein inventory, and because emissions of acrolein have been estimated by EPA to lead to exposures above the reference concentration for non-cancerous effects for most of the population in the U.S. (based on the National Air Toxics Assessment for 1996[52]), it was included in MOBILE6.2.

The acrolein toxic-TOG ratios used in MOBILE6 are summarized in Table 4-3. Note that these fractions were developed from baseline gasoline and Diesel fuel, and MOBILE6.2 does not account for the impacts of fuel parameter changes on them.

Table 4-3
Acrolein/TOG Fractions Used in MOBILE6.2

Vehicle Type	Acrolein/TOG Fraction
LDGV/LDGT/MC	0.0006
HDGV - Catalyst	0.0005
HDGV - No Catalyst	0.0045
LDDV/HDDV	0.0035

Off-Cycle Emissions Adjustments - As noted above, the light-duty gasoline vehicle exhaust toxic emission factors are also adjusted to account for the impacts of off-cycle, or aggressive driving, behavior. These adjustments were based on a comparison of data collected on the FTP (the basis of the toxics fractions in the Complex model), which does not include aggressive driving, and California's Unified Cycle (UC), which does account for aggressive driving. These factors, presented in Table 4-4, were based on an evaluation of 12 vehicles tested by the California Air Resources Board. Eight of the 12 vehicles were normal emitters and four were high emitters; model years ranged from 1982 through 1996.

As observed in Table 4-4, with the exception of MTBE, the off-cycle adjustment acts to increase the toxics emission rates for normal emitters. For high emitters, the off-cycle adjustments act to lower toxics emission rates for all pollutants but benzene. A complete description of the derivation of the off-cycle adjustments can be found in Appendix G of the 1999 report cited above documenting the development of MOBTOX5b ("Analysis of the Impacts of Control Programs on Motor Vehicle Toxics Emissions and Exposure in Urban Areas and Nationwide").

Table 4-4
MOBILE6.2 Off-Cycle Toxics Adjustment Factors for Light-Duty Vehicles

Toxic Compound	Normal Emitter	High Emitter
Benzene	1.315	1.126
1,3-Butadiene	1.037	0.708
Formaldehyde	1.163	0.894
Acetaldehyde	1.020	0.919
MTBE	0.825	0.965

Evaporative Emissions - MOBILE6.2 calculates evaporative emissions of benzene and MTBE, which are components of raw gasoline and therefore are emitted as part of fuel evaporation. The methodology used to estimate evaporative toxics emissions is similar to that of exhaust emissions described above. However, as one might expect, the relationships between fuel parameters and the toxic-TOG ratios are different for evaporative emissions relative to exhaust emissions.

The benzene fractions calculated by MOBILE6.2 are based on algorithms contained in the Complex model and are a function of gasoline oxygenate content, RVP, and benzene content. The MTBE fractions are based on the MTBE draft fuel effects model and are a function of gasoline oxygenate content, RVP, and MTBE content. Rather than develop evaporative toxics fractions by technology, the model determines toxics fractions separately for the evaporative emission processes: hot soak, diurnal, running loss, resting loss, and refueling. The evaporative toxics fractions calculated by MOBILE6.2 for the 2003 summertime New York City gasoline used in the exhaust evaluation above are summarized in Table 4-5. Note that Diesel vehicle evaporative HC emissions are assumed to be zero in the model, and therefore no evaporative toxics emissions are calculated for Diesel vehicles.

Table 4-5
Evaporative Toxics Fractions Calculated by MOBILE6.2 for
2003 Summertime New York City Gasoline

Evaporative Process	Benzene	MTBE
Hot Soak	0.0042	0.131
Diurnal	0.0039	0.110
Running Loss	0.0042	0.071
Resting Loss	0.0039	0.110
Refueling	0.0040	0.146

It is interesting to note that the benzene fractions for evaporative emissions are substantially lower than for exhaust emissions (e.g., about 0.004 for evaporative emissions versus 0.02 to 0.04 for exhaust emissions). That is because evaporative benzene emissions mirror the benzene content in the fuel, while benzene in exhaust can occur from unburned fuel as well as from the partial combustion of aromatic compounds in the fuel (e.g., toluene, xylene, etc.). On the other hand, MTBE is a larger fraction of evaporative TOG emissions than exhaust TOG emissions (about 0.10 in evaporative emissions and 0.02 in exhaust emissions). Again, MTBE in evaporative emissions more closely matches the MTBE content of the fuel, while most of it is combusted during vehicle operation (and it is not formed during combustion from other components in the fuel as is the case with benzene).

User-Defined Air Toxics - In addition to the seven MSATs modeled directly by MOBILE6.2 (i.e., benzene, 1,3-butadiene, formaldehyde, acetaldehyde, MTBE, acrolein, and Diesel PM), MOBILE6.2 can be used to estimate emission rates of user-specified air toxics (e.g., n-hexane, ethylbenzene, etc.). This feature, which is enabled with the "ADDITIONAL HAPS" command, allows the user to input:

- Toxics exhaust emission factors (in mg/mi);
- Toxic-TOG ratios for exhaust and evaporative emissions (in mg/mi HAP per g/mi TOG or mg/mi HAP per g/mi VOC); and/or
- Toxic-PM ratios, which are sometimes used to evaluate metal compounds (in mg/mi HAP per g/mi PM).

The user-defined fractions are entered by vehicle type and model year, and therefore very detailed analyses can be performed with this feature of the model.

Strengths and Weaknesses of the MOBILE6.2 Toxics Methodology

There are a number of strengths and weaknesses associated with the MOBILE6.2 toxics modeling methodology. Although the list of weaknesses outlined below outnumbers the strengths, this should not diminish the fact that the MOBILE6.2 model represents a significant improvement over its predecessor toxics model, MOBTOX5b.

Strengths - In general, the greatest strengths of the MOBILE6.2 methodology are:

- With MOBILE6.2, EPA has developed a framework for calculating air toxics that is easy to use and easy to modify (with the user-defined air toxics feature) as more data become available on mobile source air toxics.
- For benzene, 1,3-butadiene, formaldehyde, and acetaldehyde, FTP-based emissions from light-duty gasoline vehicles (i.e., cars and light-duty trucks) from 1981 to 1993 model years are very well characterized (i.e., prior to the implementation of Tier 1 emission standards). That is because the toxic-TOG

ratios are based on the RFG Complex model, which underwent extensive peer review and was developed with about 1800 individual test records. The MTBE estimates, while not as extensively reviewed, were based on a subset of the Complex model database using similar analytical procedures. Thus, MTBE emissions from these vehicles are also well characterized. Although the Complex model was based on 1990 technology vehicles, the individual technology groups represent vehicles that were built between 1981 and the early- to mid-1990s.

- The addition of separate toxic-TOG ratios for high-emitting vehicles and accounting for the impacts of off-cycle operation are viewed as positive features in the MOBILE6.2 toxics algorithm.
- The toxic-TOG ratios for pre-1981 model year light-duty gasoline vehicles were based on correlations prepared for the 1993 Motor Vehicle Related Air Toxics Study. In general, those correlations were developed from all data available at that time. Given the small contribution of these older vehicles to current fleet emissions, these estimates are probably sufficient.

Weaknesses - As outlined below, the primary weaknesses associated with the toxics calculations in MOBILE6.2 are associated with a lack of toxics data for vehicle technologies introduced since the mid-1990s.

- *Light-duty gasoline vehicles* - As noted above, the toxic-TOG ratios for pre-Tier 1 vehicles (i.e., prior to the mid-1990s model years) are based on considerable emissions data and are well characterized. However, as more stringent emissions standards for new vehicles are implemented, i.e., Tier 1 standards in 1994, the national low emission vehicle (NLEV) program in 1998-2001, and Tier 2 standards in 2004, the technologies used by manufacturers to meet these standards may impact toxics fractions from those vehicles. Because MOBILE6.2 applies the Complex model relationships to all 1981 and newer vehicles, there is some uncertainty surrounding the estimates for Tier 1 and newer vehicles. Thus, this is an area that deserves review when new data are available.
- *Light-duty Diesel vehicles* - The toxic-TOG fractions for light-duty Diesel vehicles are based on limited data as detailed in Appendix D of "Analysis of the Impacts of Control Programs on Motor Vehicle Toxics Emissions and Exposure in Urban Areas and Nationwide," which documents the development of toxics fractions for these vehicles in MOBTOX5b. For the most part, the toxic-TOG ratios (depending on pollutant) were developed from data collected on two to seven vehicles. At the current time, this is not a significant issue, since light-duty Diesel cars and trucks make up such a small fraction of the fleet. However, if in the future those vehicles are sold in larger numbers, additional testing (based on latest technology) is warranted.
- *Heavy-duty vehicles* - The toxic-TOG ratios used in MOBILE6.2 are also those used in MOBTOX5b. As detailed in the documentation for that model, both heavy-duty gasoline and Diesel vehicle toxics estimates are based on relatively

limited data from older technology vehicles. In general, fewer than five vehicles were used to establish toxics fractions for these vehicle classes. This is an area that needs additional research, particularly on vehicles that are certified to the more stringent standards that are to be implemented in 2004 and in 2007. The 2007 standards will likely require the use of catalyzed particulate filters on heavy-duty Diesel engines, and the emissions characteristics of those vehicles are likely to be much different than the engines upon which the MOBILE6.2 toxic-TOG fractions are based.

- *Acrolein estimates* - The acrolein/TOG fractions used in MOBILE6 for light-duty gasoline vehicles are generally based on older data using 1990 industry average gasoline. The heavy-duty gasoline vehicle acrolein/TOG fractions are based on testing of a single engine, with and without a catalyst.[53] Finally, the Diesel estimates are based on a more recent test program (1998), but that also included testing of a only a single heavy-duty Diesel engine.[54] None of the acrolein/TOG fractions account for the impacts of fuel formulation changes on acrolein emissions, nor are newer technology vehicles represented in the test data.

- *Off-cycle effects* - As noted above, the toxics estimates for light-duty gasoline cars and trucks include an adjustment for off-cycle operation (i.e., aggressive driving). Although this adjustment was a positive step and likely improved the accuracy of the estimates, it is based on very limited data (i.e., 12 vehicles covering 1982 to 1996 model years). In addition, it is likely that this off-cycle adjustment will be different (or non-existent) for vehicles that are certified to the Supplemental Federal Test Procedure regulations, which will control off-cycle emissions and are phased in beginning with the 2001 model year.

Toxics Emissions Estimates With MOBILE6.2

Emissions Versus Calendar Year - In the technical description of the MOBILE6.2, EPA presents gasoline specification data that were compiled for the 1999 assessment of motor vehicle air toxics with MOBTOX5b. Those data, which are also contained in Appendix A of this report, list fuel parameters for 1990, 1996, and 2007 for 10 urban areas and 14 regions of the U.S. for summer and winter. Using the summertime fuel specifications for the Northeast with RFG and the Northeast without RFG, toxics emission rates were calculated with MOBILE6.2 for 1990, 1996, 2007, and 2020. Note that the 1990 and 1996 fuel specifications were compiled from survey data, while the 2007 specifications (which were assumed to also apply to the 2020 runs) were based on refinery modeling performed by EPA and reflect the implementation of Tier 2 sulfur controls. The Northeast fuel specifications were selected for this example because these two sets of fuel parameters allowed a fair comparison between RFG and non-RFG gasoline used in the same general area, and summertime specifications were selected because the RFG rules were aimed at ozone control (as well as toxics).

The results of the MOBILE6.2 model runs described above are presented in Figures 4-1 through 4-5 for benzene, 1,3-butadiene, formaldehyde, acetaldehyde, and acrolein, respectively, which reflect fleet-average emissions over the 1990 to 2020 timeframe. As observed in those figures, substantial reductions in all air toxics are projected. That is because the toxics emission rates are directly related to the TOG emission rates, which are expected to decrease significantly as new standards are implemented.

There are a number of items worth pointing out with respect to the emission rates presented in Figures 4-1 through 4-5:

- Significant reductions in mg/mi air toxics are expected between 1990 and 2020 for all compounds investigated. As noted above, this is primarily related to implementation of more stringent emissions standards that will result in substantial fleet-average hydrocarbon reductions over this time period.

- The RFG runs show lower emissions of benzene, 1,3-butadiene, and acrolein relative to the non-RFG runs for the 1996, 2007, and 2020 runs (RFG requirements were first implemented in 1995). This is not unexpected, as the RFG rule requires a minimum level of HC and toxics reductions. It is interesting to note, however, that emissions of formaldehyde are noticeably greater under the RFG case and acetaldehyde is marginally greater under the RFG case. That is because the RFG rule requires 2% oxygen by weight which was assumed to be met with the addition of MTBE for the Northeast RFG scenario, and MTBE-containing fuels typically have a higher fraction of formaldehyde and acetaldehyde in exhaust than non-MTBE fuels.

Figure 4-1

Northeast States Fleet-Average Benzene Emissions
Calculated with MOBILE6.2 Using Summertime Fuels

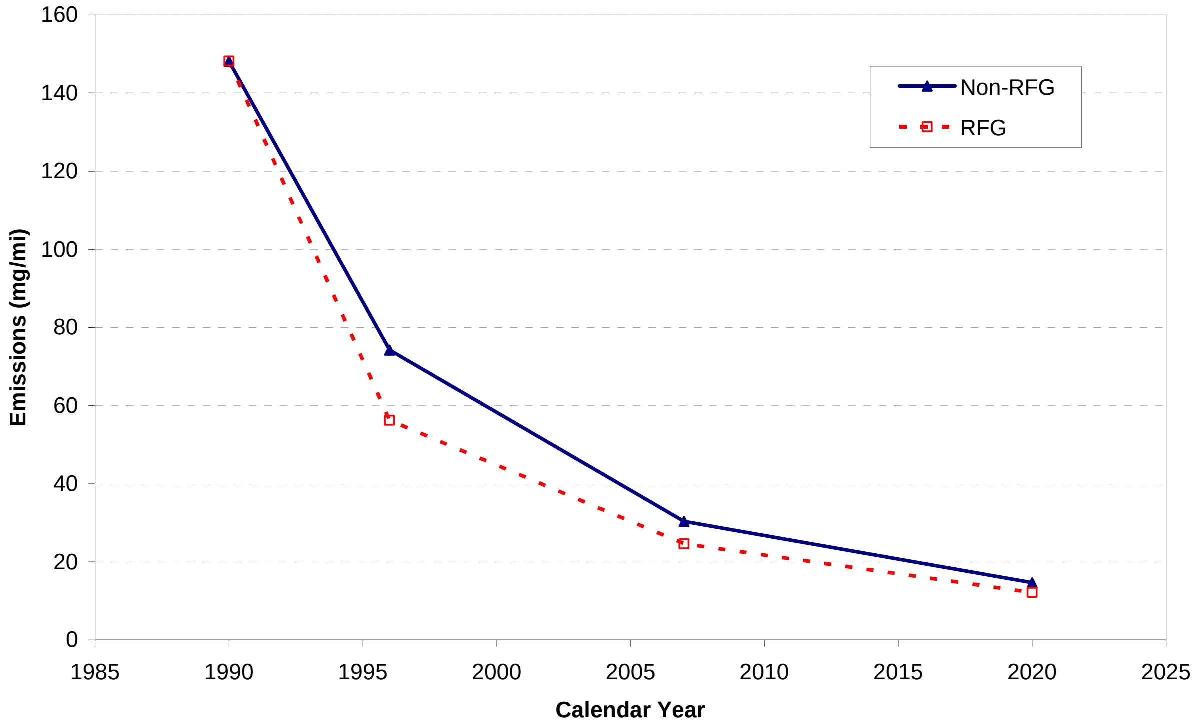


Figure 4-2

Northeast States Fleet-Average 1,3-Butadiene Emissions Calculated with MOBILE6.2 Using Summertime Fuels

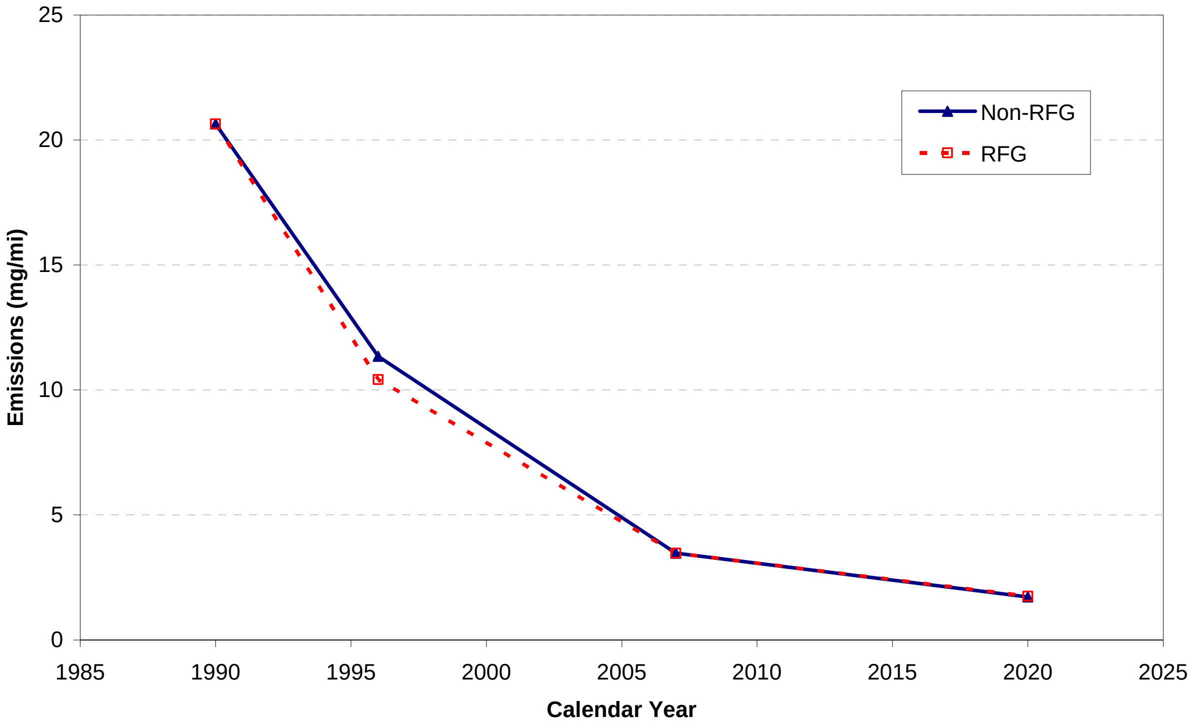


Figure 4-3

Northeast States Fleet-Average Formaldehyde Emissions Calculated with MOBILE6.2 Using Summertime Fuels

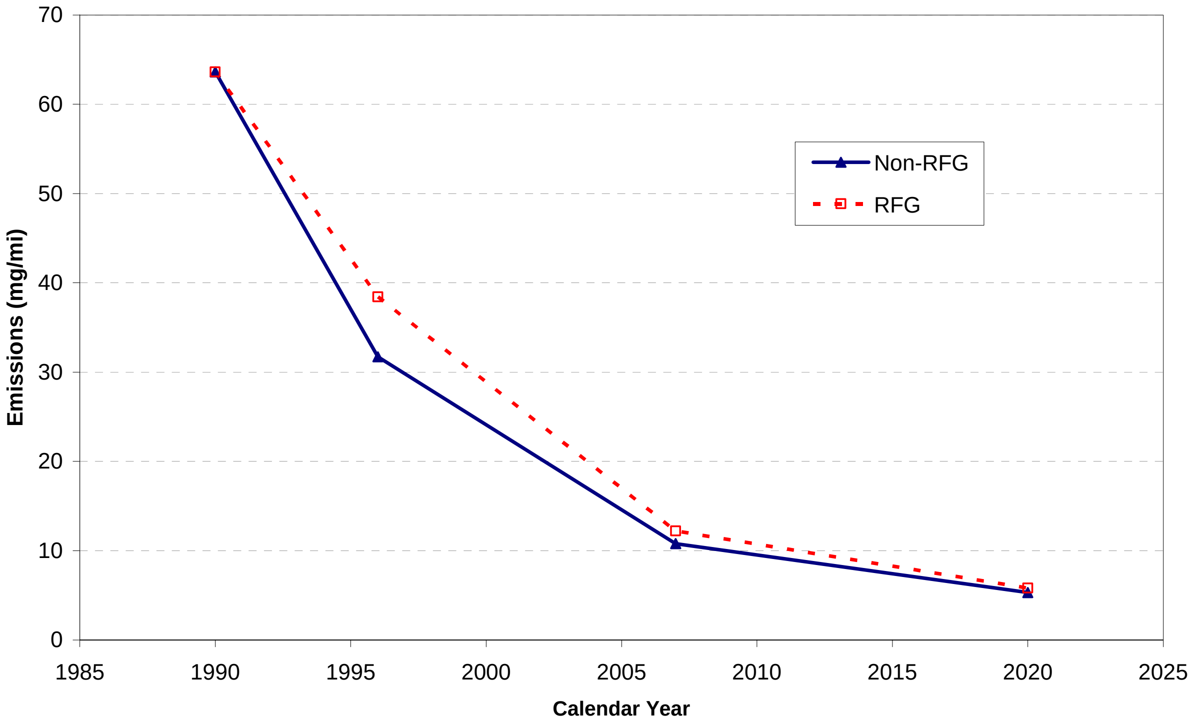


Figure 4-4

Northeast States Fleet-Average Acetaldehyde Emissions Calculated with MOBILE6.2 Using Summertime Fuels

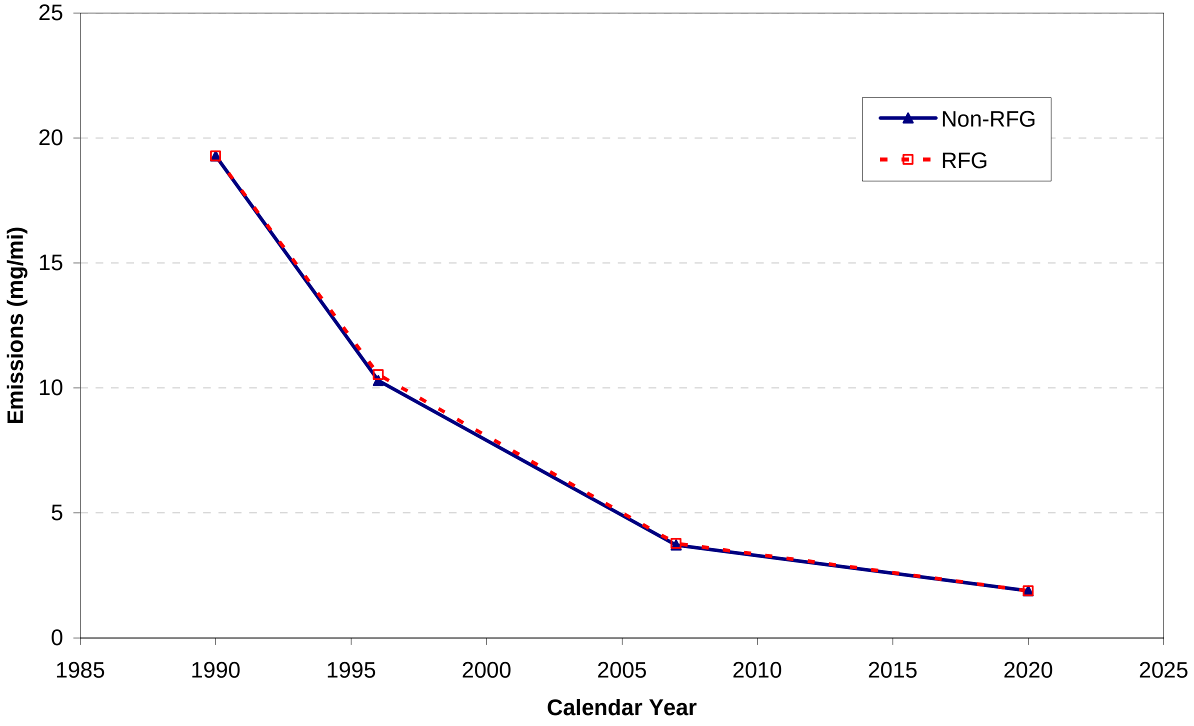
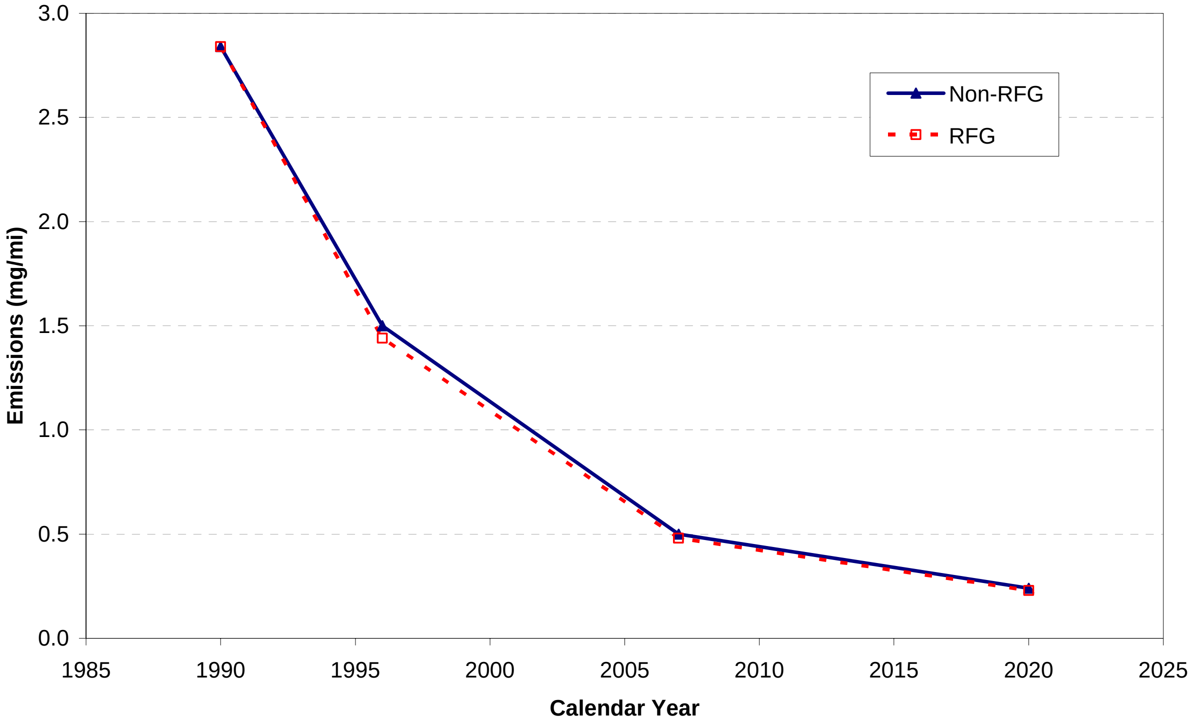


Figure 4-5

Northeast States Fleet-Average Acrolein Emissions Calculated with MOBILE6.2 Using Summertime Fuels



Emissions Versus Fuel Parameters - As discussed in detail above, when performing toxics runs, the MOBILE6.2 model requires users to specify gasoline parameters for the area being modeled. This is important because the emission rates of certain toxics are very sensitive to the gasoline being used. For example, gasolines with high levels of aromatics and benzene will have higher benzene emissions than gasolines with low levels of these components. On the other hand, 1,3-butadiene emissions are very sensitive to the olefin content of the gasoline.

Based on a review of the Alliance of Automobile Manufacturers fuel survey for Summer 2003, minimum and maximum values for a number of fuel parameters were determined. Those results are presented in Table 4-6 along with national average values. (The survey data collected in Fairbanks, Alaska, were not included in this compilation because that fuel is not reflective of fuels available in the Lower-48 states.) As observed in Table 4-6, the fuel parameters used in the MOBILE6.2 toxics algorithms can vary substantially.

Based on the gasoline parameters summarized in Table 4-6, MOBILE6.2 was run using the minimum and maximum benzene, aromatics, and olefin content, and the results for light-duty gasoline vehicles (LDGVs) are presented in Figures 4-6 to 4-8, respectively.[*] As expected, gasoline benzene content and gasoline aromatics content can have a significant impact on benzene emissions calculated by MOBILE6.2. This is observed in Figures 4-6 (gasoline benzene content) and 4-7 (gasoline aromatics content). Figure 4-8 shows that olefin content can have a substantial impact on 1,3-butadiene emissions, as higher levels of olefins result in greater emissions of 1,3-butadiene.

Table 4-6
Minimum, Maximum, and Average Gasoline Parameter Values for Summer 2003 Based on the Alliance of Automobile Manufacturers Fuel Survey Data (Excluding Fairbanks, Alaska)

Parameter	Minimum	Maximum	Average
Benzene (vol%)	0.1	3.4	0.9
Aromatics (vol%)	4.1	47.0	26.5
Olefins (vol%)	0.5	21.9	7.4
E200	26.9	67.2	44.8
E300	71.4	93.9	83.0
Sulfur (ppm)	10	950	140
MTBE (vol%)	0	13.9	--[a]
Ethanol (vol%)	0	9.9	--[a]

[a] Most fuels either contain MTBE or ethanol, or they do not contain MTBE or ethanol. Thus, an average across all fuels is not very relevant when many are at 0% MTBE and ethanol.

---

[*] Note that the remaining fuel parameters required for the model runs matched the fuels containing the minimum and maximum values being evaluated. This is more realistic than simply assigning a range for certain parameters while keeping all other fuel specifications constant.

Figure 4-6

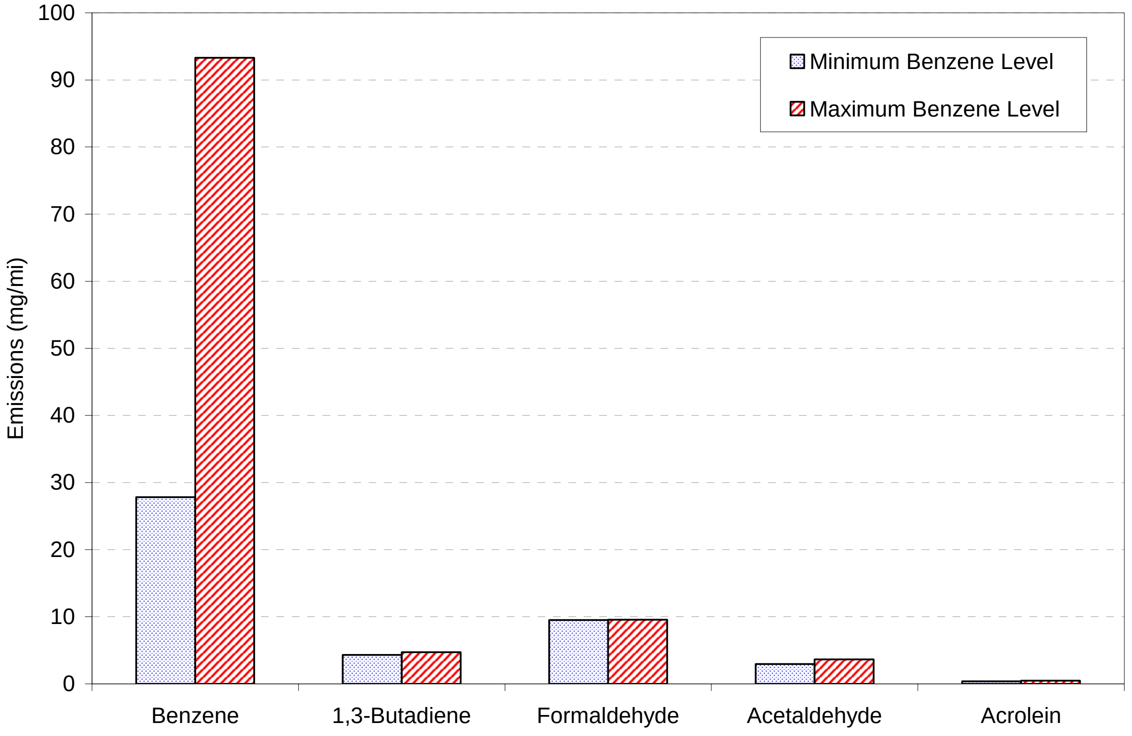


Figure 4-7

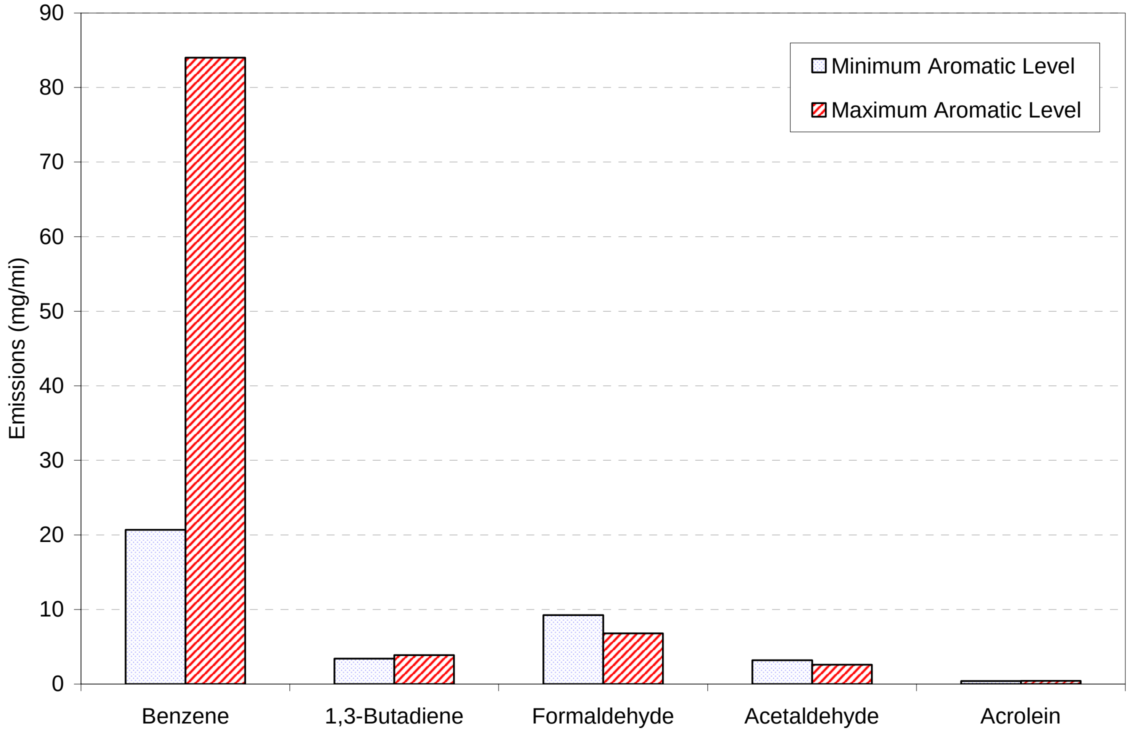
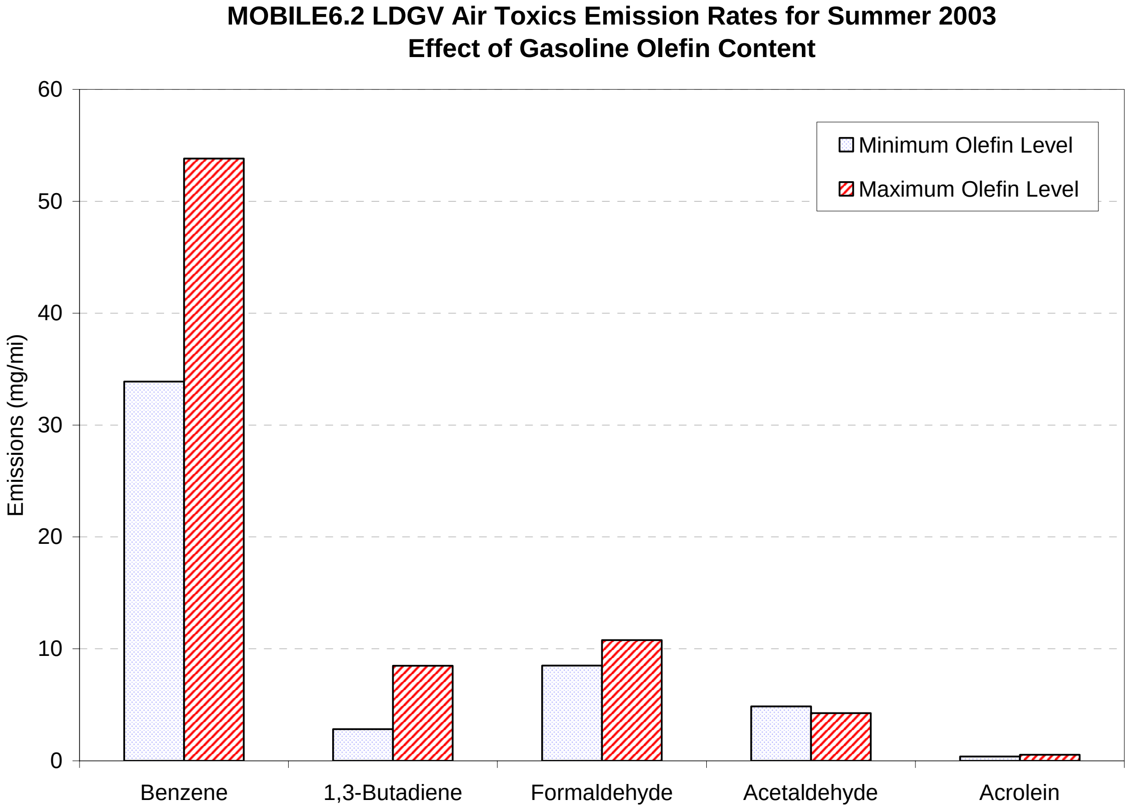


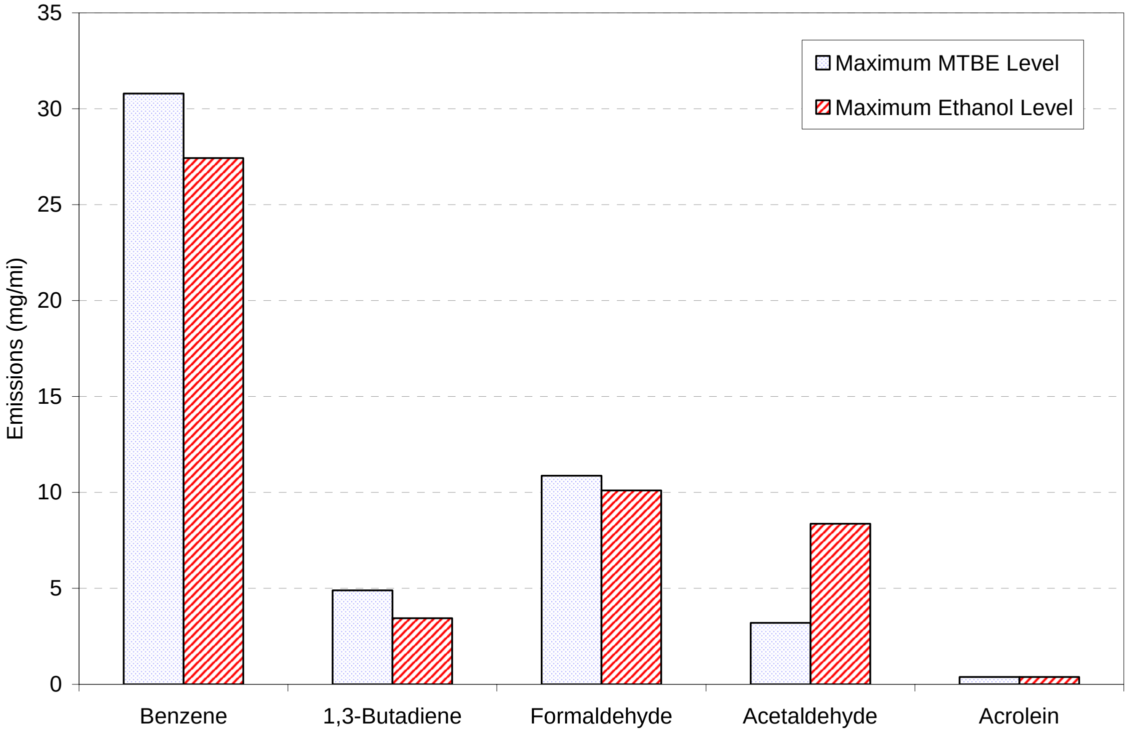
Figure 4-8



Another comparison that was made in this evaluation was the air toxics emissions of MTBE-containing and ethanol-containing fuels at their maximum limits. For this analysis, both areas selected were subject to RFG requirements in order to allow a more balanced comparison between the two fuels. The results of this analysis are shown in Figure 4-9. As observed in that figure, the MTBE-containing fuel has higher emissions of formaldehyde, while the ethanol-containing fuel has higher emissions of acetaldehyde. That is because MTBE is a single-carbon oxygenate and ethanol is a two-carbon oxygenate, while formaldehyde is a single-carbon aldehyde and acetaldehyde is a two-carbon aldehyde.

Figure 4-9

MOBILE6.2 LDGV Air Toxics Emission Rates for Summer 2003
Effect of Gasoline Oxygenate Type



5. EMISSIONS MODELING OF NATURAL GAS VEHICLES WITH MOBILE6

A new feature added to the MOBILE model with the release of MOBILE6 is the capability to model the emissions impacts of natural gas vehicles (NGVs). This section of the report reviews the methodology used in MOBILE6 to estimate emissions from NGVs. In addition, the results of a limited literature search conducted to determine the availability of alternative emission factors for NGVs is also presented.

MOBILE6 Methodology

The basic methodology used in MOBILE6 to model the emissions impacts of natural gas vehicles is to apply an implementation schedule of NGVs by vehicle type and model year (supplied by the user) to the emission rates of NGVs that are hard-coded into the model (but can be modified by the user). The non-NGV vehicles are then assigned emission rates equivalent to the gasoline or Diesel vehicle class being modeled, and the model reports a weighted average emission rate of NGVs and non-NGVs. Because the implementation schedule and the emission factors are independent parameters in the calculations, they are discussed separately below.

Implementation Schedule - In order to account for the emissions impact of natural gas vehicles, the user must develop an implementation schedule that is read by MOBILE6. In general, most areas will have a very low fraction of NGVs, and therefore it is sometimes useful to enter a value of 100% to obtain emissions estimates that reflect only emissions from NGVs. Values are entered by vehicle class and model year, beginning with 1994 and ending with 2050. MOBILE6 does not model NGV emissions prior to the 1994 model year. That is because only vehicles certified to operate on natural gas when new are modeled by MOBILE6, and those were not generally available prior to 1994.

Gasoline vehicles retrofitted to operate on natural gas are not modeled by MOBILE6. Historically, the durability of retrofits has been very poor, and emission rates from retrofit vehicles have often far exceeded emissions of their gasoline vehicle counterparts. As a result, there is no option to model the impacts of retrofits in MOBILE6.

Emission Factors - The other primary input parameter used by MOBILE6 to estimate the emissions impacts of NGVs is the emission factor assigned to NGVs. MOBILE6 contains default NGV emission factors that are built into the model, and the user can supply alternative emission factors if desired. The discussion below is focused at the default factors used in MOBILE6, which are described in the EPA technical report M6.FUL.004.[55] Alternative emission factors are discussed later in this section of the report.

Light-Duty Vehicles - An inherent emissions benefit with NGVs is the fact that the fuel system is sealed. As a result, evaporative HC emissions from the fuel are negligible, and the MOBILE6 model assumes zero evaporative emissions from these vehicles. For cases in which a vehicle develops a leak in the fuel system, there would be associated HC emissions. However, because natural gas is composed primarily of methane (with most of the remainder being ethane), HC emissions from fuel leaks would not be expected to contribute to ozone formation.

The NGV exhaust emission factors for light-duty vehicles were assumed to be equivalent to emission factors that EPA had developed for gasoline-fueled ultra-low-emission vehicles (ULEVs),[*] with a few important differences. The derivation of the ULEV emission factors is described in two EPA reports: M6.EXH.007[56] (for HC and NOx) and M6.EXH.009[57] (for CO). As a point of comparison, ULEV emission standards for light-duty gasoline vehicles (i.e., passenger cars) are presented in Table 5-1 along with the Tier 0 standards (i.e., pre-1994 model year), Tier 1 standards (phased in beginning with the 1994 model year), National Low Emission Vehicle (NLEV) standards, and Tier 2 standards (phased in beginning with the 2004 model year).

Table 5-1
Light-Duty Vehicle Certification Standards at 50,000 miles
(g/mi)

Certification Category	HC	CO	NOx
Tier 0	0.41	3.4	1.0
Tier 1	0.25	3.4	0.4
NLEV	0.075	3.4	0.2
ULEV (NGVs)	**0.040**	**1.7**	**0.2**
Tier 2 - Bin 8[*]	0.100	3.4	0.14
Tier 2 - Bin 7[*]	0.075	3.4	0.11
Tier 2 - Bin 6[*]	0.075	3.4	0.08
Tier 2 - Bin 5[*]	0.075	3.4	0.05
Tier 2 - Bin 4[*]	0.051	1.7	0.029
Tier 2 - Bin 3[*]	0.040	1.7	0.021
Tier 2 - Bin 2[*]	0.007	1.7	0.014

[*] Note that Tier 2 standards were promulgated based on a useful life of 120,000 miles. The values in the table reflect the "effective" 50,000 mile standard based on estimates used in MOBILE6.

---

[*] ULEVs are included as a distinct emissions certification category in CARB's Low Emission Vehicle regulations that were adopted in September 1990.

As observed in Table 5-1, the ULEV standards are very stringent for HC and CO, while the NOx levels are higher than the Tier 2 bins. This has implications for using the MOBILE6 NGV algorithm to forecast future year NOx emissions, which is discussed later in this section of the report.

An important difference between the gasoline vehicle ULEV emission factors developed for MOBILE6 and the emission factors used for NGVs is that the emission rates of high emitters (i.e., vehicles with emission control system malfunctions) are assumed to be much lower for NGVs than their gasoline vehicle counterparts (although the rate of failure is assumed to be the same).[*] For example, the high emitter emission rates assumed for gasoline light-duty vehicles versus what is assumed in MOBILE6 for NGVs are summarized as follows:

Fuel Type	NMHC (g/mi)	CO (g/mi)	NOx (g/mi)
Gasoline High Emitter (ULEV)[**]	1.14	38.7	0.96
NGV High Emitter	0.068	5.8	0.74

EPA supported the lower NGV emission rates for high emitting vehicles based on limited data on NGVs in inspection and maintenance (I/M) programs (supplied by the Natural Gas Vehicle Association) that indicated NGVs failing I/M tests had lower emissions than gasoline vehicles failing I/M tests. In addition, EPA stated that engineering rationales support the assumption that NGV failures would be less severe than gasoline vehicles. This position makes sense for NMHC emissions (since most of the hydrocarbon emissions from NGVs is methane that is not included in NMHC), but that argument is less clear for CO because CO emissions from malfunctioning NGVs can be significantly higher than the 5.8 g/mi value assumed in the model.

A comparison of light-duty gasoline vehicle and NGV emission rates versus age for 2004 model year vehicles is shown in Figures 5-1 through 5-3 for NOx, VOC, and CO, respectively. (These runs reflect typical summertime temperatures and fuels, and no I/M program was applied.) As observed in Figure 5-1, the NOx levels are very similar for gasoline vehicles and NGVs when these vehicles are new. However, as the vehicles age, the lower emission rate assumed for NGV high emitters results in lower overall deterioration for NGVs. Figure 5-2 compares VOC emission rates for 2004 model year vehicles, and the difference between gasoline vehicles and NGVs is quite striking. Part of that difference is a result of NGVs having zero evaporative emissions. Additional contributing factors include: (1) the NMHC exhaust emission standard for ULEVs is lower than the average 2004 gasoline vehicle standard, and (2) NGVs have a much lower NMHC emission rate assigned to high emitters. The CO results illustrated in Figure 5-3 also show lower emissions assigned to NGVs for model year 2004 vehicles.

---

[*] When modeling emissions from light-duty vehicles and light-duty trucks, the MOBILE6 model segregates the fleet into "normal" emitters and "high" emitters. As the fleet ages (and vehicle emission control systems deteriorate), an increasing fraction of normal emitters become high emitters. Thus, emissions deterioration with age includes both the gradual deterioration associated with normal emitters and the more significant deterioration associated with vehicles malfunctioning to become high emitters.

[**] Note that the MOBILE6 model assumes that emission rates of high emitters are reduced slightly for vehicles subject to Tier 2 emission standards.

Figure 5-1

**MOBILE6 NOx Emissions vs. Age for MY2004 LDVs (Passenger Cars)
Natural Gas vs. Gasoline Vehicles**

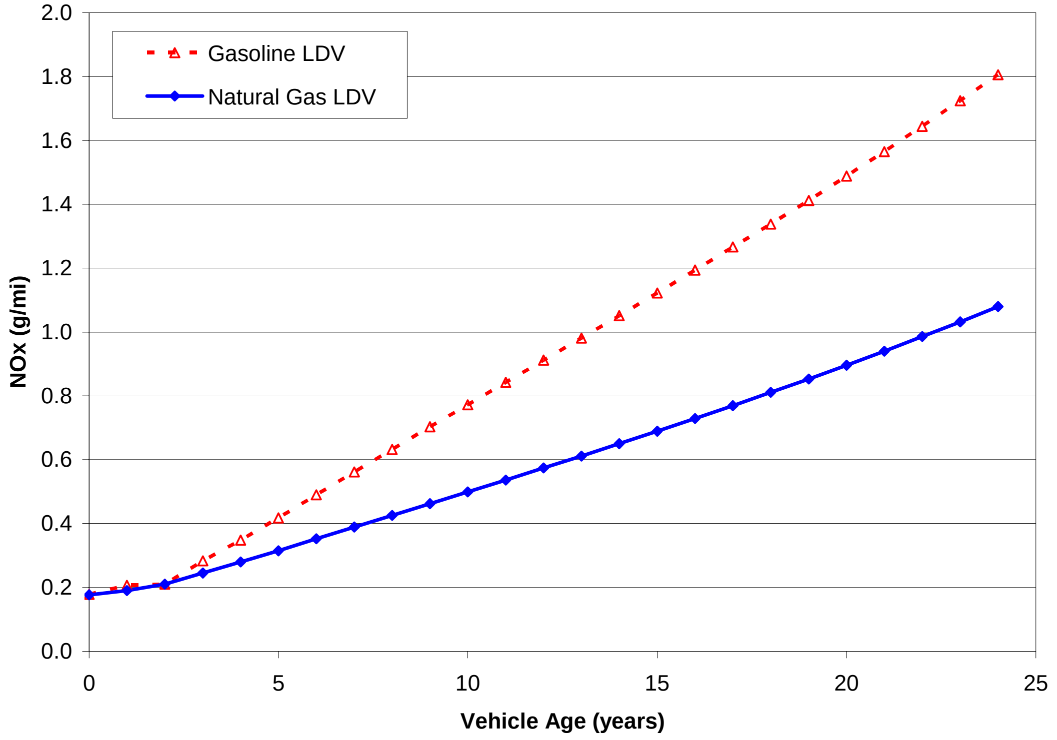


Figure 5-2

**MOBILE6 VOC Emissions vs. Age for MY2004 LDVs (Passenger Cars)
Natural Gas vs. Gasoline Vehicles**

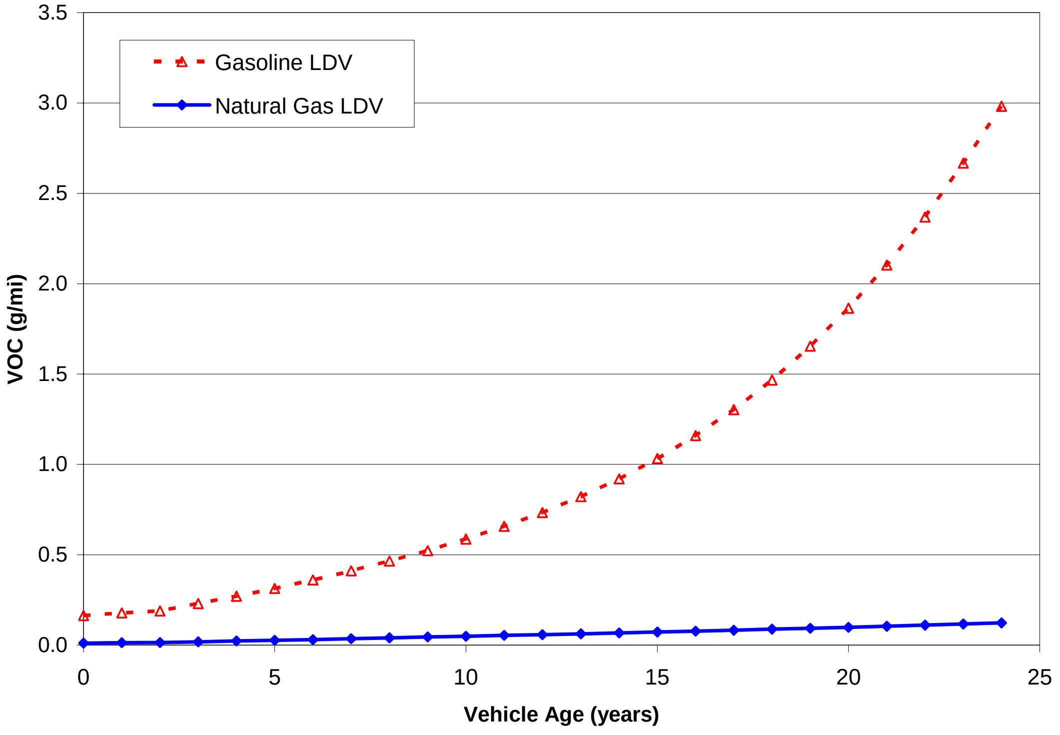
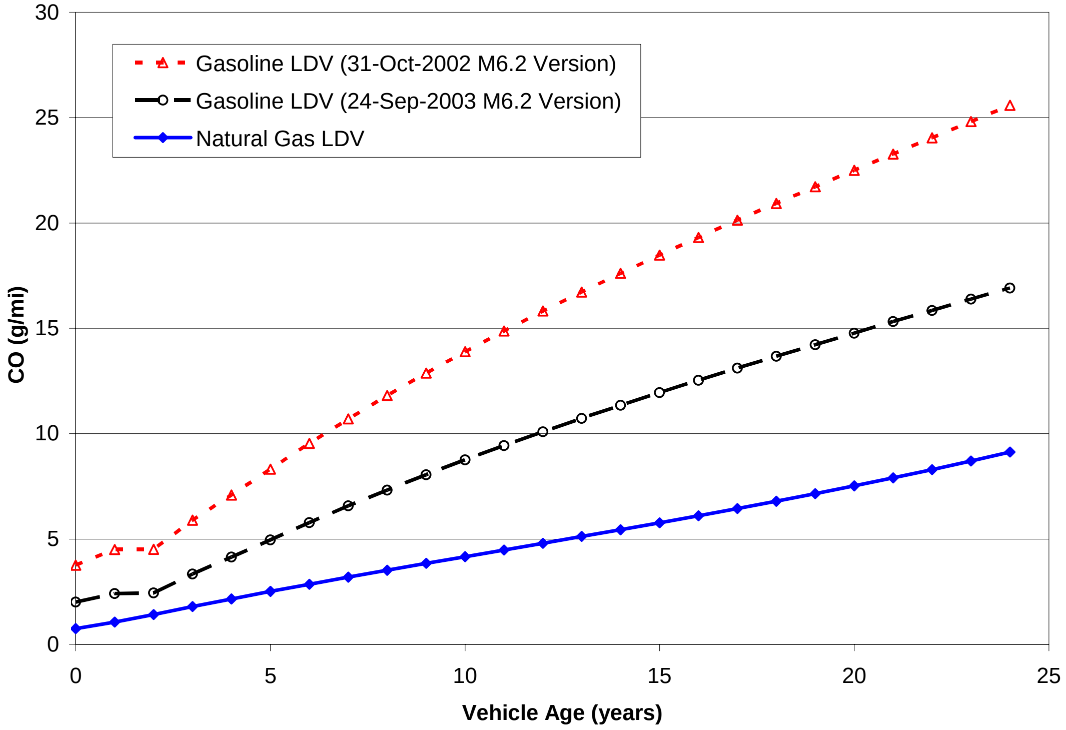


Figure 5-3

MOBILE6 CO Emissions vs. Age for MY2004 LDVs (Passenger Cars)
Natural Gas vs. Gasoline Vehicles



Note that two sets of gasoline vehicle CO emissions estimates are presented in Figure 5-3 -- one based on the November 2002 release of MOBILE6.2 and one based on the February 2004 release of MOBILE6.2. (The November 2002 release actually has a date stamp in the model of October 31, 2002, while the February 2004 release has a date stamp of September 24, 2003. To avoid confusion, these two versions of the model will be referred to by their date stamp instead of the date of release in this section of the report.) As observed in Figure 5-3, the model year 2004 gasoline vehicle CO emission rates calculated by the 24-Sep-2003 version of MOBILE6.2 are substantially lower than the CO rates calculated by the 31-Oct-2002 version of the model. That is because EPA made an adjustment to the CO emission rates to better reflect CO reductions that occur as a result of the more stringent HC standards applicable to NLEV and Tier 2 vehicles. Based on a review of available certification data, EPA found that NLEVs emitted about 50% less CO than Tier 1 vehicles, even though they were certified to the same CO standard (e.g., 3.4 g/mi for light-duty vehicles). Based on this review, it was clear that the technologies used to meet the more stringent HC standard (e.g., 0.25 g/mi for Tier 1 vehicles and 0.075 g/mi for NLEVs) also act to reduce CO emissions. This was not accounted for in the 31-Oct-2002 version of the model, which assumed NLEVs and Tier 1 vehicles had essentially the same CO emission rate because they were certified to equivalent CO emission standards.

It is also interesting to compare light-duty gasoline vehicle and NGV emission rates as a function of model year. The results of this analysis are presented in Figures 5-4 to 5-6 for NOx, VOC, and CO, respectively. These runs were prepared for vehicles five years old so that the results reflect a small level of emissions deterioration. Consistent with Figures 1 to 3, the runs used to prepare Figures 5-4 to 5-6 reflect summertime temperatures and fuels, and do not include the impacts of an I/M program. Model years ranged from 1994 (the first year that NGVs can be modeled with MOBILE6) to 2020.

Figure 5-4 illustrates the trend in NOx emissions for light-duty gasoline vehicles and NGVs. As seen in that figure, significant reductions in NOx emissions are expected from the light-duty gasoline vehicle fleet between the 1994 and 2010 model years. Between 1994 and 2000 NOx emissions decline as a result of the Tier 1 emissions standards being fully implanted (these standards were phased in beginning with the 1994 model year). The large drop in NOx emissions between 2000 and 2001 reflects implementation of the NLEV program and controls on off-cycle emissions, and the decrease between 2004 and 2010 reflects implementation of Tier 2 emission standards and gasoline sulfur regulations. During this same time period, NOx emissions assigned to light-duty NGVs remains relatively flat (the small reduction in the early 2000s reflects control of off-cycle emissions). Beyond the 2005 model year, NOx emissions from NGVs are assumed to be higher than NOx emissions from their gasoline vehicle counterparts. <u>This is not a reasonable assumption, as these NGVs would also be subject to Tier 2 NOx standards</u>. Thus, care should be taken when modeling the emissions impacts of NGVs with MOBILE6.2 during time periods in which Tier 2 standards are in effect, and serious consideration should be given to developing alternative NGV emission factors.

Figure 5-4

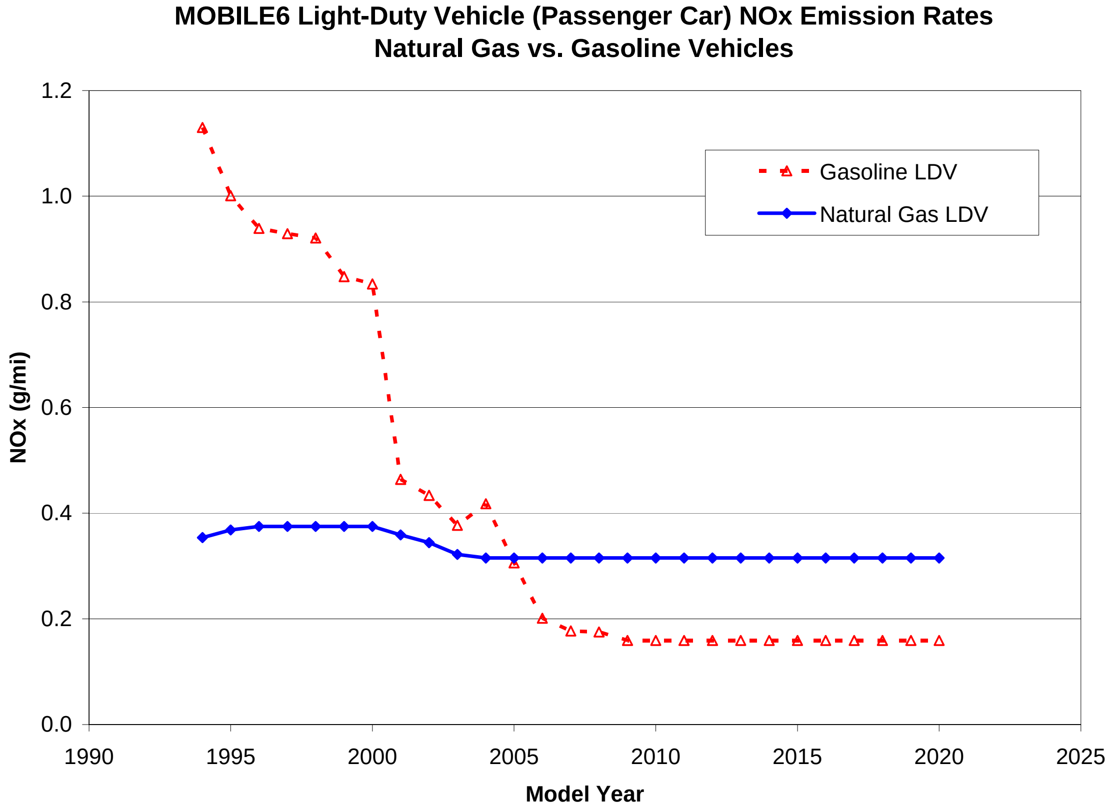


Figure 5-5

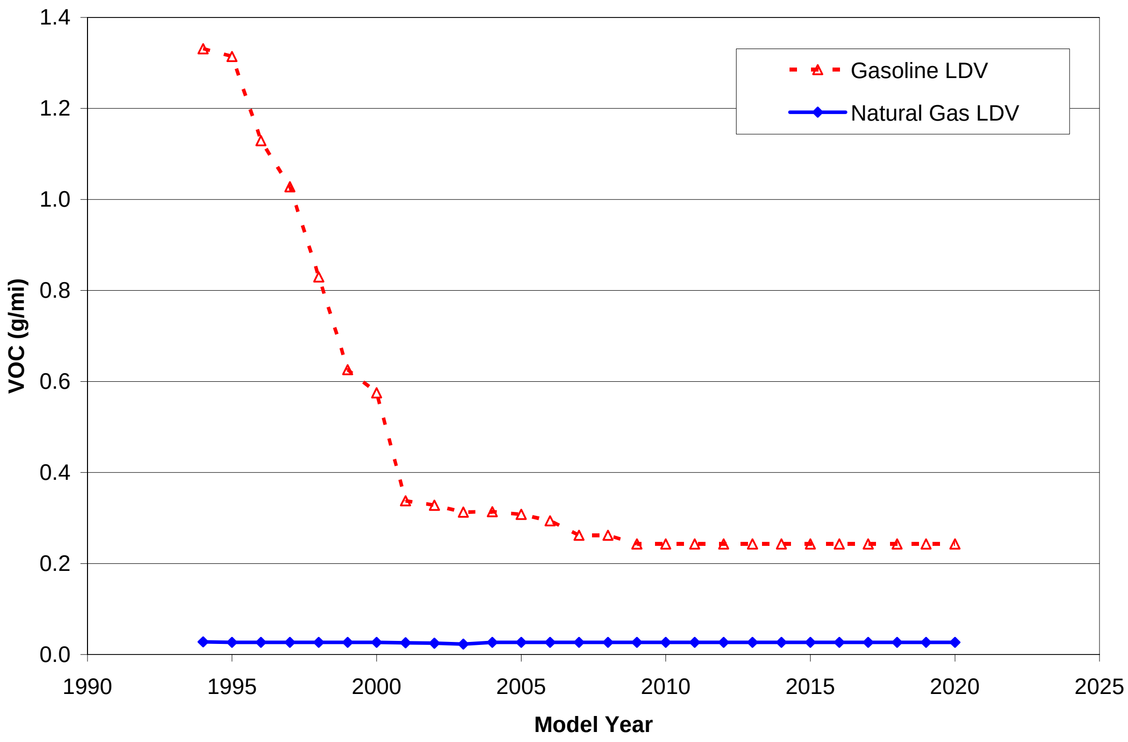


Figure 5-6

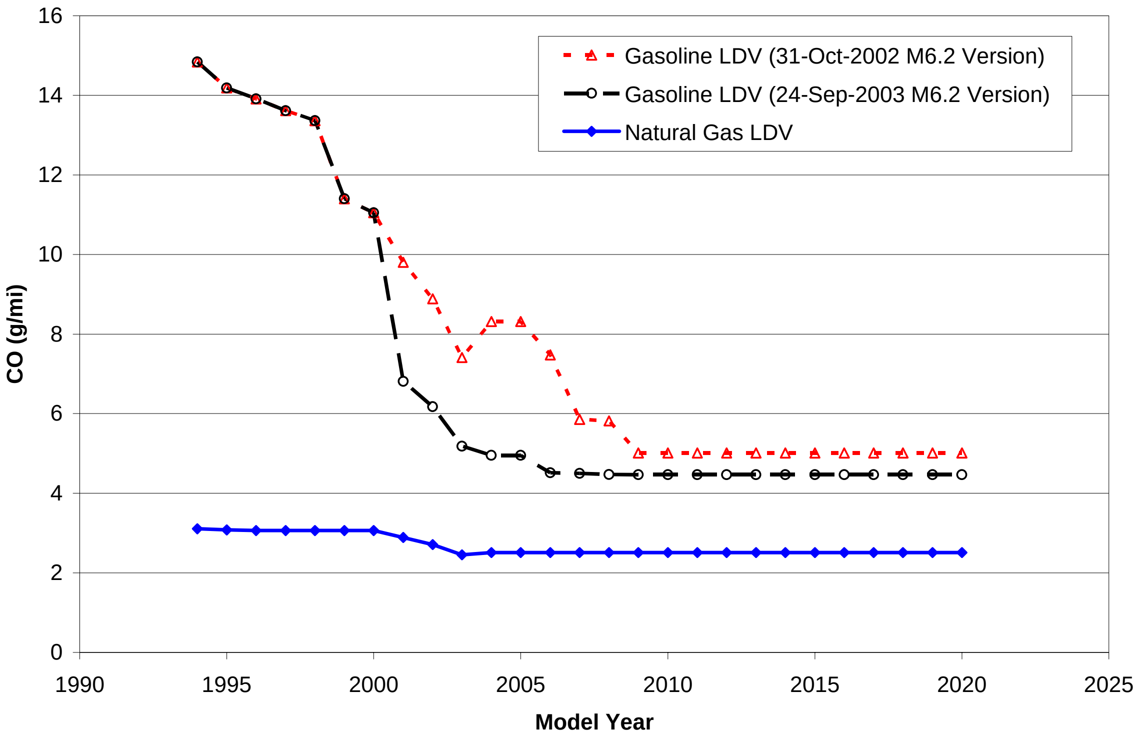
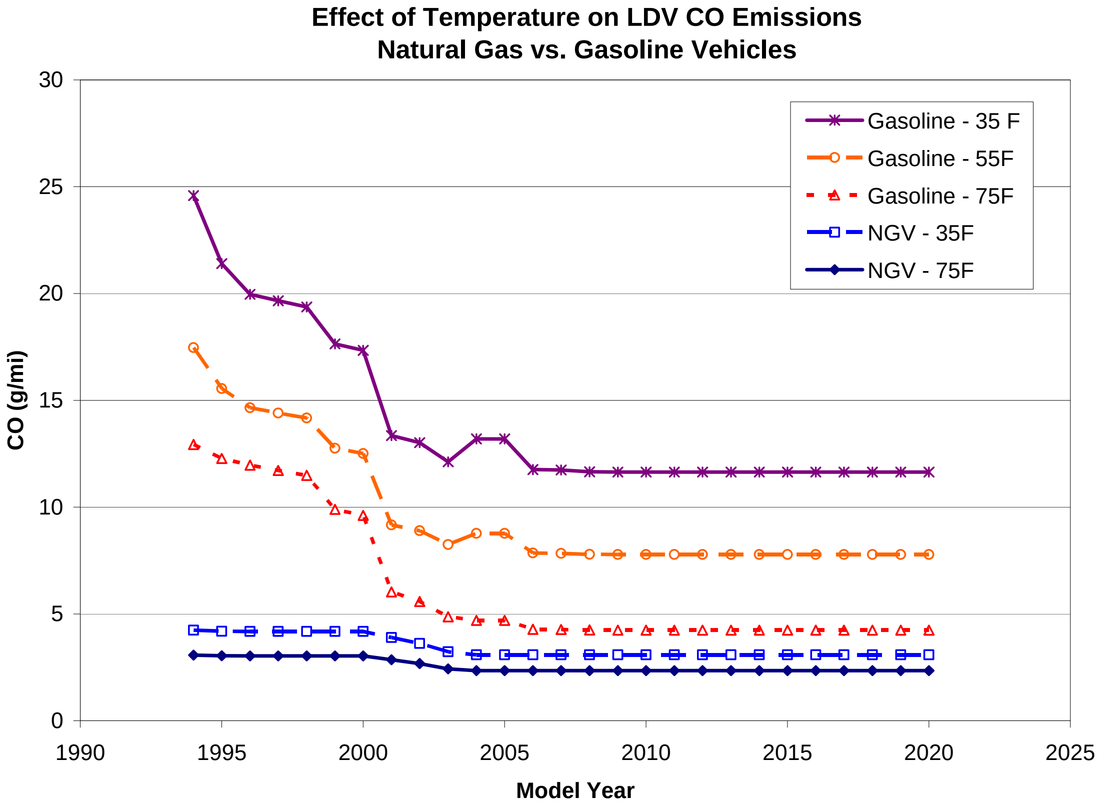


Figure 5-5 shows VOC emission rates for gasoline-fueled light-duty vehicles and for natural gas light-duty vehicles. As observed in that figure, VOC emissions from NGVs are much lower than VOC emissions from gasoline vehicles. As explained above, this is a result of: (1) no evaporative emissions from NGVs; and (2) the majority of exhaust hydrocarbon emissions from NGVs is methane, which is relatively non-reactive in the atmosphere and is therefore not included in VOC. Finally, Figure 5-6 presents CO emission rates for light-duty gasoline vehicles versus NGVs. As with Figure 5-3, two sets of MOBILE6.2 estimates are presented for gasoline light-duty vehicles -- one based on the 31-Oct-2002 version of the model and one base on the 24-Sep-2003 version of the model. The gasoline vehicle CO emission rates calculated by the two model versions are equivalent between the 1994 and 2000 model years. When the NLEV program is implemented in 2001, the 24-Sep-2003 version provides lower CO estimates as a result of better CO control than originally assumed. For all model years, the NGV CO emission rates are much lower than the CO emission rates of gasoline vehicles.

One of the inherent advantages of natural gas as a motor vehicle fuel is that it is delivered into the intake system as a gas rather than a liquid that must then evaporate into a gaseous state (as is the case with gasoline). Because gasoline tends to puddle on intake valves and can condense on the cylinder walls during a cold start, gasoline vehicles are over-fueled during the first portion of an engine start to maintain stable engine operation. This results in high HC and CO emissions during start-up, which is exacerbated at cold temperature. Since natural gas is already in a vapor state when delivered to the combustion chamber (even under very cold ambient conditions), there is no need for fuel enrichment during start-up, and emissions from natural gas vehicles are relatively insensitive to ambient temperature. This has been observed in a number of prior test programs.[58,59,60]

Based on the above arguments and test data showing very little increase in emissions when NGVs were tested at 75° and 20°F, EPA decided to set the temperature correction factors for NGVs in MOBILE6 to unity. Figure 5-7 presents the impact of temperature on CO emissions for light-duty gasoline vehicles and for NGVs as a function of model year. (These runs were prepared with the 24-Sep-2003 version of the model and therefore the estimates include the impact of LEV technology improvements on CO emissions.) That figure shows very large increases in CO emission rates for gasoline vehicles as the temperature decreases from 75° to 35°F. On the other hand, only a slight increase in NGV CO emission rates is observed over the same temperature range. (It is unclear whether or not this increase was intentional or whether it was the result of a coding error. The EPA technical report states that the temperature correction factors were set to unity, which is true for start emissions. However, during stabilized running operation, temperature correction factors are applied to NGVs.)

Figure 5-7



Based on the 24-Sep-2003 Version of MOBILE6.2

Heavy-Duty Vehicles - The emission factors used in MOBILE6.2 to represent natural gas heavy-duty vehicles were based primarily on test data from NGVs. The exception to this approach was for NOx emissions for medium-heavy duty vehicles (14,001 to 33,000 lbs. gross vehicle weight rating, GVWR) and heavy-heavy duty vehicles (above 33,000 lbs. GVWR). For those vehicle types, it was assumed that NGVs would have emissions equivalent to Diesel vehicles certified to the 2004 emission standard of 2.5 g/bhp-hr NMHC+NOx.

Figures 5-8 and 5-9 compare NGV and gasoline/Diesel vehicle NOx emissions versus vehicle age for 2004 model year class 2B heavy-duty vehicles (i.e., 8,501 - 10,000 lbs. GVWR) and class 8B heavy-duty vehicles (>60,000 lbs. GVWR), respectively. Figure 5-8 shows that the NOx emission rate from model year 2004 NGVs falls well below that of gasoline and Diesel class 2B heavy-duty vehicles. For class 8B vehicles, Figure 5-9 shows that MOBILE6 predicts similar NOx emission rates for NGVs and Diesel vehicles.

Figure 5-8

MOBILE6 NOx Emissions vs. Age for MY2004 Class 2B HDVs
Natural Gas, Gasoline, and Diesel

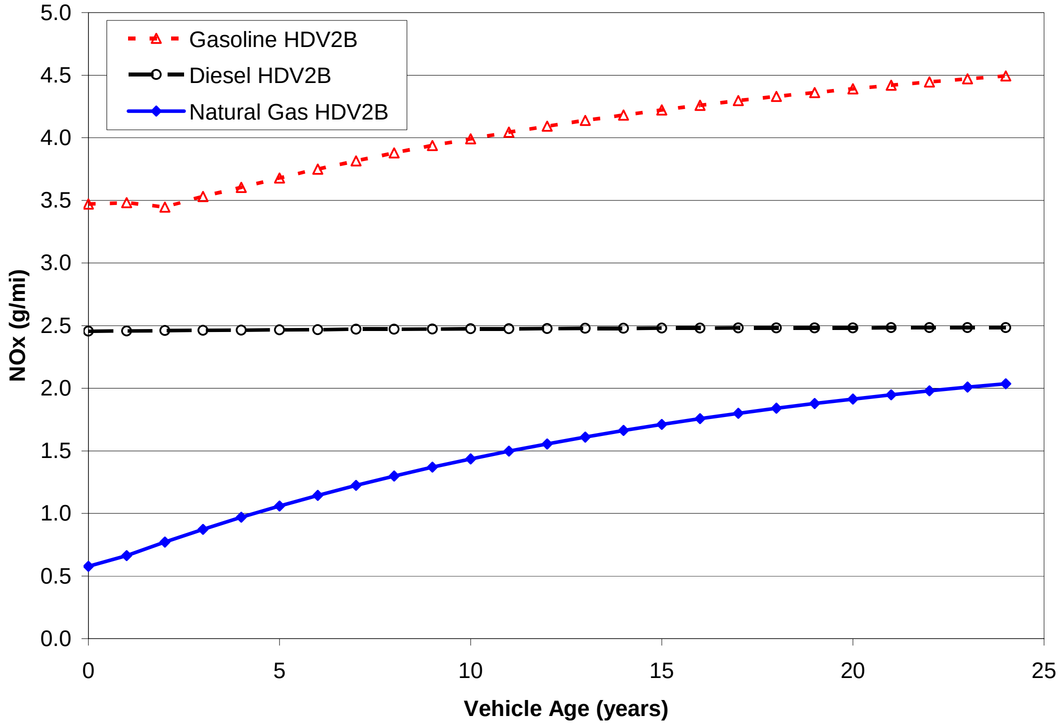
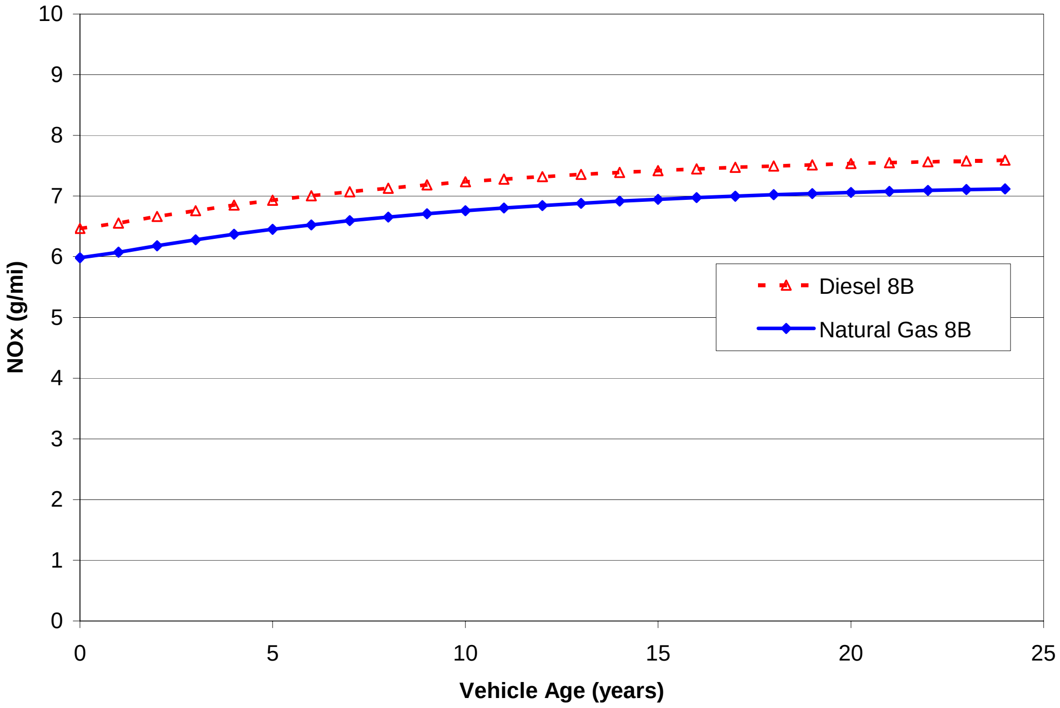


Figure 5-9

MOBILE6 NOx Emissions vs. Age for MY2004 Class 8B HDVs
Natural Gas vs. Diesel Vehicles



NOx emission rates as a function of model year are shown in Figures 5-10 and 5-11 for class 8B heavy-duty vehicles and for urban buses, respectively. Consistent with the figures prepared for light-duty vehicles, these figures show NOx emissions for 5-year old vehicles from 1994 through 2020 model years. Significant reductions in NOx emissions are observed between 1994 and 2010 for Diesel vehicles, while the NGV estimates are constant throughout this time period. As a result, MOBILE6 users who specify NGVs for time periods after 2006 need to recognize that the 2007 heavy-duty NOx standards are not accounted for in the NGV estimates. The same is true of the NOx estimates for urban buses shown in Figure 5-11.

Figure 5-12 presents PM10 emission rates for Diesel and natural gas urban buses. As observed in that figure, the natural gas urban bus PM emission rates track those from Diesel buses, with the NGV emission rates being slightly below those of Diesel buses. This clearly is incorrect, as the PM emission rates of NGVs are supposed to be calculated based on equivalent gasoline vehicles operating on low-sulfur fuel. Instead, if NGVs are specified for any Diesel vehicle class, MOBILE6 simply zeros out the sulfate component of PM, while leaving the elemental carbon and organic carbon emission factors the same as for Diesel vehicles. Thus, users are cautioned that if PM emission factors are desired for NGVs, an equivalent gasoline vehicle class should be evaluated.

Figure 5-10

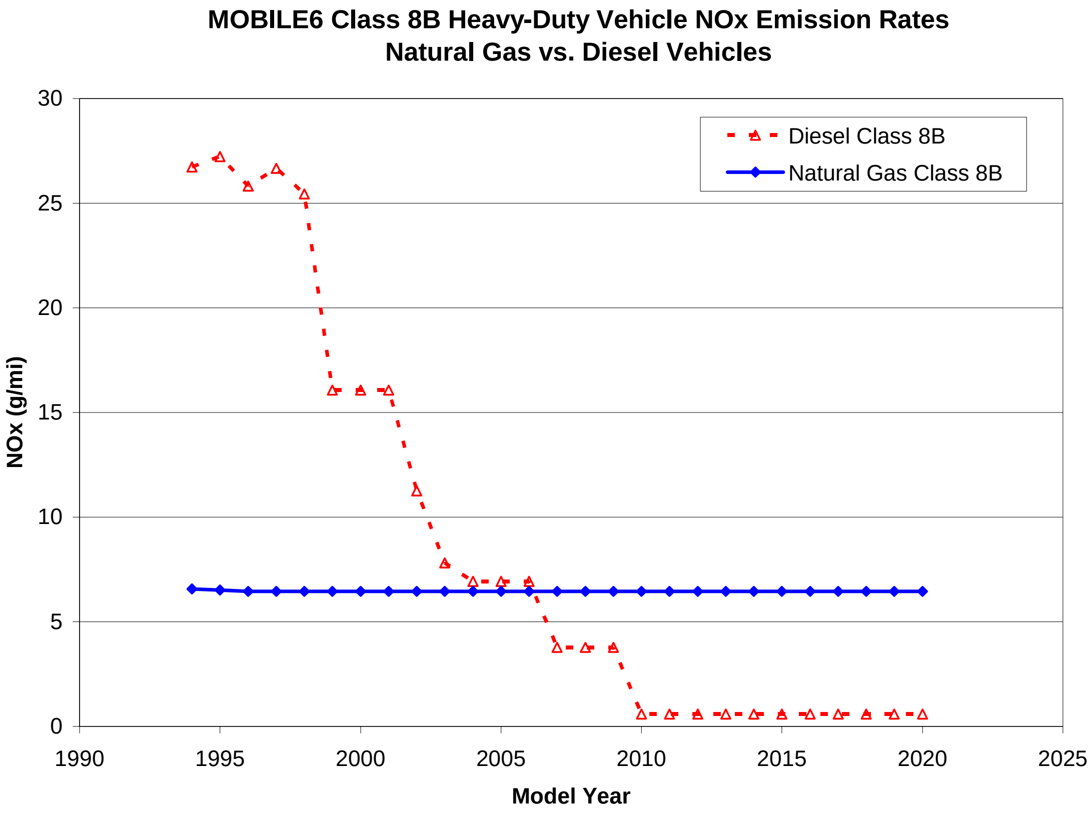


Figure 5-11

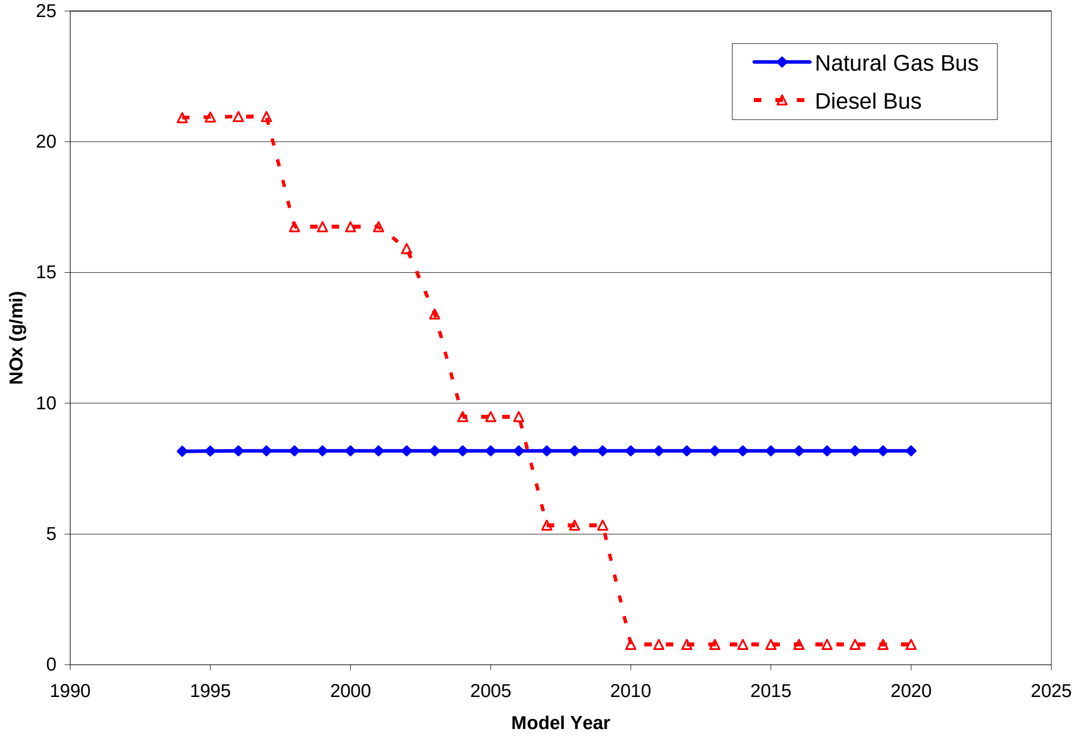
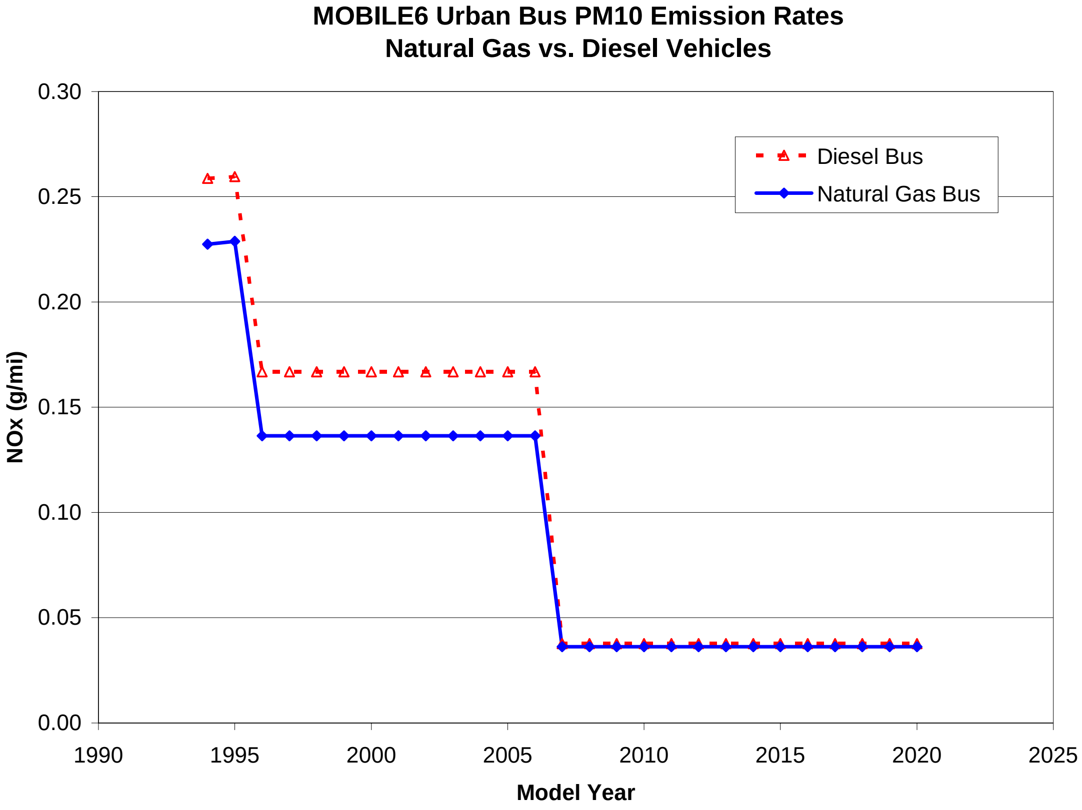


Figure 5-12



Literature Review

This section of the report summarizes literature related to NGV test programs and emissions data identified by Sierra during the course of this project. Because of resource limitations, the literature review was limited primarily to publications and technical papers contained in Sierra's in-house library, which has an extensive collection of publications related to motor vehicle emissions issues published by EPA, CARB, the Society of Automotive Engineers (SAE), the Air and Waste Management Association (AWMA), and other organizations. In addition, the review also included a search of federal publication databases accessed via the Internet, including the DOE-funded National Renewable Energy Laboratory (NREL). Because several fairly comprehensive studies and literature reviews related to alternative fuels were published in the late 1980s to early 1990s,[61,62,63] the focus of this review was on material published since 1995.

While reviewing the information below, the reader is cautioned that the emission results from the various programs are often mixed, with some programs showing lower emissions from NGVs and other programs showing higher emissions from NGVs relative to gasoline or Diesel vehicles. This is sometimes related to making comparisons between vehicles in different states of development (e.g., it is not fair to compare emissions from a NGV certified to ULEV emission standards to emissions from a 1990-technology gasoline vehicle), or not accounting for emission control system durability in customer service. Nonetheless, the review presented below offers insights about the emission characteristics of currently available natural gas vehicles.

SAE Papers

Numerous SAE papers related to NGVs and emissions have been published. However, only those that included relevant emissions data (i.e., tests conducted over a standardized test cycle [e.g., the FTP] with road-ready vehicles) were reviewed in this effort. Those are briefly summarized below separately for light- and medium-duty vehicles and for heavy-duty vehicles. In recent years, the bulk of new research has been associated with heavy-duty vehicles.

Light- and Medium-Duty Vehicles

2000-01-1959 - *Statistical Analysis of Emissions and Deterioration Rates for In-Use, High-Mileage CNG and Gasoline Vehicles*[64] - This paper compares emissions of seven CNG-fueled and seven gasoline-fueled 1996 model year Crown Victoria taxicabs operated on reformulated gasoline. Three rounds of emissions measurements were made -- at 60,000, 90,000, and 120,000 miles -- over the cold-start FTP. Emissions from the CNG fleet were lower for CO, CO_2, and NMHC, while NOx emissions were similar for the two fleets. It is important to note, however, that the NGVs in this program were certified to California ULEV emissions standards, while the gasoline vehicles were certified to federal Tier 1 standards. Thus, a direct comparison of the two fleets is not appropriate. In fact, both vehicle fleets maintained emissions levels that were within the applicable certification standards.

971661 - *Fuel Management and Exhaust Emissions of Light- and Heavy-Duty Trucks Operating on CNG and LPG*[65] - This paper discusses the fuel management systems and exhaust emission rates of General Motors GMC and Chevrolet dual-fuel pickup trucks converted to operate on CNG/gasoline (1991, 1995, 1996, and 1997 model years) and LPG/gasoline (1991 and 1996 model years). The 1997 model year CNG GM C2500 pickup, with a fuel system designed by IMPCO, is certified to CARB and EPA LEV standards. Emissions results from this testing indicated that NOx emissions were reduced on both CNG and LPG relative to gasoline. THC and CO emissions from the LPG vehicles were also reduced. THC from the CNG vehicles increased substantially, while CO results were mixed.

962069 - *NYSERDA AFV-FDP Light-Duty CNG Vehicle Fleet Operating Experience*[66] - Since 1989 the New York State Energy Research and Development Authority (NYSERDA) has been conducting a demonstration program on alternative-fuel vehicles with the intent of obtaining "real-world" answers to the questions about their benefits. This paper summarizes the operating experience and emissions results from light-duty CNG vehicles. Eighty-eight vehicles were included in this test program, 87 of those were converted from gasoline operation and 1 was an OEM vehicle (a Chrysler B350 van). Four different types of natural gas fuel systems were studied: mechanical open-loop (45 vehicles), mechanical closed-loop (33 vehicles), electronic single-point closed-loop (9 vehicles), and electronic multi point closed-loop (1 vehicle, the Chrysler B350 van). The emission results from this program indicated that the older conversion technology did not reliably provide emission reductions except for NMHC. The more sophisticated technologies (especially the OEM vehicle) showed reductions relative to the gasoline controls.

961091 - *Round 1 Emissions Results from Compressed Natural Gas Vans and Gasoline Controls Operating in the U.S. Federal Fleet*[67] - The Alternative Motor Fuels Act of 1988 and the Energy Policy Act of 1992 have resulted in a requirement for federal fleets to purchase alternative-fuel vehicles. DOE is responsible for tracking the performance of those vehicles. As part of this effort, emissions of alternative-fuel vehicles in actual service are to be compared to otherwise identical vehicles operating on conventional fuel (i.e., gasoline or Diesel fuel). This paper compares the initial (i.e., undeteriorated) emissions results of 37 dedicated CNG Dodge B250 vans to the emissions results of 38 standard gasoline controls tested on California Phase 2 reformulated gasoline. Vehicles in the program were either 1992 or 1994 model year. Results indicated significant reductions in NMHC emissions (80%) for the CNG vehicles, with moderate reductions in NOx (30%). The CO reductions were dependent on the area where the vehicles were in service and tested. The CNG vehicles operated and tested in the Denver area exhibited only a 3% CO reduction relative to gasoline, while CNG vehicles in the Washington, D.C. and New York City metropolitan areas had a 66% reduction in CO emissions relative to the gasoline controls.

952507 - *Comparison of CNG and Gasoline Vehicle Exhaust Emissions: Mass and Composition - The Auto/Oil Air Quality Improvement Research Program*[68] - As part of the Auto/Oil Air Quality Improvement Research Program, the exhaust emissions of three CNG-fueled vehicles (representing OEM technology for dedicated CNG application) were compared to the emissions of three counterpart gasoline vehicles (1992 and 1993 model years certified to Tier 0 emission standards). The results of the emissions tests indicated that NMHC emissions were consistently lower for the CNG vehicles. CO and NOx emissions were generally lower with CNG, but the magnitude of the differences was not consistent.

952437 - *Evaluations of Current Natural Gas Vehicle Technology Exhaust Emissions at Various Operating Temperatures*[69] - Four vehicles converted to operate on CNG and gasoline using commercially available conversion systems were tested at 24EC (75EF) and -18EC (0EF) over the Urban Dynamometer Driving Schedule. On CNG operation, significant reductions in NMHC were observed relative to gasoline at both temperatures. In addition, when operated on CNG, the vehicles exhibited a much smaller dependence on temperature than on gasoline operation, particularly for CO emissions (e.g., cold start CO emissions were 2 to 18 times higher for gasoline operation compared to natural gas operation at 0EF).

952380 - *Correcting Emissions Problems in Existing Propane and Natural Gas Vehicles in British Columbia*[70] - Based on an analysis of vehicles in the British Columbia I/M program, the authors found a significantly higher failure rate for vehicles converted to operate on natural gas or propane relative to their gasoline-fueled counterparts (e.g., for 1994 model year vehicles, the failure rates for gasoline, CNG, and LPG vehicles were 0.44%, 9.61%, and 13.95%, respectively). These high failure rates were observed despite a policy being in place that: (1) required conversions to have air/fuel ratio feedback control if the original configuration was so equipped, and (2) explicitly prohibited the removal of emission control system components. Overall, the in-use emissions performance of CNG and LPG vehicles was found to be inferior to that of OEM gasoline vehicle performance.

The following two papers do not offer an emissions comparison between NGVs and gasoline vehicles, but describe Ford's and Honda's experiences in developing natural gas vehicles and present the emission levels from those vehicles.

972643 - *Near-Zero Emissions Natural Gas Vehicle, Honda Civic GX*[71] - The development of the CNG-powered Honda Civic is described in this paper. Emissions from this vehicle are about 1/10th of those from a gasoline ULEV, with just a small loss in performance relative to its gasoline-fueled counterpart.

971662 - *Ford's SULEV Dedicated Natural Gas Trucks*[72] - This paper presents an overview of the design considerations and emissions results from the 1997 model year dedicated CNG F250 full-size pickup and the E250/E350 full-size vans. These vehicles have been certified to CARB's SULEV emission standards and to EPA's ULEV and ILEV standards. No emissions comparisons to gasoline vehicles are made in this paper.

952743 - *Ford's 1996 Crown Victoria Dedicated Natural Gas Vehicle*[73] - This paper presents an overview of the design considerations and emissions results from the 1996 model year dedicated CNG Ford Crown Victoria. This vehicle was certified to CARB's ULEV emission standards and to EPA's ILEV standards. Although performance characteristics of gasoline- and CNG-fueled models are compared in this paper, emissions differences are not presented.

Heavy-Duty Vehicles

2003-01-1381 - *Comparison of Exhaust Emissions, Including Toxic Air Contaminants, from School Buses in Compressed Natural Gas, Low Emitting Diesel, and Conventional Diesel Engine Configurations*[74] - This study measured exhaust emissions from school buses equipped with a conventional Diesel engine meeting 1998 standards, a low-emission Diesel engine with a catalyzed particulate filter, and a natural gas engine without a catalyst. The buses were tested on a chassis dynamometer using the federal City Suburban Heavy Vehicle Cycle developed by West Virginia University. The results of the testing showed that NOx, NMHC, and CO emissions were highest for the CNG bus, while the conventional Diesel had the highest PM emissions. The low-emission Diesel configuration had the lowest emissions of PM, NOx, NMHC, and CO of the three vehicles in the test program.

2003-01-0300 - *Performance and Emissions Evaluation of Compressed Natural Gas and Clean Diesel Buses at New York City's Metropolitan Transit Authority*[75] - This paper compares emissions of buses equipped with Detroit Diesel Corporation (DDC) Series 50 Diesel engines and buses equipped with DDC Series 50 CNG engines. The buses in this program were 1999 model year. Two Diesel engines were equipped with an oxidation catalyst and a particulate filter; three CNG buses were not equipped with a catalyst. All CNG buses had lower PM emissions and much higher CO emissions relative to the Diesel buses. Average NOx levels were higher for the CNG buses, but that was driven by one of the three buses that experienced misfire problems.

2002-01-2737 - *An Emission and Performance Comparison of the Natural Gas Cummins Westport Inc. C-Plus Versus Diesel in Heavy-Duty Trucks*[76] - In this study, two pre-production C8.3G Cummins natural gas engines (equipped with a catalyst) designed to meet CARB's low-NOx optional standards (2.0 g/bhp-hr) were compared to similar C8.3 1997 model year Diesel engines. Testing was conducted with West Virginia University's transportable chassis dynamometer using the Heavy-Duty Urban Dynamometer Driving Schedule (UDDS) as well as a newly created Viking Freight test cycle. The emissions testing showed that the natural gas vehicles had lower NOx (24% and 45% on the UDDS and Viking Freight test cycle, respectively) and lower PM (greater than 90%) than their Diesel counterparts.

2002-01-1722 - *Diesel and CNG Heavy-Duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview*[77] - Chassis dynamometer testing was conducted on three vehicle configurations -- a CNG bus equipped with a DDC Series 50G engine (no catalyst), a conventional Diesel bus with a 1998 DDC Series 50 Diesel engine (equipped with a catalyzed muffler), and the same Diesel engine equipped with a Diesel particulate filter (DPF). The natural gas bus had the highest CO and THC emissions, while PM emissions fell between the conventional Diesel bus and the Diesel bus equipped with a DPF. NOx emissions from the NGV were below the Diesel buses, but there was a significant increase in NOx from the NGV when it was retested after two months.

2000-01-3473 - *Comparison of In-Use Emissions from Diesel and Natural Gas Trucks and Buses*[78] - This study analyzed data primarily from NREL's emissions database for trucks and buses equipped with 1994 and later model year heavy-duty Diesel and natural gas engines. These data were supplemented with more recent data from the literature. The data, which were collected on West Virginia University's transportable chassis dynamometer over different test cycles, were converted to units of g/bhp-hr for comparison across vehicles and test cycles. Overall, PM emissions were about 90% lower for NGVs compared to Diesel vehicles. NOx emissions from line-haul trucks were 78% lower for NGVs relative to Diesel vehicles, while NGV buses had NOx emissions 41% lower than the Diesel buses in the NREL database.

2000-01-2822 - *An Evaluation of Natural Gas versus Diesel in Medium-Duty Buses*[79] - This study compared emissions, performance and cost between three natural gas and three Diesel buses equipped with Cummins B-series engines. Both CNG and Diesel engines were equipped with catalysts. Emissions were collected with West Virginia University's transportable chassis dynamometer in Boulder, CO. The CNG buses emitted 58% lower NOx and 98% lower PM than the Diesel buses.

1999-01-1507 - *In-Use Emissions from Natural Gas Fueled Heavy-Duty Vehicles*[80] - This study compared in-use emissions and performance of closed-loop controlled, heavy-duty CNG engines with similar Diesel engines. Vehicles in the program were tested on a chassis dynamometer at the Colorado Institute for Fuels and High Altitude Engine Research (CIFER). Nine CNG buses, three CNG trucks, five Diesel buses, and one Diesel truck were emissions tested. CO, NOx, and PM emissions were substantially lower for the CNG vehicles relative to the Diesel vehicles. Idle emissions were also collected, and the same conclusion could be made.

1999-01-1469 - *Diesel and CNG Transit Bus Emissions Characterization by Two Chassis Dynamometer Laboratories: Results and Issues*[81] - Emissions of three Diesel transit buses equipped with the 1997 model year Cummins 5.9 liter engine were compared to emissions from three CNG transit buses equipped with the corresponding 1997 model year Cummins 5.9 liter natural gas engine (LEV certified). Diesel vehicles and CNG vehicles were equipped with a catalyst. Testing was conducted on West Virginia University's transportable chassis dynamometer as well as at the dynamometer facility at CIFER. The Diesel vehicles averaged 0.7 g/mi PM and 18.4 g/mi NOx. PM emission rates for the CNG vehicles were well below 0.1 g/mi and NOx emissions averaged 11.2 g/mi.

981393 - *Emissions from Trucks and Buses Powered by Cummins L-10 Natural Gas Engines*[82] - In this study, emissions from class 8 tractors with the Cummins L-10 engine operating on liquefied natural gas are compared to similar tractors with Diesel engines. In addition, emissions from CNG buses with the Cummins L-10 engine are compared to a Diesel-powered fleet. The data collected in this program revealed generally lower NOx and PM emissions from heavy-duty NGVs, but several of the CNG buses exhibited high NOx emissions.

973203 - *Natural Gas and Diesel Transit Bus Emissions: Review and Recent Data*[83] - Emissions data from 10 CNG powered buses equipped with the DDC Series 50 engine (all 1996 model year) are compared to 10 similar Diesel powered buses (seven 1996 and three 1994 model year) in this study. Testing was conducted with West Virginia

University's transportable chassis dynamometer over the Central Business District test cycle. The results of the testing indicated that CNG buses had PM emissions that were more than 90% lower than the Diesel buses, and NOx emissions from the CNG buses were 33% lower than the Diesel buses.

962071 - *NYSERDA AFV-FDP CNG Transit Bus Fleet Operating Experience*[84] - As part of the NYSERDA AFV demonstration program, 31 CNG transit buses operating in New York state were evaluated. These buses were equipped with a lean-burn Cummins L10-240G engine that included an oxidation catalyst. The buses were purchased in 1992, and ten of them were emission tested in 1993, 1994, and 1995 over the New York Bus Cycle (along with two Diesel buses). The CNG buses showed higher emissions of THC and lower emissions of NMHC than the Diesels. On average, the CNG CO emissions were lower than Diesel CO emissions in tests conducted in 1993 and 1995. Testing conducted in 1994, however, revealed very high CO emissions on three of the ten CNG buses, which were subsequently repaired. NOx emissions were also lower for the CNG buses relative to the Diesels, but significant deterioration was observed between 1993 and 1995. PM emissions were significantly lower for the CNG buses.

952746 - *Comparative Emissions from Natural Gas and Diesel Buses*[85] - Emissions data from 57 CNG and 33 Diesel buses were collected using the West Virginia University transportable emissions laboratory and compared in this study. Fifty-two of the CNG buses were equipped with early demonstration Cummins L10 engines, and five were equipped with late-model Cummins L10 engines meeting certification standards. The early model CNG bus engines showed significantly greater emissions variability (particularly for CO) than the late-model engines, with the newer engines having lower emissions than the Diesel engines. (The higher CO values for some of the early model CNG engines was related to faulty catalysts or rich idle settings.) NOx emissions from CNG engines were similar to NOx from the Diesel engines, while NMOG and PM from the CNG engines were much lower compared to Diesel.

NREL Literature

The Alternative Motor Fuels Act of 1988 (AMFA) mandated a demonstration of performance, operational costs, maintenance, and fuel economy associated with the use of alternative-fuel vehicles. To comply with that mandate, NREL is managing a series of alternative-fuel vehicle emissions test programs for DOE. Below is a summary of recent reports published by NREL on this subject. Note that many of the projects sponsored by NREL are also described in the SAE literature summarized above.

Light- and Medium-Duty Vehicles

SuperShuttle CNG Fleet Evaluation[86] - In this study, emissions data were collected on a fleet of 13 passenger vans. All vehicles were 1999 model year Ford E-350 passenger vans. Five vans were dedicated CNG (certified to California SULEV standards), Five were bi-fuel CNG/gasoline (certified to LEV standards on CNG and Tier 1 standards on gasoline), and three were conventional gasoline vans (certified to Tier 1 standards). FTP emissions tests were conducted at three mileage points: 10,000 miles, 40,000 miles, and

60,000 miles. Compared to gasoline vehicles, the dedicated CNG vehicles had 92-96% lower NMHC, 94% lower CO, and 70-96% lower NOx. In addition, the dedicated vans showed lower emissions deterioration than their gasoline counterparts.

Light-Duty Alternative Fuel Vehicles: Federal Test Procedure Emission Results[87] - As part of a broader summary of alternative fuel vehicle emissions, results of light-duty NGV testing are presented in this report. Two vehicle models were included in this study: a Dodge B250 van (1992 and 1994 model year) and a 1994 model year Dodge Caravan. The gasoline version of the B250 was certified to Tier 0 emissions standards, while the CNG version received a waiver from emissions certification. Both the gasoline and CNG versions of the Caravan were certified to Tier 1 standards. Measured emissions of NMHC, CO, and NOx were all lower for the NGVs relative to their gasoline counterparts.

Barwood CNG Cab Fleet Study[88] - The emissions results from this study are described in SAE Paper No. 2000-01-1959, which is summarized above.

Alternative Fuel Light-Duty Vehicles: Summary of Results from the National Renewable Energy Laboratory's Vehicle Evaluation Data Collection Efforts[89] - This report summarizes alternative-fuel vehicle emissions data that have been collected by NREL over a span of about four years. Data have been collected on ten OEM vehicle models (1991 to 1995 model years) designed to operate on methanol, ethanol, and CNG and on a number of vehicles converted to operate on CNG or LPG. (See the following report synopsis for a summary of the converted vehicle results.) The most extensive CNG or LPG OEM vehicle testing has been conducted on a fleet of Dodge B250 vans. The results of that testing can be found in SAE paper 961091, which is summarized above.

Compressed Natural Gas and Liquefied Petroleum Gas Conversions: The National Renewable Energy Laboratory's Experience[90] - In order to comply with the vehicle acquisition requirements of the Energy Policy Act of 1992 (EPACT), approximately 900 federal fleet vehicles were converted to operate on CNG or LPG during 1993 and 1994. Sixteen of those vehicles were selected by NREL for emissions testing - 13 were converted to operate on CNG, 3 were converted to LPG. All conversions were dual fuel using higher quality closed-loop feedback kits. (To obtain the best possible conversions, companies were selected on the basis of experience and capabilities rather than price.) Emissions from the alternative-fuel vehicles were compared to pre-conversion and post-conversion emissions on CARB Phase 2 reformulated gasoline. The results from testing showed that emission levels of HC, CO, and NOx were improved or unchanged on only 2 of the 16 vehicles in the program when operated on the alternative fuel. In general, NMHC emissions of CNG were lower than gasoline, but this was accompanied by an increase in CO, NOx, or both. The three LPG conversions demonstrated higher emissions on gasoline operation after conversion than before conversion. The authors concluded that the "disappointing emissions performance" of these converted vehicles raises questions regarding their emissions contribution to the environment.

Heavy-Duty Vehicles

An Emission and Performance Comparison of the Natural Gas C-Plus Engine in Heavy-Duty Trucks[91] - This study is described above under SAE Paper No. 2002-01-2737.

United Parcel Service (UPS) CNG Truck Fleet: Final Results[92] - Three Diesel and 13 CNG delivery trucks were tested in this program. Testing was conducted with West Virginia University's transportable chassis dynamometer. The CNG vehicles were equipped with Cummins B5.9G engines and included a catalyst, while the Diesel control vehicles were equipped with the Cummins B5.9 Diesel engine. The CNG trucks were built in 1996 and started operating in 1997; the Diesel trucks were built in 1995 and started operating in 1996. The CNG trucks had 75% lower CO emissions, 49% lower NOx emissions, and 95% lower PM emissions than Diesel trucks of similar age.

Raley's LNG Truck Fleet: Final Results[93] - In this project, eight heavy-duty LNG trucks (1997 model year) and three Diesel control trucks (1996 model year) were evaluated. The LNG trucks were equipped with Cummins L10-300G engines and the Diesel trucks were equipped with Cummins M11-330 engines. Emissions tests were conducted with West Virginia University's transportable chassis dynamometer over WVU's "5-Mile Route." The LNG trucks had 80% lower NOx emissions and 96% lower PM emissions than the Diesel control trucks.

Alternative Fuel Transit Buses: Final Results from the National Renewable Energy Laboratory Vehicle Evaluation Program[94] - A total of 20 CNG-powered buses were emissions tested in this program over the CBD driving cycle on a transportable chassis dynamometer. Ten buses were equipped with Cummins L10 non-emissions certified demonstration engines, and ten were equipped with CARB-certified versions of the engine. Compared to Diesel controls, the certified CNG engines emitted about one-half the NOx and one-tenth the CO. Total HC was significantly higher for the CNG engines, while PM emissions were very low. The authors concluded that natural gas buses have the potential to significantly lower PM and NOx emissions. However, early generation technologies have shown high variability in some emissions levels relative to the Diesel controls.

Other Reports and Papers

A number of other reports and papers related to CNG missions issues were identified in our literature search. These are described below.

CleanFleet Final Report (Battelle)[95] - Formally known as the South Coast Alternative Fuels Demonstration, this was a two-year demonstration of alternative-fuel vehicle use in daily commercial service. The demonstration ran from April 1992 through September 1994 and included testing of five alternative fuels: CNG, LPG, methanol, reformulated gasoline, and electricity. Vehicles in the program were 1992 model year delivery vans operated by FedEx in the South Coast Air Basin. It should be noted that the vehicles in the program represented a snapshot in time of the available 1992 technologies supported by OEMs (Chrysler, GM, and Ford). Results of the CNG testing revealed that exhaust emission levels of most pollutants were lower than any of the other fuels tested. NOx emissions from two OEMs were lower than the gasoline controls (49% and 43%), while NOx emissions of the Ford vehicles were higher than the gasoline controls (63%). CO emissions were reduced by 68% to 77%, and NMOG emissions were significantly reduced relative to the gasoline controls.

Comparison of MOBILE6 NGV Emission Factors to Available Data

As described above, there is a substantial literature of emissions data from natural gas vehicles. Unfortunately, it is difficult to select a single study or even several studies with which to compare NGV emission rates to estimates from MOBILE6. Many of the NGV test results reflect technologies at various states of development, and oftentimes the gasoline and Diesel "control" vehicles were certified to different emissions standards than the NGVs in the programs. In addition, only a few studies measured emissions over an extended time period so that emissions deterioration could be accounted for. Nonetheless, presented below is a comparison of MOBILE6 NGV emissions estimates for light-duty vehicles to estimates presented in SAE Paper No. 2000-01-1959 described above.

The NGVs evaluated in SAE 2000-01-1959 were Crown Victoria taxicabs certified to ULEV emissions standards, which are the same emissions standards that are assumed in MOBILE6 for NGVs. As a result, emissions from the model and from the test program should be comparable. For this evaluation, the cold-start FTP NMHC and NOx emission rates were read from figures contained in SAE 2000-01-1959, and the following emission factors, i.e., zero-mile level (ZM) and deterioration rate (DR), were obtained for these NGVs:

Pollutant	ZM (g/mi)	DR (g/mi per 10,000 mi)
NHMC	0.050	0.000
NOx	0.160	0.013

These values were then used in conjunction with the MOBILE6 command "NGV EF" to specify alternative NGV emission factors in the model. However, for light-duty cars and trucks, that command requires users to specify emission rates for both normal and high emitters, and emission rates must be specified for both running and start emissions.*

For this analysis, it was assumed that the NGV fleet evaluated in SAE 2000-01-1959 contained both normal emitters and high emitters. Thus, it was not necessary to calculate separate emission factors. However, the model requires that high-emitter emission rates be entered. As a result, the high emitter emission rate was assumed to be equivalent to the normal emitter emission rate (at 100,000 miles) for this modeling exercise.

---

* Note that when specifying alternative emission factors for heavy-duty vehicles there is no distinction between normal and high emitters and there is no distinction between running and start emissions (i.e., composite emission factors are entered by the user).

Within the model, the conversion from FTP emission rates to running and start emission rates is performed by multiplying the FTP emissions by the following factors (CO is included for completeness):

Pollutant	Running Factor	Start Factor
NMHC	0.230	11.00
CO	0.338	4.149
NOx	0.900	1.270

Thus, these same factors were used to develop running and start emission factors for input to MOBILE6.

The results of this analysis are presented in Figures 5-13 and 5-14 for VOC and NOx, respectively. As seen in Figure 5-13, the alternative NGV VOC emission rates calculated from SAE 2000-01-1959 match the default MOBILE6 factors very closely. The NOx emission rates shown in Figure 5-14 are also similar, but at higher mileage the alternative NOx emission factors fall below the default MOBILE6 estimates. That is because the normal and high emitter emission rates were very similar in the alternative analysis, while the default MOBILE6 NGV emission factors are significantly different for normal and high emitters.

Figure 5-13

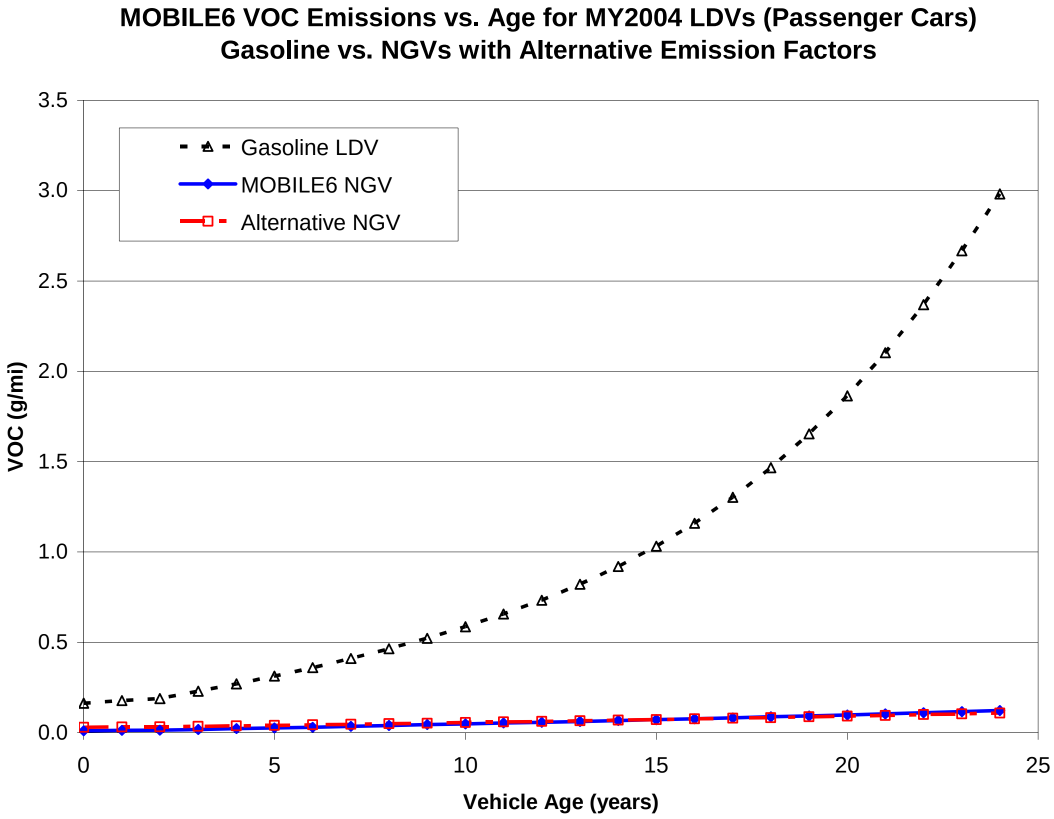
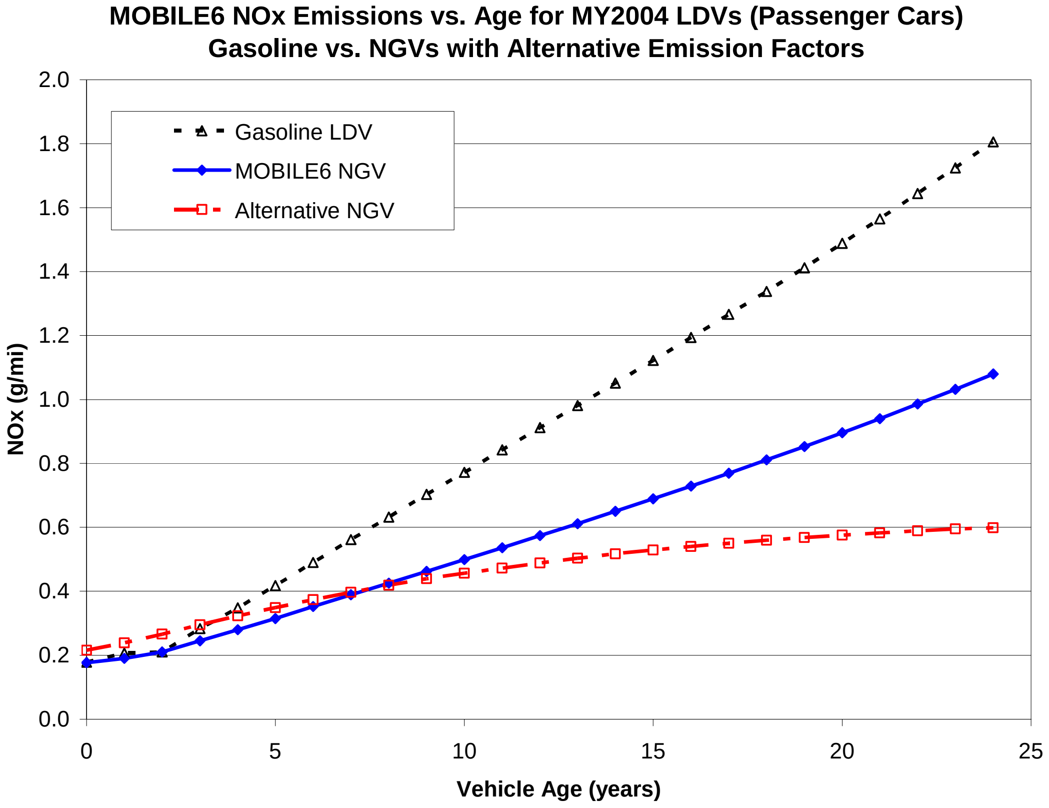


Figure 5-14


MOBILE6 NOx Emissions vs. Age for MY2004 LDVs (Passenger Cars)
Gasoline vs. NGVs with Alternative Emission Factors
Gasoline LDV
MOBILE6 NGV
Alternative NGV
NOx (g/mi)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
Vehicle Age (years)

6. CARBON DIOXIDE (CO_2) EMISSIONS ESTIMATES WITH MOBILE6

In addition to calculating emissions of criteria pollutants (CO, particulate matter, lead, and sulfur dioxide), ozone precursors (HC and NOx), ammonia, and air toxics from on-road motor vehicles, MOBILE6 also has algorithms built into it to estimate CO_2 emissions from on-highway vehicles. This capability was added in draft form with the November 2002 release of the model (MOBILE6.2), and the CO_2 component is often referred to as MOBILE6.3. This section of the report reviews the methodology used to generate CO_2 estimates in MOBILE6 and presents results from the model.

MOBILE6.3 CO_2 Methodology

The basic methodology for estimating CO_2 in MOBILE6 is to perform a mass balance on carbon in the fuel, assuming that all carbon is emitted as CO_2.* The starting point of the calculation is fuel economy, which is stored in the model for each vehicle class and model year. (Recall that fuel economy estimates are used in conjunction with fuel sulfur content to estimate particulate sulfate emissions and gaseous SO_2 emissions. In addition, fuel economy estimates are used in the model to convert refueling losses from a gram per gallon basis to a gram per mile basis.) For example, gasoline typically has a hydrogen-carbon ratio of about 1.85 to 1; thus, gasoline can be represented by the chemical formula $CH_{1.85}$. If all of the fuel is combusted to form CO_2 and water, the chemical reaction can be written as:

$$80CH_{1.85} + 117O_2 \rightarrow 80CO_2 + 74H_2O$$

Thus, if a gasoline vehicle achieves a fuel economy of 20 miles per gallon and all of the carbon in the gasoline is emitted as CO_2, the gasoline usage per mile can be calculated as:

$$1/FE = 1/20 \text{ gal/mi} = 0.05 \text{ gal/mi}$$

However, the density of gasoline is about 2800 grams per gallon, and the gasoline usage rate is therefore:

$$CH_{1.85} = \quad 0.05 \text{ gal/mi} * 2800 \text{ g/gal} = 140 \text{ g/mi gasoline used}$$

---

* Note that as originally proposed, MOBILE6 CO_2 estimates also accounted for gasoline being converted to HC and CO. However, the February 2004 release of MOBILE6 now only accounts for the conversion of gasoline to CO_2. According to EPA, this better reflects atmospheric CO_2 emissions. This is discussed in more detail later in this section of the report.

If all the carbon in the gasoline is converted to CO_2, the $CO_2/CH_{1.85}$ molecular weight ratio (44/13.85) is applied to the 140 g/mi gasoline usage estimate to give the following CO_2 estimate:

$$\begin{aligned} CO_2 &= 140 \text{ g/mi } CH_{1.85} * (44/13.85) \\ &= 445 \text{ g/mi} \end{aligned}$$

As originally proposed in the November 2002 release of MOBILE6.2, it was assumed that all carbon not exhausted as CO_2 is exhausted as HC or CO. Thus, HC and CO estimates also entered into the CO_2 equation used in the November 2002 version of the model. The equation used in that version of the model for gasoline vehicles was derived from the fuel economy calculations contained in the Code of Federal Regulations (40 CFR 600.113) for pre-1988 model year vehicles, i.e.,

$$MPG = 2421 / [(0.866*HC) + (0.429*CO) + (0.273*CO_2)]$$

Rearranging the above to solve for CO_2 gives:

$$CO_2 = 8868.13/MPG - 3.172*HC - 1.571*CO$$

Thus, assuming 20 mi/gal fuel economy, an HC emission rate of 0.5 g/mi, and a CO emission rate of 5 g/mi gives:

$$\begin{aligned} CO_2 &= 8868.13/(20 \text{ mi/gal}) - 3.172*(0.5 \text{ g/mi}) - 1.571*(5 \text{ g/mi}) \\ CO_2 &= 434 \text{ g/mi} \end{aligned}$$

In this case, if all of the carbon was converted to CO_2 (i.e., HC and CO equal 0 in the equation above), the CO_2 emission rate would be 443 g/mi, which is slightly lower than the 445 g/mi calculated above. That difference is likely a result of slightly different estimates of fuel density in the 40 CFR 600.113 equation relative to that assumed above.

With the February 2004 release of MOBILE6, EPA removed the dependence on HC and CO emission rates and now simply assumes that all carbon in the fuel is converted to CO_2. According to the email announcing the release of the February 2004 version of the model,[96] this change was made to "better estimate atmospheric CO_2." Although not discussed in that announcement, one of the atmospheric fates of CO is oxidation to CO_2.

Diesel vehicles are treated in a similar fashion. However, because the density of Diesel fuel is different than gasoline (i.e., Diesel is a heavier fuel than gasoline) and has a different hydrogen-carbon ratio, the equation used in MOBILE6 to estimate CO_2 emissions is slightly different. As with gasoline vehicles, the February 2004 release of the model removed the dependency on HC and CO, assuming instead that all carbon in the fuel is ultimately converted to CO_2. Below are the original and revised versions of the equations used to estimate CO_2 emissions from Diesel vehicles.

$CO_{2\ \mathrm{Diesel}}$ = 10175.82/MPG - 3.172*HC - 1.571*CO (Original Equation)

$CO_{2\ \mathrm{Diesel}}$ = 10175.82/MPG (February 2004 Version)

It is worth noting that CO_2 emissions are also impacted by the presence of oxygenate in the fuel. However, this effect, which is relatively minor, is not modeled by MOBILE6. In addition, although MOBILE6 provides emissions estimates for natural gas vehicles, it does not calculate CO_2 emissions for these vehicles.

Basis of the Fuel Economy Estimates in MOBILE6

As described above, the CO_2 emission rate from motor vehicles is directly related to the fuel economy of the vehicle. Unless a vehicle is in extremely poor condition (resulting in high HC and CO emissions), almost all of the gasoline and Diesel fuel combusted in an engine is converted to CO_2 and water (e.g., 98% in the example presented above), and the revised version of MOBILE6 assumes that all carbon in the fuel is exhausted as CO_2. Thus, it is important to obtain good fuel economy estimates to accurately predict CO_2 emissions from the on-road motor vehicle fleet.

The fuel economy estimates were updated for MOBILE6 as described in MOBILE6 report number M6.GHG.001.[97] The methodology and data sources used for that update are briefly described below separately for light-duty and heavy-duty vehicles.

Light-Duty Vehicles - For over 25 years, EPA has calculated the corporate average fuel economy (CAFE) for each vehicle manufacturer at the end of each model year. These estimates are used by the Department of Transportation (DOT) to determine compliance with the CAFE standards established by Congress beginning with the 1978 model year for passenger cars and the 1979 model year for light-duty trucks. The CAFE standards apply to light-duty vehicles and light-duty trucks with a gross vehicle weight rating (GVWR) of 8,500 lbs. or less. Currently, manufacturers are required to meet a fuel economy standard of 27.5 mpg for passenger cars and a standard of 20.7 mpg for light-duty trucks.

The data used to determine fuel economy are collected during the vehicle certification process and consist of dynamometer test results over the Federal Test Procedure (FTP) and the Highway Fuel Economy Test (HFET). To determine compliance with CAFE standards, a combined fuel economy estimate is obtained by weighting the FTP results by 55% and weighting the HFET results by 45%.[*]

---

[*] Note that this calculation is performed with a harmonic weighting of the FTP and HFET results, i.e.,

$$\text{Combined FE} = 1 / (0.55/\mathrm{FTP}_{\mathrm{MPG}} + 0.45/\mathrm{HFET}_{\mathrm{MPG}})$$

This can be thought of as converting the miles per gallon estimates for each test to a gallons per mile basis before weighting the results by the 55/45 FTP/HFET split.

The results of the fuel economy testing are published annually by EPA in its Fuel Economy Trends reports.[98] However, the results published by EPA are adjusted to better reflect real-world fuel economy. (In-use fuel economy is generally lower than that calculated from dynamometer testing on the FTP and HFET cycles.) This adjustment is performed by scaling the FTP fuel economy with a multiplicative factor of 0.90 and the HFET value is scaled by 0.78 prior to weighting by the 55/45 FTP/HFET split.

For the MOBILE6 update, the 2001 version of EPA's Fuel Economy Trends report[99] was used to compile fuel economy estimates for light-duty cars and trucks. All fuel economy estimates were based on the adjusted values reported in that document. Estimates were prepared separately for gasoline and Diesel vehicles, and adjustments had to be made to generate estimates for the lighter LDTs (i.e., the LDT12 classes) versus heavier LDTs (i.e., the LDT34 classes), which are not reported separately in the Fuel Economy Trends report. This was done by assuming that the LDT12 class makes up about 75% of all LDTs, and that historical data indicate the ratio of fuel economies of LDT12 to LDT34 classes is about 1.3. Thus, if the combined fuel economy for all trucks is 17.2 mpg, the fuel economy of the individual light-duty gasoline truck classes is calculated as follows:

$$1/FE = 0.75/FE_{T12} + 0.25/FE_{T34}$$

$$1/17.2 = 0.75/FE_{T12} + 0.25/(FE_{T12}/1.3)$$

$$1/17.2 = 0.75/FE_{T12} + 0.325/FE_{T12}$$

$$FE_{T12} = 18.5 \text{ mpg}$$

Putting 18.5 mpg into the first equation above for FE_{T12} and solving for FE_{T34} results in a value of 14.2 mpg for the heavier light-duty trucks (i.e., the T34 category).

Heavy-Duty Vehicles - The fuel economy estimates for heavy-duty vehicles were obtained from the MOBILE6 EPA report M6.HDE.002.[100] That report generated revised fuel economy estimates for use in heavy-duty engine emission conversion factors for MOBILE6,[*] but those estimates are also used in the model for a number of other calculations, including CO_2. The primary source of fuel economy estimates for heavy-duty vehicles was from the 1992 Truck Inventory and Use Survey (TIUS). This survey, which is now known as the Vehicle Inventory and Use Survey (VIUS), is conducted by the U.S. Census Bureau every five years. The stated purpose of the survey, which is mandated by law, is to "measure the physical and operational characteristics of the Nation's truck population,"[101] and it includes data on fuel economy, annual and lifetime miles driven, weeks operated, etc. as a function of truck class and model year. These data were used to estimate fuel economy for heavy-duty trucks in MOBILE6.

Summary of Fuel Economy Estimates in MOBILE6 - The fuel economy estimates contained in MOBILE6 are illustrated in Figure 6-1 for a number of selected vehicle

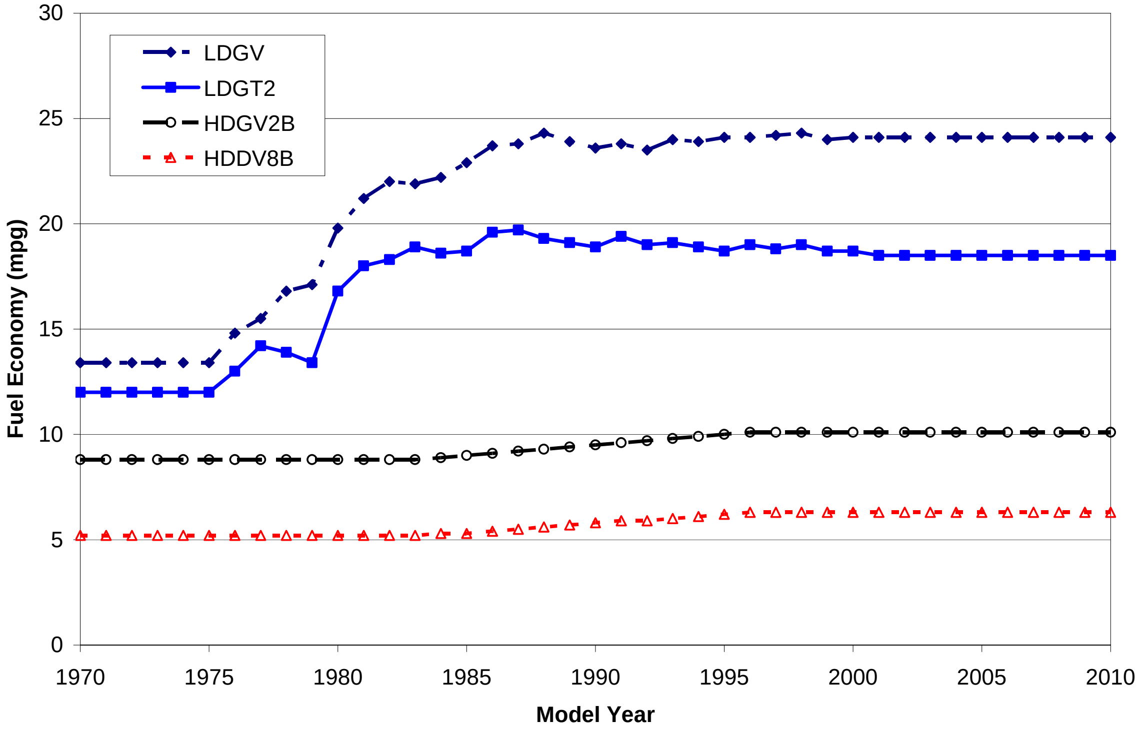
---

[*] Recall that heavy-duty engine emission conversion factors are used to convert emissions measurements taken on an engine dynamometer (in units of grams per brake-horsepower-hour) to a gram per mile basis.

classes (light-duty gasoline vehicles, light-duty gasoline trucks between 3750 and 5750 lbs. test weight, class 2B heavy-duty gasoline trucks, and class 8B heavy-duty Diesel trucks). As expected, significant increases in light-duty vehicle fuel economy are observed between the 1975 and 1990 model years as a result of CAFE regulations (and improvements in fuel management technology, i.e., the shift from carburetion to fuel injection). For heavy-duty Diesel vehicles, slight improvements in fuel economy are observed between 1985 and 1995. Much of this improvement was a result of the use of more aerodynamic trucks and tires with lower rolling resistance.

Figure 6-1

MOBILE6 Fuel Economy Estimates by Vehicle Class and Model Year (Miles per Gallon)



CO_2 Estimates with MOBILE6

Using the fuel economy estimates illustrated in Figure 6-1, along with the calculation methodology described above, MOBILE6 estimates CO_2 emissions from the in-use vehicle fleet. The CO_2 results from the model are shown as a function of model year in Figure 6-2, and fleet-average results are shown by calendar year in Figure 6-3. The CO_2 estimates in Figures 6-2 and 6-3 are inversely proportional to the fuel economy estimates shown in Figure 6-1 (i.e., better fuel economy translates to lower CO_2 emissions). Thus, as fuel economy has improved over the years, CO_2 emissions have decreased.

Figure 6-2

MOBILE6 Carbon Dioxide Estimates by Vehicle Class and Model Year

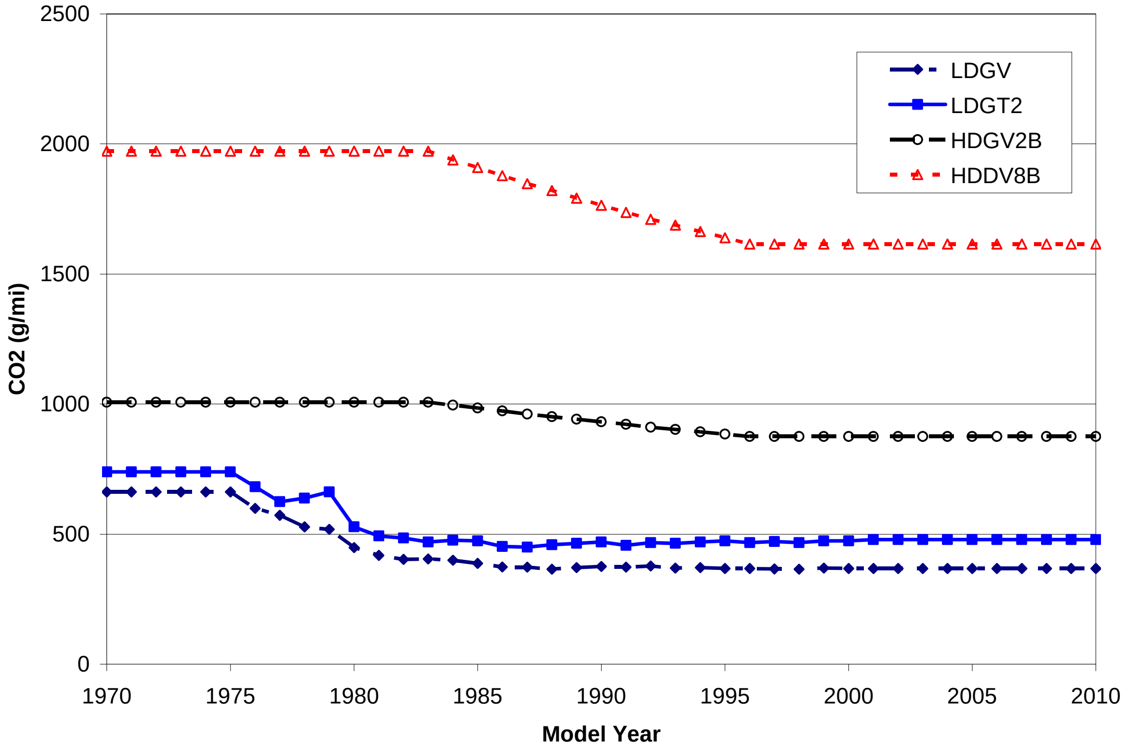
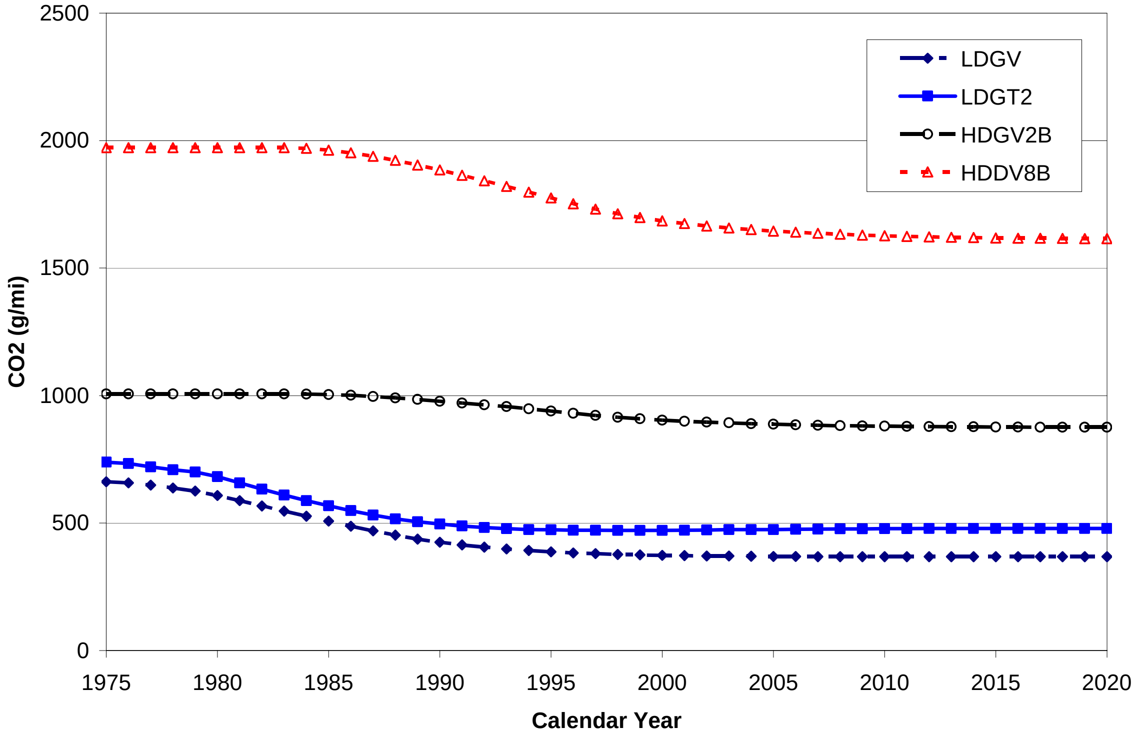


Figure 6-3

MOBILE6 Carbon Dioxide Estimates by Vehicle Class and Calendar Year



7. MOBILE6 VALIDATION STUDIES

This section of the report reviews available studies on the validation of MOBILE6, with an emphasis on PM and toxics. In addition, a summary of a recently released report sponsored by the Coordinating Research Council (CRC) and EPA on the validation of MOBILE6 with respect to HC, CO, and NOx is also included. That study, conducted by ENVIRON, compared output from MOBILE6 to available "real-world" data. In general, other than this CRC study, there have been few validation studies directed at MOBILE6.

Before summarizing the results of validation studies, a brief discussion of the methods that can be used to validate calculated emissions estimates is presented.

Validation Methods

A number of different methods can be used to help validate (or verify) emissions estimates prepared with an emissions model such as MOBILE6. Among those methods are:

- *Tunnel Studies* - Since the late-1980s, considerable work has been done to measure emissions from on-road motor vehicles in tunnels. A number of tunnels throughout the U.S. have been used to estimate emissions from the on-road motor vehicle fleet. These include the Fort McHenry tunnel in Baltimore, the Tuscarora Mountain tunnel in Pennsylvania, the Caldecott tunnel near San Francisco, and the Sepulveda tunnel in Los Angeles. The results from early tunnel studies revealed that the emission factor models at that time may have been under-predicting emissions from the motor vehicle fleet, and that helped spur research into off-cycle emissions and ultimately the development of the Supplemental Federal Test Procedure (SFTP) regulations for light-duty vehicles.

- *Ambient Pollutant Concentration Ratios* - In areas with a relatively large fraction of emissions from on-road motor vehicles, it is possible to compare the ratio of pollutants in ambient air to the ratios predicted in the emissions inventory. Most commonly this is done for HC/NOx ratios and for CO/NOx ratios. There are, however, a number of shortcomings associated with this approach. First, it is not possible to compare the overall magnitude of the MOBILE predictions, only how well the pollutant ratios line up with those observed in the ambient air. Second, because HC and NOx participate in atmospheric reactions (e.g., to form ozone), the ambient data must be carefully selected (e.g., data from mornings are typically used to minimize the impact of photochemical reactions).

- *Remote Sensing Pollutant Ratios* - In addition to ambient pollutant concentrations, data from remote sensing devices (RSDs) can be used to develop pollutant ratios with which to compare to MOBILE output. Current RSD technology includes measurements of HC, CO, NOx, and CO_2 in the exhaust plume from individual vehicles being driven on the road. These measurements are typically reported in terms of tailpipe concentration (e.g., % CO, ppm HC) or in terms of grams of pollutant per kilogram of fuel consumed. A shortcoming of RSD technology is that it captures vehicle operation for only about one-half of a second, and therefore emissions measurements are sensitive to the driving patterns at the RSD site (e.g., cruise versus acceleration). More recent RSD studies have tried to account for this by evaluating speed and acceleration during the RSD measurement.

- *Fuel Consumption Estimates* - As described in the previous section of this report, fuel economy estimates are contained in the MOBILE6 model. Using those estimates, along with fleet VMT data collected by FHWA, it is possible to estimate annual fuel consumption in the U.S. (or any region of the U.S.). Because gasoline and Diesel fuel used in on-highway vehicles are taxed, good records exist for fuel sales and usage. Thus, the fuel consumption estimates generated with MOBILE6 can be compared to fuel sales volumes based on tax records.

- *Comparison of Model Output to Available Chassis-Dynamometer Data* - As noted in Section 3 of this report, emission factors for heavy-duty vehicles in MOBILE6 are based on data collected with an engine dynamometer (i.e., the engine is removed from the vehicle and connected to a test stand) which are then converted to a gram per mile basis using "conversion factors." For the last 10 years, a database of heavy-duty vehicle emissions has been building, primarily through the use of transportable chassis dynamometers developed and operated by West Virginia University. In addition, chassis dynamometer testing of heavy-duty vehicles has been conducted at the Colorado School of Mines and in Southern California through a cooperative effort between the California Air Resources Board and the Los Angeles Metropolitan Transit Authority. Thus, it is possible to compare these chassis-dynamometer results to output from MOBILE6.

Validation of MOBILE6 PM Estimates

As noted above, few studies were identified that focused on the validation of MOBILE6 PM estimates. However, a recent RSD study conducted in Las Vegas used a new technique to measure PM in the exhaust plume from passing vehicles, and those results were compared to estimates from PART5. In addition, as discussed above and presented in Section 3 of this report, there has been considerable chassis-dynamometer data collected on heavy-duty vehicles in recent years that can be compared to MOBILE6 output.

RSD Studies – Between April 2000 and May 2002, the Desert Research Institute conducted an RSD study in Las Vegas in which emissions from almost 150,000 vehicles were measured in Clark County, Nevada.[102] As part of that study, a new technique for remote sensing of vehicle particulate emissions was used, and the results were compared to output from PART5. (Recall that the basis for the MOBILE6 PM estimates was PART5, so this comparison is also relevant to MOBILE6.)

Table 7-1 summarizes the comparison presented in the above report, where the PM emission factors are reported in terms of grams of PM per kilogram of fuel. As observed in that table, the PART5 and RSD emission rates are in reasonable agreement for the LDGV, LDDV, and HDDV vehicle classes, with PART5 predicting somewhat higher emissions for gasoline and Diesel light-duty vehicles and somewhat lower emissions for heavy-duty Diesel vehicles. For HDGVs, the RSD results are well below PART5 estimates. The final row of Table 7-1 presents RSD results for large trucks with trailers. The authors attributed the low RSD emission rate for those vehicles to the fact that they generally had elevated exhaust pipes and therefore the RSD device did not measure directly across the plume. Instead, emissions were measured in the wake of the vehicle, which resulted in significant dilution and may have lowered PM concentrations below the detection limit of the instrumentation.

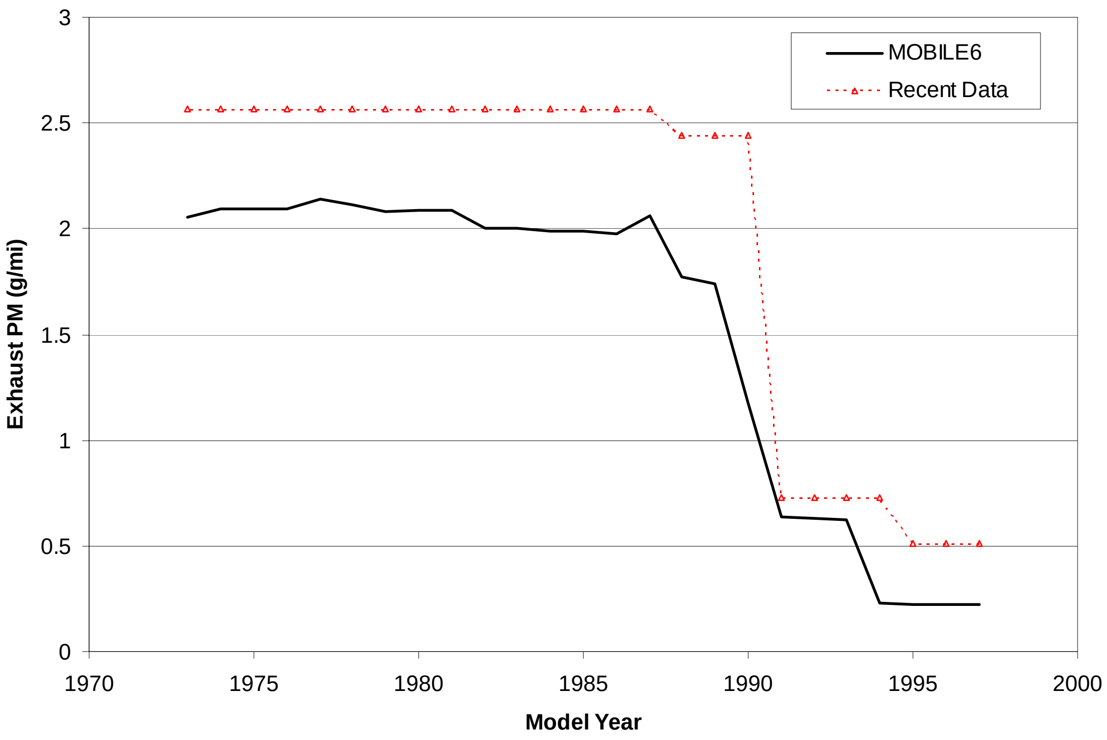
Table 7-1
Comparison of Fleet-Average PM Emission Rates
RSD Versus PART5

Vehicle Class	RSD Emission Rate (g PM/kg Fuel)	PART5 Emission Rate (g PM/Kg Fuel)	Percent Difference
LDGV	0.10	0.13	+30%
LDDV	1.5	1.9	+27%
HDGV	0.07	0.25	+257%
HDDV	1.5	1.0	-33%
Large Trucks w/Trailers	0.20	--	--

Note: Table adapted from reference 102.

<u>Comparison to Chassis-Dynamometer Data</u> - Another comparison that can be made to validate the PM estimates from MOBILE6 is with chassis-dynamometer data. This is particularly relevant for heavy-duty Diesel vehicles, as there is considerable uncertainty in the conversion from engine-dynamometer results (in grams per brake horsepower-hour) to a gram per mile basis. Such a comparison was presented in Section 3 of this report, and Figure 7-1 shows a comparison of PM emission rates for Class 8B HDDVs calculated with MOBILE6 to data from recent test programs. As observed in that figure, the MOBILE6 estimates are lower than estimates based on recent data collected with a chassis dynamometer. This is consistent with the findings of the RSD program summarized in Table 7-1.

Figure 7-1



Comparison of MOBILE6 HDDV8B Exhaust PM Emissions to Results of Recent Test Programs

Validation of MOBILE6 Toxics Estimates

To our knowledge, the toxics emissions estimates from MOBILE6 have not been independently validated. However, as part of the development of MOBILE6, model output was compared to results from its predecessor model, MOBTOX5b, for Atlanta.[103] In general, those results showed that MOBILE6 predicts higher emission rates of benzene, 1,3-butadiene, formaldehyde, and acetaldehyde through about 2010, and by 2020 estimates from the two models converge.

Although not directly related to the MOBILE6 toxics estimates, results from MOBTOX5b were used in conjunction with CO estimates to generate predicted exposure levels to air toxics as part of the 1999 assessment of mobile source air toxics prepared for EPA.[104] In that study, ambient toxics concentration measurements were compared to modeled exposure estimates. Based on the contribution of on-road motor vehicles to ambient levels of hydrocarbons (and air toxics), and the fact that the exposure estimates are based on time spent indoors as well as outdoors, the modeled motor-vehicle related exposure levels should be about 15% to 25% of the ambient concentrations.

Table 7-2 summarizes the modeled motor-vehicle related exposure estimates and the ambient concentrations presented in reference 104. Comparing the modeled motor vehicle related exposure to the ambient concentrations, one observes that the exposure/ambient concentration ratios align reasonably well with expectations (i.e., between 0.15 and 0.25) for a number of urban areas and pollutants. However, the benzene exposure estimate for Minneapolis appears too high while the 1,3-butadiene estimate for Houston appears too low relative to ambient concentrations.

Table 7-2
Comparison of Ambient Concentration Measurements to Modeled 1996 Motor Vehicle Related Exposure Estimates (µg/m^3) Based on MOBTOX5b

Pollutant	Urban Area	Motor Vehicle Related Exposure	Ambient Concentration	Exposure/ Amb. Conc.
Benzene	Chicago	0.48	1.4	0.344
	Houston	0.54	2.9	0.185
	Minneapolis	1.11	1.9	0.583
	New York	0.79	1.9	0.414
Acetaldehyde	Minneapolis	0.27	1.4	0.192
	New York	0.15	2.5	0.058
Formaldehyde	Minneapolis	0.46	2.0	0.230
	New York	0.51	3.1	0.164
1,3-Butadiene	Houston	0.06	1.0	0.057

Note: Table adapted from reference 104.

Validation of MOBILE6 Fuel Economy Estimates

In the technical report describing the update of fuel economy estimates for MOBILE6 (M6.GHG.001),[105] EPA presented a comparison of national fuel consumption calculated with MOBILE6 to estimates prepared by the Department of Transportation (see, for example, “National Transportation Statistics 2000” published by the Bureau of Transportation Statistics). The MOBILE6 estimates can be considered “bottom-up” estimates in that they are based on dividing national VMT (reported by DOT) by the fuel economy estimates contained in MOBILE6. The DOT fuel consumption estimates, on the other hand, can be considered “top-down” estimates in that they are based on fuel sales as reported to FHWA by the states.

The MOBILE6-based analysis resulted in a total of 153,455 million gallons of fuel used in calendar year 1998 (gasoline and Diesel fuel) in on-highway vehicles. As a point of comparison, DOT estimated that 154,833 million gallons of fuel was used in on-highway vehicles in 1998. These two estimates are within 1% of each other. However, larger differences existed when the two sources of estimates were compared by vehicle class. DOT estimated a larger fraction of fuel usage in passenger cars than MOBILE6, while the MOBILE6 estimates for trucks (light- and heavy-duty) were greater than the DOT estimates.

Although the total fuel usage estimates developed with MOBILE6 and those published by DOT line up remarkably well, it should be noted that there are a number of uncertainties associated with the DOT estimates. In particular, allocating fuel sales between on-highway use and off-highway use is often a source of error, as it is very difficult to determine how much fuel is consumed in each sector. This is particularly true for Diesel fuel. Thus, the fact that the MOBILE6-based and DOT fuel consumption estimates are nearly equivalent should not be given too much significance.

Validation of MOBILE6 HC, CO, and NOx Estimates

As noted above, CRC recently released a report summarizing the results of a project specifically aimed at validation assessments of MOBILE6 (CRC Project E-64).[106] The primary findings from that study are summarized below. When reviewing these findings, the reader should keep in mind that the alternative emissions estimates to which MOBILE6 is compared are subject to their own limitations and uncertainties.

Tunnel Studies - A number of tunnel studies were reviewed and compared to modeled emission rates from MOBILE5 and MOBILE6. Overall, it was found that MOBILE6 over-predicted fleet-average emissions compared to measured emissions in the tunnels. The MOBILE6 over-prediction was most apparent for CO emission rates, while fleet-average NOx emissions estimates from MOBILE6 most closely match the observed data.

Ambient Pollutant Concentration Ratios - Ratios of pollutant species in ambient air were compared to ratios from emissions inventories developed with MOBILE6 for five locations in the U.S. (Recall that this type of analysis only provides insight on the relative contribution of different species calculated by the model, not the absolute magnitude of the estimates.) The focus of this analysis was on data collected in urban areas with a high fraction of motor vehicle use during the morning commute hours. In addition, ambient ratios from data collected on weekends were also compared to inventory results prepared with MOBILE6. HC/NOx and CO/NOx ratios were compared in this effort.

The authors found that HC/NOx ratios found in ambient air generally agreed with the ratios developed from emissions inventory data, suggesting that the MOBILE6 HC/NOx ratios are reasonably accurate. On the other hand, the CO/NOx ratios found in ambient air generally exceeded the MOBILE6-based inventory estimates. However, the authors cautioned that this does not necessarily mean that MOBILE6 under-predicts CO (or over-predicts NOx) because: (1) the potential influence of background CO on the estimates, and (2) NOx and CO monitors were at different locations in each city.

Remote Sensing Pollutant Ratios - This evaluation focused at comparing MOBILE6 to RSD-based measurements of CO/NO and HC/NO ratios as well as the change in HC, CO, and NO mass emission rates with vehicle age.* Based on the review of the RSD CO/NO ratios, it was found that MOBILE6 over-predicts CO relative to NO for newer vehicles by up to a factor of three compared to RSD measurements. On the other hand, the HC/NO ratios calculated with MOBILE6 for light-duty gasoline vehicles were in much better agreement with the RSD data. For light-duty trucks, however, the MOBILE6 HC/NO ratios exceeded the RSD ratios by up to a factor of four (indicating a potential over-prediction of HC or under-prediction of NOx by MOBILE6 relative to RSD). For both vehicle classes, the impact of vehicle age on HC/NO ratios and on the HC emission factors is consistent between MOBILE6 and the RSD data, while MOBILE6 appears to over-estimate CO deterioration with vehicle age.

Comparison of Model Output to Chassis-Dynamometer Data - The CRC E-64 report also compared MOBILE6 output to chassis-dynamometer data for heavy-duty Diesel vehicles. The results of this analysis indicated that MOBILE6 predictions of HC and CO for heavy-duty Diesel vehicles matched the available test data reasonably well. NOx emissions for older model year vehicles (pre-1979) appear to be over-estimated by MOBILE6, while NOx emissions for newer model year vehicles (1994 and later) appear to be under-estimated by MOBILE6 relative to available test data.

---

* Note that RSD measures %NO, while MOBILE6 reports emission factors in terms of NOx. Because most of the NOx emitted from the tailpipe of motor vehicles is NO, it was assumed in the CRC study that the MOBILE6 NOx emission factors were equivalent to NO. However, the calculation used in the FTP to report NOx is based on all nitrogen oxides being reported as NO_2. Thus, it appears that the MOBILE6 NOx values should have been scaled by 30/46, i.e., the ratio of the molecular weights of NO to NO_2, if the mass of NO is desired from the MOBILE6 NOx estimates. Making this correction to the MOBILE6 NOx output, however, would not have a large enough impact to change the basic conclusions that were made with respect to the RSD-MOBILE6 comparisons.

Appendix A

Gasoline Specification Data

Compiled from:

“Analysis of the Impacts of Control Programs on Motor Vehicle Toxics Emissions and Exposure in Urban Areas and Nationwide,” Prepared by Sierra Research and Radian International/Eastern Research Group for the U.S. Environmental Protection Agency, Contract No. 68-C7-0051, Work Assignment 1-06, November 30, 1999.

1990 Baseline Fuel Specifications

Area	Season	RVP, psi	Aromatics %	Olefins %	Benzene %	Sulfur ppm	E200 %	E300 %	MTBE %	ETBE %	EtOH %	TAME %	Oxygen wt %
Atlanta	Summer	8.5	27.9	10.5	1.16	344	40.7	79.0	0.0	0.0	0.0	0.0	0.00
Atlanta	Winter	12.5	26.2	14.4	1.49	267	49.1	82.4	0.0	0.0	0.0	0.0	0.00
Chicago	Summer	8.7	28.8	8.6	1.35	512	47.2	78.6	0.0	0.0	0.0	0.0	0.00
Chicago	Winter	13.7	23.0	9.1	1.69	450	54.4	82.6	0.0	0.0	0.0	0.0	0.00
Denver	Summer	8.3	24.8	12.2	1.41	375	45.1	79.4	0.0	0.0	0.0	0.0	0.00
Denver	Winter	12.1	19.3	12.8	1.23	272	62.0	85.5	11.6	0.0	0.0	0.0	2.06
Houston	Summer	8.3	30.2	10.9	1.36	375	46.7	79.4	0.5	0.0	0.0	0.0	0.10
Houston	Winter	12.8	23.0	14.4	1.22	454	52.4	80.2	0.0	0.0	0.0	0.0	0.00
Minneapolis	Summer	9.5	29.8	8.3	1.69	422	45.9	78.9	0.0	0.0	0.0	0.0	0.00
Minneapolis	Winter	13.2	24.9	9.3	1.86	701	56.0	81.6	0.0	0.0	0.0	0.0	0.00
New York	Summer	8.3	31.9	13.9	1.08	367	43.1	78.8	2.4	0.0	0.0	0.0	0.42
New York	Winter	13.3	26.4	16.7	1.55	274	49.5	81.8	0.0	0.0	0.0	0.0	0.00
Philadelphia	Summer	8.4	29.2	13.7	0.86	371	43.6	79.0	0.0	0.0	0.0	0.0	0.00
Philadelphia	Winter	13.9	23.5	13.2	1.63	206	50.5	82.9	0.0	0.0	0.0	0.0	0.00
Phoenix	Summer	8.1	33.0	5.9	2.15	123	41.1	78.5	0.0	0.0	0.0	0.0	0.00
Phoenix	Winter	10.9	26.4	5.6	1.88	157	56.5	82.9	11.4	0.0	0.0	0.0	2.04
Spokane	Summer	8.6	21.0	8.0	1.36	739	46.6	82.6	0.0	0.0	0.0	0.0	0.00
Spokane	Winter	13.1	19.2	10.3	1.58	698	51.1	84.9	0.0	0.0	0.0	0.0	0.00
St. Louis	Summer	8.8	28.9	8.9	1.11	372	45.2	78.9	0.0	0.0	0.0	0.0	0.00
St. Louis	Winter	13.2	22.0	11.4	1.71	319	54.0	82.7	0.0	0.0	0.0	0.0	0.00
Western WA/OR - Win 95/96	Summer	9.4	29.0	10.0	2.34	449	43.5	81.0	1.8	0.0	0.0	0.0	0.32
Western WA/OR - Win 95/96	Winter	12.9	30.9	8.2	2.47	314	49.7	83.7	0.5	0.0	0.0	0.0	0.08
Western WA/OR - Win 96/97	Summer	9.4	29.0	10.0	2.34	449	43.5	81.0	1.8	0.0	0.0	0.0	0.32
Western WA/OR - Win 96/97	Winter	12.9	30.9	8.2	2.47	314	49.7	83.7	0.5	0.0	0.0	0.0	0.08
Northern California	Summer	8.3	29.9	11.5	2.17	104	41.8	82.2	0.0	0.0	0.0	0.0	0.00
Northern California	Winter	12.4	29.9	9.6	2.14	135	49.3	84.3	0.5	0.0	0.0	0.0	0.08
Southern California	Summer	8.2	29.1	7.6	2.12	172	40.8	80.8	2.8	0.0	0.0	0.0	0.50
Southern California	Winter	11.3	29.8	8.6	1.81	205	45.9	82.6	0.5	0.0	0.0	0.0	0.08
ID/MT/WY	Summer	9.3	24.6	9.9	1.98	565	47.5	84.1	0.2	0.0	0.0	0.0	0.04
ID/MT/WY	Winter	13.0	22.5	13.7	1.71	681	53.6	86.5	0.5	0.0	0.0	0.0	0.09
UT/NM/NV	Summer	8.7	23.7	11.0	1.97	235	44.6	82.8	1.3	0.0	0.0	0.0	0.22
UT/NM/NV	Winter	13.0	23.5	13.5	2.13	159	56.3	87.4	0.0	0.0	0.0	16.5	2.70
ND/SD/NE/IA/KS/Western MO	Summer	8.8	26.6	9.6	1.50	328	47.4	81.3	0.7	0.0	1.5	0.0	0.64
ND/SD/NE/IA/KS/Western MO	Winter	13.3	21.0	10.8	1.29	307	55.3	84.6	0.8	0.0	1.6	0.0	0.70
AR/MS/AL/SC/Northern LA	Summer	8.6	28.8	12.8	1.62	363	43.0	79.5	1.5	0.0	0.0	0.0	0.27
AR/MS/AL/SC/Northern LA	Winter	12.3	25.6	16.9	1.47	328	50.0	81.6	1.2	0.0	0.0	0.0	0.22
Florida	Summer	9.2	31.6	9.0	1.40	363	44.1	79.2	1.5	0.0	0.0	0.0	0.27
Florida	Winter	12.2	26.0	17.7	1.25	372	48.9	80.3	1.2	0.0	0.0	0.0	0.21
Northeast-NoRFG	Summer	8.8	29.7	13.7	1.77	332	42.5	80.4	1.1	0.0	0.0	0.0	0.19
Northeast-NoRFG	Winter	13.5	26.5	17.3	1.42	343	51.6	82.9	1.2	0.0	0.0	0.0	0.22
Northeast-RFG	Summer	8.8	29.7	13.7	1.77	332	42.5	80.4	1.1	0.0	0.0	0.0	0.19
Northeast-RFG	Winter	13.5	26.5	17.3	1.42	343	51.6	82.9	1.2	0.0	0.0	0.0	0.22
Ohio Valley-NoRFG	Summer	9.7	26.8	10.5	1.59	383	46.8	80.3	1.3	0.0	2.0	0.0	0.93
Ohio Valley-NoRFG	Winter	14.1	24.9	11.1	1.56	333	55.6	82.6	0.9	0.0	2.0	0.0	0.84
Ohio Valley-RFG	Summer	9.7	26.8	10.5	1.59	383	46.8	80.3	1.3	0.0	2.0	0.0	0.93
Ohio Valley-RFG	Winter	14.1	24.9	11.1	1.56	333	55.6	82.6	0.9	0.0	2.0	0.0	0.84
Northern MI/WI	Summer	9.4	27.1	8.5	1.57	363	49.2	80.8	2.5	0.0	1.8	0.0	1.06
Northern MI/WI	Winter	14.0	24.5	9.6	1.36	352	55.8	83.4	5.4	0.0	1.9	0.0	1.62
West Texas	Summer	8.0	28.6	9.6	1.83	289	45.3	81.4	2.4	0.0	0.0	0.0	0.43
West Texas	Winter	11.7	27.2	14.6	1.75	362	49.2	82.8	5.2	0.0	0.0	0.0	0.93

1996 Baseline Fuel Specifications

Area	Season	RVP, psi	Aromatics %	Olefins %	Benzene %	Sulfur ppm	E200 %	E300 %	MTBE %	ETBE %	EtOH %	TAME %	Oxygen wt %
Atlanta	Summer	7.2	32.1	11.2	0.87	343	36.9	79.8	0.7	0.0	0.0	0.0	0.13
Atlanta	Winter	12.4	24.8	13.0	0.77	447	51.2	82.7	0.3	0.0	0.0	0.0	0.06
Chicago	Summer	7.9	26.0	9.7	0.96	492	50.2	80.8	0.0	0.0	9.0	0.0	3.12
Chicago	Winter	14.0	22.4	7.8	0.80	523	58.0	83.9	0.0	0.0	9.0	0.0	3.11
Denver	Summer	8.8	27.1	8.8	1.33	296	50.1	83.1	0.0	0.0	0.0	0.0	0.00
Denver	Winter	13.6	21.9	9.2	0.94	350	62.1	88.1	0.0	0.0	8.4	0.0	2.91
Houston	Summer	7.1	27.4	13.0	0.71	261	47.8	79.8	9.8	0.0	0.0	0.0	1.74
Houston	Winter	12.8	21.1	12.8	0.70	224	59.9	83.8	7.9	0.0	0.0	0.0	1.41
Minneapolis	Summer	9.6	28.2	7.3	1.81	121	59.4	84.6	0.0	0.0	9.4	0.0	3.24
Minneapolis	Winter	14.9	23.4	5.3	1.65	70	62.3	89.1	0.0	0.0	8.0	0.0	2.77
New York	Summer	8.0	28.6	17.1	0.51	231	49.8	81.5	10.6	0.0	0.0	0.0	1.89
New York	Winter	13.2	23.3	16.6	0.47	267	57.5	85.7	14.5	0.0	0.0	0.0	2.58
Philadelphia	Summer	7.9	29.0	12.3	0.80	367	51.2	81.8	11.3	0.0	0.0	0.0	2.01
Philadelphia	Winter	13.5	25.4	10.2	0.63	337	59.3	85.9	8.8	0.0	0.0	0.0	1.58
Phoenix	Summer	6.8	36.1	6.8	1.07	118	45.7	76.2	0.8	0.0	0.0	0.0	0.14
Phoenix	Winter	8.7	34.3	7.1	1.40	216	50.2	82.6	0.0	0.0	10.2	0.0	3.53
Spokane	Summer	8.7	28.5	8.3	1.32	412	45.0	81.4	0.0	0.0	0.0	0.0	0.00
Spokane	Winter	14.8	18.6	6.9	0.97	350	59.8	87.1	0.0	0.0	9.3	0.0	3.21
St. Louis	Summer	6.8	29.9	12.0	0.70	492	39.0	78.8	0.0	0.0	0.0	0.0	0.00
St. Louis	Winter	13.6	23.8	11.4	0.89	535	52.7	82.6	0.0	0.0	0.0	0.0	0.00
Western WA/OR - Win 95/96	Summer	8.0	35.7	6.7	2.17	256	44.0	82.4	0.1	0.0	0.0	0.0	0.02
Western WA/OR - Win 95/96	Winter	13.6	27.5	6.3	1.81	342	58.8	84.5	0.0	0.0	4.3	0.0	1.49
Western WA/OR - Win 96/97	Summer	8.0	35.7	6.7	2.17	256	44.0	82.4	0.1	0.0	0.0	0.0	0.02
Western WA/OR - Win 96/97	Winter	13.4	29.4	5.8	1.81	345	52.7	84.0	0.0	0.0	1.3	0.0	0.44
Northern California	Summer	6.9	24.4	3.5	0.56	26	49.3	89.9	9.1	0.0	0.0	0.0	1.63
Northern California	Winter	10.5	20.1	2.1	0.52	30	54.4	90.8	10.5	0.0	0.0	0.0	1.87
Southern California	Summer	7.0	20.7	4.3	0.52	10	51.0	86.8	11.0	0.0	0.0	0.0	1.96
Southern California	Winter	10.6	17.7	3.5	0.57	31	56.3	88.6	11.6	0.0	0.0	0.0	2.08
ID/MT/WY	Summer	8.5	28.3	8.1	1.64	318	46.8	84.6	0.5	0.0	0.0	0.0	0.09
ID/MT/WY	Winter	13.5	22.8	6.4	1.40	252	53.7	84.6	0.5	0.0	0.0	0.0	0.09
UT/NM/NV	Summer	8.0	30.7	10.6	1.75	207	45.2	83.6	1.1	0.0	0.0	0.0	0.20
UT/NM/NV	Winter	14.4	20.4	8.3	1.14	106	72.2	85.2	0.0	0.0	10.3	0.0	3.54
ND/SD/NE/IA/KS/Western MO	Summer	8.3	29.0	8.0	1.33	229	45.4	81.8	0.1	0.0	1.7	0.0	0.59
ND/SD/NE/IA/KS/Western MO	Winter	13.4	22.4	6.8	1.12	224	56.0	85.0	0.4	0.0	1.8	0.0	0.68
AR/MS/AL/SC/Northern LA	Summer	7.7	30.7	13.2	0.84	349	38.8	78.1	0.5	0.0	0.0	0.0	0.08
AR/MS/AL/SC/Northern LA	Winter	12.2	24.5	13.0	0.81	271	50.5	82.3	0.4	0.0	0.0	0.0	0.08
Florida	Summer	7.6	33.6	10.1	0.79	280	40.3	79.4	0.5	0.0	0.0	0.0	0.09
Florida	Winter	12.1	24.6	12.8	0.82	289	50.5	82.7	0.4	0.0	0.0	0.0	0.07
Northeast-NoRFG	Summer	8.6	28.1	12.4	1.03	308	43.2	80.7	1.5	0.0	0.0	0.0	0.27
Northeast-NoRFG	Winter	13.2	23.8	16.2	0.73	222	52.2	83.3	0.8	0.0	0.0	0.0	0.14
Northeast-RFG	Summer	7.9	24.7	11.7	0.65	234	50.5	82.4	10.9	0.0	0.0	0.0	1.94
Northeast-RFG	Winter	12.5	19.7	9.6	0.66	265	59.1	87.0	10.5	0.0	0.0	0.0	1.87
Ohio Valley-NoRFG	Summer	8.7	30.2	10.4	1.24	334	45.3	80.3	0.9	0.0	1.5	0.0	0.68
Ohio Valley-NoRFG	Winter	14.1	25.5	8.8	1.04	310	54.0	82.6	0.4	0.0	1.2	0.0	0.48
Ohio Valley-RFG	Summer	7.8	27.3	8.1	0.99	300	45.5	81.1	9.5	0.0	0.0	0.0	1.69
Ohio Valley-RFG	Winter	12.9	18.9	8.8	0.97	355	59.4	88.4	10.0	0.0	0.0	0.0	1.79
Northern MI/WI	Summer	8.5	28.4	9.1	1.32	277	49.0	80.9	0.5	0.0	2.8	0.0	1.04
Northern MI/WI	Winter	14.0	25.3	8.4	1.46	206	57.6	83.1	0.2	0.0	2.4	0.0	0.85
West Texas	Summer	8.0	30.1	9.7	1.48	263	41.5	81.6	0.2	0.0	0.0	0.0	0.03
West Texas	Winter	11.8	25.8	8.1	1.21	361	47.3	83.7	0.0	0.0	0.0	0.0	0.00

2007/2020 30 ppm Sulfur Fuel Specifications

Area	Season	RVP, psi	Aromatics %	Olefins %	Benzene %	Sulfur ppm	E200 %	E300 %	MTBE %	ETBE %	EtOH %	TAME %	Oxygen wt %
Atlanta	Summer	7.0	30.9	8.9	0.87	30	38.1	80.2	1.7	0.0	0.0	0.0	0.30
Atlanta	Winter	12.4	24.0	11.4	0.77	30	50.8	82.7	0.6	0.0	0.0	0.0	0.10
Chicago	Summer	6.6	24.1	6.2	0.93	30	51.2	82.7	0.0	13.7	0.0	0.0	2.10
Chicago	Winter	14.0	17.6	2.9	0.80	30	60.1	87.3	0.0	0.0	10.7	0.0	3.70
Denver	Summer	8.8	26.1	7.0	1.33	30	51.3	83.5	0.0	0.0	0.0	0.0	0.00
Denver	Winter	13.6	21.2	8.0	0.94	30	61.7	88.1	0.0	0.0	8.4	0.0	2.90
Houston	Summer	6.7	26.8	9.7	0.78	30	48.5	82.5	11.2	0.0	0.0	0.0	2.00
Houston	Winter	12.8	19.7	5.0	0.67	30	56.5	86.4	10.6	0.0	0.0	0.0	1.90
Minneapolis	Summer	9.6	27.2	5.8	1.81	30	60.6	85.1	0.0	0.0	9.6	0.0	3.30
Minneapolis	Winter	14.9	22.7	4.7	1.65	30	61.9	89.1	0.0	0.0	8.1	0.0	2.80
New York	Summer	6.8	25.8	11.9	0.59	30	49.9	83.8	11.2	0.0	0.0	0.0	2.00
New York	Winter	13.2	19.3	5.8	0.53	30	58.1	88.0	14.6	0.0	0.3	0.0	2.70
Philadelphia	Summer	6.7	25.0	10.3	0.65	30	51.1	84.1	11.8	0.0	0.0	0.0	2.10
Philadelphia	Winter	13.5	21.0	5.2	0.62	30	56.5	87.6	11.2	0.0	0.0	0.0	2.00
Phoenix	Summer	7.0	22.0	4.0	0.80	30	50.0	92.0	0.0	0.0	6.1	0.0	2.10
Phoenix	Winter	10.6	17.7	3.5	0.57	30	56.3	88.6	0.0	0.0	10.2	0.0	3.50
Spokane	Summer	8.7	27.5	6.6	1.32	30	46.2	81.8	0.0	0.0	0.0	0.0	0.00
Spokane	Winter	14.8	17.9	6.0	0.96	30	59.8	87.2	0.0	0.0	10.2	0.0	3.50
St. Louis	Summer	6.4	28.8	11.3	0.72	30	45.0	79.6	0.0	13.7	0.0	0.0	2.10
St. Louis	Winter	13.6	20.7	4.9	0.89	30	52.5	84.7	0.0	0.0	6.1	0.0	2.10
Western Washington/Oregon	Summer	8.0	34.5	5.3	2.17	30	45.2	82.8	0.0	0.0	0.0	0.0	0.00
Western Washington/Oregon	Winter	13.5	27.6	5.3	1.81	30	55.4	84.2	0.0	0.0	2.9	0.0	1.00
Western Washington/Oregon	Summer	8.0	34.5	5.3	2.17	30	45.2	82.8	0.0	0.0	0.0	0.0	0.00
Western Washington/Oregon	Winter	13.5	27.6	5.3	1.81	30	55.4	84.2	0.0	0.0	2.9	0.0	1.00
Northern California	Summer	7.0	22.0	4.0	0.80	30	50.0	92.0	0.0	0.0	6.1	0.0	2.10
Northern California	Winter	10.5	20.1	2.1	0.52	30	54.4	90.8	0.0	0.0	6.1	0.0	2.10
Southern California	Summer	7.0	22.0	4.0	0.80	30	50.0	92.0	0.0	0.0	6.1	0.0	2.10
Southern California	Winter	10.6	17.7	3.5	0.57	30	56.3	88.6	0.0	0.0	6.1	0.0	2.10
Idaho/Montana/Wyoming	Summer	8.5	27.3	6.5	1.64	30	48.0	85.0	1.1	0.0	0.0	0.0	0.20
Idaho/Montana/Wyoming	Winter	13.5	22.1	5.6	1.40	30	53.3	84.6	0.6	0.0	0.0	0.0	0.10
Utah/New Mexico/Nevada	Summer	8.0	29.6	8.5	1.75	30	46.4	84.0	2.2	0.0	0.0	0.0	0.40
Utah/New Mexico/Nevada	Winter	14.4	19.8	7.2	1.14	30	71.7	85.2	0.0	0.0	10.4	0.0	3.60
ND/SD/NE/IA/KS/Western MO	Summer	8.3	28.0	6.4	1.33	30	46.6	82.2	0.0	0.0	3.5	0.0	1.20
ND/SD/NE/IA/KS/Western MO	Winter	13.4	21.7	6.0	1.12	30	55.6	85.0	0.6	0.0	1.7	0.0	0.70
AR/MS/AL/SC/Northern LA	Summer	7.7	29.6	10.5	0.84	30	40.0	78.5	1.1	0.0	0.0	0.0	0.20
AR/MS/AL/SC/Northern LA	Winter	12.2	23.7	11.3	0.81	30	50.1	82.3	0.6	0.0	0.0	0.0	0.10
Florida	Summer	7.6	32.4	8.1	0.79	30	41.5	79.8	1.1	0.0	0.0	0.0	0.20
Florida	Winter	12.1	23.8	11.2	0.82	30	50.1	82.7	0.6	0.0	0.0	0.0	0.10
Northeastern states - non RFG	Summer	8.6	27.1	9.9	1.03	30	44.4	81.1	3.4	0.0	0.0	0.0	0.60
Northeastern states - non RFG	Winter	13.2	23.1	14.1	0.73	30	51.8	83.3	0.6	0.0	0.0	0.0	0.10
Northeastern states- with RFG	Summer	6.7	24.0	11.0	0.67	30	50.8	83.2	11.2	0.0	0.0	0.0	2.00
Northeastern states- with RFG	Winter	12.5	18.2	4.8	0.66	30	59.6	89.7	10.6	0.0	0.0	0.0	1.90
Ohio Valley - non-RFG	Summer	8.7	29.1	8.3	1.24	30	46.5	80.7	1.7	0.0	2.9	0.0	1.30
Ohio Valley - non-RFG	Winter	14.1	24.7	7.7	1.04	30	53.6	82.6	0.6	0.0	1.2	0.0	0.50
Ohio Valley - with RFG	Summer	6.5	27.1	7.6	1.02	30	45.6	81.9	9.5	0.0	0.0	0.0	1.70
Ohio Valley - with RFG	Winter	12.9	17.4	4.4	0.97	30	59.9	91.1	10.1	0.0	0.0	0.0	1.80
Northern MI/WI/MN	Summer	8.5	27.4	7.3	1.32	30	50.2	81.3	1.1	0.0	5.8	0.0	2.20
Northern MI/WI/MN	Winter	14.0	24.5	7.3	1.46	30	57.2	83.1	0.0	0.0	2.3	0.0	0.80
West Texas	Summer	8.0	29.1	7.8	1.48	30	42.7	82.0	0.6	0.0	0.0	0.0	0.10
West Texas	Winter	11.8	24.9	7.1	1.21	30	46.8	83.7	0.0	0.0	0.0	0.0	0.00

8. REFERENCES

1. "Policy Guidance on the Use of MOBILE6.2 and the December 2003 AP-42 Method for Re-Entrained Road Dust for SIP Development and Transportation Conformity," Memorandum from Margo Tsirigotis Oge and Steve Page to EPA Regional Air Division Directors, U.S. Environmental Protection Agency, February 24, 2004.

2. "MOBILE6.1 Particulate Emission Factor Model Technical Description - Final Report," U.S. Environmental Protection Agency, EPA420-R-03-001, Report No. M6.PM.001, January 2003.

3. "Control of Emissions of Air Pollution from 2004 and Later Model Year Heavy-Duty Highway Engines and Vehicles; Revision of Light-Duty On-Board Diagnostics Requirements," Final Rule, U.S. Environmental Protection Agency, Federal Register, October 6, 2000.

4. "Draft User's Guide to PART5: A Program for Calculating Particle Emissions from Motor Vehicles," U.S. Environmental Protection Agency, EPA-AA-AQAB-94-2, February 1995.

5. "Draft Study of Particulate Emissions from Motor Vehicles," U.S. Environmental Protection Agency, July 1983.

6. "Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements; Final Rule," U.S. Environmental Protection Agency, Federal Register, Vol. 66, No. 12, January 18, 2001.

7. Scarbro, C. and G. Tierney, "Phoenix PM Testing and EPA's Future Plans," Presented at the 13th CRC On-Road Vehicle Emissions Workshop, San Diego, CA, April 7-9, 2003.

8. "Regulatory Impact Analysis: Control of Sulfur and Aromatics Contents of On-Highway Diesel Fuel," U.S. Environmental Protection Agency, June 1990.

9. Smith, M., "Heavy-Duty Vehicle Emission Conversion Factors 1962 - 1997," U.S. Environmental Protection Agency, August 1984.

10. "Update Heavy-Duty Engine Emission Conversion Factors: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors," Prepared for the U.S. Environmental Protection Agency by ARCADIS Geraghty & Miller, EPA420-R-02-005, Report No. M6.HDE.004, January 2002.

11. "Update of Heavy-Duty Emission Levels (Model Years 1988-2004+) for Use in MOBILE6," U.S. Environmental Protection Agency, EPA420-R-99-010, Report No. M6.HDE.001, April 1999.

12. Cadle, S.H. and R.L. Williams, “Gas and Particle Emissions from Automobile Tires in Laboratory and Field Studies,” Journal of the Air Pollution Control Association, 28(5): 502-507, 1978.

13. Pierson, W.R. and W.W. Brachaczek, “Airborne Particulate Debris from Rubber Tires,” Rubber Chem. Technol., 47(5): 1275-1229, 1974.

14. Fishman, R.L. and J.R. Turner, “Tire Wear Contributions to Ambient Particulate Matter,” Presented at the 1999 Air & Waste Management Annual Meeting, St. Louis, MO, June 20-24, 1999.

15. Lee, Y.K. and M.J. Kim, J. Analyt. Appl. Pyrolysis, 1989, 16, 49-55.

16. Bogdan, L. and T.M. Albrechcinski, “Characterization of Tire Wear Particulates,” Prepared by Advanced Technology Center for the U.S. Environmental Protection Agency, Contract #68-03-2781, 1981.

17. Garg, B.D, S.H. Cadle, P.A. Mulawa, P.J. Groblicki, C. Laroo, and G.A. Parr, “Brake Wear Particulate Matter Emissions,” Environmental Science and Technology, 34(21): 4463-4469, 2000.

18. Cha, S., P. Carter, and R.L. Bradow, “Simulation of Automobile Brake Wear Dynamics and Estimation of Emissions,” SAE Paper No. 831036, 1983.

19. Garg, B.D, S.H. Cadle, P.A. Mulawa, P.J. Groblicki, C. Laroo, and G.A. Parr, “Brake Wear Particulate Matter Emissions,” Environmental Science and Technology, 34(21): 4463-4469, 2000.

20. Harvey, C.A., R.J. Garbe, T.M. Baines, J.H. Somers, K.H. Helman, and P.M. Carey, “A Study of the Potential Impact of Some Unregulated Motor Vehicle Emissions,” SAE Paper No. 830987, 1983.

21. Durbin, T.D., R.D. Wilson, J.M Norbeck, J.W. Miller, T. Huai, and S. Rhee, “Emissions of Ammonia from Light-Duty Vehicles,” Presented a the 10th International Emission Inventory Conference, Denver Colorado, May 1-3, 2001.

22. “The Effect of Fuel Sulfur on NH_3 and Other Emissions from 2000-2001 Model Year Vehicles,” Prepared by U.C. Riverside College of Engineering - Center for Environmental Research and Technology for the Coordinating Research Council and CONCAWE, CRC Project No. E-60, May 2003.

23. “Characterization of Particulate Emissions from Gasoline-Fueled Vehicles,” Prepared by U.C. Riverside College of Engineering - Center for Environmental Research and Technology for the California Air Resources Board, September 1998.

24. “Measurement of Primary Particulate Matter Emissions from Light-Duty Motor Vehicles,” Prepared by U.C. Riverside College of Engineering - Center for Environmental Research and Technology for the Coordinating Research Council and

---

the South Coast Air Quality Management District, CRC Project No. E-24-2, December 1998.

25. Ubanwa, B., et al., "An Analysis of Exhaust Particulate Matter Emission Factors for In-Use Motor Vehicles," Presented at the 10th CRC On-Road Vehicle Emissions Workshop, San Diego, California, March 26-29, 200.

26. Sanders, P.G. et al., "Airborne Brake Wear Debris: Size Distributions, Composition, and a Comparison of Dynamometer and Vehicle Tests," Environmental Science and Technology, 37(18): 4060-4069, 2003.

27. Fauser, P., "Particulate Air Pollution with Emphasis on Traffic Generated Aerosols," Risø National Laboratory, Report No. Risø-R-1053 (EN), Roskilde, Denmark, February 1999.

28. Sagebiel, J.C. et al., "PM-10 Exhaust Samples Collected During IM-240 Dynamometer Tests of In-Service Vehicles in Nevada," Environmental Science and Technology, 31(1): 75-83, 1997.

29. "Characterization of Particulate Emissions from Gasoline-Fueled Vehicles," Prepared by U.C. Riverside College of Engineering - Center for Environmental Research and Technology for the California Air Resources Board, September 1998.

30. Cadle, S.H. et al., "Measurement of Particulate Matter Emissions from In-Use Light-Duty Motor Vehicles in the Denver, Colorado Area," CRC Project No. E-24-1, March 16, 1998.

31. "Measurement of Primary Particulate Matter Emissions from Light-Duty Motor Vehicles," Prepared by U.C. Riverside College of Engineering - Center for Environmental Research and Technology for the Coordinating Research Council and the South Coast Air Quality Management District, CRC Project No. E-24-2, December 1998.

32. Cadle, S.H. et al., "In-Use Light-Duty Gasoline Vehicle Particulate Matter Emissions on the FTP, REP05, and UC Cycles," CRC Project No. E-46, June 2, 1999.

33. Graham, L., "Gaseous and Particulate Matter Emissions from In-Use Light-Duty Gasoline Motor Vehicles," Environment Canada, Emissions Research and Measurement Division (EMRD) Report #99-67, 1999.

34. Knapp, K.T. et al., "Central Carolina Vehicle Particulate Emissions Study," CRC Project No. E-54, 2000.

35. Lawson, D.R., "DOE's Gasoline/Diesel PM Split Study," Presented at the 13th CRC On-Road Vehicle Emissions Workshop, San Diego, California, April 7-9, 2003.

36. Scarbro, C. and G. Tierney, "Phoenix PM Testing and EPA's Future Plans," Presented at the 13th CRC On-Road Vehicle Emissions Workshop, San Diego, California, April 7-9, 2003.

37. "Public Meeting to Consider Approval of Revisions to the State's On-Road Motor Vehicle Emissions Inventory – Technical Support Document," California Air Resources Board, May 2000.

38. Graboski, M.S., R.L. McCormick, J. Yanowitz, and L. Ryan, "Heavy-Duty Diesel Vehicle Testing for the Northern Front Range Air Quality Study," Colorado School of Mines, February 24, 1998.

39. "Update of Heavy-Duty Emission Levels (Model Years 1988-2004+) for Use in MOBILE6," U.S. Environmental Protection Agency, EPA420-R-99-010, Report No. M6.HDE.001, April 1999.

40. "Characterizing Particulate Emissions from Medium- and Light-Heavy-Duty Diesel-Fueled Vehicles," Prepared by U.C. Riverside College of Engineering - Center for Environmental Research and Technology for the South Coast Air Quality Management District, September 1998.

41. "Upgrading MOBILE to Include Particulate Emissions - Proposed Project Description," U.S. Environmental Protection Agency, March 12, 2001. Available at: http://www.epa.gov/otaq/models/mobile6/m61scop.pdf.

42. "Section 4.12 Total Particulate Matter Emission Factors," EMFAC2000 Technical Support Documents, http://www.arb.ca.gov/msei/on-road/doctable_test.htm.

43. "Section 10.0 Heavy-Duty Trucks Emission Factors Development," EMFAC2000 Technical Support Documents, http://www.arb.ca.gov/msei/on-road/doctable_test.htm.

44. "Motor Vehicle-Related Air Toxics Study," U.S. Environmental Protection Agency, April 1993.

45. "Control of Emissions of Hazardous Air Pollutants from Mobile Sources; Final Rule," U.S. Environmental Protection Agency, Federal Register, Vol. 66, No. 61, March 29, 2001.

46. "Estimation of Motor Vehicle Toxic Emissions and Exposure in Selected Urban Areas," Prepared by Sierra Research, Radian International, and Energy and Environmental Analysis for the U.S. Environmental Protection Agency, Work Assignment 0-07, Contract No. 68-C7-0051, October 15, 1998.

47. "Analysis of the Impacts of Control Programs on Motor Vehicle Toxics Emissions and Exposure in Urban Areas and Nationwide," Prepared by Sierra Research and

Radian International/Eastern Research Group for the U.S. Environmental Protection Agency, Work Assignment 1-06, Contract No. 68-C7-0051, November 30, 1999.

48. "Final Regulatory Impact Analysis for Reformulated Gasoline," U.S. Environmental Protection Agency, December 13, 1993.

49. Wyborny, L., "Methyl Tertiary Butyl Ether (MTBE) Emissions from Passenger Cars," Draft Technical Report, U.S. Environmental Protection Agency, Office of Mobile Sources, April 1998.

50. "Technical Description of the Toxics Module for MOBILE6.2 and Guidance on Its Use for Emission Inventory Preparation," U.S. Environmental Protection Agency, EPA420-R-02-029, November 2002.

51. "Alliance of Automobile Manufacturers North American Fuel Survey," Alliance of Automobile Manufacturers, Summer 2003.

52. "National Air Toxics Assessment; Summary of Results," U.S. Environmental Protection Agency, http://www.epa.gov/ttn/atw/nata/risksum.html, 2002.

53. Cook, R., "Source Identification and Base Year 1990 Emission Inventory Guidance for Mobile Source HAPs on the OAQPS List of 40 Priority HAPs," Memorandum to Anne Pope, U.S. Environmental Protection Agency, June 11, 1997.

54. Truex, T.J. et al, "Evaluation of Factors that Affect Diesel Exhaust Toxicity," Prepared by U.C. Riverside CE-CERT for the California Air Resources Board, June 25, 1998.

55. "MOBILE6 Emission Factors for Natural Gas Vehicles," U.S. Environmental Protection Agency, Report No. M6.FUL.004, EPA420-R-01-033, April 2001.

56. "Determination of NOx and HC Basic Emission Rates, OBD and I/M Effects for Tier 1 and Later LDVs and LDTs," U.S. Environmental Protection Agency, Report No. M6.EXH.007, EPA420-R-01-056, November 2001.

57. "Determination of CO Basic Emission Rates, OBD and I/M Effects for Tier 1 and Later LDVs and LDTs," U.S. Environmental Protection Agency, Report No. M6.EXH.009, EPA420-R-01-032, April 2001.

58. Fleming, R.D. and J.R. Allsup, "Emission Characteristics of Natural Gas as an Automotive Fuel," SAE Paper No. 710833, 1971.

59. Gabele, P. et al, "Ambient Temperature and Driving Cycle Effects on CNG Motor Vehicle Emission," SAE Paper No. 902069, 1990.

---

60. Howes, P. and G. Rideout, "Evaluations of Current Natural Gas Vehicle Technology Exhaust Emissions at Various Operating Temperatures," SAE Paper No. 952437, 1995.

61. "Natural Gas Vehicles - A Review of the State of the Art," Prepared by Sierra Research for the Natural Gas Vehicle Coalition, Report No. SR89-04-01, April 13, 1989.

62. "Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel. Volume I: Passenger Cars and Light Trucks," U.S. Environmental Protection Agency, April 1990.

63. "Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel. Volume II: Heavy-Duty Vehicles," U.S. Environmental Protection Agency, April 1990.

64. Winebrake, J.J. et al, "Statistical Analysis of Emissions and Deterioration Rates for In-Use, High-Mileage CNG and Gasoline Vehicles," SAE Paper No. 2000-01-1959, 2000.

65. Sun, X. et al, "Fuel Management and Exhaust Emissions of Light- and Heavy-Duty Trucks Operating on CNG and LPG," SAE Paper No. 971661, 1997.

66. Vatsky, A. et al, "NYSERDA AFV-FDP Light-Duty CNG Vehicle Fleet Operating Experience," SAP Paper No. 962069, 1996.

67. Kelly, K. et al, "Round 1 Emissions Results from Compressed Natural Gas Vans and Gasoline Controls Operating in the U.S. Federal Fleet," SAE Paper No. 961091, 1996.

68. Hoccauser, A. et al, "Comparison of CNG and Gasoline Vehicle Exhaust Emissions: Mass and Composition - The Auto/Oil Air Quality Improvement Research Program," SAE Paper 952507, 1995.

69. Howes, P. and G. Rideout, "Evaluations of Current Natural Gas Vehicle Technology Exhaust Emissions at Various Operating Temperatures," SAE Paper No. 952437, 1995.

70. Stewart, S. et al, "Correcting Emissions Problems in Existing Propane and Natural Gas Vehicles in British Columbia," SAE Paper No. 952380, 1995.

71. Suga, S. et al, "Near-Zero Emissions Natural Gas Vehicle, Honda Civic GX," SAE Paper No. 972643, 1997.

72. Vermiglio, E. et al, "Ford's SULEV Dedicated Natural Gas Trucks," SAE Paper No. 971662, 1997.

73. Fulton, B. et al, “Ford’s 1996 Crown Victoria Dedicated Natural Gas Vehicle,” SAE Paper No. 952743, 1995.

74. Ullman, T.L. et al, “Comparison of Exhaust Emissions, Including Toxic Air Contaminants, from School Buses in Compressed Natural Gas, Low Emitting Diesel, and Conventional Diesel Engine Configurations,” SAE Paper No. 2003-01-1381, 2003.

75. Lanni, T. et al, “Performance and Emissions Evaluation of Compressed Natural Gas and Clean Diesel Buses at New York City’s Metropolitan Transit Authority,” SAE Paper No. 2003-01-0300, 2003.

76. Kamel, M. et al, “An Emission and Performance Comparison of the Natural Gas Cummins Westport Inc. C-Plus Versus Diesel in Heavy-Duty Trucks,” SAE Paper No. 2002-01-2737, 2002.

77. Ayala, A. et al, “Diesel and CNG Heavy-Duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview,” SAE Paper No. 2002-01-1722, 2002.

78. Weaver, C.S. et al, “Comparison of In-Use Emissions from Diesel and Natural Gas Trucks and Buses,” SAE Paper No. 2000-01-3473, 2001.

79. Frailey, M. et al, “An Evaluation of Natural Gas versus Diesel in Medium-Duty Buses,” SAE Paper No. 2000-01-2822, 2000.

80. McCormick, R.L. et al, “In-Use Emissions from Natural Gas Fueled Heavy-Duty Vehicles,” SAE Paper No. 1999-01-1507, 1999.

81. Clark, N.N. et al, “Diesel and CNG Transit Bus Emissions Characterization by Two Chassis Dynamometer Laboratories: Results and Issues,” SAE Paper No. 1999-01-1469, 1999.

82. Clark, N.N., et al, “Emissions from Trucks and Buses Powered by Cummins L-10 Natural Gas Engines,” SAE Paper No. 981393, 1998.

83. Clark, N.N. et al, “Natural Gas and Diesel Transit Bus Emissions: Review and Recent Data,” SAE Paper No. 973203, 1997.

84. Marinetti, D. et al, “NYSERDA AFV-FDP CNG Transit Bus Fleet Operating Experience,” SAE Paper No. 962071, 1996.

85. Clark, N.N. et al, “Comparative Emissions from Natural Gas and Diesel Buses,” SAE Paper No. 952746, 1995.

86. Eudy, L. “SuperShuttle CNG Fleet Evaluation,” Prepared by the National Renewable Energy Laboratory for the Department of Energy, October 2000.

87. "Light-Duty Alternative Fuel Vehicles: Federal Test Procedure Emission Results," Prepared by the National Renewable Energy Laboratory for the Department of Energy, September 1999.

88. Walen, P. et al, "Barwood CNG Cab Fleet Study -- Final Results," National Renewable Energy Laboratory, May 1999.

89. Whalen, P. et al, "Alternative Fuel Light-Duty Vehicles: Summary of Results from the National Renewable Energy Laboratory's Vehicle Evaluation Data Collection Efforts," U.S. Department of Energy, May 1996.

90. Motta, R. et al, "Compressed Natural Gas and Liquefied Petroleum Gas Conversions: The National Renewable Energy Laboratory's Experience," U.S. Department of Energy, April 1996.

91. Lynford-Pike, E.J. "An Emission and Performance Comparison of the Natural Gas C-Plus Engine in Heavy-Duty Trucks," Prepared by Cummins, Inc. for the National Renewable Energy Laboratory, April 2003.

92. Chandler, K. et al, "United Parcel Service (UPS) CNG Truck Fleet: Final Results," Prepared by the National Renewable Energy Laboratory for the Department of Energy, August 2002.

93. Chandler, K. et al, "Raley's LNG Truck Fleet: Final Results," Prepared by the National Renewable Energy Laboratory for the Department of Energy, March 2000.

94. Motta, R. et al, "Alternative Fuel Transit Buses: Final Results from the National Renewable Energy Laboratory Vehicle Evaluation Program," U.S. Department of Energy, October 1996.

95. "CleanFleet Final Report," Battelle Memorial Institute, December 1995.

96. "Final Release of MOBILE6.2," Email from EPA to the epa-mobilenews mailing list, February 26, 2004.

97. "Updating Fuel Economy Estimates in MOBILE6.3 - DRAFT," U.S. Environmental Protection Agency, EPA420-P-02-005, Report No. M6.GHG.001, August 2002.

98. "Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2003," U.S. Environmental Protection Agency, EPA420-R-03-006, April 2003.

99. "Light-Duty Automotive Technology and Fuel Economy Trends, 1975 Through 2001," U.S. Environmental Protection Agency, EPA420-R-01-008, September 2001.

100. "Update Heavy Duty Engine Emission Conversion Factors for MOBILE6: Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements and Fuel Densities,"

Prepared by ARCADIS Geraghty & Miller for the U.S. Environmental Protection Agency, EPA420-R-02-006, Report No. M6.HDE.002, January 2002.

101. "VEHICLE INVENTORY AND USE SURVEY (VIUS)," U.S. Census Bureau, http://www.census.gov/econ/www/viusmain.html, Last Revised: 04/26/2000.

102. "Remote Sensing of Gaseous and Particle Emissions from Onroad Vehicles in Clark County, Nevada," Prepared by Desert Research Institute for the Clark County Department of Air Quality Management and the Federal Transit Administration, September 2002.

103. "Technical Description of the Toxics Module for MOBILE6.2 and Guidance on Its Use for Emission Inventory Preparation," U.S. Environmental Protection Agency, EPA420-R-02-029, November 2002.

104. "Analysis of the Impacts of Control Programs on Motor Vehicle Toxics Emissions and Exposure in Urban Areas and Nationwide," Prepared by Sierra Research and Radian International/Eastern Research Group for the U.S. Environmental Protection Agency, Work Assignment 1-06, Contract No. 68-C7-0051, November 30, 1999.

105. "Updating Fuel Economy Estimates in MOBILE6.3 - DRAFT," U.S. Environmental Protection Agency, EPA420-P-02-005, Report No. M6.GHG.001, August 2002.

106. "Evaluation of the U.S. EPA MOBILE6 Highway Vehicle Emission Factor Model," Prepared by ENVIRON International Corporation for the Coordinating Research Council and the U.S. Environmental Protection Agency, CRC Project E-64, March 2004.