Final Report

VALIDATION OF THE U.S. EPA MOBILE6 HIGHWAY VEHICLE EMISSION FACTOR MODEL
TASK 1 -
ON-ROAD TUNNEL STUDIES

CRC PROJECT E-64

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ACRONYMS/ABBREVIATIONS

A/C	air conditioning
AOAQIRP	Auto/Oil Air Quality Improvement Research Program
API	American Petroleum Institute
ATP	anti-tampering program
CA	California
CO	carbon monoxide
CRC	Coordinating Research Council
DRI	Desert Research Institute
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
g/bhp-hr	grams of pollutant per brake horsepower-hour
h	hour
HC	hydrocarbon
HD	heavy-duty vehicles
HEI	Health Effects Institute
HI	heat index
I/M	inspection and maintenance program
LD	light-duty vehicles
m	meter
M41	MOBILE4.1
M50	MOBILE5.0
M60	MOBILE6.0
mph	miles per hour
MY	model year
NAMVECC	North American Motor Vehicle Emissions Control Conference
NCDC	National Climate Data Center
NIPER	National Institute for Petroleum and Energy Research
NMHC	non-methane hydrocarbon
NOx	nitrogen oxides
NREL	National Renewable Energy Laboratory
PM10	particulate matter less than 10 micrometers in diameter
RFG	reformulated gasoline
RVP	Reid vapor pressure
SCAQMD	South Coast Air Quality Management District
SIP	State Implementation Plan
SOS	Southern Oxidants Study
UCB	University of California, Berkeley
VOC	volatile organic compound

EXECUTIVE SUMMARY

The US Environmental Protection Agency (EPA) released the final version of its on-road mobile source emission factor model, MOBILE6, in January, 2002. This version contains numerous updates of data as well as methodology from the prior model version (MOBILE5, originally released in 1993) for estimating emission factors for current and future year vehicles. Since states (except California, which has its own model) are required to use MOBILE6 in their State Implementation Plan and conformity emissions inventory development, it is important to understand the relationship of model predictions to real-world observations. The purpose of this study is to compare MOBILE6 predictions against data from tunnel studies in order to evaluate the effects of model revisions upon its ability to accurately estimate in-use emission factors.

A number of tunnel studies were available for analysis, all of which were conducted during summer months. Three levels of evaluation were carried out: fleet average emission factors, light-duty vehicle emission factors, and heavy-duty vehicle emission factors. Table ES-1 shows the tunnel studies used, and the assessments performed for each tunnel study. Both emission factors and ratios of pollutants were evaluated for the tunnel studies in comparison to model predictions.

Table ES-1. Tunnel study data.

Tunnel	Year of Study	Fleet Average	Light-duty	Heavy-duty
Fort McHenry	1992	x	x	X
Tuscarora	1992, 1999	x	x	X
Callahan	1995	x		
Caldecott	1997			X

MOBILE6 modeling included the use of local data where available (e.g., speed, temperature, age distribution, and fleet mix). Although each specific experimental run was modeled as a separate scenario, vehicle class comparisons were ultimately made using weighted averages of the run-specific results. This was required because the ‘observed’ light- and heavy-duty emission factors were derived from fleet average data using regression analyses. The result was a single estimated emission factor for each tunnel study.

The results indicate that the model’s accuracy varies with pollutant. Other factors that seem to exert strong influence on the ability of MOBILE6 to accurately predict emission factors are speed and age distribution. Aside from these, there were other important phenomena whose influence on emission factors could not be assessed – grades and high emitters.

The following is a list of major findings and subsequent conclusions:

- Fleet average NOx predictions at Fort McHenry and Tuscarora generally agreed with observed data as well as MOBILE5 estimates. The models under predict at bore 3 (which restricted traffic to light-duty vehicles) for runs with relatively high observed emission factors. Closer examination of these experimental runs shows lower total vehicle counts as well as high heavy-duty presence (on a percentage basis). (Not all trucks complied with the restriction on bore 3). The presence of heavy-duty vehicles will inevitably increase the observed NOx emission rates, but because there were few of them their exact behavior and contribution cannot be modeled with high certainty.

- Fleet average NMHC estimates are slightly above observed values at Fort McHenry and Tuscarora. Once again, the model underpredicts for higher observed values.
- Fleet average CO emission factors are well overpredicted at all tunnels used for fleet level comparisons. The greatest deviation from previous model results is seen for CO, with MOBILE6 being considerably higher. This may be due to the revised effects of off-cycle operation, sulfur, and facility-specific speed correction factors.
- The fleet average predictions at Callahan are all overestimated. Factors that differentiate this tunnel from the other two are older fleet, lower speed, and larger speed variation among the experimental runs. Speed corrections seem to be responsible for the MOBILE6/MOBILE5 comparison results but do not explain the large differences between modeled and observed. The older fleet distribution, if responsible, would imply that deterioration of older vehicles is overestimated in the models.
- MOBILE6 overpredicts the light-duty emission factors at both Fort McHenry and Tuscarora. Except for CO, the new model shows more accurate predictions than MOBILE5 at both tunnels.
- For heavy-duty vehicles, the modeled NMHC and CO emissions are higher than those observed, especially for CO. In this case, MOBILE5 has the better agreement with the observed data. The situation for NOx was special in that two additional studies were available for analysis. 1999 Tuscarora data showed NOx to be overpredicted while the emission factor derived at Caldecott is significantly higher than the model prediction. The relationship between observed and modeled estimates at Tuscarora may be due to the excess NOx corrections within the model, which affect model years 1988-2000. At Caldecott, one reason for the high observed NOx is that the tunnel is constant uphill unlike Fort McHenry (both up and downhill) and Tuscarora (flat). The underprediction is further compounded by corrections made to model outputs to lower emissions based upon certification standards.

Overall, MOBILE6 updates generally resulted in overpredictions of fleet average emission factors, most noticeably for CO. This is despite the lack of explicit accounting for the effects of grades.

1. INTRODUCTION

OBJECTIVE

Task 1 of CRC Project E-64 entails the use of emission rate data collected from US tunnels to assess the accuracy of MOBILE6 emission factors. Both mass emission rates and ratios of pollutants were evaluated. For this effort, the performance of MOBILE6 was also compared to the performance of previous versions of MOBILE with respect to their predictions at specific tunnels in order to identify the effects of various data and methodology updates. The work was divided into three subtasks, each with a specific focus: Subtask 1.1 involved the use of non-California tunnel data to assess fleet average emission factors. Subtasks 1.2 and 1.3 focused upon validation of the light-duty (LD) and heavy-duty (HD) emission factors, respectively.

BACKGROUND

Tunnel studies have historically served as a major means of validating emission factor models. In the late 1980s and throughout the 1990s, tunnel studies were used to validate both California's and US EPA's emission factor models. The 1987 study performed at the Van Nuys Tunnel in Southern California as part of the Southern California Air Quality Study (SCAQS) was the first study to show the discrepancy between model predictions and observed data. In general, nitrogen oxides (NOx) predictions agreed well with tunnel data, but carbon monoxide (CO) and hydrocarbon (HC) emission rates were typically underpredicted by the models. At the time of the Van Nuys study, the existing version of EMFAC underestimated CO and HC emission factors by at least half (Ingalls, 1989). Later assessments of MOBILE (Robinson et. al, 1996) showed that versions 4.1 and 5 underpredict under complex traffic conditions and overpredict when vehicles are operating under steady speeds.

Tunnel studies are typically conducted by taking pollutant concentration measurements during several discrete runs throughout a day. The runs are principally designed to capture varying fleet mix, and oftentimes they capture fluctuating temperature, humidity and speed as well. Emission rates are back-calculated from concentrations, air flow rates, vehicle counts, and other physical parameters. From these emission factors, ratios of pollutants can be directly computed.

Emission rates and ratios of pollutants obtained from tunnel measurements contain a combination of in-use effects. In some instances, it is possible to gauge the influence of individual factors. An illustration is the Caldecott Tunnel studies, which were performed before and after the implementation of California Phase II RFG. This allowed the effects of this fuel to be studied without interfering factors other than fleet turnover. As discussed below, through regression or apportionment analysis, tunnel data also provide a means to validate light-duty and heavy-duty emission factors separately. Finally, speciation of hydrocarbon measurements yields estimates of exhaust and evaporative fractions. The latter portion is generally relatively small in tunnel experiments.

In most tunnels, the light- and heavy-duty vehicles are not routed through separate bores. Thus, the emission rates derived from raw data are representative of the overall fleet. Vehicle class-specific emission factors can be obtained by regressions performed on the fleet emission rate as a function of light-duty (LD) and heavy-duty (HD) fractions. The regressions are then extrapolated back to zero to determine the complementary emission factor. For example, a regression of fleet average emission factors against LD fraction, when extrapolated to zero LD fraction, yields the HD emission factor and vice versa. This method was first employed by Pierson et. al. (Pierson et. al, 1996) Some tunnels exclude heavy-duty traffic in designated bores so that light-duty emission factors can be estimated directly and compared with model predictions. Heavy-duty emission factors at such tunnels are obtained by 'subtracting' the light-duty portion from the total observed.

Despite their usefulness, tunnel study data present inherent problems for model validation. First, the data often include the effects of road grade and vehicle loads which are both very difficult to accurately quantify. The MOBILE6 model does account for off-cycle and air conditioning effects, but these may not specifically reflect the tunnel conditions. In addition, since tunnels involve smaller samples of the overall fleet, the effect of high emitters may not only be more pronounced but is also more uncertain. (This topic can be addressed in more detail in Task 3 of this project.) Another difficulty is encountered when attempting to quantify the penetration of in-use controls such as inspection/maintenance (I/M) programs or low Reid Vapor Pressure (RVP) fuels. This is significant when vehicles passing through a tunnel come from areas with different fuels and control programs. Finally, it may be difficult to assess the combination of modes (cold start, hot start, hot stabilized) under which the vehicles are operating.

2. AVAILABLE TUNNEL STUDIES

Table 2-1 lists the tunnel study data available for use in validating the MOBILE6 emission factor model predictions. Some tunnels were studied in one year only, and two were repeatedly studied in several years. In each tunnel study (by which we mean one tunnel in one year), there are always multiple "runs" at different times of day and different days. These studies have all been performed by either Desert Research Institute (DRI) or UC Berkeley. Brief descriptions of each tunnel are provided in Appendices A (DRI tunnel studies) and B (UC Berkeley Caldecott tunnel studies). Where appropriate, grades and other special tunnel conditions that affect operation within the measurement zone are noted in these appendices to serve as caveats qualifying the resulting comparisons. Finally, with the exception of a January Deck Park study, all these data were collected during summer months.

Table 2-1. Summary of available tunnel studies.

Tunnel	Location	Length (m)	Fleet	Year(s)
Non-California tunnels				
Fort McHenry Tunnel	Baltimore, Maryland	2174	Highway	1992, 1993, 1995
Tuscarora Mountain Tunnel	Pennsylvania Turnpike, Pennsylvania	1623	Highway	1992, 1999
Cassiar Connector	Vancouver, British Columbia	730	Urban	1993
Callahan Connector	Boston, Massachusetts	1545	Urban	1995
Deck Park Tunnel	Phoenix, Arizona	804	Urban	1995
Lincoln Tunnel	New York/New Jersey	2440	Urban	1995
California tunnels				
Caldecott Tunnel	San Francisco Bay Area, California	965	Urban	1994-1997, 1999, 2001
Sepulveda Tunnel	Los Angeles, California	582	Urban	1995, 1996
Van Nuys Tunnel	Los Angeles, California	222	Urban	1995

There are four tunnel studies listed in Table 2-1 that were excluded from consideration for MOBILE6 comparisons:

- The 1995 Fort McHenry study focused on measuring dioxin and furan emissions from the in-use fleet. Emissions of CO, HC, and NO_x were not measured.

- The 1993 Fort McHenry study quantified only PM_{10} emissions. MOBILE6.1 will include PM_{10} emission factors, but was not available in time for use in this project.

- The Cassiar connector is a Canadian tunnel. It is not being considered for comparison to MOBILE6 because of the large number of changes that would be required to MOBILE6 to reflect Canadian fleet and fuel differences.

In addition, only the Caldecott study performed in 1997 includes heavy-duty emission factors; all other Caldecott tunnel studies measured light-duty emissions only.

TUNNEL STUDIES SELECTED FOR COMPARISON WITH MOBILE6

For Subtask 1.1, the tunnel studies that were used to compare fleet average (i.e., cars and trucks combined) emission factors to model predictions are:

- Fort McHenry, 1992;
- Tuscarora, 1992 and 1999;
- Callahan, 1995.

These tunnels and years were chosen to ensure that a relatively wide range of operating parameters is included in this study. These include effects of newer technologies, grades, speeds, fleet mix, and ambient conditions. They were also used because the measured emissions were readily available and reliable. Finally, for the Fort McHenry and Tuscarora (1992) tunnels, MOBILE5 results were also available.

For the purpose of validating light-duty vehicle emission factor predictions (Subtask 1.2), the same tunnel studies identified above can be used. However, regression analysis is required for tunnels that do not separate LD and HD. Run-specific results are lost and one cannot develop a single modeling scenario whose results are directly comparable (because the regressions implicitly include the effects of changing temperature, speed, humidity, and other factors). Tunnels where the vehicle classes are separated are thus most useful because vehicle class-specific emission rates can be derived with less uncertainty. The 1992 Fort McHenry tunnel data were preferred for this analysis since LD vehicles were essentially the only occupants in one of the bores measured (bore 3). The Tuscarora (1992) and 1992 Fort McHenry (bore 4) data were also added because of the wide-ranging fleet mix among the runs which enhances the regression technique. This is discussed further below.

To assess the accuracy of MOBILE6 estimates of heavy-duty emission factors (Subtask 1.3), California tunnels were used as well as non-California tunnels with appropriate adjustments to by-model-year emission factors for differences in certification standards. For this subtask, we relied on the 1997 Caldecott and the 1992 Fort McHenry tunnel studies, as these both have bores in which HD vehicles are restricted. (Note that for HD vehicles, only NOx and $PM_{2.5}$ data were derived from the 1997 Caldecott Tunnel measurements.)

In addition, we utilized the regression approach described above to obtain HD emission factors from the Tuscarora, Callahan, Lincoln, and Deck Park data. (The Lincoln and Deck Park results were ultimately excluded. See discussion below.) The HD truck emission factors estimated from the regression analyses were compared to MOBILE6 HD-specific emission factors, with the comparisons being made to the weighted average.

Table 2-2 summarizes major characteristics of the tunnels and fleets used in this assessment. The information shown is of particular importance in subsequent discussions of the comparison results. Some noteworthy observations are (1) the Callahan tunnel has the largest speed variation; (2) measurements at the Fort McHenry and both Tuscarora studies captured a wide range of LD/HD fractions; and (3) Fort McHenry and Callahan results include the effects of an uphill and downhill operation while only one direction (uphill) is captured at Caldecott.

The observations for multiple slope tunnels presented in subsequent sections are averages except where noted.

Table 2-2. Selected characteristics of tunnels chosen for comparison with MOBILE6.

Tunnel	Grade	Speeds (mph)	LD Fraction
Fort McHenry	-3.76%/+3.76%	38 to 53	0.28 to 0.99 (bore 4)
Tuscarora 1992	Flat (<0.3%)	55 to 60	0.20 to 0.94
Tuscarora 1999	Flat (<0.3%)	54 to 62	0.14 to 0.88
Callahan	-3.8%/+3.25%	14 to 35	0.94 to 0.98
Caldecott	+4.0%	41 to 56	0.95 to 0.97

3. MOBILE6 MODELING

GENERAL APPROACH

MOBILE6 requires a number of input parameters to specify a run scenario. At a minimum, these include

- fleet composition data – model year registration, vehicle class distribution;
- operating conditions – speed, operating mode (controlled via the SOAK DISTRIBUTION and STARTS PER DAY commands);
- ambient conditions – temperature, humidity;
- fuel parameters – RVP, sulfur content, RFG status; and
- control program status – I/M and ATP.

We used inputs derived from local data where available. When local data are not available from the existing tunnel studies, we attempted to obtain the most representative data available from local agencies and other publicly available sources of historical data. Fleet composition, ambient conditions, and operating conditions were available for most of the tunnel studies. Fuel parameters and I/M controls were obtained from local regulatory or SIP documentation. Operating modes fractions and facility class selection must be developed based upon engineering judgment; DRI and UCB were consulted to define these parameters.

MOBILE6 METEOROLOGICAL INPUT PARAMETERS

In the MOBILE6 modeling of the tunnel study runs, historical meteorological data were used whenever possible for the input parameters. We chose to use MOBILE6 defaults for two meteorological parameters, (cloud cover and peak sun), because no reliable historical data could be found. Default cloud cover is assumed to be a 100% clear day. To gain an understanding of the effect of using the default value, we note that above a heat index (HI) of about 100, there is no difference in air conditioning (A/C) demand between 0 and 100% cloud cover. Below that HI, this difference varies as a function of the HI, with the maximum being about 20% demand. (EPA, 2001) Thus on average, we may expect less than a difference of 10% in demand between using the default and the actual cloud cover. The default peak sun period is indicative of early summertime so its use is appropriate for the modeling scenarios in this work. The following sections discuss the sources of data for meteorological parameters that were modified for each run.

Temperatures

Temperatures for the Tuscarora and Callahan tunnel study runs were obtained from DRI’s data. In general, a specific temperature was reported for the hour of each run. The Caldecott Tunnel 1997 temperatures were obtained from historical Oakland airport readings. In all cases, MOBILE6 was run at constant temperature throughout the day, but only the hour corresponding to the experimental run was used.

Sunrise/Sunset

Historical sunrise and sunset times for each test run were obtained from the US Naval Observatory web site, found at http://aa.usno.navy.mil/data/docs/RS_OneDay.html. Data for the nearest available city for each tunnel were used. In accordance with MOBILE6 sunrise/sunset input structure, the times were all rounded to the nearest hour.

Absolute Humidity

MOBILE6 accepts a daily average absolute humidity value that is calculated from barometric pressure and relative humidity readings. For all runs, except for the 1999 Tuscarora Tunnel and the 1997 Caldecott Tunnel studies, pressure and relative humidity values were obtained from the National Climate Data Center web site, at http://www4.ncdc.noaa.gov/, using the nearest available weather station. Values for each specific test day were read from historical monthly data graphs. 1999 data were not available at the NCDC web site, so an alternate data source was found for the 1999 Tuscarora runs. Daily pressure, average temperature and dewpoint temperature values for 1999 were found at http://www.wunderground.com/cgi-bin/findweather/getForecast?query=huntingdon%2C+PA. The average and dewpoint temperatures were used to calculate relative humidity using the calculator found at http://www.weatherlord.com/weather/calculator/humidity/. The Caldecott Tunnel 1997 pressures and relative humidities were obtained from historical Oakland airport readings.

Using the MOBILE6 methodology detailed at http://www.epa.gov/otaq/m6.htm, the pressure and relative humidity data were combined with ambient temperature for each run to calculate absolute humidity.

MOBILE6 TIME AND GEOGRAPHICAL INPUT PARAMETERS

Month of Year

MOBILE6 has the capability of modeling either a January 1 or July 1 run for any given year. The tunnel studies used in this work had performance periods that ranged from May to September. Thus the July 1, or summer, setting was used in all cases.

Weekday/Weekend

MOBILE6 was set to use either weekday or weekend vehicle activity rates, depending on the historical day of week of each experimental run.

Altitude

MOBILE6 has a low and a high altitude setting. The low altitude setting translates to approximately 500 feet above mean sea level while the high altitude setting represents areas of about 5,500 feet above mean sea level. In all cases in this work, the elevation of the areas around the tunnels was much closer to 500 than 5,500 feet above mean sea level. Thus, the low altitude setting was always used.

Facility Type

The MOBILE6 facility type was designated as "Freeway" for all tunnels except Callahan. For that particular tunnel, the speed range is relatively wide from 14 to 35mph with a corresponding low average. For these reasons, we believed that neither the Freewaynor Arterial cycle correctly represents the tunnel conditions. We chose to model the tunnel as "Arterial". (To check the effects of this assumption, we modeled the tunnel under both designations. For the conditions at this tunnel, the maximum differences (within this speed range) between freeway and arterial fleet average results are about 5% for CO, 3% for NMHC, and 8% for NOx.)

FUEL AND I/M PROGRAM INPUTS

Fuel Inputs

All fuel inputs were obtained from NIPER data. We had access to NIPER data for the summer of 1993 and the summer of 1995. The nearest available year was chosen for each test run. NIPER provided RVP, sulfur, and oxygenate data. Oxygenate data of about 2% volume MTBE or less was determined to be insignificant and was not used as MOBILE6 input.

Additionally, each tunnel area was checked for federal RFG status at the website http://www.eia.doe.gov/emeu/steo/pub/special/rfg2.html. Only two tunnel and year combinations fell within federal RFG areas, Lincoln and Callahan tunnels for 1995. For these two cases, the RFG flag was set in MOBILE6, which automatically defines RVP and oxygenate content.

I/M and ATP Inputs

I/M and ATP program status for each tunnel area was determined based on data available at http://www.epa.gov/oms/epg/state.htm which summarizes the latest programs (i.e., enhanced I/M). According to the programs and start years specified at this web site, only one state was affected by enhanced I/M: California. However, the San Francisco Bay Area is exempt from CA enhanced I/M program. Thus MOBILE6 I/M and ATP inputs for Caldecott were set according to the latter information. (Note that this does not influence the results since only HD emissions are included from this tunnel.) In addition, the Maryland, Pennsylvania, and Massachusetts state I/M offices were polled regarding historic programs for their respective states. Since the Tuscarora Mountain tunnel was distant from any Pennsylvania I/M areas, no I/M was modeled. Maryland and Massachusetts operated basic I/M programs starting in 1984 and 1983, respectively. These were modeled as two-speed idle programs.

MOBILE6 OUTPUT PROCESSING

MOBILE6 database output was used to obtain emission factors for each specific test hour. Only running exhaust and evaporative emissions were used, as all other start and evaporative emissions were assumed to be insignificant under the conditions of each study. The output was delineated by both vehicle class and model year. Fleet-average values were calculated from these model year and vehicle class-specific emission factors, using observed and MOBILE6 default (for vehicle classes with no observed data) age distribution and fleet mix data to appropriately weight the emissions.

Fleet-average emission factors obtained in the manner described above were compared directly to values observed in the tunnels. The corresponding pollutant ratios were also evaluated. Additional calculations were necessary before the vehicle class-specific comparisons can be made. The MOBILE6 LD and HD factors for each experimental run were computed by combining the appropriate vehicle classes' emission factors (i.e., vehicle classes 1 through 5, 14, and 15 were combined into LD and classes 6-13, 16-23, and 25-27 were combined into HD.) Then, the emission factors for the individual runs at a single tunnel/bore were combined into a weighted average using the number of vehicles in each run as the weights.

For HD diesel vehicles, an additional issue must be resolved before comparisons can be made. This is the issue of NOx defeat devices. These devices purportedly increase NOx emissions from HD diesel trucks under steady-state operating conditions. MOBILE6 assumes that certain model years' experience increased NOx emissions due to the presence of such mechanisms. Thus, it is important to determine whether the traffic conditions within a tunnel are conducive to these devices being in operation. If not, the MOBILE6 emission factors associated with the tunnel/run must be adjusted to reduce NOx emissions. We attempted to determine the exact operational criteria under which increased NOx would result (so that these can be compared to the tunnel conditions) but were unsuccessful. EPA documentation of this feature did not clearly specify the precise parameters. It stated that the on/off status of these devices for particular fleets and facility class/operational scenarios was determined using "proprietary and confidential data submitted by the engine manufacturers, limited testing of affected engines, and engineering judgment by experts in engine control and emission control software." (EPA, 2002) Thus, no adjustment for excess NOx was made to the default model outputs.

Caldecott HD diesel NOx results were obtained in a different manner than the federal tunnels used in this study. Using a carbon balance and the observed concentration, the emission factor was originally calculated on a fuel-specific (g/kg fuel) basis. To convert to a g/mile basis, the fuel density (0.77331 g/ml) and the fuel economy (4.8 mile/gal) were required. Both of these values were taken from (Pierson et. al, 1996), with the fuel economy representing HD vehicles moving uphill at the Fort McHenry Tunnel.

MOBILE6 results for the Caldecott Tunnel were also adjusted to reflect differences in CA and Federal HD NOx emission standards. In particular, a ratio-of-standards approach was used to correct model years 1987 to 1989. The CA and Federal standards for these model years were 6 and 10.7 g/bhp-hr, respectively. No adjustments were made to other model years because the standards were equivalent.

4. RESULTS AND DISCUSSION

Graphical results are presented below by subtask. A discussion follows at the end of the presentation of results.

SUBTASK 1.1 – FLEET-AVERAGE EMISSION FACTORS (FEDERAL AREA TUNNELS)

This subtask focused upon validating the MOBILE6 estimates of fleet-average emission factors using tunnel studies outside California. Model-predicted emission factors as well as pollutant ratios are compared to observed data. In addition to the direct comparison between MOBILE6 and tunnel study data, analogous MOBILE4.1 and MOBILE5 predictions are also shown to assess model changes. Figures 4-1 through 4-14 show the predicted run-specific fleet average emission factors plotted against the corresponding observed value for Fort McHenry, both years of Tuscarora, and Callahan. (1999 Tuscarora NMHC data are faulty and thus are omitted.) Table 4-1 and Figures 4-15 and 4-16 present the pollutant ratios, where available.

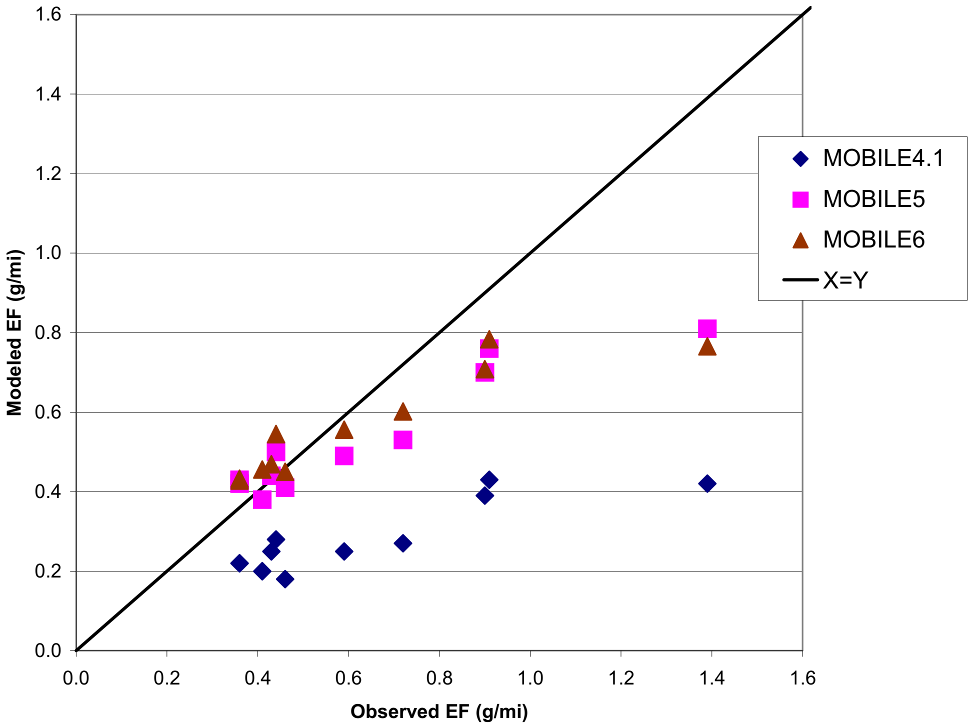

Figure 4-1. Comparison of observed to modeled fleet average NMHC emission factors at Fort McHenry (1992), Bore 3.

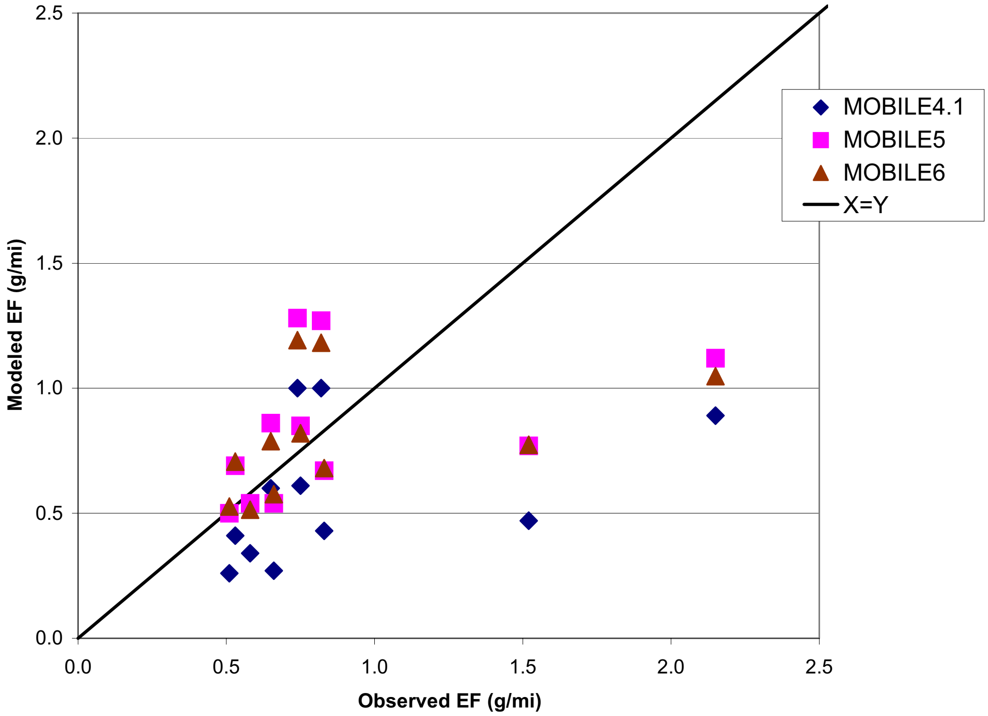

Figure 4-2. Comparison of observed to modeled fleet average NMHC emission factors at Fort McHenry (1992), Bore 4.

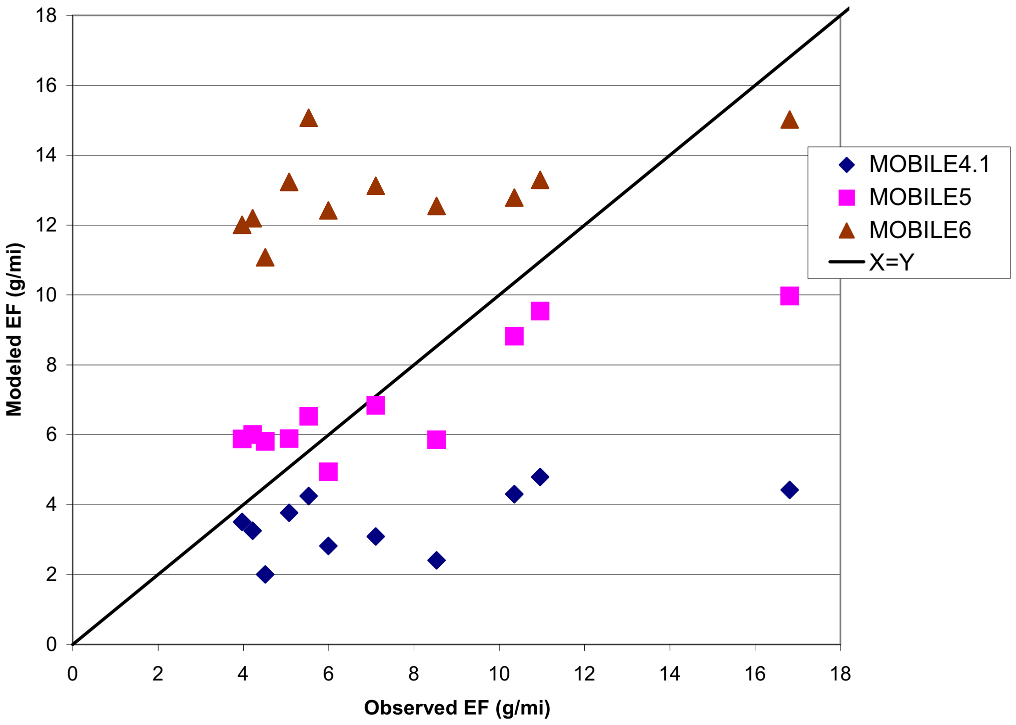

Figure 4-3. Comparison of observed to modeled fleet average CO emission factors at Fort McHenry (1992), Bore 3.

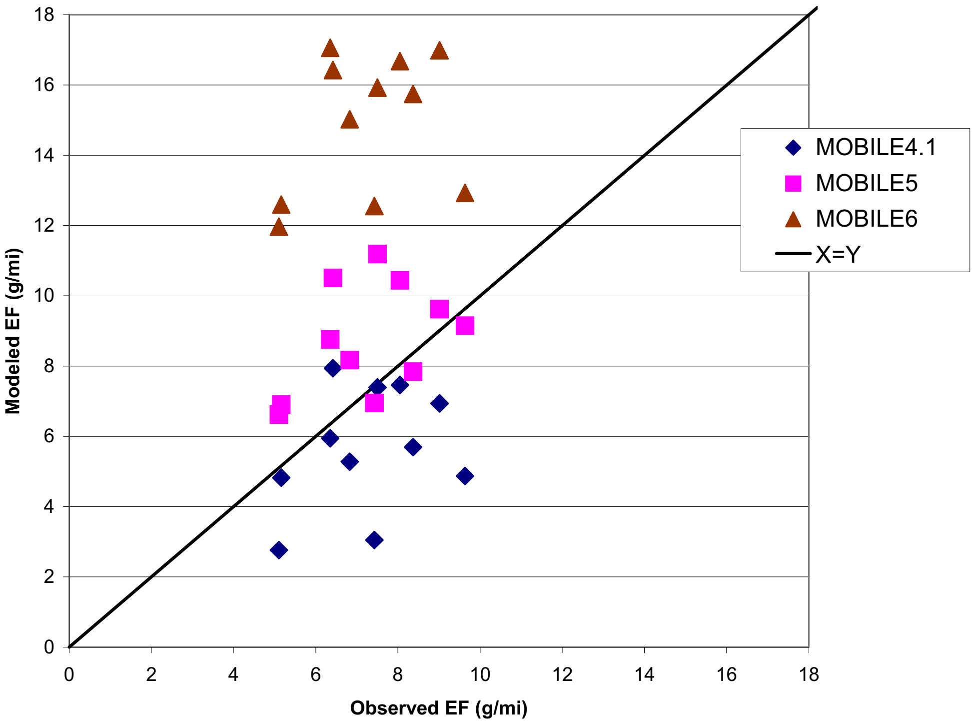

Figure 4-4. Comparison of observed to modeled fleet average CO emission factors at Fort McHenry (1992), Bore 4.

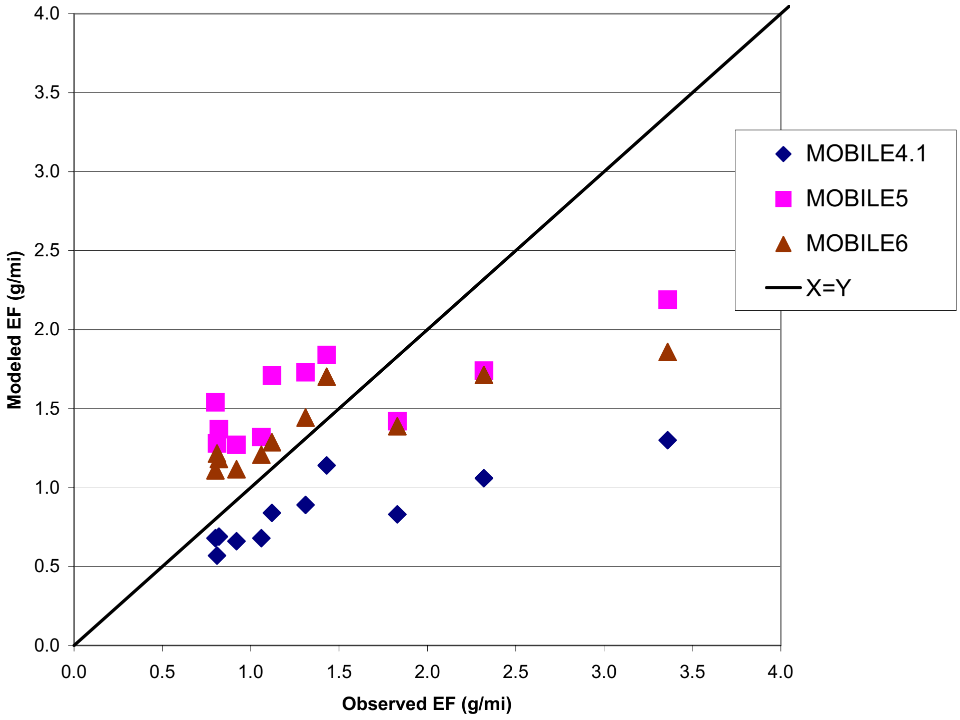

Figure 4-5. Comparison of observed to modeled fleet average NOx emission factors at Fort McHenry (1992), Bore 3.

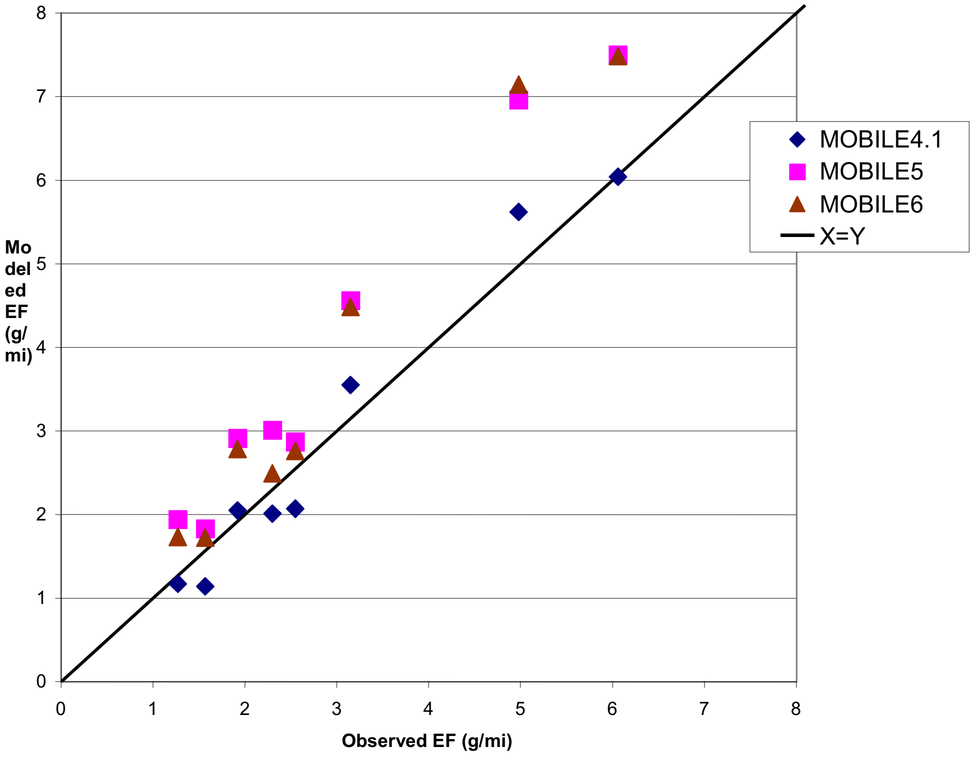

Figure 4-6. Comparison of observed to modeled fleet average NOx emission factors at Fort McHenry (1992), Bore 4.

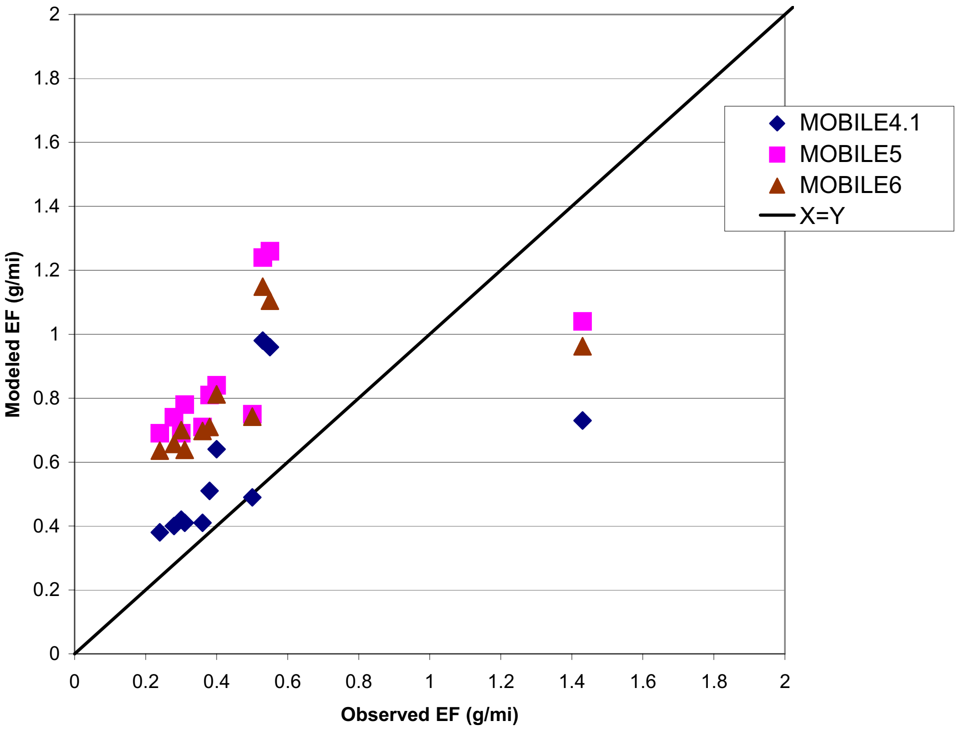

Figure 4-7. Comparison of observed and modeled fleet average NMHC emission factors at Tuscarora Mountain (1992).

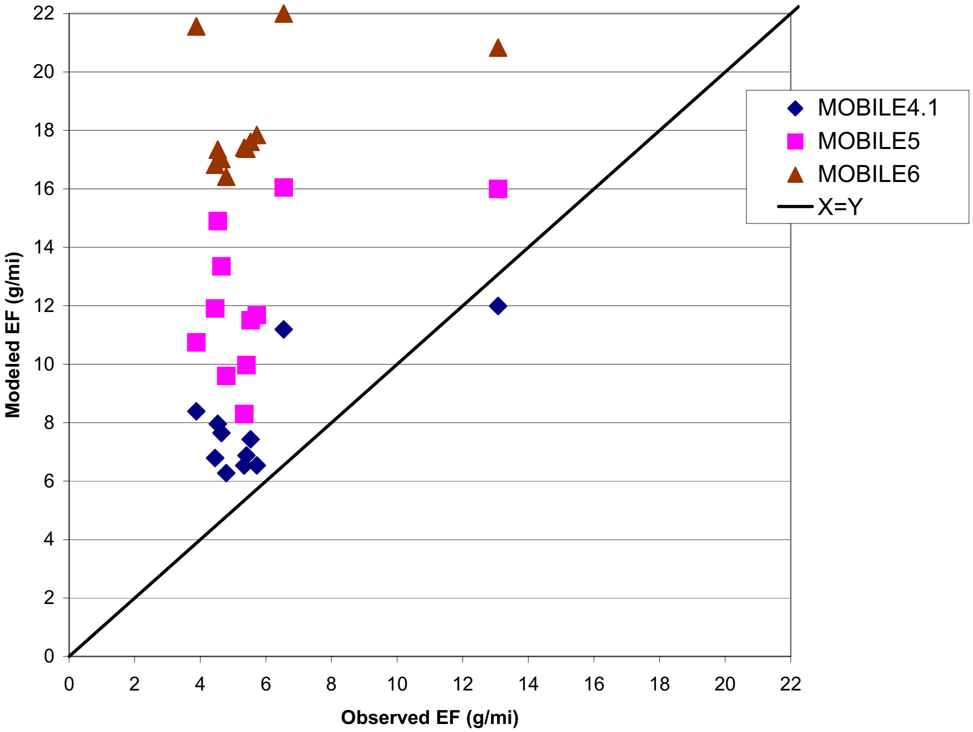

Figure 4-8. Comparison of observed and modeled fleet average CO emission factors at Tuscarora Mountain (1992).

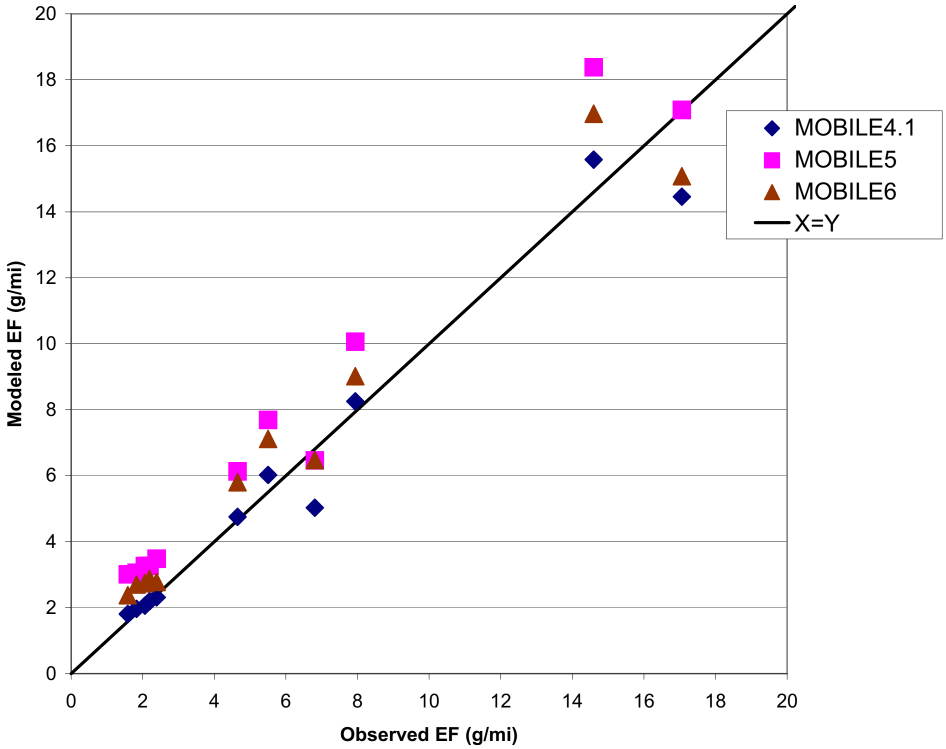

Figure 4-9. Comparison of observed and modeled fleet average NOx emission factors at Tuscarora Mountain (1992).

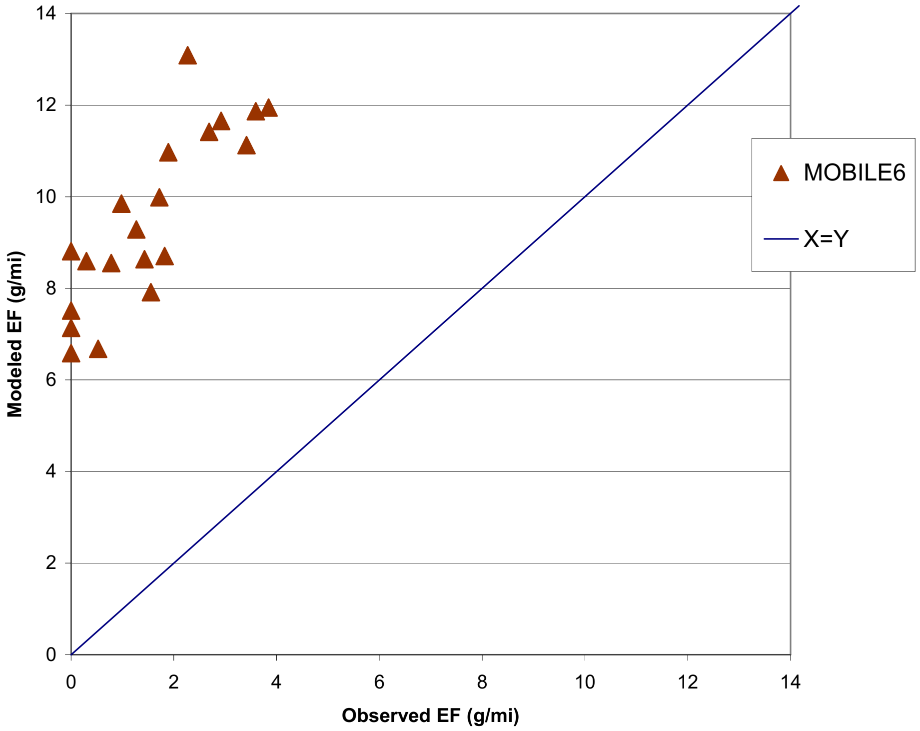

Figure 4-10. Comparison of observed and modeled fleet average CO emission factors at Tuscarora Mountain (1999).

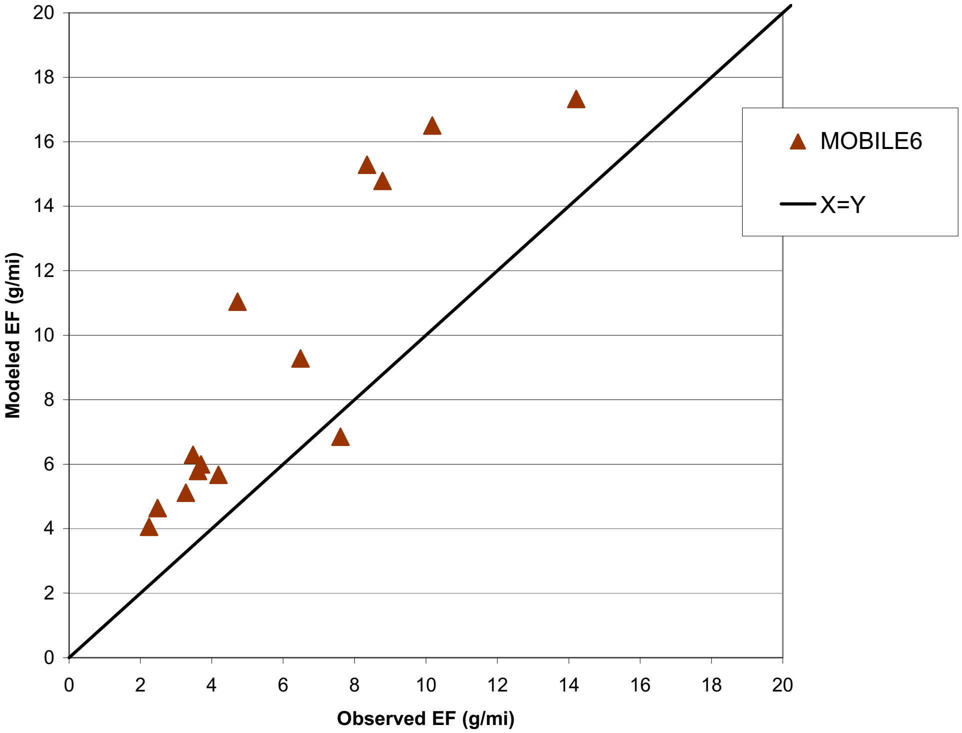

Figure 4-11. Comparison of observed and modeled fleet average NOx emission factors at Tuscarora Mountain (1999).

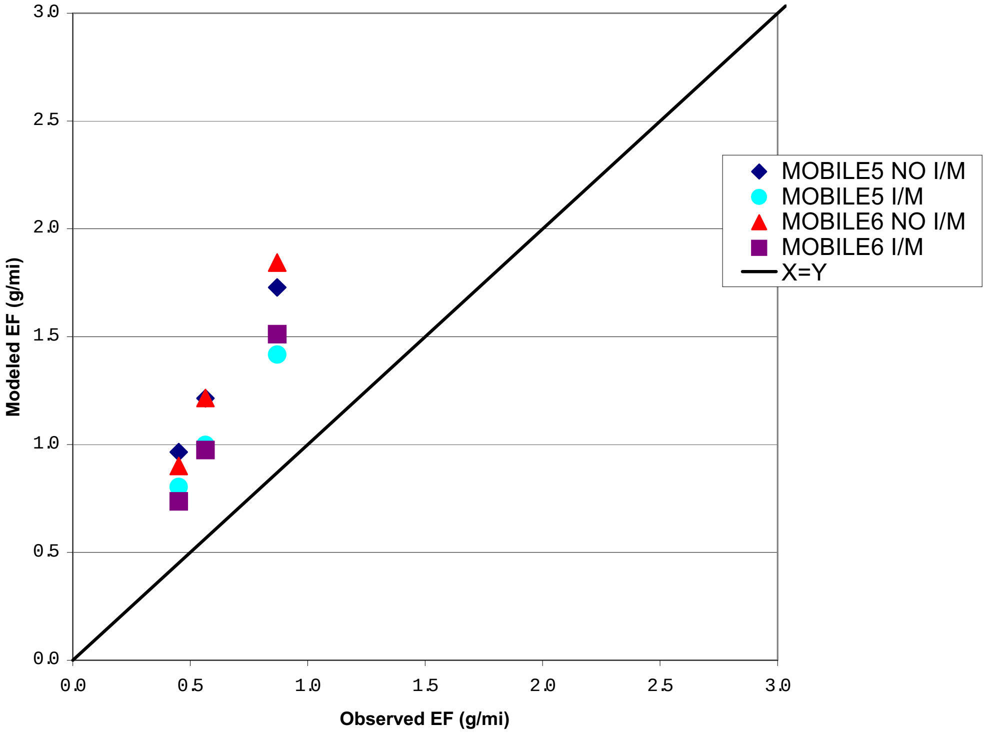

Figure 4-12. Comparison of observed and modeled fleet average NMHC emission factors at Callahan Tunnel (1995).

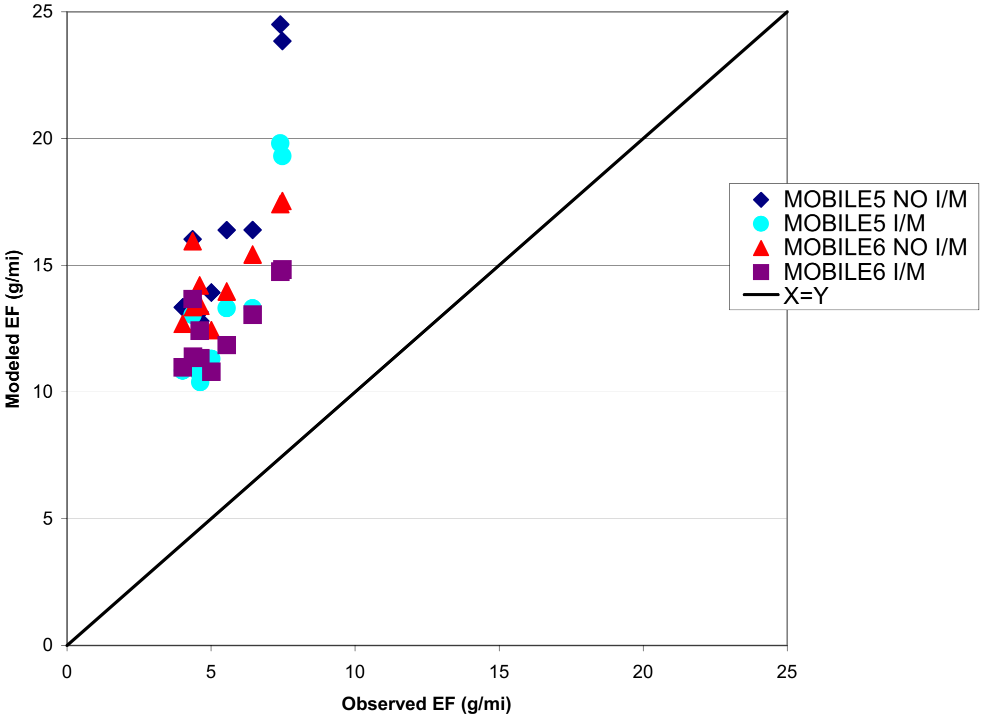

Figure 4-13. Comparison of observed and modeled fleet average CO emission factors at Callahan Tunnel (1995).

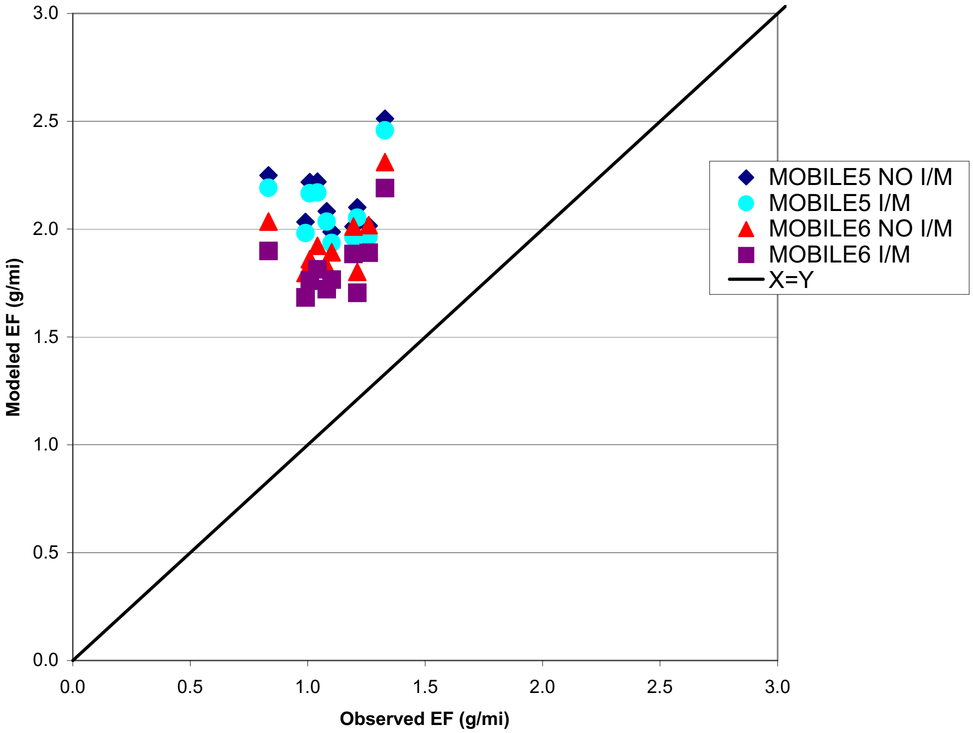

Figure 4-14. Comparison of observed and modeled fleet average NOx emission factors at Callahan Tunnel (1995).

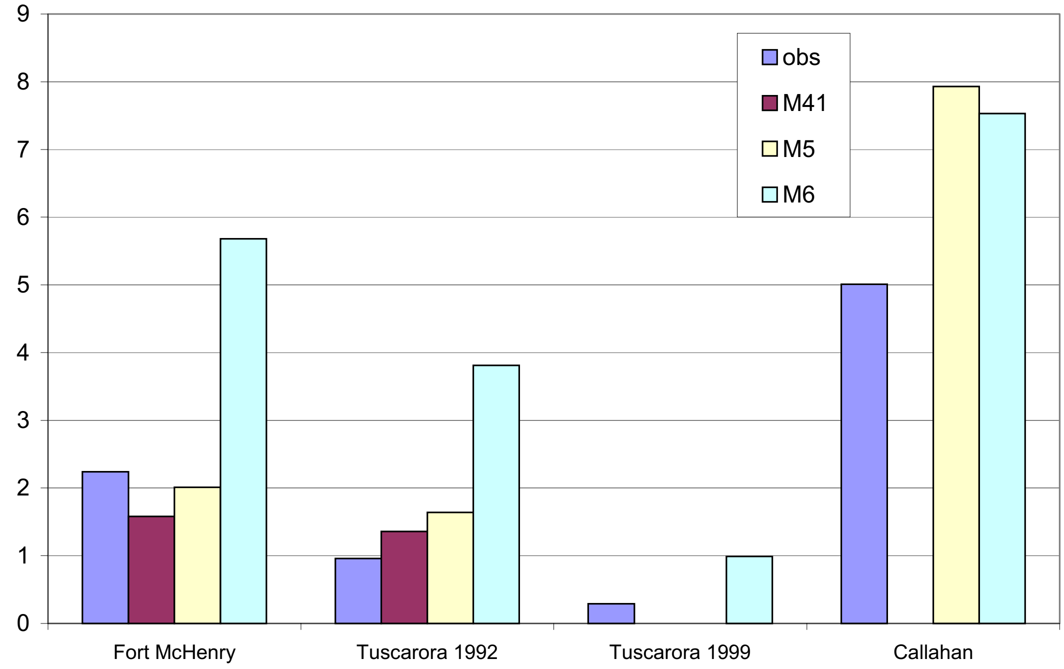

Figure 4-15. Observed and predicted CO/NOx ratios.

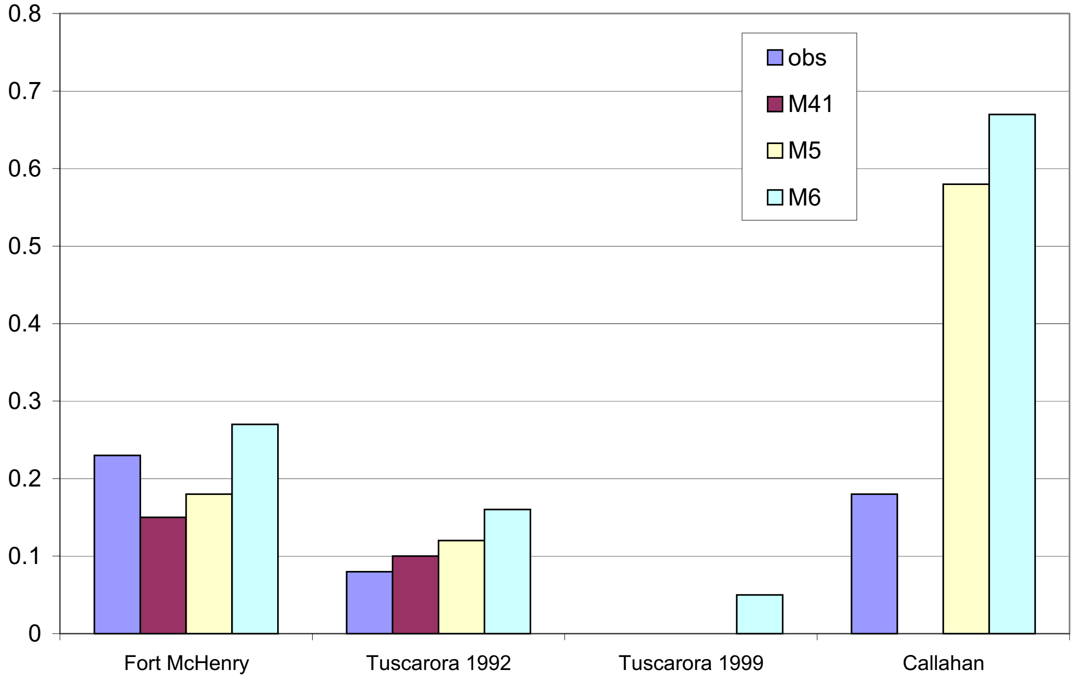

Figure 4-16. Observed and predicted NMHC/NOx ratios.

Table 4-1. Ratio of pollutants for the overall fleet.

CO/NOx	Fort McHenry	Observed	2.24
		MOBILE4.1	1.58
		MOBILE5	2.01
		MOBILE6	5.19
	Tuscarora 1992	Observed	0.96
		MOBILE4.1	1.36
		MOBILE5	1.64
		MOBILE6	3.89
	Callahan	Observed	5.01
		MOBILE4.1	na
		MOBILE5	7.93
		MOBILE6	6.93
	Tuscarora 1999	Observed	0.29
		MOBILE4.1	na
		MOBILE5	na
		MOBILE6	0.99
NMHC/NOx	Fort McHenry	Observed	0.23
		MOBILE4.1	0.15
		MOBILE5	0.18
		MOBILE6	0.23
	Tuscarora 1992	Observed	0.08
		MOBILE4.1	0.10
		MOBILE5	0.12
		MOBILE6	0.16
	Callahan	Observed	0.18
		MOBILE4.1	na
		MOBILE5	0.58
		MOBILE6	0.57
	Tuscarora 1999	Observed	na
		MOBILE4.1	na
		MOBILE5	na
		MOBILE6	0.05

SUBTASK 1.2 – LIGHT-DUTY VEHICLE EMISSION FACTORS (FEDERAL AREA TUNNELS)

This task sought to validate a specific portion of the fleet emission factors, namely, the light-duty fleet emission factors. The observed, MOBILE4.1, and MOBILE5 LD emission factors were derived from fleet average values via regression analysis. Pierson et al. derived the MOBILE4.1 and MOBILE5 LD emission factors from fleet average values using weighted regressions in order to attenuate the influence of high emitters (Pierson et al. 1996). The standard errors associated with the regressions are shown below as error bars. (Note that MOBILE6 factors used in this work were not derived but rather came directly from the model. We felt that using the direct vehicle class specific model results would give a clearer assessment of the model's estimates. As such, these emission factors do not have predicted errors since these errors would be associated solely with the error in the model, the determination of which is beyond the scope of this work.) Figures 4-17 through 4-19 depict comparisons of observed and modeled emission factors for Fort McHenry and 1992 Tuscarora data. Table 4-2 and Figures 4-20 and 4-21 summarize the corresponding NMHC/NOx and CO/NOx ratios. Fort McHenry LD data, as shown, were combined for both bores. As discussed in Section 3, the MOBILE6 values are weighted averages, with the total number of vehicles in each run as the weighting factors.

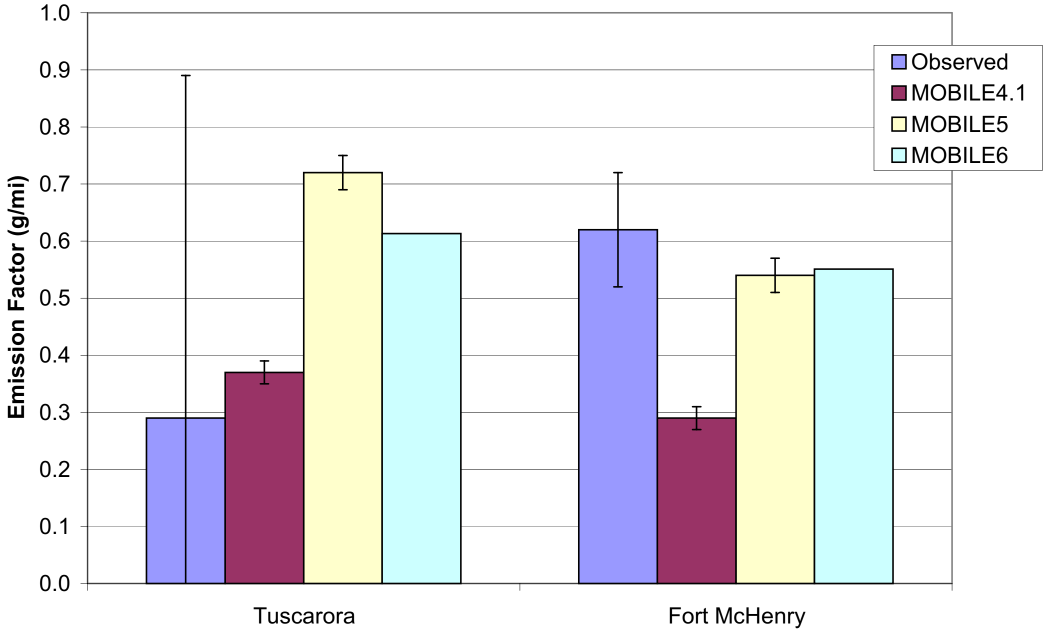

Figure 4-17. Comparison of observed and modeled light-duty NMHC emission factors at Fort McHenry and Tuscarora Mountain (both 1992).

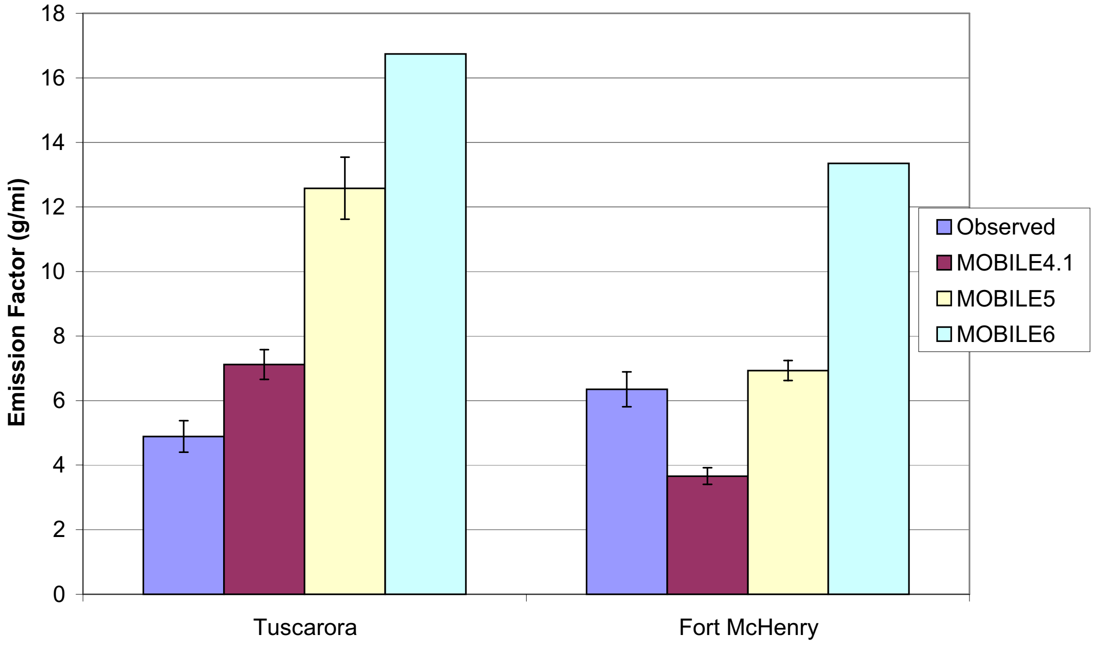

Figure 4-18. Comparison of observed and modeled light-duty CO emission factors at Fort McHenry and Tuscarora Mountain (both 1992).

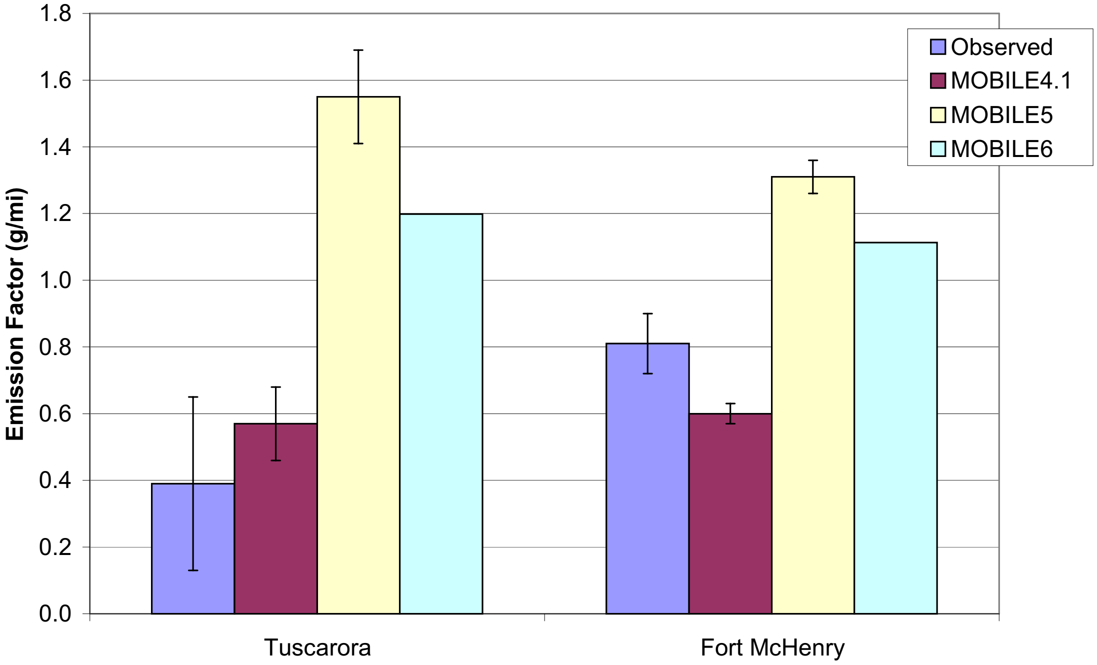

Figure 4-19. Comparison of observed and modeled light-duty NOx emission factors at Fort McHenry and Tuscarora Mountain (both 1992).

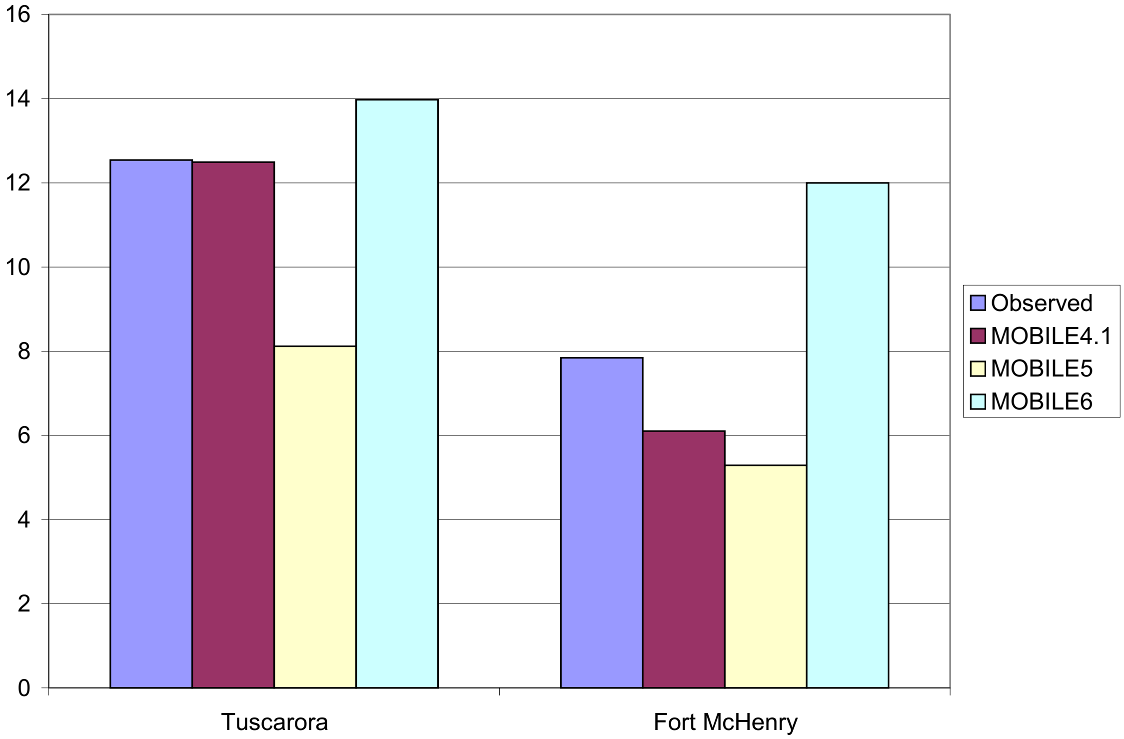

Figure 4-20. Observed and predicted light-duty CO/NOx ratios.

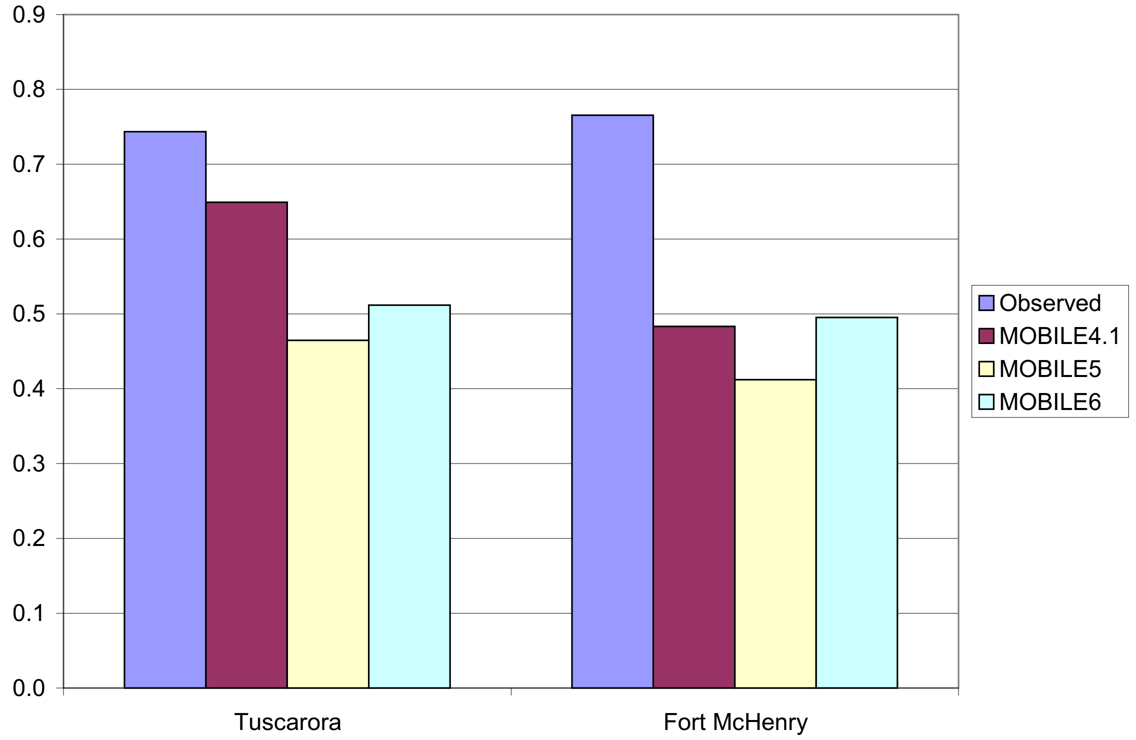

Figure 4-21. Observed and predicted light-duty NMHC/NOx ratios.

Table 4-2. Ratio of pollutants for light-duty vehicles.

CO/NOx	Fort McHenry	Observed	7.8 ± 1.15
		MOBILE4.1	6.1 ± 0.5
		MOBILE5	5.3 ± 0.3
		MOBILE6	12.0
	Tuscarora 1992	Observed	12.7 ± 8.5
		MOBILE4.1	12.5 ± 2.5
		MOBILE5	8.1 ± 1.0
		MOBILE6	14.0
NMHC/NOx	Fort McHenry	Observed	0.76 ± 0.14
		MOBILE4.1	0.48 ± 0.04
		MOBILE5	0.41 ± 0.03
		MOBILE6	0.51
	Tuscarora 1992	Observed	0.76 ± 0.53
		MOBILE4.1	0.65 ± 0.13
		MOBILE5	0.46 ± 0.05
		MOBILE6	0.50

SUBTASK 1.3 – HEAVY-DUTY VEHICLE EMISSION FACTORS (FEDERAL AREA AND CA TUNNELS)

The purpose of this subtask was to verify MOBILE6-predicted HD vehicle emission factors. The components of this analysis are similar to those for LD vehicles described above. However, both Federal and CA tunnel data were used. The emission factor results and ratio of pollutants are shown in Figures 4-23 through 4-25 and Table 4-3, respectively. Uncertainties in the emission factors were estimated similarly to the LD case discussed above. Figures 4-26 and 4-27 present the ratios graphically. Because data collected at the Lincoln and Deck Park Tunnels reflect a very narrow range of fleet mixes, the regression method cannot be reliably applied to derive HD emission rates. Note that although the fleet mix at the Caldecott Tunnel shows a similar narrow variation, the HD emission factor was derived using a carbon mass balance approach. Thus the result was not nullified by limitations of a regression approach. Figure 4-22, which shows NMHC results for Deck Park, is an illustration of this unreliability; all of the LD fractions are between 0.9 and 1.0 and extrapolating back to zero LD fraction to estimate the HD emission factor would be highly uncertain (in fact in this case, it is negative). 1999 Tuscarora CO readings were very low and therefore also adversely affected our ability to resolve LD/HD contributions. Thus, although some of these results are available, they are not used in the assessments of model performance with regard to HD vehicles.

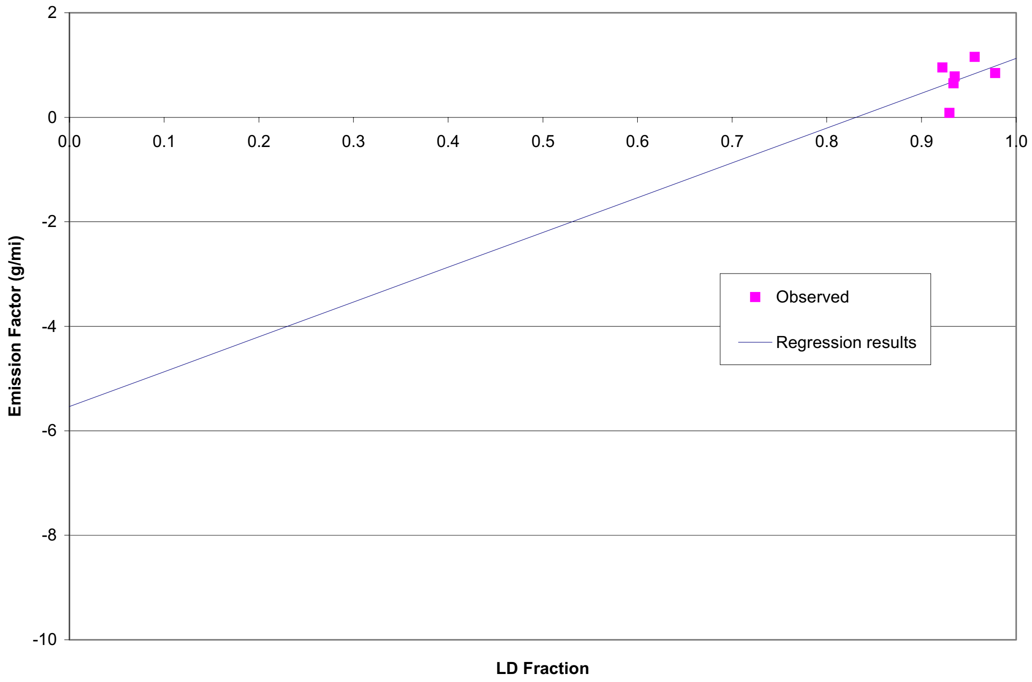

Figure 4-22. Illustration of inappropriate results obtained via regression.

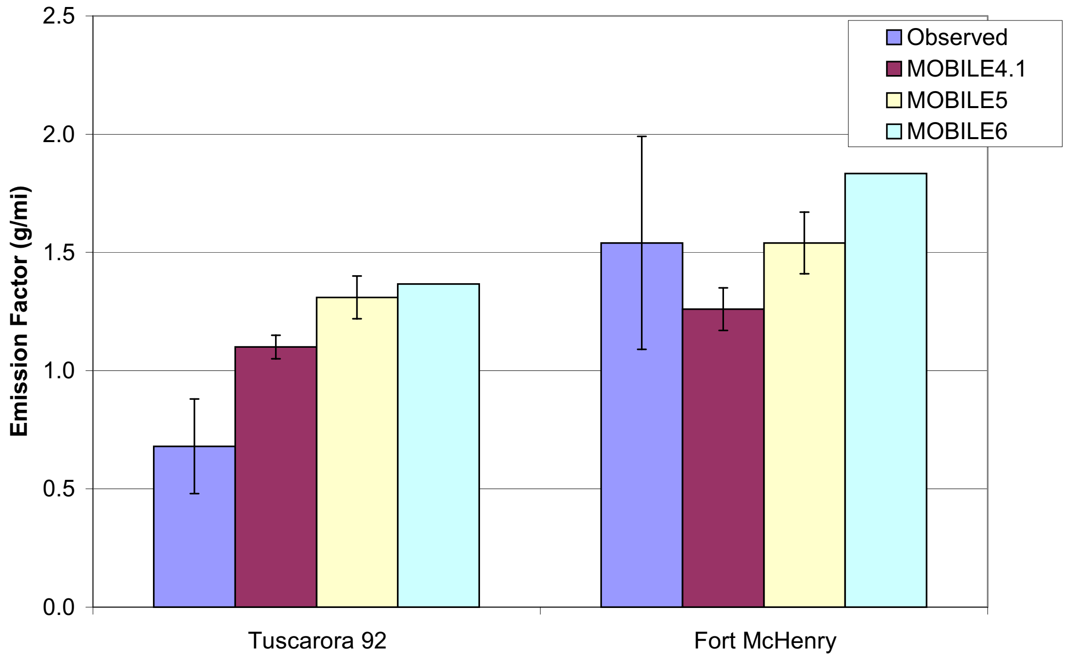

Figure 4-23. Comparison of observed and modeled heavy-duty NMHC emission factors at Fort McHenry and Tuscarora Mountain (both 1992).

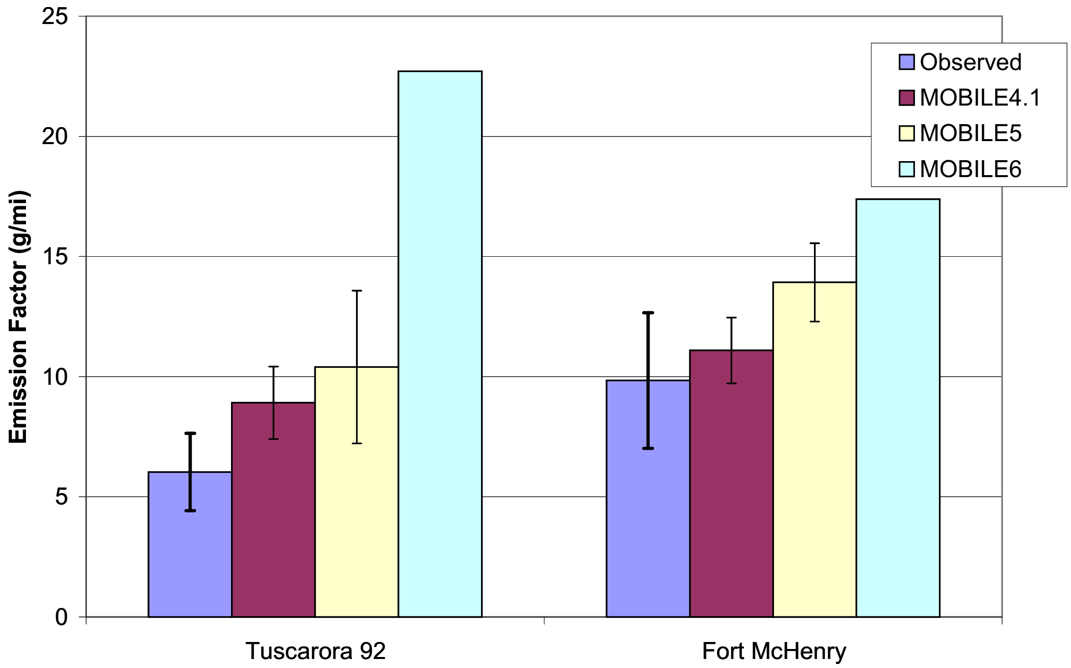

Figure 4-24. Comparison of observed and modeled heavy-duty CO emission factors at Fort McHenry and Tuscarora Mountain (both 1992).

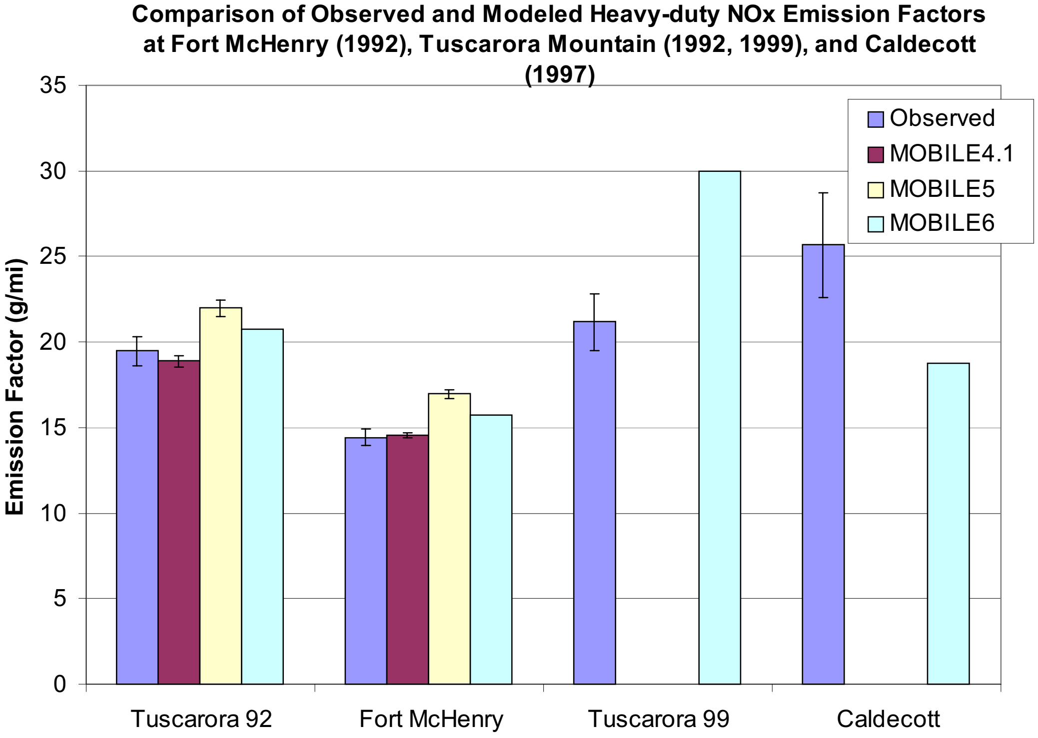

Figure 4-25. Comparison of observed and modeled heavy-duty NOx emission factors at Fort McHenry (1992), Tuscarora Mountain (1992, 1999), Lincoln and Deck Park (both 1995), and Caldecott (1997).

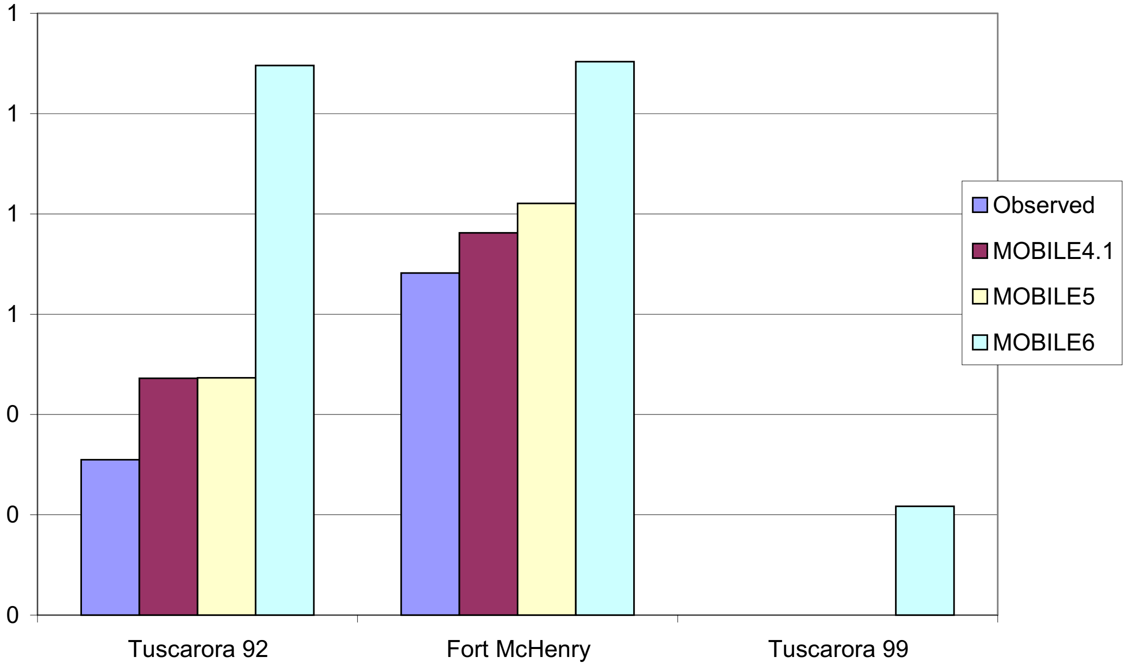

Figure 4-26. Observed and predicted heavy-duty CO/NOx ratios.

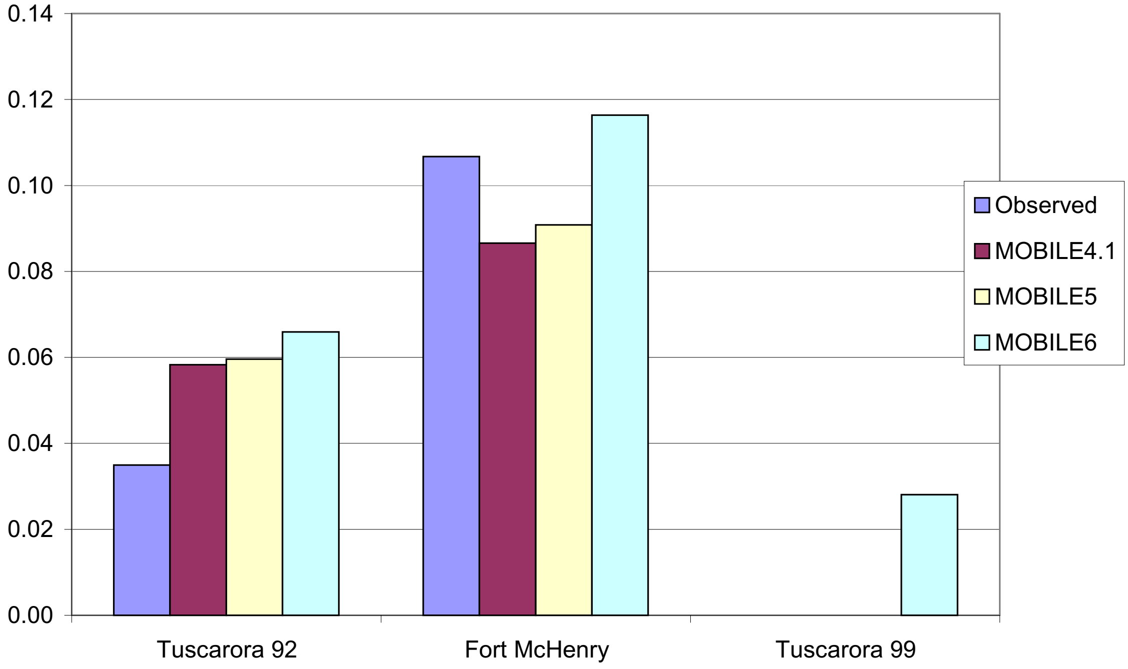

Figure 4-27. Observed and predicted heavy-duty NMHC/NOx ratios.

Table 4-3. Ratio of pollutants for heavy-duty vehicles.

CO/NOx	Fort McHenry	Observed	0.68 ± 0.20
		MOBILE4.1	0.76 ± 0.09
		MOBILE5	0.82 ± 0.10
		MOBILE6	1.10
	Tuscarora 1992	Observed	0.31 ± 0.08
		MOBILE4.1	0.47 ± 0.08
		MOBILE5	0.47 ± 0.14
		MOBILE6	1.10
	Tuscarora 1999	Observed	na
		MOBILE4.1	na
		MOBILE5	na
		MOBILE6	0.22
	Caldecott	Observed	na
		MOBILE4.1	na
		MOBILE5	na
		MOBILE6	na
NMHC/NOx	Fort McHenry	Observed	0.107 ± 0.032
		MOBILE4.1	0.086 ± 0.006
		MOBILE5	0.091 ± 0.008
		MOBILE6	0.12
	Tuscarora 1992	Observed	0.035 ± 0.010
		MOBILE4.1	0.058 ± 0.003
		MOBILE5	0.059 ± 0.004
		MOBILE6	0.07
	Tuscarora 1999	Observed	na
		MOBILE4.1	na
		MOBILE5	na
		MOBILE6	0.03
	Caldecott	Observed	na
		MOBILE4.1	na
		MOBILE5	na
		MOBILE6	na

DISCUSSION

Due to competing factors, it is difficult to predict MOBILE6 results relative to previous versions for any *particular* set of conditions. We approach this analysis by first identifying the general trends due to changes between versions and then seek probable explanations for deviations from these trends.

Major factors updated in MOBILE6 that affect exhaust emissions include:

- Off-cycle driving and air conditioning
- Sulfur on catalysts
- HD excess NOx (only on MY 1988-2000)
- Newer technologies' deterioration

For reference, Table 4-4 shows national fleet-average increases (relative to MOBILE5), incorporating all changes in MOBILE6.

Table 4-4. National fleet level increases in emission factors from MOBILE5 to MOBILE6.

Year	CO	NOx	VOC
1992	60%	25%	50%
1995	50%	25%	45%

Source: EPA presentation on MOBILE5/MOBILE6 at NAMVECC, 2001.

Updated speed corrections also have significant impacts and the directional effects depend upon the speed and pollutant. For the speeds involved in the tunnels above, the following approximate effects (relative to MOBILE5) are noted for LD vehicles:

Table 4-5. Selected speed effects changes from MOBILE5 to MOBILE6.

Tunnel	Average Speed (mph)	CO	NOx	VOC
Fort McHenry	48	+100%	-25%	+40%
Tuscarora 1992	58	+100%	-40%	+15%
Callahan	26	+20%	-15%	+15%

Source: EPA MOBILE6 documentation of speed corrections, Figures 6a-c.

According to EPA's recent analysis of MOBILE6 model sensitivity (available at http://www.epa.gov/ttn/chief/conference/ei11/mobile/giannelli.pdf), age distribution, average daily temperature, and average speed are the three most influential factors. Of these, only the age distribution is *directly* influential since neither the 'Average Speed' nor 'Min/Max Temperature' commands were used in the modeling. As an illustration of the effects of age distribution, according to the above reference, a 20 percent shift to older vehicles results in approximately 50%, 50%, and 40% increases in HC, CO, and NOx, respectively. However, it should be clarified that MOBILE6 is also highly sensitive to inputs of speed and temperature so that uncertainties in the tunnel parameters will affect the agreement between the observed and modeled emissions results.

Fleet-average Results

Fleet-average MOBILE6 NOx predictions are generally lower than MOBILE5 results but not by much, and with the exception of the Callahan Tunnel, they still remain within the vicinity of the observed data. This continues the historic trend (observed by Gertler and others) that NOx is generally the pollutant most accurately predicted by these models.

Comparisons of NMHC results indicate small differences between MOBILE6 and MOBILE5. In some instances, these differences lead to slightly better agreement with observed data and in others, they do not. From the tables above, MOBILE6 LD results are expected to be higher; however, the presence of a sizeable HD fleet acts to reduce the increases predicted in Tables 4-4 and 4-5. In all these cases, MOBILE5/6 still tends to over-predict when the observed emission factors are small and under-predict when these are large. Upon examining the experimental data corresponding to the high observed emissions, we note that three out of the four runs have much lower total vehicle counts than the other experimental runs in the same tunnel. Noteworthy is that neither extreme speed nor temperature was present in these three runs. (Even if there were, these effects, along with fleet mix, should have been accounted for in the model.) A plausible explanation is that high emitters might have been present and strongly affected the observed emission factors, and in fact according to DRI, three high emitters were observed during Run 8 at Tuscarora Mountain through use of remote sensing. Table 4-6 summarizes the experimental runs with high emission factors. (Run 11 in Bore 4 at Fort McHenry seems to have experienced congestion.)

Table 4-6. NMHC results and other information related to experimental runs with high emission factors.

Run Description	Number of Vehicles*	Avg. Speed* (mph)	Temperature* (F)	EF* (g/mi)	MOBILE5.0/ MOBILE6 (g/mi)
Ft. McHenry Bore3, Run 8	102 (1133)	45 (48)	64 (70)	1.39 (0.63)	0.81/1.00
Ft. McHenry Bore4, Run 2	279 (1291)	46 (48)	70 (70)	2.15 (0.89)	1.12/1.10
Ft. McHenry Bore4, Run 11	1836 (1291)	38 (48)	70 (70)	1.52 (0.89)	0.77/0.90
Tuscarora 1992, Run 8	79 (539)	58 (58)	65 (67)	1.4 (0.48)	1.0/0.96

* Average values across all runs for the particular tunnel study are shown in parentheses.

MOBILE6 CO results are much higher than MOBILE5 values (and hence observed values) for Ft. McHenry (both bores) and Tuscarora Mt (1992). From the speed effects noted above in Table 4-5, this is not surprising. However, they are slightly lower for the Callahan Tunnel. The lower humidity (61 grains/lb air vs. 79 and 91 for Ft. McHenry and Tuscarora) which decreases A/C usage contributes to this observation in a minor way. More importantly, the speed assumed in Table 4-5 is an average. Speeds at the Callahan Connector show the largest variation (see Table 2-2) and Figure 4-28 shows that MOBILE5 has larger speed correction factors at the lower speeds. These facts corroborate to yield the lower MOBILE6 predictions.

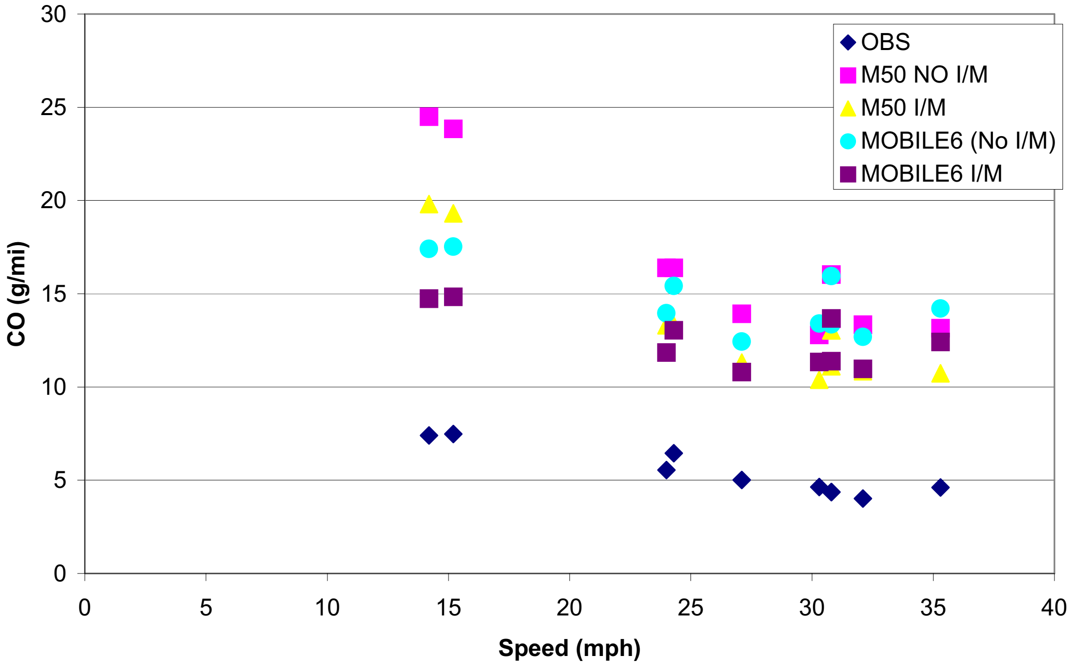

Figure 4-28. Speed effects on CO emission factors at Callahan (1995).

MOBILE also overpredicts NOx and NMHC at Callahan. The fleet at this tunnel is the oldest of the three, with 27.2 percent being older than ten years while the next oldest fleet (Tuscarora 1992) has only 17.8 percent older than ten years. (Model year distributions were all obtained by matching video license plate data.) This seems to suggest that the emission factors from the older model years are overestimated. Another factor is that no toll plaza exists so that traffic flow is smooth, albeit slow (i.e. very little acceleration inside the tunnel).

In the foregoing discussion, all observed data presented were a combination of uphill and downhill measurements (except Tuscarora, which is flat). Thus, the effects of grades were implicit. Robinson et. al (1996) explicitly reported the effects of grades at the Fort McHenry Tunnel. (A sampler was placed at a mid-tunnel point in order to separate the uphill and downhill portions.) The average results are presented in Table 4-7. (MOBILE6 results are from this study.) Note that the differences between uphill and downhill are more pronounced in Bore 4, which has a considerable number of HD trucks. In other words, grades have a larger impact on the HD vehicles. Also important is the fact that MOBILE6 predictions can be greater than the ascending value despite the fact that the model does not account for the effects of grades.

Table 4-7. Effects of grades at the Fort McHenry Tunnel. Based on Tables 5 and 6 of (Robinson et.al, 1996).

		Bore 3	**Bore 4**
CO (g/mi)	DESCEND	5.06	5.11
	ASCEND	9.28	9.90
	M41	3.67	5.01
	M50	6.80	8.32
	M60	14.79	16.39
NMHC (g/mi)	DESCEND	0.54	0.55
	ASCEND	0.64	1.17
	M41	0.28	0.43
	M50	0.52	0.69
	M60	0.69	0.89
NOx (g/mi)	DESCEND	0.81	2.04
	ASCEND	1.70	4.79
	M41	0.82	2.97
	M50	1.57	3.94
	M60	1.44	5.98

The two studies performed at the Tuscarora Mountain tunnel provide some insight into the trends in fleet-average emissions as well as the MOBILE6's ability to predict those trends. Table 4-8 summarizes the observed and modeled CO and NOx emission factors. The most striking change is the decrease in average CO emissions which is by a factor of about three. In fact, the raw data show several runs where the derived CO emission factor is below the detection limit. Not surprisingly, the observed NOx increased between 1992 and 1999. This is expected due to the purported heavy-duty off-cycle NOx. Overall, modeled emission factors seem to match the observed values more closely in 1992 than 1999 for both pollutants, with CO being the weaker match.

Table 4-8. Changes in fleet-average observed and modeled emission factors between 1992 and 1999 at Tuscarora Mountain Tunnel.

	CO				**NOx**			
	1992		**1999**		**1992**		**1999**	
Description	OBS	M6	OBS	M6	OBS	M6	OBS	M6
Minimum	3.88	16.42	0.00	6.58	1.58	2.38	2.25	4.06
Maximum	13.08	22.00	3.84	13.09	17.06	16.97	20.23	26.04
Average	5.81	18.39	1.55	9.52	6.06	6.72	9.14	13.39

Light-duty Results

MOBILE6 results for NOx are lower than for MOBILE5, probably due to the speed effects noted above in Table 4-5. Note, though, that the fleet-average increases shown in Table 4-4 are strongly affected by HD vehicles so they are not as directly applicable here.

NMHC emission factors seem to agree well with the observed data (if the large standard error is taken into account at Tuscarora).

CO emission factors are consistently higher in MOBILE6 than MOBILE5. However, there is little difference between the two tunnels for MOBILE6 while MOBILE5 results show a large difference. This is consistent with a large upturn in the MOBILE5 LD CO speed correction curve for 1981-1992 model years which only affects the Tuscarora speed.

Heavy-duty Results

MOBILE6 seems to agree well with NOx observations at Fort McHenry, Tuscarora (1992), and Caldecott. (Recall that Lincoln and Deck Park results are not suitable for inclusion in this discussion due to reasons given above.) The observed NOx at Tuscarora (1999) is considerably lower. Examination of the by-model-year outputs indicates that the assumptions regarding excess NOx were implemented from model year 1988 onward. This is the major driving force behind the 1999 Tuscarora NOx prediction. Note also that MOBILE6 predicts higher NOx at Tuscarora and Fort McHenry but underpredicts at Caldecott. This is because travel at the latter is one-way uphill while the other tunnels have averaged results or no significant grade. As mentioned above, the effects of grades on the HD vehicles is more pronounced, and in this situation, the inability of the model to account for slopes is clearly shown.

With respect to NOx, there are small differences between the two latest versions of the model. MOBILE6 yields slightly lower estimates for the tunnels for which MOBILE5 predictions are available. However, this may simply be due to the different manners in which these values were derived. MOBILE5 HD emission factors used herein were obtained through regression analysis of experimental run-specific fleet average predictions while the MOBILE6 values are weighted averages of run-specific vehicle class-specific values. (Using vehicle class-specific factors gives a more direct assessment of the model’s accuracy. A weighted average was used to combine all runs, with the vehicle count in each run as the weights).

For CO and NMHC, MOBILE6 predicts the highest emission factors, with NMHC still tracking the observed values better than CO. Since there are no speed effect changes in MOBILE6 for HD, these increases are due to basic emission rate changes (including deterioration).

SUMMARY AND CONCLUSION

The use of tunnel data to assess MOBILE6 model performance has some limitations that must be accounted for before drawing conclusions from result comparisons. Notwithstanding these difficulties, tunnel data used as described above produce good insights into the accuracy of model predictions as well as factors that drive these results. In particular, the fleet average comparisons showed that NOx continues to be reasonably well predicted under most circumstances. However, the age distribution assumed for these calendar years play major roles in determining whether the model will overpredict. Light-duty emission rates are also being overpredicted, with speed being a major factor. Heavy-duty NOx is influenced by assumptions on defeat device operation, which is most clearly seen in the 1999 Tuscarora results. The effects of grades are not observed except perhaps in the Caldecott data. Taken together, the CO and NMHC results for all vehicle classes suggest that MOBILE6 tends to overpredict even more than MOBILE5 for these calendar years and tunnels. For NOx, the predictions for these precise operating conditions have decreased and more closely approximate the observed values.

In addition, the US EPA has released a draft version of MOBILE6.1, which estimates emission factors for on-road PM. This version is currently available for review at the Office of Transportation and Air Quality (OTAQ) web site at http://www.epa.gov/otaq/m6.htm#extens. Since a few of the tunnel studies discussed in this report also examined particulate matter emissions (e.g., Caldecott and Tuscarora 1999), it is possible to use them to validate the MOBILE6.1 emission factors as well.

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APPENDIX A

DRI TUNNEL STUDY LOCATIONS AND RUN DESCRIPTIONS

(written by Alan Gertler, Desert Research Institute)

During the period 1992 through 1999, DRI performed a series of on-road emissions studies in highway tunnels. These studies were supported by a number of organizations including API, AOAQIRP, CRC, Environment Canada, EPA, FHWA, HEI, NREL, SCAQMD, and SOS. Table A-1 lists the tunnel locations, length of the tunnels, tunnel classification (urban/interstate), and year the studies were performed.

Table A-1. Summary of DRI tunnel locations and year measurements performed.

Tunnel	Location	Length (m)	Fleet	Year
Fort McHenry Tunnel	Baltimore, Maryland	2174	Highway	1992, 1993, 1995
Tuscarora Mountain Tunnel	Pennsylvania Turnpike, Pennsylvania	1623	Highway	1992, 1999
Cassiar Connector	Vancouver, British Columbia	730	Urban	1993
Callahan Connector	Boston, Massachusetts	1545	Urban	1995
Deck Park Tunnel	Phoenix, Arizona	804	Urban	1995
Lincoln Tunnel	New York/New Jersey	2440	Urban	1995
Sepulveda Tunnel	Los Angeles, California	582	Urban	1995, 1996
Van Nuys Tunnel	Los Angeles, California	222	Urban	1995

Data for all the studies listed in Table A-1 may be used for comparing observed emissions with mobile source emission factor model predictions except for the 1995 Fort McHenry study sponsored by API. This project focused on measuring dioxin and furan emissions from the in-use fleet. Emissions of CO, HC, and NO_x were not measured. Results of the 1993 Fort McHenry study, sponsored by FHWA, are of limited use for comparing observed and predicted emissions. The only pollutant quantified in this study was PM_{10}. Descriptions of the tunnels follow.

Fort McHenry Tunnel, Baltimore (1992, 1993, 1995)

The Fort McHenry Tunnel is a four-bore tunnel, two lanes per bore, carrying Interstate 95 east-west under the Baltimore Harbor. The downgrade reaches –3.76% and the upgrade reaches +3.76%, with no significant level portion. Average grade from west portal to bottom is 1.8% and, from bottom to east portal, +3.3%. The four tunnel bores are designated 1 and 2 westbound (toward Washington, DC), and 3 and 4 eastbound (toward Philadelphia). The 1992 study was conducted in Bores 3 and 4, the eastbound bores (length 2174 meters), measuring in the two bores simultaneously (Table A-2). LD vehicles are allowed in both bores; however, trucks are directed into Bore 4, the right-hand bore and all but 3% of them complied in the June 1992 experiment. Posted speed was 50 mi/hr in the tunnel, 55 outside. Traffic flowed freely except for sporadic light braking/slowdown at the exit at rush hour during a few sampling runs. The nearest entrance ramps before the tunnel eastbound, and carrying any significant amount of traffic, range upwards of 2200 meters west of the entrance portal; all of these ramps connect with arteries, not local streets and DRI concludes that the vehicles were in hot stabilized operation.

The ventilation system of the Fort McHenry Tunnel comprises two sections. Ventilation air from above each end of the tunnel is supplied through ducts beneath the roadway, and tunnel air is removed through overhead exhaust ducts. In addition, there is a dividing plane between the east and west supply ducts 95 meters before the low point of the tunnel. Thus DRI was able to measure emissions for the downhill, uphill, and total tunnel.

Descriptions of the 1993 and 1995 experiments are not presented, since they are of limited use for the current study. The 1993 study measured only PM emissions and gaseous emission rates were not determined. In the 1995 study, DRI focused on dioxin and furan emissions from HD vehicles.

Table A-2. Run description, Fort McHenry Tunnel, 1992.

	Run 1		**Run 2**		**Run 3**		**Run 4**		**Run 5**		**Run 6**		**Run 7**		**Run 8**		**Run 9**		**Run 10**		**Run 11**	
Bore	3	4	3	4	3	4	3	4	3	4	3	4	3	4	3	4	3	4	3	4	3	4
Date	18-Jun		19-Jun		19-Jun		20-Jun		21-Jun		21-Jun		22-Jun		23-Jun		23-Jun		24-Jun		24-Jun	
Day	Thu		Fri		Fri		Sat		Sun		Sun		Mon		Tue		Tue		Wed		Wed	
Start Time	1230		1030		1600		1200		1200		1600		1100		300		1300		400		1600	
T (°C)	24		21		25		24		20		20		17		17.5		22		20		21	
Av. Sp. (mph)	51		46		52		43		48		53		52		45		53		45		38	
Total Vehicles	356	1809	164	279	2519	2451	954	2052	995	2136	1960	1144	1265	938	102	262	1194	1041	125	257	2826	1836
F LD	0.99	0.79	0.98	0.32	0.99	0.90	0.99	0.95	0.99	0.96	1.00	0.92	0.99	0.62	0.98	0.28	0.98	0.66	0.98	0.28	0.96	0.88
F HD	0.01	0.21	0.02	0.69	0.01	0.10	0.01	0.05	0.01	0.04	0.00	0.08	0.01	0.38	0.02	0.73	0.02	0.35	0.02	0.72	0.04	0.12

Tuscarora Mountain Tunnel, Pennsylvania Turnpike (1992, 1999)

The Tuscarora Mountain Tunnel is a two-bore tunnel, two lanes each bore, 1623.2 meters (5325.4 ft) long, carrying the Pennsylvania Turnpike (Interstate 76) east-west through Tuscarora Mountain in south-central Pennsylvania at an altitude of ~ 305 meters. The tunnel is flat (grades + 0.30% towards the middle from either end) and straight. Posted speed is 55 mi/hour both in and outside the tunnel. The nearest interchange west of the tunnel is 10 km west of the tunnel entrance. It is very lightly used. Other accesses from the west are the Sideling Hill service plaza (22 km to the west), the interchange with Interstate 70 (40 km to the west, heavily used), and other interchanges and service plazas farther west. Effectively the minimum trip length before reaching the tunnel is 15 minutes (much of it following hot start) and DRI estimates that trips longer than 50 minutes before reaching the tunnel constitute some 75% of all trips. Accordingly, cold-start and hot-start operations are inconsequential in Tuscarora eastbound. The Tuscarora Mountain Tunnel is ventilated entirely by the traffic piston effect and the prevailing westerly wind; there is a supply ventilation system but it was not operated during either the 1992 or 1999 experiments. Run descriptions for both studies are summarized in Tables A-3 and A-4.

Table A-3. Run description, Tuscarora Mountain Tunnel, 1992.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**	**Run 11**
Date	2-Sep	2-Sep	3-Sep	4-Sep	5-Sep	6-Sep	6-Sep	7-Sep	7-Sep	8-Sep	8-Sep
Day	Wed	Wed	Thu	Fri	Sat	Sun	Sun	Mon	Mon	Tue	Tue
Start Time	300	1500	400	1700	1130	1130	1300	200	1300	800	2101
T (°C)	13	20.5	20.5	24	21	19	19	18.5	20.5	21	19.5
Av. Sp. (mph)	56	55	59	57	58	56	58	58	59	60	58
Total Vehicles	186	530	185	928	661	585	659	79	1329	435	351
F LD	0.242	0.736	0.200	0.909	0.920	0.916	0.921	0.734	0.940	0.703	0.590
F HD	0.758	0.264	0.800	0.091	0.080	0.084	0.079	0.266	0.060	0.297	0.410

Table A-4. Run Description, Tuscarora Mountain Tunnel, 1999.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**	**Run 11**	**Run 12**	**Run 13**	**Run 14**	**Run 15**	**Run 16**	**Run 17**	**Run 18**	**Run 19**	**Run 20**
Date	18-May	18-May	18-May	19-May	19-May	19-May	19-May	19-May	20-May	20-May	21-May	21-May	21-May	21-May	22-May	22-May	22-May	22-May	23-May	23-May
Day	Tue	Tue	Tue	Wed	Wed	Wed	Wed	Wed	Thur	Thur	Fri	Fri	Fri	Fri	Sat	Sat	Sat	Sat	Sun	Sun
Start Time	1200	2000	2200	0000	200	1900	2100	2300	100	1600	500	700	900	1700	1100	1300	1500	1700	1000	1200
Av Spd. (mph)	54.9	54.8	57	54.9	55.1	57.7	54.4	53.6	55	53.2	58.1	57.5	53.8	56.9	57	56.5	57	59.5	58.1	61.7
Total Vehicles	529	385	293	206	192	454	359	252	201	730	248	402	473	814	554	539	488	442	529	1681
LD	334	177	104	31	26	240	148	70	43	505	88	208	366	706	490	444	406	377	435	1400
HD (4-6)	24	11	10	4	10	14	20	4	6	23	9	27	17	16	11	15	12	14	14	29
HD (7-8)	171	197	179	171	156	200	191	178	152	202	151	167	90	92	53	80	70	51	80	252
F LD	0.631	0.460	0.355	0.150	0.135	0.529	0.412	0.278	0.214	0.692	0.355	0.517	0.774	0.867	0.884	0.824	0.832	0.853	0.822	0.833
F HD (7-8)	0.323	0.512	0.611	0.83	0.813	0.441	0.532	0.706	0.756	0.277	0.609	0.415	0.19	0.113	0.096	0.148	0.143	0.115	0.151	0.15

Cassiar Connector, Vancouver (1993)

The Cassiar Connector is an urban two-bore tunnel 730 meters in length, with two lanes of traffic per bore. It is situated on the Trans-Canadian Highway, Highway 1, in Vancouver, BC. Traffic is generally heavy during the day with an average speed of around 90 km/h. During this study, hourly traffic counts ranged from around 100 vehicles during the early morning hours to almost 3000 vehicles during the afternoon rush hours. The grade varies from +1.66% at the south end of the tunnel to -1.29% at the north end. The nearest entrance ramps before the tunnel are over 1,000 meters to the south and connect with major arteries. Cold-start operation should therefore be minimal in the tunnel. Ventilation for the tunnel is achieved from the piston effect of the vehicles traversing it, and from the fans positioned along the ceiling throughout the tunnel. The fans were used only when high levels of CO were present in the tunnel. They were never activated throughout the course of this study. The area surrounding the tunnel is primarily residential at both the north and south ends of the tunnel. There is one major urban street located approximately over the middle of the tunnel. Descriptions of the sixteen runs are presented in Table A-5.

Table A-5. Run description, Cassiar Connector, Vancouver.

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15	Run 16
Date	13-Aug	13-Aug	13-Aug	13-Aug	14-Aug	15-Aug	16-Aug	16-Aug	16-Aug	18-Aug	18-Aug	18-Aug	18-Aug	18-Aug	18-Aug	18-Aug
Start Time	200	600	1000	1500	900	900	200	600	800	200	600	800	1000	1200	1400	1600
T (°F)	56.1	55.9	59.7	62.6	59.5	59.5	57.6	58.3	59.5	55	56.1	62.4	66.9	68	70.3	72.5
Av. Sp (mph)	57.9	59.1	56.6	57	57.9	57.4	58.8	59.7	57.2	57	60	56.8	55.7	55.9	56.1	55.6
Std. Dev (mph)	9.1	12.6	12.8	17.2	14	10.1	5.7	22.1	18.8	6.5	9.6	15.4	14.1	16.9	18.3	22
Total Vehicles	125	1678	1821	2502	1470	948	93	1622	1859	100	1650	2074	1769	1850	1977	2975
LDSI	111	1532	1607	2354	1356	897	75	1434	1605	90	1471	1837	1546	1638	1800	2866
HDSI	4	58	79	81	52	39	4	86	121	2	76	108	110	99	67	66
HDD	10	88	135	67	62	12	14	102	133	8	103	129	113	113	110	43
F LD	0.888	0.913	0.882	0.941	0.922	0.946	0.806	0.884	0.863	0.900	0.892	0.886	0.874	0.885	0.910	0.963
F HD	0.112	0.087	0.118	0.059	0.078	0.054	0.194	0.116	0.137	0.100	0.108	0.114	0.126	0.115	0.090	0.037

Callahan Tunnel, Boston (1995)

The Callahan Tunnel, 1545 m in length, is the eastbound tunnel of a pair of tunnels (Sumner and Callahan) carrying traffic between North Boston and East Boston and Logan International Airport. It is a one-bore tunnel with two lanes in the bore. There is no toll plaza on the Callahan Tunnel, which makes the traffic flow slightly smoother; although there was significant variability in the observed average speed for the ten experimental periods (Table A-6). The tunnel ventilation is transverse in design, similar to other underwater tunnels. The Callahan ventilation buildings are placed virtually right at the portals, which greatly simplified the experiment. Both the Sumner and Callahan tunnels are controlled from a single control building in East Boston. Ventilation fans are on virtually all the time although during the experiment DRI observed several times when the supply air was not on. Actual airflow was monitored continuously with anemometers. The ventilation system in the Callahan Tunnel is divided into two sections, each with a separate blower (fresh air) and exhaust duct. With the addition of the inlet portal and exit portal made a total of six samples per run.

Table A-6. Run description, Callahan Tunnel, Boston.

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Date	18-Sep	18-Sep	18-Sep	18-Sep	19-Sep	19-Sep	19-Sep	19-Sep	19-Sep	19-Sep
Day	Mon	Mon	Mon	Mon	Tues	Tues	Tues	Tues	Tues	Tues
Start Time	1100	1300	1500	1700	600	800	1000	1200	1400	1600
T (ºC)	20.0	20.6	18.3	17.2	10.0	13.3	16.1	16.7	17.8	17.2
Avg. Speed (mph)	30.2	27.0	14.1	24.3	30.8	35.3	32.1	30.7	24.0	15.2
Std Dev (mph)	5.2	6.7	4.6	7.4	4.3	5.0	5.5	4.9	5.9	2.3
Total Vehicles	2943	3072	3437	3189	3247	1988	2437	2677	3436	3498
Total LD	2824	2934	3350	3116	3151	1858	2332	2553	3334	3414
Total HD	119	138	87	73	96	130	105	124	102	84
F LD	0.960	0.955	0.975	0.977	0.970	0.935	0.957	0.954	0.970	0.976
F HD	0.040	0.045	0.025	0.023	0.030	0.065	0.043	0.046	0.030	0.024

Deck Park Tunnel, Phoenix (1995)

The Deck Park Tunnel is a 3-bore, urban freeway tunnel 804 m in length, running east/west under Deck Park in downtown Phoenix. The center bore is unused and there are plans to complete it for use as a bus station. There are five lanes and two emergency lanes in the south and north bores. The tunnel has complex ventilation, with fans at each end that can provide either supply or exhaust air. The fans were shut down prior to each run. In both experiments, samplers were located in the center bore and samples were collected from the north side of the south bore. One problem with the Deck Park Tunnel was its large cross section (217 m^2 at the narrowest point). This complicated the sampler placement. Sampling proved problematic for two reasons: air flow inhomogeneities and concentration gradients across the tunnel. This was resolved in the summer experiment through the use of a non-reactive tracer (SF_6) to characterize the airflow in the tunnel. While results of the winter could be corrected, they have a higher degree of uncertainty than those obtained in the other tunnel studies. Descriptions of the eight January experimental runs and nine July experimental runs are presented in Tables A-7 and A-8, respectively.

Table A-7. Run description, Deck Park Tunnel, Phoenix, January 1995.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**
Date	24-Jan	24-Jan	24-Jan	25-Jan	25-Jan	26-Jan	26-Jan	26-Jan
Day	Tues	Tues	Tues	Wed	Wed	Thur	Thur	Thur
Start Time	600	800	1600	600	800	600	800	1000
T (°C)	12.6	13.2	21.6	18.7	17.8	13.3	14.4	14.7
Avg. Speed (mph)	59.8	58.2	59.8	59.0	56.3	59.3	57.3	60.1
Std Dev (mph)	3.8	3.8	5.2	4.2	4.5	4.7	4.4	4.8
Total Vehicles	7330	5770	7210	7300	7740	6980	6798	4613
Total LD	7132	5650	7052	7094	7400	6752	6488	4344
Total HD	198	120	158	206	340	228	310	269
F LD	0.973	0.979	0.978	0.972	0.956	0.967	0.954	0.942
F HD	0.027	0.021	0.022	0.028	0.044	0.033	0.046	0.058

Table A-8. Run description, Deck Park Tunnel, Phoenix, July 1995.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**
Date	25-Jul	25-Jul	26-Jul	26-Jul	26-Jul	26-Jul	27-Jul	27-Jul	27-Jul
Day	Tues	Tues	Wed	Wed	Wed	Wed	Thur	Thur	Thur
Start Time	1230	1700	730	1000	1300	1500	600	900	1100
T (°C)	43.8	46.1	31.1	38.3	43.8	45.5	29.4	36.6	41.6
Av. Speed (mph)	58.8	58.7	58.0	60.7	60.2	59.1	60.4	61.9	59.7
Std Dev (mph)	5.4	5.6	5.5	6.4	5.7	5.7	4.8	6.2	5.7
Total Vehicles	4307	6520	8405	5022	5468	5999	7112	4978	5089
Total LD	3992	6375	8062	4668	5101	5762	6626	4648	4752
Total HD	315	145	343	354	367	237	486	330	337
F LD	0.927	0.978	0.959	0.930	0.933	0.960	0.932	0.934	0.934
F HD	0.073	0.022	0.041	0.070	0.067	0.040	0.068	0.066	0.066

Lincoln Tunnel, NY/NJ (1995)

The Lincoln Tunnel is a three-bore tunnel with two lanes per bore running under the Hudson River between Weehawken, New Jersey and Manhattan Island. The tunnel is the world's only three-tube underwater vehicle tunnel and the world's busiest underwater tunnel. The Center tube (2,280 m long) opened December 22, 1937, the North tube (2,504 m long) opened February 1, 1945, and the South tube (2,440 m long) opened May 25, 1957. The average eastbound weekday traffic volume in 1993 was 56,153 vehicles. The tunnel is operated such that under normal circumstances the North tube is for westbound traffic, the Center tube is switched depending on need, and the South tube is for eastbound traffic. The experiment was conducted exclusively in the South tube. The tunnel ventilation is transverse in design, similar to other underwater tunnels. The ventilation system in the Lincoln Tunnel is divided into four sections, each with a separate blower (fresh air) and exhaust duct. The ventilation sections are numbered 1 to 4, with 1 being the first 271 m in from New Jersey, 2 and 3 being the center sections of the tunnel, and 4 being the last 488 m into New York. Due to the complexity of the entrance section, DRI decided to begin sampling 271 m into the tunnel, at the New Jersey ventilation building. A total of eight sampling stations were required to determine the emissions from motor vehicles traveling through the tunnel. Eleven periods were sampled during this study (Table A-9).

Table A-9. Run description, Lincoln Tunnel, New York.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**	**Run 11**
Date	16-Aug	16-Aug	16-Aug	16-Aug	16-Aug	17-Aug	17-Aug	17-Aug	18-Aug	18-Aug	18-Aug
Day	Wed	Wed	Wed	Wed	Wed	Thur	Thur	Thur	Fri	Fri	Fri
Start Time	700	900	1100	1700	1900	800	1000	1300	730	930	1130
T (ºC)	26.4	27.5	30.6	30.6	28.6	26.7	28.9	31.9	27.8	29.4	32.8
Av. Spd (mph)	26.5	28.7	26.3	20.4	24.9	25.6	29.7	30.0	26.8	29.6	29.1
Std Dev (mph)	4.3	3.6	5.6	3.4	3.7	3.4	4.6	4.5	5.0	4.0	4.8
Total Vehicles	2749	2316	2133	2215	2804	2912	2003	1733	2689	1899	1750
Total LD	2417	2047	1861	1718	2458	2628	1749	1432	2438	1645	1465
Total HD	332	269	272	497	346	284	254	301	251	254	285
F LD	0.879	0.884	0.872	0.776	0.877	0.902	0.873	0.826	0.907	0.866	0.837
F HD	0.121	0.116	0.128	0.224	0.123	0.098	0.127	0.174	0.093	0.134	0.163

Sepulveda Tunnel, Los Angeles (1995, 1996)

The Sepulveda Tunnel was chosen to represent a more affluent and potentially lower emitting fraction of the LA fleet than operates in the Van Nuys Tunnel. The tunnel is a covered roadway with the top portion being part of the airplane runway and taxiway for the Los Angeles International Airport (LAX). The covered portion of the roadway is 582 m long, straight, and approximately flat in the covered portions, although there is a downgrade approaching the tunnel and an upgrade leaving it. There are two bores, three lanes each with a sidewalk on the right side of each bore. A concrete wall running most of the length of the tunnel separates the two bores of the tunnel. There are 17 openings in this wall, each approximately 10 ft wide by 12 to 14 ft tall. In order to obtain mass emission factors in the tunnel, DRI needed to seal off these openings so there would be no air transfer between the two bores. There is a ventilation system in the tunnel, although it was not in operation when DRI was sampling. The 1995 and 1996 experiments were conducted in the west bore, which carries Sepulveda Boulevard southbound from the LAX terminals. Immediately after the tunnel there is a turn lane to allow access to the on-ramps to highway 105 which connects to the 405. During some time periods, considerable numbers of the vehicles going through the tunnel head toward these freeways and if the freeway metering lights are on, these vehicles occasionally back up into the tunnel. Congestion in the tunnel was more pronounced during the 1996 study and additional sampling runs were performed in order to obtain a sufficient number of runs with an average speed > 40 mph for comparison with the 1995 data (Tables A-10 and A-11).

Table A-10. Run description, Sepulveda Tunnel, 1995.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**
Date	3-Oct	3-Oct	3-Oct	3-Oct	3-Oct	4-Oct	4-Oct	4-Oct
Day	Tues	Tues	Tues	Tues	Tues	Wed	Wed	Wed
Start Time	700	900	1200	1500	1700	600	800	1100
T (oC)	19.4	25.6	26.7	25.0	23.3	18.3	20.6	27.8
Av. Spd. (mph)	47.5	47.7	44.2	44.4	39.9	49.2	48.6	44.5
Std Dev (mph)	8.3	7.2	8.0	8.7	9.2	6.5	8.8	7.4
Total Vehicles	2650	1998	2908	3371	4167	1495	2654	2807
Total LD	2596	1935	2853	3304	4096	1454	2589	2724
Total HD	54	63	55	67	71	41	65	83
F LD	0.980	0.968	0.981	0.980	0.983	0.973	0.976	0.970
F HD	0.020	0.032	0.019	0.020	0.017	0.027	0.024	0.030

Table A-11. Run description, Sepulveda Tunnel, 1996.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**	**Run 11**	**Run 12**	**Run 13**	**Run 14**	**Run 15**	**Run 16**	**Run 17**	**Run 18**
Date	23-Jul	23-Jul	23-Jul	24-Jul	24-Jul	24-Jul	24-Jul	25-Jul	25-Jul	25-Jul	25-Jul	26-Jul	26-Jul	26-Jul	26-Jul	27-Jul	27-Jul	27-Jul
Day	Tues	Tues	Tues	Wed	Wed	Wed	Wed	Thur	Thur	Thur	Thur	Fri	Fri	Fri	Fri	Sat	Sat	Sat
Start Time	1100	1500	1700	600	800	1000	1400	700	900	1900	2100	1400	1600	1800	2000	700	830	1000
T (°C)	20.0	20.6	20.6	18.3	18.9	20.6	23.3	20.0	22.8	22.8	22.2	27.8	26.7	25.0	22.2	20.0	22.8	22.8
Avg. Spd (mph)	41.7	18.8	21.4	48.0	44.5	41.7	26.9	47.3	45.2	42.4	40.7	24.9	21.4	26.1	41.6	50.2	47.9	45.7
Std Dev (mph)	7.0	8.7	8.3	7.4	7.1	5.9	9.4	8.1	5.6	6.9	8.4	8.5	5.4	8.3	8.2	5.7	5.8	6.4
Model Year	86.7	87.4	86.7	86.9	85.4	87.8	87.1	86.9	87.5	86.6	88.1	87.5	87.3	86.3	86.5	87.1	87.0	86.6
Total Vehicles	2888	3459	4131	1864	3875	2402	3578	3007	2237	3393	2631	3718	4157	4186	2786	1953	1622	2785
Total LD	2781	3369	4060	1813	3799	2315	3504	2933	2140	3329	2579	3617	4074	4093	2739	1881	1571	2737
Total HD	107	90	71	51	76	87	74	74	97	64	52	101	83	93	47	72	51	48
F LD	0.963	0.974	0.983	0.973	0.980	0.964	0.979	0.975	0.957	0.981	0.980	0.973	0.980	0.978	0.983	0.963	0.969	0.983
F HD	0.037	0.026	0.017	0.027	0.020	0.036	0.021	0.025	0.043	0.019	0.020	0.027	0.020	0.022	0.017	0.037	0.031	0.017

Van Nuys Tunnel, Los Angeles (1996)

The Van Nuys Tunnel is a two-bore, urban tunnel, 222 m in length, running east/west under the runway of the Van Nuys Airport. There are three lanes per bore along with a narrow walkway adjacent to the north and south lanes. Vent buildings are located on the southeast and northeast edges of the tunnel and were not in operation during the experiment. There are nine door-size openings between the bores. The openings were covered with plywood prior to the commencement of sampling. Traffic lights are located within a few hundred meters of both the tunnel exit and entrance. Because of the lights, vehicles accelerated upon entering the tunnel and often decelerated at the exit. A total of nine periods were sampled (Table A-12) in the North Bore, the same as in the 1987 experiment.

Table A-12. Run description, Van Nuys Tunnel, 1995.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**
Date	9-Jun	9-Jun	9-Jun	10-Jun	10-Jun	11-Jun	12-Jun	12-Jun	12-Jun
Day	Fri	Fri	Fri	Sat	Sat	Sun	Mon	Mon	Mon
Start Time	700	1000	1800	1100	2100	1900	730	1200	1500
T (^{o}C)	30.1	32.3	29.0	38.9	31.3	37.1	34.8	42.1	42.7
Av. Spd. (mph)	42.6	42.4	43.3	44.7	43.4	45.4	43.2	43.6	44.2
Std Dev (mph)	6.1	5.3	5.4	5.0	4.7	5.3	5.7	5.3	5.5
Total Vehicles	1558	1624	1554	1603	670	1046	2183	2021	1315
Total LD	1489	1559	1530	1581	665	1040	2092	1973	1259
Total HD	69	65	24	22	5	6	91	48	56
F LD	0.956	0.960	0.985	0.986	0.993	0.994	0.958	0.976	0.957
F HD	0.044	0.040	0.015	0.014	0.007	0.006	0.042	0.024	0.043

APPENDIX B

UC BERKELEY CALDECOTT TUNNEL FIELD STUDY DESCRIPTION

(written by Rob Harley, UC Berkeley)

The Caldecott Tunnel is located in the San Francisco Bay area on state highway 24 between Alameda and Contra Costa Counties. The tunnel comprises 3 two-lane traffic bores, with the direction of traffic in the middle bore switched to accommodate commuter peaks. Light-duty vehicle emissions have been measured in the middle bore of the tunnel in summers 1994-97, 1999, and 2001. Heavy-duty vehicle emission factors for NO_x and $PM_{2.5}$ were inferred from additional pollutant measurements made in the southernmost bore (bore 1) of the tunnel in summer 1997.

For each tunnel sampling period in 1997, traffic was counted in three weight categories: light (cars plus 2-axle/4-tire trucks), medium (2-axle/6-tire), and heavy (3 or more axles). Survey data indicate that about half the medium and almost all the heavy vehicles are diesel-powered. From 1230-1530 h in bore 1, the fraction of diesel trucks ranged from 3 to 5% of total traffic, whereas in the middle bore from 1530-1830 h, the diesel truck fraction was much lower. In all cases, vehicles were traveling uphill on a 4.0% grade. Heavy trucks traveled through bore 1 on the uphill grade more slowly (65 ± 11 km/h, N = 13) than light-duty vehicles (89 ± 11 km/h, N = 8 for 21 July; 70 ± 9 km/h, N = 17 for 22-24 July). A license plate survey indicated an average model year of 1988 for 156 heavy-duty diesel trucks sampled at random in bore 1.

Diesel trucks were estimated to contribute 3-5% of total CO, 15-19% of total CO_2, 38-41% of total NO_x, and 76-79% of total $PM_{2.5}$ concentrations measured in bore 1 from 1230-1530 h. Using a carbon balance, HD diesel emission factors for NO_x and $PM_{2.5}$ were estimated to be 42 ± 5 and 2.5 ± 0.2 grams per kg of diesel fuel burned, respectively. Uncertainties in CO_2 apportionment affect both of these emission factors, and uncertainty in the NO_X apportionment is also important. Uncertainty in $PM_{2.5}$ apportionment is less important because diesel trucks were responsible for such a high fraction ($>75\%$) of total $PM_{2.5}$ emissions in bore 1.