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Update of Heavy-Duty Emission Levels (Model Years 1988-2004) for Use in MOBILE6

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Introduction

To estimate emissions from heavy-duty vehicles, the MOBILE6 model uses updated emission factors for 1988-and-later model year vehicles. This report describes the development of work-specific heavy-duty engine emission factors for hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx) for model years 1988 through 2004. This final version of the report includes changes to improve clarity and to fix errors in the draft version. It also includes comments received on heavy-duty conversion factors.

As in previous versions of the MOBILE model, gram per mile (g/mi) emission factors used in the model were determined by multiplying the work-specific emission factor (in units of grams per horsepower-hour (g/bhp-hr)) by a conversion factor which converts work units into mileage units (bhp-hr/mi). The conversion factors are detailed in MOBILE6 report M6.HDE.004.[1] Comments on this report are listed in Appendix A, below. Heavy-duty engine emission factors for model years 2005-and-later are described in MOBILE6 report M6.EXH.004.[2] Emission factors for particulate matter (PM) are described in the technical report for MOBILE6.1.[3]

Note, after the emissions factors described here were developed, EPA discovered that some heavy-duty engines were equipped with alleged "defeat devices" such that certification tests did not accurately represent the steady-state NOx emissions. A settlement between the engine manufacturers and EPA requires additional emissions improvements beyond the standards described in this report. In MOBILE6, the emission factors described here are adjusted to account for both the excess NOx emissions due to the alleged defeat devices and the emissions improvements required in the settlement. The adjustments are described in the MOBILE6 report M6.HDE.003.[4]

Background

EPA defines heavy-duty vehicles as those vehicles exceeding 8,500 lbs. gross vehicle weight (GVW). As noted in Table 1, this broad class of vehicles is divided into those requiring gasoline or diesel fuels, and is further subdivided into more specific classes based on GVW categories. EPA uses this more detailed subdivision scheme to account for different characteristics and general uses of the engines included in each GVW class.

Emissions of air pollutants from heavy-duty vehicles, particularly heavy-duty diesel vehicles, have come under increased scrutiny in recent years. This increased attention is due to three main factors: 1) EPA's past emphasis on control of emissions from passenger cars and light-duty trucks has effectively reduced the proportional contribution of these sources to mobile source air pollution, and hence has increased the relative significance of heavy-duty emissions; 2) the public has become increasingly concerned about the human health and environmental impacts of emissions of particulate matter and nitrogen oxides, both of which are emitted in relatively large amounts from heavy-duty diesel engines; and 3) advances in emission control technology have increased the cost effectiveness of regulating heavy-duty engines.

Table 1. Heavy-Duty Vehicle Classifications used in MOBILE6

Designation	Description	Gross Vehicle Weight (lbs.)
Gasoline Vehicles		
HDGV (class 2B)	Light heavy-duty gasoline trucks	8,501-10,000
HDGV (class 3)	Light heavy-duty gasoline trucks	10,001-14,000
HDGV (class 4)	Light heavy-duty gasoline trucks	14,001-16,000
HDGV (class 5)	Light heavy-duty gasoline trucks	16,001-19,500
HDGV (class 6)	Medium heavy-duty gasoline trucks	19,501-26,000
HDGV (class 7)	Medium heavy-duty gasoline trucks	26,001-33,000
HDGV (class 8a)	Heavy heavy-duty gasoline trucks	33,001-60,000
HDGV (class 8b)*	Heavy heavy-duty gasoline trucks	>60,000
Diesel Vehicles		
HDDV (class 2B)	Light heavy-duty diesel trucks	8,501-10,000
HDDV (class 3)	Light heavy-duty diesel trucks	10,001-14,000
HDDV (classes 4)	Light heavy-duty diesel trucks	14,001-16,000
HDDV (class 5)	Light heavy-duty diesel trucks	16,001-19,500
HDDV (class 6)	Medium heavy-duty diesel trucks	19,501-26,000
HDDV (class 7)	Medium heavy-duty diesel trucks	26,001-33,000
HDDV (class 8A)	Heavy heavy-duty diesel trucks	33,001-60,000
HDDV (class 8B)	Heavy heavy-duty diesel trucks	>60,000
Buses		
HDGB	Heavy-duty gasoline buses (all types)	all
HDDB (school)	Heavy-duty diesel school buses	all
HDDB (transit & urban)	Heavy-duty diesel transit & urban buses	all

*Few HDGV8b exist.

EPA has been regulating air pollutant emissions from heavy-duty gasoline and diesel vehicles since the 1970s. Since manufacturers of individual types of heavy-duty engines may sell these engines to multiple vehicle manufacturers for use in different applications (for both on-highway and off-highway vehicles), EPA has developed emission standards for heavy-duty *engines* instead of vehicles.

In response to the need to further reduce air pollution at the national level, EPA has finalized a new set of combined emission standards for nitrogen oxides (NOx) and non-methane hydrocarbons (NMHC, hereafter referred to as HC) from heavy-duty engines, to become effective in model year 2004 (for diesel) and 2005 (for gasoline), and additional standards to become effective in 2007. Tables 2 and 3 list the emission standards for heavy-duty gasoline and heavy-duty diesel vehicles respectively from the mid-1980s until 2004. (The 2005 and 2007 standards are described in the report M6.EXH.004 [2]).

Table 2. Emission Standards for New Heavy-Duty Gasoline Engines

Model Year		Pollutant (g/bhp-hr)			
		Hydrocarbons (HC)	Carbon Monoxide (CO)	Nitrogen oxides (NOx)	Particulate Matter (PM)
1987	(A)*	1.1	14.4	10.6	N/A
	(B)*	1.9	37.1	10.6	
1988-1990	(A)*	1.1	14.4	6.0	N/A
	(B)*	1.9	37.1	6.0	
1991-1997	(A)*	1.1	14.4	5.0	N/A
	(B)*	1.9	37.1	5.0	
1998-2004	(A)*	1.1	14.4	4.0	N/A
	(B)*	1.9	37.1	4.0	

***** (A) refers to heavy-duty gasoline engines less than 14,000 lbs. GVW.
(B) refers to heavy-duty gasoline engines greater than 14,000 lbs. GVW.

Table 3. Emission Standards for New Heavy-Duty Diesel Engines

Model Year	Pollutant (g/bhp-hr)			
	Hydrocarbons (HC)	Carbon Monoxide (CO)	Nitrogen oxides (NOx)	Particulate Matter (PM)
1985-1987	1.3	15.5	10.7	None
1988-1989	1.3	15.5	10.7	0.6
1990	1.3	15.5	6.0	0.6
1991-1992	1.3	15.5	5.0	0.25
1993	1.3	15.5	5.0	0.25 truck 0.10 urban bus
1994-1995	1.3	15.5	5.0	0.10 truck 0.07 urban bus
1996-1997	1.3	15.5	5.0	0.10 truck 0.05 urban bus
1998-2003	1.3	15.5	4.0	0.10 truck 0.05 urban bus
2004+	**2.5 combined NMHC + NOx	15.5	**2.5 combined NMHC + NOx	0.10 truck 0.05 urban bus

****** The 2004 standards apply to all GVW classes, and is defined as a combined non-methane hydrocarbon plus nitrogen oxides (NMHC + NOx) emission standard of 2.5 g/bhp-hr**.**

In the above tables, one should note that heavy-duty gasoline emission standards are GVW-specific, while heavy-duty diesel emission standards apply to all GVWs. Also note that, for the most part, technical changes to engine design over the years were made in response to these emission standards. That is, engine design changes rather than emission control technology per se (e.g., catalytic converters, O_2 sensors) have been the primary means of compliance with heavy-duty engine emission standards to date.

Emissions Testing

Testing of heavy-duty vehicles to determine emissions may be performed in two ways. The first method involves removing the engine from the test vehicle's chassis (frame), mounting it on a test stand, and operating the engine on a testing apparatus known as an engine dynamometer. The second method involves testing the engine while it is still in the vehicle by operating the entire vehicle on what is known as a chassis dynamometer. The latter method is very similar to the approach used to test light-duty vehicle and light-duty truck emissions. Emission levels produced on the engine dynamometer are measured in grams per brake horsepower-hour (g/bhp-hr) or grams per kilowatt-hour (g/kW-hr) for a given test cycle, while emissions produced on a chassis dynamometer are measured in grams per mile (g/mi) or grams per kilometer (g/km). The results of these emissions tests are used to develop emission factors for heavy-duty vehicles that are then used in mobile source modeling and inventory development.

Both testing methods have certain limitations. Use of chassis dynamometers allows the investigator to directly account for the impacts of factors such as load and grade on emissions, thus providing a better sense of emissions due to real-world driving conditions. However, in-use emission factors for heavy-duty engines are more difficult to determine than for light-duty engines because chassis dynamometers capable of testing these heavy, larger vehicles are not widely available. Furthermore, manufacturers of heavy-duty engines may sell these engines for use in a variety of applications. Given these factors, the usual test procedure for emission certification is testing the engine on an engine dynamometer.

Heavy-duty engine testing tends to be very costly. Due to the prohibitive costs involved in obtaining in-use emissions data on heavy-duty vehicles, very little recent test data existed at the time MOBILE5b, the previous version of the MOBILE model, was developed. Therefore, the heavy-duty emissions factors in MOBILE5b (1996) are the same ones that were developed for use in MOBILE4 (1989). The 1980 through 1990 model year emissions factors used in the models are based on data derived from a cooperative test program between EPA and engine manufacturers, involving 18 heavy-duty gasoline engines (model years 1979 to 1982) and 22 heavy-duty diesel engines (model years 1979 to 1984). In MOBILE5b, emissions rates from the cooperative program were used unless the certification results were higher than those produced from the test program. In cases where the certification results were greater, that rate was used instead.

<u>Changes for MOBILE6</u>

Since the release of MOBILE5b, very little new data on in-use heavy-duty engines, using representative driving cycles, have been produced. In lieu of actual data on in-use engines, EPA proposed the use of test data required by EPA from engine manufacturers for new engine certification as a surrogate for in-use emissions data.

Under the EPA certification test procedure, manufacturers are required to submit emissions data on new engines using an engine dynamometer test. The engines are run on a transient engine dynamometer test cycle (developed from in-use data), and emission results are given in grams of pollutant per brake horsepower-hour.

Using this EPA engine dynamometer test cycle in the cooperative test program between EPA and engine manufacturers, the test results indicated that emission-control performance in heavy-duty vehicles does not suffer from significant deterioration over time. Given that these test data indicate that emission controls on these engines do not deteriorate greatly, and because the EPA engine dynamometer test cycle was developed to closely represent the in-use behavior of these engines, EPA assumed for this analysis that the emission levels produced by the certification test procedure are representative of the average in-use emission levels.

Methodology

Engine certification data consist of zero-mile level (ZML) emissions (new engine emissions) typically given in grams of pollutant per brake horsepower-hour (g/bhp-hr), and additional g/bhp-hr deterioration at the end of the vehicles "useful life." For heavy-duty diesel engines, the certification data sets also generally include an intended service class for each engine model (light, medium, heavy, and bus).

Table 4. Intended service classes and useful life for heavy-duty engines

Engine Class	Useful Life (miles)
All heavy-duty gasoline engines	110,000
Light heavy-duty diesel engines	110,000
Medium heavy-duty diesel engines	185,000
Heavy heavy-duty diesel engines and buses	290,000*

* Under the 2004-and-later standards, the useful life for Heavy HDDEs is 435,000 miles.

The sum of the ZML and the deterioration at useful life must be less than the emission standard for each pollutant for the engine model to receive EPA certification. While this is true for individual engines only if no averaging, banking and/or trading provisions are used to offset excess emissions, for the purpose of modeling average, in-use emissions, as in MOBILE6, such programs can be ignored.

For this analysis, the emission levels from the certification data were weighted by engine sales and rated power to produce average emission levels for gasoline and diesel-fueled heavy-duty engines, beginning with the 1988 model year and ending with 1995 model year data (the most current available during this analysis). This calculation was performed for ZML and deterioration emissions, and is illustrated by the following equation:

$$Emission\ Level\ (EL) = \frac{\sum (Sales_i * HP_i * EL_i)}{\sum (Sales_i * HP_i)}$$

Where:

Sales = Sales of a given engine or engine family
HP = Rated horsepower of given engine or engine family
EL = Certification emission data (ZML or deterioration)

A second method of averaging emission levels was identified; this method involved simply averaging emission level weighted by engine sales. However, EPA opted to use the method defined by the above equation because this method accounts for differences in rated power of various engine models. However, the second method does not produce significantly different results.

The above calculations were performed using certification and sales data for both gasoline and diesel heavy-duty engines by engine model year. Separate calculations were performed for hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM). The draft version of this report included PM estimates that were not used in MOBILE6.0 (which estimates only HC, CO and NOx.). To avoid confusion, PM estimates have been removed from this final report. The emission factors used in the draft MOBILE6.1 model (which does estimate PM) are described elsewhere. [3]

In addition to calculating average emission levels for all heavy-duty diesel engines, calculations were performed for each of the service classes as well. Heavy-duty gasoline engine certification reports do not include intended service class specification; therefore, for gasoline a single average emission level for each model year is given.

There are several peculiarities within the certification data that must be noted by anyone working with the results provided in this report. Manufacturers often supply multiple emission results for a given engine family, because tests are often run on engines in the same engine family that are rated at different power levels. For this analysis, multiple results were averaged by emission level and rated power to avoid double counting the sales information. Another unusual characteristic of the certification data is that deterioration rates are sometimes given as multiples of the zero-mile emission rate and at other times as additive emissions to the zero-mile emission rate. The emission level results presented in this analysis account for these peculiarities and provide emission rates at the zero mile level and the incremental increase at the end of useful life.

A third caveat involves the reporting of deterioration rates in certification data reports. A manufacturer is not permitted to report a negative deterioration. In cases where the manufacturer observed negative deterioration results, the certification report states that zero deterioration was found. Therefore, the average deterioration rates calculated from the certification data inflate the deterioration that the manufacturers have determined. And lastly, because all engines tested for certification meet the specifications of the manufacturer, the effects of engine malmaintenance and tampering on emissions are not included in the analysis.

Results of Analysis

Gasoline Engines

The certification data set for heavy-duty gasoline engines is sparsely populated. Close examination of the data sets seems to indicate that certification data for engine models which have been "carried over," or sold in subsequent years, have not been recorded in much of the certification data that EPA acquired for this analysis. This is especially true for the 1992 and 1993 data where only one major manufacturer's engines were reported for 1992 and another manufacturer's engines were reported for 1993. As it is quite unlikely that only one manufacturer sold heavy-duty gasoline engines in a given year, we assume that this lack of sales and emission data is due to a reporting anomaly. This hypothesis is further supported by the fact that manufacturers of light-duty vehicles may not be required to re-certify models that carry-over; it is possible that the reporting assumptions were made in the heavy-duty gasoline database. Due to the data limitations, there is some concern as to the reliability of the emission level calculations derived from these data sets, particularly 1992 and 1993.

The results of the current analysis are compared to emission levels reported in MOBILE5b model. Tables 5, 6 and 7 present these comparisons for hydrocarbon, carbon dioxide, and nitrogen oxide emissions, respectively, by model year (1988 through 1995). Model years 1992 and 1993 are in italics to signify the greater uncertainty involved with the calculations in these years, as explained above.

Table 5. Comparison of MOBILE5b and Certification Calculation Results for Emission Levels of Hydrocarbon from Heavy-Duty Gasoline Engines

Model Year	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr at useful life)	
	MOBILE5b	Certification	MOBILE5b	Certification
1988	0.92	0.59	1.10	0.26
1989	0.92	0.65	1.10	0.24
1990	0.92	0.35	1.10	0.25
1991	0.92	0.30	1.10	0.21
1992	0.92	*0.32*	1.10	*0.27*
1993	0.92	*0.29*	1.10	*0.15*
1994	0.92	0.42	1.10	0.29
1995	0.92	0.38	1.10	0.23

Table 6. Comparison of MOBILE5b and Certification Calculation Results for Emission Levels of Carbon Monoxide from Heavy-Duty Gasoline Engines

Model Year	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr at useful life)	
	MOBILE5b	Certification	MOBILE5b	Certification
1988	12.48	12.18	7.92	2.32
1989	12.48	15.65	7.92	3.12
1990	12.48	6.89	7.92	2.34
1991	12.48	6.11	7.92	1.95
1992	12.48	*6.59*	7.92	*4.35*
1993	12.48	*9.77*	7.92	*1.22*
1994	12.48	7.57	7.92	3.76
1995	12.48	7.69	7.92	3.50

Table 7. Comparison of MOBILE5b and Certification Calculation Results for Emission Levels of Nitrogen oxides from Heavy-Duty Gasoline Engines

Model Year	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr at useful life)	
	MOBILE5b	Certification	MOBILE5b	Certification
1988	5.82	5.10	0.33	0.49
1989	5.82	4.82	0.33	0.48
1990	4.78	3.61	0.55	0.29
1991	3.99	3.52	0.55	0.34
1992	3.99	*3.13*	0.55	*0.62*
1993	3.99	*3.58*	0.55	*0.00*
1994	3.99	2.80	0.55	0.54
1995	3.99	2.79	0.55	0.56

Diesel Engines

The following three tables present the calculated emission level results from this analysis for hydrocarbons, carbon monoxide, and nitrogen oxides. Each table includes a total average emission level of the pollutant by model year (1988 through 1995), plus average emission levels by intended service class. For hydrocarbons, certification data for 1988 through 1994 was used; the certification data employed in the 1997 heavy-duty engine rule regulatory impact analysis (containing projected sales) [5] was used for this analysis for purposes of consistency. For purposes of comparison, each table includes emission levels used in MOBILE5b.

Table 8. Modeled and Calculated Hydrocarbon Emission Levels for Heavy-Duty Diesel Engines

Model Year	Zero Mile Level (g/bhp-hr)						Deterioration (g/bhp-hr at useful life)					
	MOBILE5b	Certification Data Calculations					MOBILE5b	Certification Data Calculations				
	Modeled Total	Total	Heavy	Med.	Light	Bus	Modeled Total	Total	Heavy	Med.	Light	Bus
1988	1.03	0.56	0.42	0.67	0.74	NA	0.00	0.03	0.02	0.05	0.02	NA
1989	1.03	0.55	0.51	0.65	0.54	NA	0.00	0.02	0.02	0.04	0.02	NA
1990	1.03	0.52	NA	NA	NA	NA	0.00	0.01	NA	NA	NA	NA
1991	1.03	0.37	0.29	0.40	0.51	0.62	0.00	0.01	0.00	0.00	0.01	0.01
1992	1.03	0.45	0.21	0.52	0.25	NA	0.00	0.01	0.00	0.01	0.03	NA
1993	1.03	0.35	0.33	0.38	0.31	0.30	0.00	0.01	0.01	0.01	0.01	0.00
1994	1.03	0.26	0.22	0.31	0.26	0.11	0.00	0.01	0.02	0.00	0.01	0.01

Table 9. Modeled and Calculated Carbon Monoxide Emission Levels for Heavy-Duty Diesel Engines

Model Year	Zero Mile Level (g/bhp-hr)						Deterioration (g/bhp-hr at useful life)					
	MOBILE5b	Certification Data Calculations					MOBILE5b	Certification Data Calculations				
	Modeled Total	Total	Heavy	Med.	Light	Bus	Modeled Total	Total	Heavy	Med.	Light	Bus
1988	4.68	1.87	1.84	2.11	1.65	NA	1.16	0.38	0.34	0.44	0.40	NA
1989	4.68	0.94	0.84	1.28	0.78	NA	1.16	0.13	0.10	0.22	0.08	NA
1990	4.68	1.81	NA	NA	NA	NA	1.16	0.13	NA	NA	NA	NA
1991	4.68	1.32	1.81	1.22	0.28	2.70	1.16	0.11	0.08	0.25	0.00	0.00
1992	4.68	1.12	0.97	1.23	0.69	NA	1.16	0.05	0.00	0.04	0.07	NA
1993	4.68	1.56	1.85	1.29	0.98	2.90	1.16	0.12	0.08	0.16	0.22	0.00
1994	4.68	1.05	1.09	0.77	1.20	1.01	1.16	0.08	0.10	0.11	0.04	0.01
1995	4.68	1.09	1.05	0.98	1.19	1.12	1.16	0.10	0.10	0.22	0.01	0.01

Table 10. Modeled and Calculated Nitrogen Oxide Emission Levels for Heavy-Duty Diesel Engines

Model Year	Zero Mile Level (g/bhp-hr)						Deterioration (g/bhp-hr at useful life)					
	MOBILE5b	Certification Data Calculations					MOBILE5b	Certification Data Calculations				
	Modeled Total	Total	Heavy	Med.	Light	Bus	Modeled Total	Total	Heavy	Med.	Light	Bus
1988	7.93	6.0	6.47	6.64	4.38	NA	0.00	0.2	0.28	0.14	0.02	NA
1989	7.93	5.7	6.08	6.21	4.29	NA	0.00	0.2	0.27	0.18	0.02	NA
1990	5.64	4.9	NA	NA	NA	NA	0.00	0.1	NA	NA	NA	NA
1991	4.60	4.5	4.59	4.51	4.41	4.55	0.00	0.1	0.11	0.23	0.03	0.10
1992	4.60	4.5	4.46	4.57	4.06	NA	0.00	0.1	0.04	0.08	0.00	NA
1993	4.60	4.5	4.53	4.53	4.37	4.26	0.00	0.	0.11	0.06	0.01	0.00
1994	4.60	4.3	4.52	4.56	3.85	4.70	0.00	0.	0.12	0.01	0.00	0.01
1995	4.60	4.6	4.70	4.67	4.36	5.09	0.00	0.	0.05	0.03	0.01	0.01

The certification data file for 1990 model year heavy-duty diesel engines did not report different emissions for each of the three service classes or for buses. Therefore, EPA has only reported a total ZML and a total deterioration rate for this model year.

For NOx emissions, the results of the calculations using the certification data are close to those produced by the MOBILE5b. However, the MOBILE5b emission level estimates for HC and CO are higher than those produced by the certification data-based calculations.

Grams per Brake-horsepower-hour Emission Factors for Use in MOBILE6

After reviewing the results of the above calculations, EPA decided to re-compute the emission levels and deterioration rates based on specific model year groups. These model year groups represent changes in EPA emission standards.

Table 11. Model-year groups for heavy-duty gasoline engines, heavy-duty diesel engines and heavy-duty diesel buses for use in MOBILE6

Heavy-duty gasoline engines		**Heavy-duty diesel engines**		**Heavy-duty diesel Buses**	
Model Year Group	Emission Limit	Model Year Group	Emission Limit	Model Year Group	Emission Limit
1988-1989	10.6 g/bhp-hr NOx	1988-1989	10.7 g/bhp-hr NOx, 0.6 g/bhp-hr PM	1988-1989	10.7 g/bhp-hr NOx
1990	6.0 g/bhp-hr NOx	1990	6.0 g/bhp-hr NOx	1990	5.0 g/bhp-hr NOx
1991-1997	5.0 g/bhp-hr NOx	1991-1993	5.0 g/bhp-hr NOx , 0.25 g/bhp-hr PM	1991-1992	0.25 g/bhp-hr PM
				1993	0.10 g/bhp-hr PM (urban buses only)
		1994-1997	0.10 g/bhp-hr PM	1994-1995	0.07 g/bhp-hr PM (urban buses only)
				1996-1997	0.05 g/bhp-hr PM (urban buses only)
1998-2004	4.0 g/bhp-hr NOx*	1998-2003	4.0 g/bhp-hr NOx	1998-2003	4.0 g/bhp-hr NOx
		2004+	2.5 g/bhp-hr HC + NOx	2004+	2.5 g/bhp-hr HC+NOx

* Complete HDGVs could meet optional lower standards in 2003 and 2004. These were not included in the MOBILE6 model.

The certification data values in the previous tables were averaged across these model year groups to reduce the impact of the data inconsistencies and caveats described above.

To improve the flexibility of MOBILE6's emission factors, EPA has opted to use the individual emission rates for each intended service class for heavy-duty diesels instead of a single emission rate. For heavy-duty gasoline engines, since no separate intended service classes are defined, MOBILE6 will continue to use a single g/bhp-hr emission rate, although, as for all heavy-duty emission factors, the g/mile rate will be based on service-class specific conversion factors (see M6.HDE.004 [1]).

Projections for post-1995 model years were also computed. Tables presenting the re-computed ZMLs and deterioration rates, as well as explanations of the assumptions used in the projections, follow. All tables below present deterioration rates as g/bhp-hr at 10,000 miles, for consistency with the MOBILE5b framework. Italicized emission rates are projections.

Heavy-Duty Gasoline Engine Inputs for MOBILE6

The heavy-duty gasoline zero mile levels and deterioration rates for HC, CO and NOx are presented below in Tables 12 through 14. Note that the heavy-duty gasoline engine emission rates and deterioration levels will also be applied to a separate heavy-duty gasoline bus category in the model.

HC projections are based on the assumption that no changes occur beyond the 1997 model year**.**

NOx projections for 1998+ are based on proportioning the emission rates calculated for 1991-1997 by a ratio of the standard in effect in 1998 (4.0 g/bhp-hr) to the standard in effect for the 1991-1997 model years (5.0 g/bhp-hr).

Since no standard changes occurred between 1988 and 2004 for CO, EPA has assumed the emission rate calculated for 1991-1997 applies for the 1998-2003 and 2004+ model year classes. All deterioration rates remain the same as in the 1991-1997 model year group.

Table 12. Heavy-duty Gasoline Engine Emission Rates for Hydrocarbons

Model Year Class	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr/ 10,000 miles)	
	MOBILE5b	MOBILE6	MOBILE5b	MOBILE6
1988-1989	0.92	0.62	0.10	0.023
1990	0.92	0.35	0.10	0.023
1991-1997	0.92	*0.33*	0.10	*0.021*

1998-2004	0.92	*0.33*	0.10	*0.021*

Table 13. Heavy-duty Gasoline Engine Emission Rates for Carbon Monoxide

Model Year Class	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr/10,000 miles)	
	MOBILE5b	MOBILE6	MOBILE5b	MOBILE6
1988-1989	12.48	13.84	0.72	0.246
1990	12.48	6.89	0.72	0.213
1991-1997	12.48	7.10	0.72	0.255
1998-2004	12.48	*7.10*	0.72	*0.255*

Table 14. Heavy-duty Gasoline Engine Emission Rates for Nitrogen Oxides

Model Year Class	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr/10,000 miles)	
	MOBILE5b	MOBILE6	MOBILE5b	MOBILE6
1988-1989	5.82	4.96	0.05	0.044
1990	5.82	3.61	0.05	0.026
1991-1997	3.99	3.24	0.05	0.038
1998-2004	3.19	*2.59*	0.05	*0.038*

Heavy-Duty Diesel Engine Inputs for MOBILE6

Zero mile levels and deterioration rates for HC, CO, and NOx are presented for heavy-duty diesel engines in Tables 15 through 17. Since no standard changes have occurred for CO during the 1988-2004 period, emission projections are assumed to be the same as in the 1994-1997 model year class.

EPA has assumed that HC and CO zero mile levels and deterioration rates for 1998-2003 engines are the same as for 1994-1997 engines**.** For NOx, a ratio of 4.0 g/bhp-hr to 5.0 g/bhp-hr has been used to proportion the 1994-1997 emission rates as a means of projecting 1998-2003 emissions.

The 2004 values are based on the split between HC and NOx described in the 2000 heavy-duty regulatory impact analysis. [6]

Table 15. Heavy-duty Diesel Engine Emission Rates of Hydrocarbons

Model Year Class	Zero Mile Level (g/bhp-hr)				Deterioration (g/bhp-hr/10,000 miles)			
	MOBILE5b	MOBILE6			MOBILE5b	MOBILE6		
		Heavy	Med.	Light		Heavy	Med.	Light
1988-1989	1.03	0.47	0.66	0.64	0.00	0.001	0.002	0.002
1990*	1.03	0.52	0.52	0.52	0.00	0.000	0.001	0.001
1991-1993	1.03	0.30	0.40	0.47	0.00	0.000	0.001	0.001
1994-1997	1.03	0.22	0.31	0.26	0.00	0.001	0.001	0.001
1998-2003	*1.03*	*0.22*	*0.31*	*0.26*	*0.00*	*0.001*	*0.001*	*0.001*
2004+	*1.03*	*0.17*	*0.17*	*0.14*	*0.00*	*0.001*	*0.001*	*0.001*

*1990 data was not available by service class.

Table 16. Heavy-duty Diesel Engine Emission Rates of Carbon Monoxide

Model Year Class	Zero Mile Level (g/bhp-hr)				Deterioration (g/bhp-hr/10,000 miles)			
	MOBILE5b	MOBILE6			MOBILE5b	MOBILE6		
		Heavy	Med.	Light		Heavy	Med.	Light
1988-1989	4.68	1.34	1.70	1.21	0.04	0.008	0.018	0.022
1990*	4.68	1.81	1.81	1.81	0.04	0.005	0.007	0.012
1991-1993	4.68	1.82	1.26	0.40	0.04	0.003	0.010	0.004
1994-1997	4.68	1.07	0.85	1.19	0.04	0.004	0.009	0.003
1998-2003	*4.68*	*1.07*	*0.85*	*1.19*	*0.04*	*0.004*	*0.009*	*0.003*
2004+	*4.68*	*1.07*	*0.85*	*1.19*	*0.04*	*0.004*	*0.009*	*0.003*

*1990 data was not available by service class.

Table 17. Heavy-duty Diesel Engine Emission Rates of Nitrogen Oxides

Model Year Class	Zero Mile Level (g/bhp-hr)				Deterioration (g/bhp-hr/10,000 miles)			
	MOBILE5b	MOBILE6			MOBILE5b	MOBILE6		
		Heavy	Med.	Light		Heavy	Med.	Light
1988-1989	7.93	6.28	6.43	4.34	0.00	0.010	0.009	0.002
1990*	5.64	4.85	4.85	4.85	0.00	0.004	0.006	0.011
1991-1993	4.60	4.56	4.53	4.38	0.00	0.004	0.007	0.003
1994-1997	4.60	4.61	4.61	4.08	0.00	0.003	0.001	0.001
1998-2003	*3.68*	*3.68*	*3.69*	*3.26*	*0.00*	*0.003*	*0.001*	*0.001*
2004+	*3.68*	*2.11*	*2.10*	*1.99*	*0.00*	*0.003*	*0.001*	*0.001*

*1990 data was not available by service class.

Heavy-duty diesel bus engines

In MOBILE6, diesel school buses of model year 1988-and-later use the g/bhp-hr emission factors for Medium Heavy-duty Diesel engines, listed above.

Projections for diesel urban and transit buses essentially follow the same pattern as heavy-duty diesels, grouping model years according to changes in emission standards, and computing future emissions in proportion to the future standards.

Table 18. HD Diesel Transit and Urban Bus Engine Emission Rates of Hydrocarbons

Model Year Class	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr/10,000 miles)	
	MOBILE5b	MOBILE6	MOBILE5b	MOBILE6
1988-1989	1.03	0.47	0.00	0.001
1990	1.03	0.52	0.00	0.000
1991-1992	1.03	0.62	0.00	0.000
1993	1.03	0.30	0.00	0.000
1994-1995	1.03	0.08	0.00	0.000
1996-1997	*1.03*	*0.08*	*0.00*	*0.000*
1998-2003	*1.03*	*0.08*	*0.00*	*0.000*
2004+	*1.03*	*0.08*	*0.00*	*0.000*

Table 19. HD Diesel Transit and Urban Bus Engine Emission Rates of Carbon Monoxide

Model Year Class	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr/10,000 miles)	
	MOBILE5b	MOBILE6	MOBILE5b	MOBILE6
1988-1989	4.68	1.34	0.04	0.001
1990	4.68	1.81	0.04	0.005
1991-1992	4.68	2.7	0.04	0.000
1993	4.68	2.9	0.04	0.000
1994-1995	4.68	1.06	0.04	0.000
1996-1997	*4.68*	*1.06*	*0.04*	*0.000*
1998-2003	*4.68*	*1.06*	*0.04*	*0.000*
2004+	*4.68*	*1.06*	*0.04*	*0.000*

Table 20. HD Diesel Bus Transit and Urban Bus Emission Rates of Nitrogen Oxides

Model Year Class	Zero Mile Level (g/bhp-hr)		Deterioration (g/bhp-hr/10,000 miles)	
	MOBILE5b	MOBILE6	MOBILE5b	MOBILE6
1988-1989	7.93	6.28	0.00	0.000
1990	5.64	4.85	0.00	0.004
1991-1992	4.60	4.55	0.00	0.000
1993	4.60	4.26	0.00	0.000
1994-1995	4.60	4.88	0.00	0.000
1996-1997	*4.60*	*4.88*	*0.00*	*0.000*
1998-2003	*3.68*	*3.90*	*0.00*	*0.000*
2004+	*3.68*	*1.95*	*0.00*	*0.000*

Conversion of Emission Factors to Grams/Mile

The g/bhp-hr emission factors listed above were multiplied by conversion factors [1] to generate g/mile emission factors actually used in MOBILE6. Note that no conversion factors were available for 1987+ HDGV8b, so conversion factors for these model years were generated by using the ratio of 1986 HDGV8a and HDGV8b conversion factors. Also, the categories of buses used for heavy-duty bus conversion factors were more detailed than the categories used for heavy-duty bus emission factors, so composite conversion factors were generated by using a sales-weighted average of the original conversion factors.

Altitude Adjustment Factors

The MOBILE6 model will calculate emission factors for heavy-duty vehicles at both low- and high-altitude. Low-altitude emission factors are based on conditions representative of approximately 500 feet above mean sea level and high-altitude emission factors represent conditions of approximately 5,500 feet above sea level.

To update the altitude-specific adjustment factors, EPA sought available test data for heavy-duty gasoline vehicles and heavy-duty diesel vehicles at “low” and “high” altitude. The following sections describe the data sources used to determine altitude adjustment factors and the resulting emission rates.

Heavy-duty Gasoline Vehicles Altitude Adjustment Factors

At the time of this analysis, EPA was unable to identify any new studies of the effects of varying altitude on exhaust emissions from heavy-duty gasoline vehicles. Therefore, MOBILE6 applies the same altitude adjustment factors for heavy-duty gasoline vehicles that were used in MOBILE5. The high altitude adjustment factors for heavy-duty gasoline vehicles are listed below in Table 21.

Table 21. Heavy-duty Gasoline Vehicle High Altitude Adjustment Factors for HC, CO, and NOx

	Altitude Adjustment Factors		
Model Year	**Hydrocarbons**	**Carbon Monoxide**	**Oxides of Nitrogen**
1987 and later	1.855	3.182	0.818

Heavy-duty Diesel Vehicle Altitude Adjustment Factors

EPA identified a small number of studies evaluating the effects of altitude changes on emissions of hydrocarbons, carbon monoxide, and oxides of nitrogen. These studies are listed in Table 25, and full citations are provided in the bibliography. To develop new altitude adjustment factors for heavy-duty diesel vehicles in MOBILE6, EPA calculated the ratio between the average emission rate at low altitude and the average emission rate at high altitude. Note that there was some variability in the altitudes used for testing; however, EPA deemed these differences and their effects on the reported emission levels to be negligible and used all of the available data. The ratio between low altitude and high altitude will be used in MOBILE6 for all heavy-duty diesel categories to characterize the effect of altitude changes on emissions. Table 22 lists reported low-and high altitude emission rates, the average emission rates, and the altitude adjustment factors for heavy-duty diesel vehicles.

Table 22. Heavy-duty Diesel Vehicle High Altitude Adjustment Factors for HC, CO, NOx, and PM

Data Source	Report Year	Engine Type	Model Year	HC		CO		NOx		PM		Test Altitude	
				Low	High	Low	High	Low	High	Low	High	Low	High
EPA-68-03-4044 [7]	1989	EPA Caterpillar 3208	1980	0.90	3.76	5.48	20.90	9.63	8.59	0.63	1.30	500	6000
EPA-68-03-4044 [7]	1989	EPA Cummins NTC-350	1984	0.95	1.14	2.37	4.47	5.21	4.83	0.47	0.68	500	6000
ES&T Volume 31 #4 [8]	1998	DDC Series 60	1989	0.14	0.15	2.80	4.01	8.00	5.13	0.42	0.25	500	5280
NFRAQS [9]	1998	DDC Series 50 6047GK28DD2	1993	0.10	0.04	0.90	3.13	4.70	5.88	0.08	0.13	500	5280
NFRAQS [9]	1998	DDC Series 50 6047GK28DD3	1993	0.10	0.05	0.90	3.51	4.70	8.88	0.08	0.10	500	5280
NFRAQS [9]	1998	Navistar DTA-466 E250	1993	0.30	0.20	0.90	1.95	4.50	4.43	0.22	0.23	500	5280
SAE940669 [10]	1994	DDC Series 60	1994	0.09	0.14	2.77	4.42	4.44	4.39	0.21	0.32	800	5540
SAE961166 [11]	1996	DDC Series 60	1991	0.10	0.16	2.20	4.46	4.70	4.64	0.13	0.30	500	5280
SAE961974 [12]	1996	DDCSeries 50	1995	0.10	0.06	1.60	2.24	4.65	4.97	0.08	0.10	500	5280
		Average Emission Rate:		0.31	0.63	2.21	5.45	5.61	5.75	0.26	0.38		

ALTITUDE ADJUSTMENT FACTORS **HC** 2.05 **CO** 2.46 **NOx** 1.02 **PM** 1.47*

* The PM value was not used in MOBILE6.

ES&T=Environmental Science & Technology
NFRAQS=Northern Front Range Air Quality Study
SAE= Society of Automotive Engineers

References

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[2] Koupal, John. *Accounting for the Tier 2 and Heavy-Duty 2005/2007 Requirements in MOIBLE6. Final Report M6.EXH.004.* EPA Office of Transportation and Air Quality, EPA420-R-01-057. 2001

[3] Glover, Edward L., and Cumberworth, Mitch. *MOBILE6.1 Particulate Emission Factor Model Technical Description DRAFT M6.PM.001*, EPA420-R-02-012, March 2002.

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[11] Graboski, M.S., Ross, J.D., and McCormick, R. L. *Transient emissions from No. 2 diesel and biodiesel blends in a DDC Series 60 engine.* SAE International Spring Fuels and Lubricants Meeting, Society of Automotive Engineers, Inc., Warrendale, PA. 1996.

[12] Daniels, T. L., McCormick, R. L., Graboski, M.S., Carlson, P.N., Rao, V., and Rice, G. W. *The effect of diesel sulfur content and oxidation catalysts on transient emissions at high altitude from a 1995 Detroit Diesel Series 50 urban bus engine."* 1996 SAE International Fall Fuels and Lubricants Meeting and Exposition, Society of Automotive Engineers, Inc., Warrendale, PA. 1996.

Appendix A

Comments Regarding Heavy-duty Engine Emission Conversion Factors and OTAQ Responses to Comments

The following comments were submitted to OTAQ regarding *Heavy-Duty Engine Emission Conversion Factors for Mobile6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*, EPA420-P-98-015 and *Update Heavy-Duty Engine Emission Conversion Factors for Mobile6: Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements, and Fuel Densities*, EPA420-P-98-014. Because the contracts for these reports had ended, neither of the reports were revised with respect to these comments. However, we thought it was important to document the comments and our responses, and rather than creating a separate document, we have included them below. Our responses are in bold.

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July 16, 1998

Mr. Terry Newell
Mobile6 Review Comments
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2000 Traverwood Drive
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Re: Comments on
1. *Update Heavy-Duty Engine Emission Conversion Factors for Mobile6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors*, EPA420-P-98-015
2. *Update Heavy-Duty Engine Emission Conversion Factors for Mobile6: Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements, and Fuel Densities*, EPA420-P-98-014

Dear Mr. Newell:

We would like to take this opportunity to comment on the two above listed draft reports recently released by your office. Please find our comments below. If you have questions regarding our comments, please feel free to contact us.

1. We note that the first draft report acknowledges that while the conversion factor (CF) based method is reasonable for estimating NOx emissions for heavy-duty vehicles (HDVs),

the method may not be applicable to estimating of emissions of CO, HC, and PM, because not all emissions of these three pollutants are directly related to the force required to drive a vehicle. We believe that it is critical to develop and use valid methods to estimate emissions of HC, CO, and PM, as well as NOx for HDVs.

HDVs are increasingly tested on chassis dynamometers. We believe that, eventually, chassis testing data can be used to replace engine testing data and CFs in the Mobile model for estimating HDV on-road emissions. We ourselves have observed that Mobile-estimated HDV emissions are not sensitive to many factors affecting on-road emissions (factors including vehicle speed and off-cycle driving conditions), partly because the CF-based method dilutes the effects of these factors since CFs themselves do not change with them. Use of vehicle chassis testing data will help Mobile accurately predict emissions under different driving conditions.

We realize that it is not practical to produce and use vehicle chassis testing data to develop relationships for use in Mobile6 because of resource and time constraints. For Mobile6 development, we suggest that EPA compare HDV emissions estimated with the CF-based method to chassis-dynamometer-based testing results, in order to learn the differences between the two. Subsequently, EPA may use available chassis testing results to adjust CF-based emission estimates within Mobile6.

OTAQ Response: ***This is a good idea for validation of MOBILE6 and development of future OTAQ models. We will consider this as part of our future modeling efforts.***

2. While BSFC data for MY 1987 - 96 HD engines were obtained from six engine makers, BSFC data for pre-1988 and post-1995 MY HD engines were estimated with regression relationships that were established with MY 1987 - 1996 data. Technologies employed on MY 1987 - 1996 vehicles would show different MPG change patterns over time than for pre-1987 or post-1996 models. We are not entirely comfortable with the wisdom of using regression relationships here. If regression relationships have to be used, we suggest that statistics such as R2 and t-test be presented.

Similarly, HDV MPG for MY 1993 - 96 HDVs was projected with regression relationships that were developed from data for pre-1993 MY HDVs. Again, we question the wisdom of using regression relationships to predict MPG, since the implementation of new MPG improvement technologies and enforcement of new emission standards can invalidate applications of the relationships. It seems more reasonable to use MPG values rated by vehicle manufacturers for MY 1993 - 96 to estimate MPG for MY 1993 - 96 HDVs. If the regression relationships have to be used, their R2 and t-test values should be presented.

OTAQ Response: ***Unfortunately, MPG values rated by vehicle manufacturers were not provided in the contractor's work. In the future, OTAQ will explicitly ask for such statistics.***

3. In projecting CFs for post-1996 MY HDVs, it was assumed in the reports that the all available non-engine MPG improvement technologies were already implemented in the U.S. by MY 1996, and that MPG improvements for future HDVs will be from engine-related

technologies, which affect CFs very little. This assumption takes one step backward from the 1988 report, in which penetrations of non-engine MPG improvements were assumed for MY 1986 - 2000 HDVs.

We note that the draft reports considered the following non-engine MPG improvement technologies for post-1997 MY HDVs -- aerodynamic improvement devices, drivetrain optimization, low-profile radial tires, speed control, and fan drives. Additional non-engine MPG improvement technologies could include: (1) additional gains from tires (e.g. "super singles"), (2) additional reductions in aerodynamic drag by reducing the radiator profile through improved cooling, and aerodynamic treatments underneath the HDV, (3) lightweight materials, This improvement would increase payload, so fuel consumption per ton of cargo hauled would decline. and, indirectly, (4) hybrid powertrains. These technologies may be implemented on post-1996 MY HDVs, and their use will certainly help reduce CFs of future HDVs. We estimate that through improved HDV systems in the near-term (by 2005), reducing power requirements of a 80,000 lb GVW Class 8 HDV at 65 mph from 215 hp to 181 hp (a 16% decrease), is achievable. Of course, at lower speeds, gains will be smaller. Reference: OHVT Technology Roadmap, report DOE/OSTI-11690 published by Office of Heavy Vehicle Technologies, U.S. Department of Energy, Washington (Oct. 1997). This includes lower aerodyanamic losses, lower wheel losses, lower drivetrain losses, and reduced accessory loads. This excludes additional gains from reduced weight (which increases payload) and hybridization (which would benefit Class 3-6 HDVs more than Class 8 HDVs).

OTAQ Response: ***OTAQ considers these comments to be valid and useful, and will keep them in mind for future modeling efforts.***

4. As a result of the assumptions made in the draft reports regarding implementation of non-engine MPG improvement technologies, the draft reports estimate constant CFs for MY 1997 – 2050 HDVs. The constant CF values for future HDVs are questionable. Note that the 1988 EPA report on CFs predicted constant CFs for MY 1986 and beyond. The values for MYs 1986 - 96 were rejected by values predicted in the draft 1998 reports. We believe the same can occur for the 1998 report in some future year when CFs are updated again. Because of development and implementation of new non-engine MPG improvement technologies for future HDVs, we believe that CFs of future HDVs will continue to be lowered. Thus, we would be more comfortable with an asymptotic trend converging on a future CF value lower than the projected (nominally, 1999) value at which improvement is frozen. We suggest that a 10% decrease in power requirements is achievable by 2010 in new Class 7-8 HDVs. This represents improvements in Class 7-8 HDVs over an average speed of about 40 mph. Additional gains in Class 3-6 HDV efficiency is possible, mainly through hybridization. However, these improvements are a result of increased engine efficiency.

OTAQ Response: ***Predicting the future is difficult. OTAQ's general approach with MOBILE6 has been a conservative one. Again, we will take these comments into account in future modeling efforts.***

Sincerely,

Michael Wang Chris Saricks Frank Stodolsky