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Development of a Comprehensive Modal Emissions Model

Matthew Barth
Feng An
Theodore Younglove
George Scora
Carrie Levine
University of California, Riverside
Center for Environmental Research and Technology
Riverside, CA

Marc Ross
University of Michigan
Ann Arbor, MI

Thomas Wenzel
Lawrence Berkeley National Laboratory
Berkeley, CA

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Table of Contents

List of Figures

List of Tables

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Abstract

In August 1995, the College of Engineering-Center for Environmental Research and Technology (CE-CERT) at the University of California-Riverside along with researchers from the University of Michigan and Lawrence Berkeley National Laboratory, began a four-year research project to develop a *Comprehensive Modal Emissions Model (CMEM)*, sponsored by the National Cooperative Highway Research Program (NCHRP, Project 25-11). The overall objective of the research project was to develop and verify a modal emissions model that accurately reflects Light-Duty Vehicle (LDV, i.e., cars and small trucks) emissions produced as a function of the vehicle's operating mode. The model is comprehensive in the sense that it is able to predict emissions for a wide variety of LDVs in various states of condition (e.g., properly functioning, deteriorated, malfunctioning). The model is now complete and capable of predicting second-by-second tailpipe emissions and fuel consumption for a wide range of vehicle/technology categories. In creating CMEM, over 350 vehicles were extensively tested on a chassis dynamometer, where second-by-second measurements were made of both engine-out and tailpipe emissions of carbon monoxide, hydrocarbons, oxides of nitrogen, and carbon dioxide. CMEM itself runs on a personal computer or on a UNIX workstation. The model and the emissions database are both available on a CD.

Summary

In August 1995, the College of Engineering-Center for Environmental Research and Technology (CE-CERT) at the University of California-Riverside along with researchers from the University of Michigan and Lawrence Berkeley National Laboratory, began a four-year research project to develop a *Comprehensive Modal Emissions Model (CMEM)*, sponsored by the National Cooperative Highway Research Program (NCHRP, Project 25-11). The overall objective of the research project was to develop and verify a modal emissions model that accurately reflects Light-Duty Vehicle (LDV, i.e., cars and small trucks) emissions produced as a function of the vehicle's operating mode. The model is comprehensive in the sense that it is able to predict emissions for a wide variety of LDVs in various states of condition (e.g., properly functioning, deteriorated, malfunctioning). The model is now complete and capable of predicting second-by-second tailpipe emissions and fuel consumption for a wide range of vehicle/technology categories.

In this project, the following work was completed:

- A literature review was performed focusing on vehicle operating factors that affect emissions. The literature was categorized into eight different groups, and over 110 documents were reviewed. The literature review is summarized in Section 2.1.

- A wide variety of data sets were collected pertaining to vehicle emissions and activity. Several of these data sets were analyzed to help determine a testing procedure for the collection of modal emission data and to provide insight on how to best develop a comprehensive modal emission model. A summary of this data collection and analysis is given in Section 2.2.

- The conventional emission models (i.e., MOBILE and EMFAC) were reviewed and evaluated in light of this NCHRP project to provide insight on how to develop the modal emission model. Section 2.3 outlines this task.

- Based on the information determined in the previous tasks, a testing protocol was designed for modal emission analysis and modeling. As part of this work, a vehicle/technology "matrix" was developed identifying the key vehicle groups that make up part of the modal model. This matrix was used to guide the recruitment of vehicles to be tested. The vehicle/technology categorization is described in Section 3.1.

- A vehicle emissions testing procedure was developed for use at the CE-CERT dynamometer facility. This procedure consists of performing second-by-second pre- and post-catalyst measurements of CO_2, CO, HC, and NO_x over three separate driving cycles: the full 3-bag FTP, EPA's SFTP Bag 4 cycle (US06), and a newly designed modal test cycle (MEC01) that focuses on specific modal events. This testing procedure is described in detail in Section 3.4.

- In order to develop the full working modal emissions model for a variety of vehicle/technology types, test vehicles were recruited for dynamometer testing at CE-CERT's Vehicle Emissions Research Laboratory. A recruitment procedure was set up and implemented so as to fill the target vehicle numbers in each "bin" of the established vehicle/technology matrix. In total, approximately 450 vehicles were recruited. Sections 3.2 and 3.3 describe the recruitment in detail.

- 357 of the recruited vehicles were tested using the developed dynamometer testing procedure. Out of these 357 tests, a total of 343 tests had valid, usable data which were used in developing the working model. The emissions testing is summarized in Section 3.5.

- Using existing modal emissions data and the emissions data collected in this project, a working modal emissions model was developed based on our physical modeling approach. Issues dealing with model parameterization and calibration were addressed for the different vehicle/technology groups, and malfunctioning/high-emitting vehicles are addressed and characterized. The model development is addressed in Chapter 4.

- In order to determine how well the model predicts emissions, comparisons were performed between the modeled output and the measured values. This type of validation was performed at the individual vehicle level as well as the composite vehicle level. Further, the validation took place at both the second-by-second time resolution and at the integrated "bag" level. The validation is described in Chapter 5.

- The massive amounts of data collected in the testing phase were analyzed in detail. The data analysis focused on items such as vehicle enrichment effects, air conditioning effects, measurement repeatability, vehicle categorization, and model sensitivity. Some of this data analysis is described in Chapter 5.

- Model executable code has been produced to run on a PC (command-line or from a graphical user interface) and under UNIX (command-line only). The command-line executable program predicts second-by-second emissions given an activity file for a *single* vehicle type. Another command-line executable predicts second-by-second emissions given an activity file for an entire *fleet* of vehicles. The operation and output of the model can be adjusted using control files. In addition, the model has been implemented to run from Microsoft Access with an easy-to-use graphical user interface. These model forms are briefly described in Chapter 6 and more fully in a companion document entitled "Comprehensive Modal Emissions Model (CMEM) User's Guide".

- Velocity/acceleration-indexed emissions/fuel lookup tables for the vehicle/technology categories were created. These lookup tables can be used by several types of microscopic transportation models, such as CORSIM, FRESIM, NETSIM, etc. These are discussed in Section 6.2.

- Roadway facility/congestion-based emission factors for the vehicle/technology categories were generated using EPA's latest facility/congestion cycles. These emission factors can be used for mesoscopic transportation models. This is discussed in detail in Section 6.3.

- A vehicle category generation methodology to go from a vehicle registration database to the CMEM categories was created and tested using a local vehicle registration database. Details of the methodology are given in Section 6.4.

- As part of the integration of the emissions model into different transportation model frameworks, vehicle category mappings were created between EMFAC/MOBILE and CMEM. This is a great advantage since vehicle activity set up for either MVEI or MOBILE can now be translated directly to the modal emission model's vehicle/technology categories. This is described in Section 6.5.

1 Introduction

In order to develop and evaluate transportation policy, agencies at the local, state, and federal levels currently rely on the mobile source emission-factor models MOBILE (developed by the US Environmental Protection Agency) or California's MVEI modeling suite (Motor Vehicle Emission Inventory model, developed by the California Air Resources Board). Both MOBILE and MVEI predict vehicle emissions based in part on average trip speeds and were built upon regression coefficients based on a large number of FTP (Federal Test Procedure) bag emission measurements. Since these models are intended to predict emission inventories for large regional areas, they are not well suited for evaluating operational improvements that are more "microscopic" in nature, such as ramp metering, signal coordination, and many Intelligent Transportation System (ITS) strategies. What is needed in addition to these "regional-type" of mobile source models is an emissions model that considers at a more fundamental level the *modal* operation of a vehicle, i.e., emissions that are directly related to vehicle operating modes such as idle, steady-state cruise, various levels of acceleration/deceleration, etc.

In August 1995, the College of Engineering-Center for Environmental Research and Technology (CE-CERT) at the University of California-Riverside along with researchers from the University of Michigan and Lawrence Berkeley National Laboratory, began a four-year research project to develop a *Comprehensive Modal Emissions Model* (CMEM), sponsored by the National Cooperative Highway Research Program (NCHRP, Project 25-11). The overall objective of this research project was to develop and verify a modal emissions model that accurately reflects Light-Duty Vehicle (LDV, i.e., cars and small trucks) emissions produced as a function of the vehicle's operating mode. The model is comprehensive in the sense that it is able to predict emissions for a wide variety of LDVs in various states of condition (e.g., properly functioning, deteriorated, malfunctioning). The model is capable of predicting second-by-second tailpipe (and engine-out) emissions and fuel consumption for a wide range of vehicle/technology categories.

1.1 MODAL EMISSIONS MODELING APPROACH

Several types of modal emission models have been developed in the past, using several different approaches. For example, a convenient method to characterize vehicle operating modes of idle, cruise, and different levels of acceleration/deceleration is to set up a speed/acceleration matrix. With such a matrix, it is possible to measure emissions associated with each "bin" or mode. This emissions matrix can then be multiplied with a similar matrix that has vehicle activity broken down so that each bin contains the time spent in each driving mode. The result is the total amount of emissions produced for the specified vehicle activity with the associated emissions matrix. The problem with such an approach is that it does not properly handle other variables that can affect emissions, such as road grade, use of accessories, etc.

Another modal emissions modeling method is to develop an emissions map that is based on engine power and speed. Second-by-second emission tests are performed at numerous engine operating points, taking an average of steady-state measurements. By basing emissions on engine power and speed, the effects of acceleration, grade, use of accessories, etc. can be taken directly into account. When creating an emission inventory, the vehicle activity parameters of engine power and speed must be derived from second-by-second velocity profiles. However, this approach can be a very time consuming and expensive process. Another problem with using such an emissions mapping approach is that it is not well suited if there is substantial time dependence in the emissions response to the vehicle operation (e.g., the use of a timer to delay command enrichment, or oxygen storage in the catalytic converter).

A problem associated with both the speed-acceleration matrix and emission mapping approaches is that they are typically based on steady-state emissions, and ignore transient operation. Further, significant errors are generated by either averaging emission rates within each bin or extrapolating/interpolating among them in the emission map grids. Without knowing the underlying relationship for emission rate versus vehicle speed and acceleration rates, or engine speed and engine load, the most widely-used methodology is to assume a simple two-dimensional linear relationship among them. Due to measurement difficulties, most speed-acceleration matrices or emission maps only have a very limited number of bins or measurement points, resulting in the repetitive use of the above procedure in real applications. The error associated with a single bin or engine operational point could be accumulated into major computing errors in the final results. The key to eliminating this kind of error is to establish a correct analytical formula among the important variables, as described below.

In order to avoid the problems associated with the methods described above, CMEM uses a physical, power-demand modal modeling approach based on a parameterized analytical representation of emissions production. In such a physical model, the entire emissions process is broken down into different components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is then modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, and emission technology. The majority of these parameters are stated as specifications by the vehicle manufacturers, and are readily available (e.g., vehicle mass, engine size, aerodynamic drag coefficient, etc.). Other key parameters relating to vehicle operation and emissions production must be deduced from a comprehensive testing program. The testing involved is much less extensive than creating emission maps for a wide range of vehicle operating points.

This type of modeling is more deterministic than descriptive. Such a deterministic model is based on *causal* parameters or variables, rather than based on simply observing the effects (i.e., emissions) and assigning them to statistical bins (i.e., a descriptive model). Further, the essence of the proposed modeling approach is that the major effort is up front, in the model-development phase, rather than in application. Once the model forms are established, data requirements for applications and for updating to include new vehicles are modest. This limited requirement for data in future applications is perhaps the main advantage of this modeling approach. Of comparable importance, this approach provides understanding, or explanation, for the variations in emissions among vehicles, types of driving, and other conditions. Analysts will be able to discuss “whys” in addition to providing numbers. This is in contrast to models based on statistical “surrogate” variables that are not necessarily linked to physical variables that can be measured. There are several other key features that make the physical, deterministic modeling approach attractive:

- It inherently handles all of the factors in the vehicle operating environment that affect emissions, such as vehicle technology, operating modes, maintenance, accessory use, and road grade. Various components model the different processes in the vehicle related to emissions.
- It is applicable to all vehicle and technology types. When modeling a heterogeneous vehicle population, separate sets of parameters can be used within the model to represent all vehicle/technology types. The total emission outputs of the different classes can then be integrated with their correctly weighted proportions to create an entire emission inventory.
- It can be used with both micro scale and macro scale vehicle activity characteristics. For example, if a second-by-second velocity profile is given, the physical model can predict highly time resolved emissions. If average vehicle activity characteristics such as average speed, peak average speed, idle time, positive kinetic energy (PKE, a measure of acceleration) are given, the physical model can still be used based on average power requirements calculated from the activity parameters.
- It is easily validated and calibrated. Any second-by-second driving profile can be applied to the model, while simultaneously measuring emissions. Modeled results can be compared with measurements and the parameters of the model can be calibrated accordingly.
- It is not restricted to pure steady-state emission events, as is an emissions map approach, or a speed-acceleration matrix approach. Therefore, emission events that are related to the transient operation of the vehicle are more appropriately modeled.
- Functional relationships within the model are well defined. So, in contrast to a model which operates by sampling numerical data, the analytical approach avoids extrapolation and interpolation. Moreover,

it will be possible to simply describe delay effects, such as with the introduction of timers for command enrichment.

- The model is transparent; results are easily dissected for evaluation. It is based on physical science, so that data are tested against physical laws and measurement errors can be identified in the model establishment phase.

- The computations performed in the model consist primarily of evaluating analytical expressions, which can be done quickly with only modest memory requirements.

There are also some potential disadvantages to such an approach. Establishment of this type of model is data intensive. There will be a large number of physical variables to be collected and/or measured for the wide variety of vehicle technology types in different states of deterioration. Because the modeling approach is based on the study of extensive emission measurements in the context of physical laws, a systematic inductive study of physical mechanisms such as energy loss and chemical equilibrium will be necessary. During the model development, it is necessary to identify a smaller set of key variables that play an important role in the generation of emissions. Models of this kind have been developed to predict fuel use, with data from the 1970s (e.g., [Feng et al., 1993a, 1993b]). Through this process one finds that the variations in fuel use and emissions among vehicles and in different driving modes are sensitive to only a few critical parameters. Satisfactory accuracy will be achievable with publicly available parameters, and with parameters which can be obtained from brief dynamometer tests.

The statement about the degree of parameterization *which is adequate* assumes that accuracy is interpreted in absolute terms on the basis of regulatory needs. For example, analytic modeling of extremely low emissions (that can occur for short periods during moderate-power driving) with high relative accuracy might complicate the model to no purpose. We are not concerned with relative accuracy where the emissions are below those of interest for regulatory purposes. Similarly, in current second-by-second data there is some temporal variability to emissions whose study may not justify more detailed measurements and model making. For regulatory purposes, accurate prediction of emissions over modes on the order of ten seconds or more may be adequate.

Another critical component of the approach is that emission control malfunctions and deterioration have to be explicitly modeled. Problems of high deterioration rates of catalyst efficiency, imprecise fuel metering, etc., must be accounted for. Modeling components that estimate the emissions of high-emitting vehicles are also an important part of this approach.

Using this physical model approach, models must be established for different engine/emissions technologies that are represented in the national vehicle fleet. This will include the appropriate combinations of engine type (spark ignition, diesel), fuel delivery system (carbureted, fuel injection), emission control system (open-loop, closed-loop technology), and catalyst usage (no catalyst, oxidation catalyst, three-way catalyst). After the models corresponding to the different technologies have been approximately established, it is necessary to identify the key parameters in each component of the models that characterize vehicle operation and emissions production. These parameters can be classified into several categories: 1) readily available (i.e., public domain) static vehicle parameters (e.g., vehicle mass, engine size, etc.); 2) measurable static vehicle parameters (e.g., vehicle accessory power demand, enrichment power threshold, etc.); 3) deterioration parameters (e.g., catalyst aging, etc.); 4) fuel type parameters; and 5) vehicle operating parameters.

When the physical models and associated parameters are established for all vehicle/technology/year combinations, they must be combined with vehicle operating parameters that are characteristic of real-world driving. These vehicle operating parameters consist of static environmental factors such as ambient temperature and air density, as well as dynamic factors such as commanded acceleration (and resultant velocity), road loads such as road grade, and use of vehicle accessories (e.g., air conditioning, electric loads, etc.).

Combining the physical models with vehicle operating parameters results in highly time resolved emission rates. These predicted rates can then be compared directly to measured emissions data, and the parameters of the modeling components—or the modeling components themselves—can be adjusted to establish an optimal fit. This calibration/validation process occurs iteratively until the models are well developed.

As previously mentioned, factors of emission control deterioration will also be considered within this model. These deterioration factors correspond to the effects of emission equipment failure, tampering, and long-term reductions of efficiencies (e.g., catalyst aging). They can be represented as modeling components within the physical model itself, and/or as simple additional parameters with the current components. The incorporation of these components is critical to the model development since their contribution to emissions production has been shown to be significant.

The developed modal emissions model is micro scale in nature, meaning it can readily be applied to evaluating emissions from specified driving cycles or integrated directly with micro scale traffic simulations (e.g., TRAF-NETSIM, FRESIM, etc.). However, its use for estimating larger, regional emissions is somewhat more complicated. Because micro scale models typically model at the vehicle level and have high accuracy, they require extensive data on the system under study and are typically restricted in size due to the non-linear complexity gain incurred with larger networks. In order to produce emission inventories of greater scope, it is possible to develop link-level emission functions for different roadway facility types (e.g., freeway section, arterials, intersections, rural highways, freeway on-ramps, etc.) using the modal emissions model. At the micro scale level, emissions can be estimated as a function of vehicle congestion on each facility type, with different degrees of geometrical variation. Statistical emission rates are then derived from the micro scale components as a function of roadway facility type and congestion level. These rates are then applied to individual links of a macro scale traffic assignment model.

1.2 PROJECT PHASES

This NCHRP research project was carried out in four distinct phases:

***Phase 1*—**The first phase of work consisted of: 1) collecting data and literature from recent related studies; 2) analyzing these data and other emission models as a starting point for the new model design; 3) developing a new dynamometer emission testing protocol to be used for the vehicle testing phase of the project; 4) conducting preliminary testing on a representative sample of vehicles (approximately 30) with the developed dynamometer emission testing protocol. These data supplement existing data which were used for 5) the development of an interim working model.

***Phase 2*—**This phase of work consisted of 1) conducting testing on a larger representative sample of vehicles (approximately 320) using the developed dynamometer testing procedure; This large collection of detailed vehicle operation and emissions data have been used to 2) iteratively refine the working model. 3) Additional testing data have been used to validate the model.

***Phase 3*—**This phase of work consisted of examining the interface between the developed modal emissions model and existing transportation modeling frameworks. The objective of this phase was to demonstrate that the emissions model is responsive to the regulatory compliance needs of transportation and air quality agencies.

***Phase 4*—**This phase of work consisted of 1) incorporating additional vehicle/technology categories in order to better estimate emission inventories into future years; 2) developing a graphical user interface (GUI) for the model, making it more user-friendly; and 3) holding a national workshop on the model, in order to help introduce the model to transportation/air quality model practitioners.

1.2.1 Phase 1 Summary

The research team has completed Phase 1 of the project in August, 1996. In Phase 1, the following tasks were accomplished:

- A literature review was performed focusing on vehicle operating factors that affect emissions. The literature was categorized into eight different groups, and over 110 documents were reviewed. The literature review is summarized in Section 2.1.

- A wide variety of data sets were collected pertaining to vehicle emissions and activity. Several of these data sets were analyzed to help determine a testing procedure for the collection of modal emission data and to provide insight on how to best develop a comprehensive modal emission model. A summary of this data collection and analysis is given in Section 2.2.

- The conventional emission models (i.e., MOBILE and EMFAC) were reviewed and evaluated in light of this NCHRP project to provide insight on how to develop the modal emission model. Section 2.3 outlines this task.

- Based on the information determined in the previous tasks, a testing protocol was designed for modal emission analysis and modeling. As part of this task, a vehicle/technology "matrix" was defined identifying the key vehicle groups that make up part of the modal model. This matrix was used to guide the recruitment of vehicles tested in Phase 2 of this project. The vehicle/technology categorization is described in Section 3.1.

- A vehicle emissions testing procedure was developed for use at the CE-CERT dynamometer facility. This procedure consists of performing second-by-second pre- and post-catalyst measurements of CO_2, CO, HC, and NO_x over three separate driving cycles: the full 3-bag FTP, EPA's SFTP Bag 4 cycle

(US06), and a newly designed modal test cycle (MEC01) that focuses on specific modal events. This testing procedure is described in detail in Section 3.4.

- Using the testing procedure, one or two vehicles from each of the different vehicle/technology groups (31 vehicles total) were tested in Phase 1. Based on this preliminary testing, the vehicle testing protocol was evaluated and modified for Phase 2 of the project. In addition, an emissions data validation procedure was developed to ensure the quality of the pre- and post-catalyst emission data (see Section 3.6 and 3.7).

- The initial mathematical formulation of the modal emission model was developed for all emissions (including CO_2) and fuel consumption. The model parameters were established for each tested vehicle. The model predictions were compared directly with actual measurements with encouraging results.

- Summary statistics of the emissions data were compiled, such as integrated bag data, average catalyst efficiency, catalyst light-off time, and emission values for 60 vehicle operating modes identified in the MEC01 modal cycle.

1.2.2 Phase 2 Summary

The research team completed Phase 2 of the project in October, 1997. In Phase 2, the following tasks were accomplished:

- In order to develop the full working modal emissions model for a variety of vehicle/technology types, test vehicles were recruited for dynamometer testing at CE-CERT's Vehicle Emissions Research Laboratory. A recruitment procedure was set up and implemented so as to fill the target vehicle numbers in each "bin" of the vehicle/technology matrix established in Phase 1. In this phase, approximately 380 vehicle were recruited. Sections 3.2 and 3.3 describe the recruitment in detail.

- 296 of the recruited vehicles were tested using three primary driving cycles: 1) the FTP; 2) the US06; and 3) the MEC01 cycle. For nearly all of the vehicles tested, second-by-second tailpipe and engine-out emissions data were collected. Combined with the 31 vehicle tests of Phase 1B, 327 vehicle tests were performed in this project. Out of these 327 tests, a total of 315 tests had valid, usable data which were used in developing the working model. The emissions testing is summarized in Section 3.5.

- Using existing modal emissions data and the emissions data collected in this project, a working modal emissions model was developed based on our physical modeling approach. Issues dealing with model parameterization and calibration were addressed for the different vehicle/technology groups, and malfunctioning/high-emitting vehicles are addressed and characterized. The model development is addressed in Chapter 4.

- In order to determine how well the model predicts emissions, comparisons were performed between the modeled output and the measured values. This type of validation was performed at the individual vehicle level as well as the composite vehicle level. Further, the validation took place at both the second-by-second time resolution and at the integrated "bag" level. The validation is described in Chapter 5.

- Preliminary analysis was completed on the emissions data, and summary statistics were compiled. This is outlined in Chapter 5.

1.2.3 Phase 3 Summary

Phase 3 of the project was completed in September, 1998. In Phase 3, the following tasks were accomplished:

- The massive amounts of data collected in Phase 2 were further analyzed. The data analysis focused on items such as vehicle enrichment effects, air conditioning effects, measurement repeatability, vehicle categorization, and model sensitivity.

- The modal emission model developed in Phase 2 were further refined. Specifically, the calibration methodology for each vehicle/technology group was improved; the vehicle compositing methodology was refined; high-emitting vehicles were further characterized and modeled; the model was validated with additional testing data; and the uncertainty of the different model components were characterized.

- As part of the integration of the emissions model into different transportation model frameworks, vehicle category mappings were created between EMFAC/MOBILE and the modal emission model. This is a great advantage since vehicle activity set up for either MVEI or MOBILE can now be translated directly to the modal emission model's vehicle/technology categories. This is described in Section 6.5.

- A vehicle category generation methodology to go from a vehicle registration database to the modal emission model categories was created and tested using a local vehicle registration database. Details of the methodology are given in Section 6.4.

- Velocity/acceleration-indexed emissions/fuel lookup tables for the vehicle/technology categories were created. These lookup tables can be used by several types of microscopic transportation models, such as CORSIM, FRESIM, NETSIM, etc. These are discussed in Section 6.2.

- Roadway facility/congestion-based emission factors for the vehicle/technology categories were generated using EPA's latest facility/congestion cycles. These emission factors can be used for mesoscopic transportation models. This is discussed in detail in Section 6.3.

1.2.4 Phase 4 Summary

Phase 4 of the project was completed in December, 1999. In this phase, the following tasks were carried out:

- In order to better estimate emission inventories into future years (e.g., 2010, 2020), additional vehicle/technology categories were incorporated into the model. These additional categories include both diesel and gasoline powered heavier trucks (>8500 gross vehicle weight); late model high-emitting vehicles; and high-mileage Tier 1 vehicles. These additional categories were tested and modeled in a similar fashion to the methodology established in Phase 2.

- The original command-line implementation of the model is somewhat rudimentary in form, and the user must be careful to structure the inputs properly. In this task, the "user-friendliness" of the model has been improved, making it much more flexible and intuitive to operate. The key milestones of this task was to create a Graphical User Interface (GUI) so that the user can easily control to model.

- In order to help introduce the modal emissions model to transportation/air-quality model practitioners, a national workshop was held in January 2000.

2 Background

2.1 LITERATURE REVIEW

There has been a great deal of research activity concerning the use of conventional emission models in recent years, centering on topics of drive cycle deficiencies, speed correction factors, vehicle modes of operation, and the necessity of modal emissions modeling. A comprehensive review of relevant literature to these topics has been conducted*, focusing on the following topics:

- driving pattern development (15);
- modal emission measurements and modeling (30);
- emission inventory assessment and modeling (26);
- speed correction factors for emission models (4);
- emission effects related to vehicle technology and fuels (23);
- variable-start operation (i.e., cold/hot start) (18);
- fuel enrichment modes of operation and load producing activities (7); and
- on-road emission measurements and malfunctioning vehicles (22).

The number of reviewed documents in each category is shown in parenthesis, for a total of more than 110. The literature primarily consists of government agency reports, conference proceedings, and journal articles. Key findings of the literature search are summarized in this chapter; an annotated bibliography of the literature is presented in Appendix A.

* This literature review was completed in late 1995, and therefore does not contain documents from 1996 to the present.

2.1.1 Driving Pattern Development

In the past few years, a great amount of research has been conducted in measuring driving patterns and developing driving cycles that better reflect today's driving in comparison with the standard Federal Test Procedure (FTP) driving cycle [FTP, 1989]. The most significant study has been the FTP Revision Project [German, 1992; Markey, 1992] consisting of a joint test program between the US Environmental Protection Agency (EPA), the California Air Resources Board (CARB) and the auto manufacturers represented by the Automobile Manufacturers Association of America (AAMA) and the Association of International Automobile Manufacturers (AIAM). As part of this project, real-world driving activity data has been collected through instrumented vehicles driving in Los Angeles, Atlanta, Baltimore, and Spokane [Enns et al., 1993; Markey, 1992]. From the real-world driving pattern data, several new driving cycles have been created, including the ARB02 and UNIFIED Cycle developed by CARB, and the HL07, REM01, US06, AC866 and SC01 developed by the EPA (these cycles are described in detail in Chapter 3 of this report). Among these cycles, the US06 is EPA's preferred method for measuring emissions from non-FTP driving behavior and has been adapted in the supplemental FTP.

2.1.2 Modal Emission Measurements and Modeling

In order to investigate vehicle emissions associated with modal events, several recent research studies have been performed using instrumented vehicles and dynamometers while simultaneously measuring emissions at high time resolutions (typically second-by-second):

Dynamometer Testing

In the early 1980s, a number of acceleration tests were conducted at the CARB primarily on carbureted vehicles [Summerfield, 1986], showing a large increase of HC and CO during hard acceleration events. Acceleration tests were also conducted under the sponsorship of the US EPA in the mid-1980s [Laboratories, 1987]. In that project, 23 vehicles were tested under various acceleration modes, and the emissions data were integrated in periods of 5 to 20 seconds depending on the mode. The study found that the total EPA acceleration cycle has 2.5 times as much CO emissions as the corresponding FTP, and 1.8 times as much HC.

Since then, CARB has conducted a nine-mode emissions analysis, finding that a single hard acceleration (e.g., 6 mi/h-s) could increase the total trip emissions (CO) nearly by a factor of two [Drachand, 1991]. More recently, CARB has collected second-by-second emissions data on ten newer technology vehicles using four different test cycles on a chassis dynamometer [Cicero-Fernandez et al., 1993]. Included in this set of driving cycles is a specially designed acceleration cycle (ACCEL). The ACCEL driving cycle consists of 10 acceleration modes, ranging from low, FTP-like accelerations to Wide Open Throttle (WOT) accelerations. It was found that CO and HC emissions are greatly affected by the various acceleration modes. Single accelerations could produce roughly twice the amount of emissions of the total FTP test. CARB has since conducted further testing with 9 additional vehicles tested with replication [Cicero-Fernandez et al., 1994].

In 1991, the EPA performed extensive mapping of emissions as a function of power and speed for 29 different vehicles [Koupal et al., 1995]. These data have since been used as the basis for the emissions model VEMISS. More recently, vehicle manufacturers in collaboration with the US EPA have conducted dynamometer tests of the engine-out and tailpipe emissions of approximately 27 modern technology vehicles as part of the FTP Revision Project [Haskew et al., 1994; Markey, 1993]. Several driving cycles were used involving high-power driving of hot-stabilized vehicles. In addition, many of the same vehicles were tested again using a “non-enrichment” (stoichiometric) chip which avoids command enrichment.

Instrumented Vehicles

In addition to dynamometer testing, several research groups have instrumented vehicles so that they can collect vehicle emissions and operation data while they are driven on the road. Staab et. al. used an instrumented VW Golf to collect emissions under urban, rural, and freeway road conditions [Staab et al., 1989]. More recently, Kelly and Groblicki instrumented a GM Bonneville to collect on-road emissions and have performed several experiments in Southern California [Kelly et al., 1993]. They found that during moderate to heavy loads on the engine, the vehicle ran under fuel enrichment conditions, resulting in CO emissions 2500 times greater than those at normal stoichiometric operation (HC was 40 times as great).

Similarly, Ford Motor Company Chemistry Department Research Staff has instrumented a 1992 Aerostar van with FTIR (Fourier Transform Infra-Red) instrumentation to measure approximately 20 species of emissions (e.g., CO, CO_2, methane, total hydrocarbons, NO, etc.) at high time resolution while on the road [Jession et al., 1994]. These emissions data are coupled with vehicle operating parameters measured with a data acquisition system. The Denver Research Institute also has begun to collect emissions (CO, HC, NO_x) from a 1991 Ford Taurus station wagon in collaboration with Ford [Lesko, 1994]. CARB has sponsored Sierra Research to instrument a 1991 Chevrolet Lumina, to collect second-by-second vehicle operating characteristics and CO, HC emissions. Researchers at Georgia Institute of Technology have begun to instrument a vehicle for on-road emissions testing [Rodgers et al., 1994].

Modal Emission Modeling

Recognizing the deficiencies of emission models based on average speed, recent attempts have been made to model emissions based on specific vehicle operating modes, e.g., acceleration, idle, cruise, and deceleration. The CARB and the US EPA have conducted preliminary modal emissions testing on a limited set of vehicles. These experiments have primarily concentrated on emissions associated with acceleration events [Drachand, 1991; Cicero-Fernandez et al., 1994; Gammariello et al., 1993; Haskew et al., 1994; Koupal et al., 1995]. As a convenient method to characterize vehicle operating modes of idle, cruise, and different levels of acceleration/deceleration, it has been proposed to set up a speed/acceleration matrix. With such a matrix, it is possible to measure emissions associated with each bin or mode (e.g., [St.-Denis et al., 1993]). This emissions matrix can then be multiplied with a similar matrix that has vehicle activity broken down so that each bin contains the time spent in each driving mode. The result is the total amount of emissions produced for the specified vehicle activity with the associated emissions matrix.

Another method is to develop an emissions map that is based on engine power and speed. Second-by-second emissions testing would be performed at numerous engine operating points, taking an average of steady-state measurements. By basing emissions on engine power and speed, the effects of acceleration, grade, use of accessories, etc. can be taken directly into account. When creating an emission inventory, the vehicle activity parameters of engine power and speed must be derived from second-by-second velocity profiles. Using emission maps from 29 vehicles, researchers at the EPA have developed the emissions model VEMISS [Koupal et al., 1995; Koupal, 1995]. Other modal emission modeling approaches exist, including Geographical Information System (GIS)-based methods [Bachman et al., 1996] and statistical methods using surrogate variables [Washington, 1996].

2.1.3 Emission Inventory Assessment and Modeling

Extensive efforts have been made by CARB and EPA to revise their regulatory models (MVEI for CARB and MOBILE for the EPA). In mid-December, 1995, CARB re-introduced version 7G of EMFAC, with the following key additions/changes: 1) refinement of starts and a redistribution of starts by vehicle age; 2) a modification of the start emissions methodology with variable soak times; 3) an adjustment for high emitting vehicles; 4) an adjustment for real-world driving patterns; and 5) an incorporation of the latest enhanced inspection and maintenance program results. Further details on these revisions are given later in this document. A comparison of EMFAC7F and EMFAC7G for the South Coast Air Basin (SCAB) found that EMFAC7G gave higher emission inventory estimates. HC emissions increased by 29% in 1990 and 5% in 2000. For CO, the increase is 82% in year 1990 and 40% in year 2000. For NOx emissions, a 41% increase in 1990 and a 10% increase in 2000 has been predicted. EMFAC7G is still based on the average trip speed, thus the methodology of using speed correction factors (SCFs) is unchanged.

EPA has also made significant revisions to its MOBILE model [EPA, 1995]. These changes focus on: 1) updated basic emission rates; 2) a revision of the speed correction factors; 3) better characterization of the fleet; 4) new evaporative emission estimates; and 5) better handling of fuel effects. All of these changes have resulted in an increase of emissions when estimating inventories.

2.1.4 Speed Correction Factors for Emission Models

The speed correction factor (SCF) techniques used in today's conventional emission models are a major focus of controversy. Using the current speed correction functions, emissions are predicted to increase non-linearly at higher vehicle speeds [CARB, 1993]. More detailed testing is required at higher speeds to obtain a better understanding of the associated emission effects, since a major goal of Intelligent Transportation Systems (ITS) and Transportation Control Measures (TCMs) is to increase the traffic flow rate, and thus traffic speed.

The major challenge is whether the utilization of SCFs adequately accounts for the impacts of speed variability. A key problem with the SCF methodology is that the relationships between speed and emissions are based on the average emissions of vehicles tested over different driving cycles with different average speeds than the FTP. They predict the average change in emissions over a driving cycle for a given change in average vehicle speed. They do not account for the effect of changes in speed (or acceleration) on instantaneous emissions.

The EPA has recently revised the speed correction factors for its MOBILE model (MOBILE5a) resulting in higher emissions at higher speeds than what was seen in previous models [EPA, 1995]. CARB has also addressed the revision of SCFs in light of previous versions of EMFAC. EMFAC7F employs a new methodology to model the SCFs, resulting in substantial increases over the predicted SCFs of previous versions [CARB, 1993]. For example, in EMFAC7E, low- and intermediate-speed SCF regression equations from MOBILE4 were combined with the CARB high speed equations. But in EMFAC7F, the actual federal SCF data were integrated with the CARB high-speed data. The subsequent regression analysis yields much simpler SCF equations for catalyst-equipped passenger cars. The EPA data covered vehicles tested over a variety of cycles with average speeds ranging from 2.5 to 48.0 mph. CARB testing covered cycles with average speeds ranging from 16.0 to 64.3 MPH. The testing was grouped by two technology groups: carburetor or throttle-body fuel injection (CARB/TBI) and multipoint fuel injection (MFI).

The SCF methodology has also been assessed by other groups. In his Ph.D. dissertation, Randall Guensler of UC Davis [Guensler, 1993] identifies his major sources of emission rate uncertainty. The research findings demonstrated that the data and analytical methods employed in the derivation of speed correction factors result in estimates with high standard errors. The statistical shortcomings of the existing modeling approach include “data screening” techniques, data aggregation techniques, and model functional form. A new weighted-disaggregate speed correction factor modeling approach was developed in this thesis. The most important component of the research was the development of confidence and prediction intervals associated with using the speed-related outputs from emission models.

2.1.5 Emission Effects Related to Vehicle Technology and Fuels

Various papers focusing on the effects of different engine/emissions technologies and fuels on tailpipe emissions have been collected. The majority of papers on engine technology are Society of Automotive Engineering (SAE) publications, and most of the fuel-related papers come from the Auto/Oil Air Quality Improvement Research Program. Since there are literally hundreds of documents in this category, we only list a small set of examples in the bibliography. Within this category, the literature can be divided into the following areas:

- *Conventional engine technology with better emissions technology*, such as air/fuel and engine system control technology, variable displacement engines, and the use of variable compression ratios;
- *New engine technology*, such as two-stroke engines, ceramic gas turbines, Stirling engines, and electric/hybrid vehicles;
- *Fuel technology*, with literature dominated by the Auto/Oil Air Quality Improvement Research Program, focusing on reformulated gasoline and other alternative fuels;
- *Catalyst technology*, such as pre-heated systems and lean-burn NOx catalysts;

- *Measurement technology*, such as on-board diagnostics and instrumented vehicle technology;

2.1.6 Variable-Start Operation (i.e., Cold/Hot Starts)

A significant amount of research has been conducted analyzing the effect of vehicle cold-start operation on total emissions. Literature dealing with the various areas concerning cold/hot-start emissions, such as vehicle soaking time, catalyst conversion modeling, heated catalyst research, etc., have been investigated.

CARB has developed a new start emissions methodology broken down into three parts: 1) variable soak fractions; 2) new cold start emission factor methodology; and 3) variable soak time activity data [Hrynchuk, 1994; Hrynchuk, 1995]. This new start emissions methodology (described further in Section 4.2.1) is used for light- and medium-duty gasoline vehicles only.

Under the new start emissions methodology, 12 rather than 2 distinct soak periods have been defined. This new soak activity distribution is combined with the corresponding cold start emission fractions and the new cold start emissions methodology to estimate total start emissions. Data from the EPA's Instrumented Vehicle Study were used to develop the new start activity distribution. The emissions impacts of the start emissions methodology changes on the total motor vehicle inventory in the South Coast Air Basin (SoCAB) for HC, NOx, and CO, respectively are the following: -7%, -7%, -26% in 1990; and, -10%, -3%, and -24% in 2010 [Hrynchuk, 1994].

2.1.7 Fuel Enrichment Modes of Operation and Load Producing Activities

Recent research has shown that fuel enrichment modes of operation play a significant role in the total emission inventory (e.g., [Kelly et al., 1993]). Several research groups have begun to study fuel enrichment in detail [St.-Denis et al., 1993; Groblicki, 1994; LeBlanc et al., 1994; Rodgers et al., 1994; An et al., 1995; An et al., 1996].

Three types of fuel enrichment have been identified by the US EPA: 1) commanded enrichment, 2) transient enrichment spikes, and 3) heavy deceleration enrichment [US EPA, 1995]. Commanded enrichment stems from a deliberate command of a rich air/fuel mixture from the engine control system to the electronic fuel ejection system. Commanded enrichment is typically used whenever an engine is under high load, such as during hard accelerations or pulling a loaded trailer. The EPA and manufacturers have also long believed that slight changes in throttle movement can impact HC and CO emissions due to rich spikes in the air-fuel ratio. These spikes do not appear to be caused by commanded enrichment since they were observed in results from both production and stoichiometric calibrations. Rather, they seem to occur for two different reasons, either from a series of short, abrupt throttle openings that happen during rapid throttle movement, or from moderate to heavy deceleration events.

EPA also found out that, when a vehicle suddenly decelerates, the manifold vacuum decreases dramatically in response to closure of the throttle blade [US EPA, 1995]. This results in the simultaneous drop of air to very low levels, due to the throttle closing, and a surge of fuel being drawn off the intake and combustion surface, resulting in an increase in emissions.

Secondary load-producing activities (in addition to driving behavior characterized by acceleration and velocity) have also been a subject of research. These secondary load-producing activities primarily consist of operating on grades, towing heavy loads, and operating high power-demand vehicle accessories such as air conditioning. The EPA has recently looked into these factors as part of the FTP Revision Project [US EPA, 1995]. Further, the CARB is conducting an ongoing project to assess driving patterns likely to promote emission excursions greater than those encountered in current dynamometer driving cycles, using an instrumented vehicle equipped for on-road testing [Cicero-Fernandez et al., 1995]. The authors found out that, when driving on grades above 3%, HC and CO were above the emission rates calculated using EMFAC's SCFs 86% and 100% of the time respectively. While driving on negative grades or flat terrain emission rates were closer to the SCF estimates. Effects on total engine load, such as passengers or AC, may also be important. On average, the emission effects are exacerbated with a fully occupied vehicle (4 passenger) while driving on a hill (4.5%) with both for HC and CO increasing by a factor of 2. For AC operation, tests were performed on two hills (4.5 and 6.7%). The HC emission rates showed an increase of 57% when AC was used at a maximum setting. For CO the increase was 268% during AC operation.

2.1.8 On-Road Emission Measurements and Malfunctioning Vehicles

Deterioration factors play an important part of the current emissions modeling methodology. Recently, with the advent of measuring vehicle emissions using roadside sensors (i.e., "remote sensing"), several studies of the in-use emissions of large number of vehicles have taken place [Bishop et al., 1994; Haskew et al., 1988; Jession et al., 1994; Kirchstetter et al., 1994; Lawson, 1992; Radian Corporation, 1995; Ross et al., 1995; Stedman et al., 1992; Stedman et al., 1995; Stephens, 1992; Stephens, 1992]. Some studies have focused on validating remote sensing readings with instrumented vehicles or roadside dynamometer testing of vehicles identified as high emitters [CARB, 1994; Stephens et al., 1994; California BAR, 1995]. Recent studies have involved repairing high emitter vehicles that have been identified by remote sensors and dynamometer tests, in order to determine the cost-effectiveness of repairs [Stephens et al., 1994].

A key finding from the on-road remote sensing studies is that the majority of real-world vehicle emissions are from a small number of high emitting vehicles [Bishop et al., 1994; Ross et al., 1995; St.-Denis et al., 1993; Stedman et al., 1992; Stedman et al., 1995; Stephens, 1992; Stephens, 1992]. Even though there is some disagreement about the accuracy of the remote sensing technology and the numbers associated with emission contribution and gross emitters, the fact that gross emitters play a dominant role in the emission inventory is certain.

Both the EPA and CARB have conducted surveys to determine the technical cause of emission control system (ECS) malfunctions. EPA divided nine specific ECS components into categories of "tampered", "arguably tampered", or "malfunctioning". Ten years worth of EPA roadside inspection surveys indicate that nearly 20 percent of all vehicles have been tampered with, and that this rate has not decreased significantly over time [US EPA, 1985 – 1990]. Two CARB reports on their tampering surveys provide more detail on component-specific tampering rates, by vehicle technology grouping [Rajan, 1990; Rajan, 1991]. These data indicate that tampering rates of modern, fuel-injected vehicles are lower than those of carbureted vehicles. However, no one has systematically analyzed the EPA or CARB data to determine if modern technology vehicles (with computer-controlled fuel injection) have lower tampering rates than older technology (carbureted) vehicles of the same age.

In addition to the tampering surveys, the EPA has conducted overt and covert audits of inspection/maintenance test stations [US EPA, 1993]. The EPA concludes from the surveys and audits that vehicles in centralized I/M programs have lower tampering rates, and therefore are more effective, than decentralized I/M programs. Others who have studied EPA's data argue that, because of methodological flaws, the surveys and audits cannot be used to justify one I/M program type over another [Walsh et al., 1994; Schwartz, 1995].

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2.2 EXISTING DATA COLLECTION AND ANALYSIS

A wide variety of existing data sets pertaining to vehicle emissions and vehicle activity[*] have been collected. Preliminary analysis was carried out on several of these data sets, in order to: 1) determine the gaps in current data which would need to be filled for model development; 2) assist in the development of a modal emissions test protocol; and 3) provide the basis in determining the sample allocation for the vehicle testing phase. The data sets have been categorized into five major groups:

- ***vehicle emissions data (modal and bag)*—**The majority of currently available second-by-second emission data coupled with vehicle operation data (velocity, acceleration, etc.) has come from modern, properly functioning vehicles.

- ***driving pattern data*—**A great deal of driving pattern data has been collected in the past few years, and has served as the basis for several new driving cycles.

- ***in-use vehicle registration data*—**In order to characterize the in-use fleet, as well as to identify specific vehicle types for the vehicle recruitment task, in-use vehicle registration information is crucial.

- ***remote sensing data*—**Remote sensing data will play an important role in vehicle recruitment since we will be targeting malfunctioning vehicles as well as properly functioning vehicles.

- ***miscellaneous data*—**Other pertinent data exists that will be useful for this project.

In this section, the different data sets are briefly described, followed by short discussions on the preliminary analyses performed. These analyses focus on existing drive cycle development, real-world vehicle emissions, and vehicle malfunctions.

2.2.1 Data Set Matrix

The data sets collected in this task are summarized in Table 2.1. This data set summary matrix contains information on number of records, vehicle identification information, vehicle engine characteristics, owner information, emissions information, and computer storage.

2.2.2 Vehicle Emissions Data

CARB LDVSP 1 to 11

California Air Resources Board Light Duty Vehicle Surveillance Program (LDVSP), Series 1 to Series 11 database contains emissions information on private vehicles randomly selected from the South Coast Air Basin (SoCAB). Vehicles were tested without modification from normal operating condition. The vehicles were run through the Federal Test Procedure (FTP) and emissions data were collected by Bag. The vehicle model years were all pre-1987.

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* This database collection was essentially completed in late 1995, and therefore does not address new databases that came into being from early 1996 on.

Database	Rec-ords	Li-cense	VIN	Make/ Model	Year	Type/ Conf.	Eng-ine	Fuel	Trans	Owner ID	Emis-sions	Test Cycles	Test Types	Stor-age
CARB LDVSP 1 to 11		No	No	Yes/Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	FTP	3 Bag	UNIX
CARB LDVSP 12	165	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	FTP Unified	3 Bag & s-by-s	PC UNIX
CARB Accel Cycle Data	10	NA	NA	Yes/Yes	Yes	Yes	Yes	Yes	Yes	NA	Yes	Accl. Cycle	s-by-s	PC
Speed Cor-rection Factors	650	No	No	No	Yes	No	Yes	No	Yes	No	Yes			PC
FTP Revision Project	27	NA	NA	Yes/Yes	Yes	Yes	Yes	Yes	Yes	NA	Yes	numerous (FTP, ..)	s-by-s	PC
EPA Steady State	29	NA	NA	Yes/Yes	Yes	Yes	Yes	Yes	Yes	NA	Yes	Emission Map	Torque-RPM	PC
Arizona IM240 1/95 – 7/97	>1 million	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	IM240 (fraction)	bag & s-by-s	UNIX
EPA/ATL (1994)	2000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	IM240	Bag	UNIX
Colorado IM240 (95-97)	> 1 million	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	IM240	Bag	UNIX
AAMA	2000	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	FTP	3 Bag	PC
EPA 3 - City Driving Study	>300	No	Yes	Yes/Yes	Yes	No	No	Yes	Yes	Yes	No	NA	NA	PC UNIX
CARB LA chase car study	>100	No	No	Yes	No	No	No	No	No	No	No	NA	NA	
DMV SCAG Region	15 million	Yes	Yes	Yes/Yes	Yes	Yes	No	No	No	Yes	No	NA	NA	PC UNIX
Cut Smog	43,760	Yes	No	Yes	Yes	No	No	No	No	Yes	No	NA	NA	PC
Caltrans Veh. Inventory	13,000	Yes	No	Yes/Yes	Yes	Yes	No	Yes	No	Yes	No	NA	NA	PC
CHP Vehicle Inventory	6,000 - 7,000	No	Yes	Yes/Yes	Yes	Yes	No	No	No	Yes	No	No	No	Hard Copy
UC Vehicle Inventory	~1300	Partial	Part	Partial	Part	Partial	Part	Part	Partial	Partial	No	NA	NA	
BAR '94 RSD Sacramento	2 million	Yes	No	Yes/No	Yes	No	No	Yes	No	No	Yes	Remote Sensing	Remote Sensing	PC UNIX
ARB So. Cal. RSD Study	90,000 +/-	Yes	Yes	Yes/No	Yes	No	No	Yes	No	No	Yes	Remote Sensing	Remote Sensing	PC
UCR RSD Data	>2000	Yes	No	Yes/No	Yes	No	No	No	No	No	Yes	Remote Sensing	Remote Sensing	PC
EPA Test Car List		NA	NA	Yes/Yes	Yes	Yes	Yes	Yes	Yes	NA	Yes	FTP	Cert-ification	PC
CARB Snap and Idle	8700	Yes	Yes	Yes/Yes	Yes	Yes	Yes	Yes	No	by City	No	NA	NA	PC
EPA tampering surveys		NA	NA	NA	Yes	Yes	Yes	Yes	No	No	No	NA	NA	

NA - Not Applicable

Table 2.1. Data Set Description Matrix.

CARB LDVSP 12

CARB Light Duty Vehicle Surveillance Program Series 12 database contains emissions information on 165 vehicles randomly selected from the SoCAB region. Vehicles were tested without modification from normal operating condition. The vehicles were run through both the Federal Test Procedure (FTP) and the UNIFIED test cycles. This is an important database because it contains the only second-by-second FTP emissions of real-world high emitter vehicles (as of late 1995).

CARB Acceleration Cycle

CARB's High-Acceleration database contains emissions data for 10 vehicles run on the CARB ACCEL test cycle. The ACCEL test cycle includes 10 high power events varying in intensity and duration. The vehicle model years range from 1988 to 1990. Tailpipe emissions of CO, HC, NOx, and CO_2 were collected on a second-by-second basis.

Speed Correction Factors

This CARB data set contains emissions (bag) information on 650 vehicles that were used in setting up the speed correction factors for the current emission inventory models. The fleet is somewhat over represented by older, domestic vehicles manufactured with automatic transmissions. The vehicles are identified by year, engine size, fuel system, and transmission type.

FTP Revision Project

This data set contains manufacturer data collected as part of the FTP revision project and reported to the EPA. Twenty-seven 1991 to 1994 vehicles were run through the FTP, ARB02, REP05, and HL07 test cycles. The test cycles used for this project cover a broad range of driving conditions including high-speed and high-power events. Data were collected on a second-by-second basis for engine speed, vehicle speed, manifold vacuum, throttle position, air-fuel ratio, engine-out and tailpipe emissions, exhaust volume, and temperatures. Additional tests were performed with accessories (i.e., air conditioning) running.

EPA Steady State

The EPA Steady State database contains dynamometer test data on 29 vehicles measured on a second-by-second basis. All study vehicles were tested during hot stabilized operation. The vehicles were 1990-1992 cars and light trucks. The vehicles were operated at approximately 60 engine speed/power combinations with approximately 60 seconds duration each. Measurements were made of vehicle speed, engine speed, throttle opening, manifold vacuum, engine-out and tailpipe emissions, temperatures, air-fuel ratio, and dynamometer torque.

Arizona IM240

Over one million records were obtained for vehicles participating in Arizona's centralized inspection/maintenance program from January 1995 to July 1997. These records include information on the vehicles tested and bag emissions data over the IM240 cycle. Only a fraction of the vehicles were given the full IM240 test. These IM240 data as well as other I/M data were used to develop the high emitting portion of the comprehensive modal emissions model.

EPA/ATL

In 1994, the US EPA sponsored inspection/maintenance testing in the Atlanta region. Approximately 2000 records were obtained. These records include information on the vehicles tested and bag emissions data over the IM240 cycle. These IM240 data as well as other I/M data were used to develop the high emitting portion of the comprehensive modal emissions model.

Colorado IM240

Over one million records were obtained for vehicles participating in Colorado's centralized inspection/maintenance program from January 1995 to December 1997. These records include information on the vehicles tested and bag emissions data over the IM240 cycle. These IM240 data as well as other I/M data were used to develop the high emitting portion of the comprehensive modal emissions model.

AAMA

In 1995, the American Automobile Manufacturer Association (AAMA) sponsored FTP testing of approximate 2000 vehicles. These records include detailed information on the vehicles tested and the 3-bag emission results of the FTP test.

2.2.3 Driving Pattern Data

EPA 3-City Driving Study

The EPA 3-city driving behavior study database contains second-by-second data on real-world driving behavior for over 300 vehicles monitored in Atlanta, Spokane, and Baltimore taken in February and March, 1992. The majority of the vehicles were monitored for speed, manifold air pressure, and engine RPM. In addition, about 60 vehicles were monitored for equivalence ratio, throttle position, and coolant temperature. This study covered a relatively large number of real-world vehicles for a short time period.

CARB Los Angeles Chase Car Study

Sierra Research under contract from CARB conducted a study in 1992 which evaluated the speed-time profiles of randomly selected routes within the Los Angeles metropolitan region [Austin et al., 1992]. The speed-time profiles were recorded utilizing a forward looking laser mounted in the front grille of an instrumented vehicle (i.e., "chase car"). Analysis of the resulting data indicated several key points: 1) vehicles operating within Los Angeles and vicinity were found to have higher acceleration rates than used in the FTP; 2) the average maximum acceleration of each trip was found to be 2.55 m/s^2 with a maximum recorded acceleration of 3.62 m/s^2; and 3) average vehicle trip speed was found to be 26.6 mph with maximum recorded speed of 80.3 mph.

2.2.4 In-Use Vehicle Registration Data

DMV SCAG Region

California Department of Motor Vehicles registration data for the Southern California Association of Governments (SCAG) region. SCAG is comprised of Los Angeles, Orange, Riverside, and San Bernardino counties. This database contains approximately 15 million registered vehicles including autos, trucks, motorcycles, trailers and buses. Both commercial and privately-owned vehicles are included.

Cut Smog

The Cut Smog database contains 43,760 individual vehicles whose license plates have been reported to the South Coast Air Quality Management District (SCAQMD) 1-800-CUT-SMOG tip line as visibly polluting vehicles.

Caltrans Vehicle Inventory

California Department of Transportation vehicle inventory, including autos, trucks, trailers and all other vehicles owned by Caltrans. The database contains about 13,000 records. Vehicles are located by Caltrans region.

CHP Vehicle Inventory

California Highway Patrol vehicle inventory containing all CHP vehicles. The list contains between 6,000 and 7,000 vehicles registered to the California Highway patrol statewide. The list is available only on hard copy at this time.

University of California Vehicle Inventories

Vehicle inventories for several of the University of California campuses have been collected. Depending on the data set, information is given on a vehicle’s make, model, year, type/configuration, engine, fuel type, transmission type, and vehicle identification number (VIN). 250 vehicles are cataloged for UC Berkeley, 644 for UC Davis, 250 for UC Irvine, and 150 for UC Riverside. The University of California typically does not keep vehicles longer than 12 years, so the fleets are relatively new.

2.2.5 Remote Sensing Data

BAR 1994 Sacramento RSD Study

This database contains close to two million observations taken by remote sensing vans in the Sacramento region in a large study conducted by the State of California, Bureau of Automotive Repair. The data were collected at several hundred sites with a variety of driving conditions represented.

CARB California RSD Study

The University of Denver, in conjunction with the California Air Resources Board collected remote sensing data at 13 sites in California in 1991. There are about 90,000 records on about 60,000 individual vehicles. CO and HC emissions were measured and recorded with license plates and VINs for the vehicles.

UCR CE-CERT RSD Data

The UCR CE-CERT RSD study contains about 2,000 observations taken by the CE-CERT RSD van, measuring CO, CO_2 and HC. The data were collected by staff and students over a three-year period on campus at UC Riverside, and contain multiple observations over several years for some of the vehicles.

2.2.6 Miscellaneous Data

EPA Test Car List

This data set contains EPA's test results for emissions certification of new vehicles (make and model) to be sold in the United States. The vehicles were run on the FTP test cycle with emissions measured at the tailpipe. In addition, standardized Miles Per Gallon (MPG) data are listed. Engine and emission control system information is also provided. Data is provided for model years 1980 - 1993.

CARB Snap and Idle

CARB Heavy Duty Diesel snap and idle testing program data with information on about 9,500 heavy duty trucks and buses. The data were collected throughout California with 82% of the vehicles California registered. According to ARB estimates, 22% to 34% of the heavy-duty trucks and buses failed the Snap and Idle test. 85% of the vehicles which failed the test were found to have been tampered with.

Tampering Surveys

EPA and CARB tampering surveys provide information on the prevalence of specific technical causes of ECS malfunction. The EPA tampering surveys examine seven ECS components that control exhaust gas emissions (filler neck restrictor, catalytic converter, oxygen and related sensors, positive crankcase ventilation or PCV system, heated air intake, air injection system, and exhaust gas recirculation or EGR system), as well as two components that control evaporative HC emissions (gas tank cap and the evaporative control system). Each of these components can be disconnected, modified, missing, malfunctioning, or replaced by non-stock equipment. EPA makes a judgment call as to whether the specific component was "tampered", "arguably tampered", or "malfunctioning".

We have obtained EPA's tampering database for the years 1985 to 1990, as well as published reports of each survey (US EPA 1985 - 1990). Two additional years of data (1991 and 1992) have been collected by EPA, but have not been publicly released. CARB has published two reports of their tampering surveys [Rajan, 1990; Rajan, 1991].

2.2.7 Drive Cycle Development

In recent years, a great amount of research has been conducted in developing driving cycles that better reflect today's actual driving in comparison with the standard Federal Test Procedure. The most significant study has been the FTP Revision Project, where real-world driving activity data has been collected through instrumented vehicles driving in Los Angeles, Atlanta, Baltimore, and Spokane (e.g., [Markey, 1992; Haskew et al., 1994]). From this real-world driving pattern data, several new driving cycles have been created to better represent modern driving. Brief descriptions of some of the key new driving cycles are given below:

Cycle Name	Description
ARB02	This cycle was developed by CARB based on data from their Los Angeles chase car study [Austin et al., 1992]. The purpose of this cycle is to test vehicles over in-use operation outside of the FTP, including extreme in-use driving events.
HL07	This cycle was developed by the EPA in coordination with the auto manufacturers, with the purpose of testing vehicles on a series of acceleration events over a range of speeds. The severity of the accelerations are such that most vehicles are tested at wide open throttle.

REP05 This cycle was developed to represent in-use driving which is outside the boundary of the current FTP driving cycle. The cycle was generated from a composite data set which equally represents Los Angeles chase car data and the Baltimore 3-parameter instrumented vehicle data. The primary purpose of the cycle is to assess in-use emissions.

ST01 This cycle was developed to characterize driving behavior of vehicle starts. This cycle represents the first 258 seconds after the start of the vehicle (excluding the initial idle).

REM01 This cycle was developed to represent in-use driving which was not captured by the ST01 or REP05 cycles. When combined, the REP05, ST01, and REM01 are intended to characterize the full range of in-use driving. The primary purpose of this cycle is to assess in-use emissions. The cycle was generated from a composite data set which equally represented Los Angeles chase car data and Baltimore 3-parameter instrumented vehicle data.

UNIF01 This cycle was developed by CARB to represent the full-range of in-use driving in a single cycle. The methodology used in generating the cycle is largely consistent with previous efforts by CARB in developing a unified cycle. The cycle was generated from a composite data set which equally represented Los Angeles chase car data and Baltimore 3-parameter instrumented vehicle data.

US06 This cycle is 600 seconds in duration and consists of segments of CARB's ARB02 cycle and EPA's REP05 cycle. This cycle targets specific high emission, non-FTP operation. The US06 is based on actual segments of in-use driving.

AC866 Bag 2 FTP cycle with a new simulation of in-use air conditioning operation.

SC01 EPA developed a new Soak Control Cycle (SC01) to be used for controlling emissions following intermediate soaks. Initial idles and start driving are addressed in SC01 by incorporating the EPA Start Cycle (ST01) in its entirety. The balance of SC01 is composed of two micro trips of moderate driving, selected from the in-use survey database in order to bring the total distance up to match the 3.6-miles distance of the FTP Bag 1 Cycle. The resulting cycle is 568 seconds long.

Among these cycles, the US06 is EPA's preferred method for determining emissions for non-FTP driving behavior. As stated above, the US06 covers the range of non-FTP driving, while targeting severe, high emission events. The US06 cycle achieves the objectives of both EPA and CARB, thus eliminating issues or costs associated with the respective agencies having two different control cycles.

In order to better assess a vehicle's "off-cycle" emissions, the EPA plans to implement a Supplemental Federal Test Procedure (SFTP) in the future. The SFTP includes three single-bag emission test cycles: 1) a hot stabilized 866 cycle run with a new simulation of in-use AC operation (sometimes referred as Bag 5 testing); 2) a new Soak Control Cycle (SC01), which is performed following the new 60-minute soak and with the new simulation of in-use AC operation; and 3) a new Aggressive Driving Cycle (US06) performed while a vehicle is in the hot stabilized condition, often referred as Bag 4 testing. The EPA recommends using a 48-inch single-roll dynamometer with electronic control of power absorption.

In order to capture modal emission events during in-use driving, part of the modal test protocol developed for this project contains the US06 cycle. We believe that a significant amount of effort went into the design of this modern in-use cycle, therefore we did not re-analyze the driving pattern data to create a new cycle to be part of the modal testing protocol.

2.2.8 Real-World Vehicle Emissions Analysis

In order to identify the critical issues of estimating vehicle tailpipe emissions as a precursor to the model development, we have extensively analyzed CARB's LDVSP Series 12 data (see Section 2.2.2 above). Under CARB's LDVSP-12, vehicles were tested on the UNIFIED driving cycle as well as the Federal Test Procedure (FTP). This consists of a three-bag test using prescribed preconditioning and soak periods.

Summary characteristics of both the FTP (i.e., LA4 driving cycle) and the UNIFIED cycle are listed in Table 2.2. This table shows that the LA4 and UNIFIED cycles have similar overall duration and distance traveled; however, the bag specific times and distances are quite different. The UNIFIED cycle also has much higher peak speed and maximum acceleration. Its Bag 2 sub-cycle includes a portion of high power enrichment driving lasting approximately 35 seconds for a typical passenger vehicle, or about 2.4% of the total cycle time.

Using the LDVSP-12 data for 165 vehicles, an analysis was performed on the following four vehicle-categories:

1) "P-car", representing a properly functioning car whose tailpipe emissions are less than the 1983-1992 FTP standards (7.0, 0.39 and 0.7 g/mi for CO, HC, and NOx respectively). A P-car is most likely a well-maintained new car with mileage less than 50,000 miles.

2) "M-car", representing a car with malfunctioning emission controls, resulting in severe tailpipe emission levels;

3) "D-car", representing a car whose emission control systems have naturally deteriorated. A D-car is most likely an older car with an odometer reading above 50,000 miles with its emission control system not grossly malfunctioning;

4) "R-cars", representing average real-world cars with fleet emissions composed of a mixture of the P-, M-, and D- car characteristics.

	UC	UC Bag 1	UC Bag 2	FTP	FTP Bag 1	FTP Bag 2
Duration (s)	1435	300	1135	1372	505	867
Distance (mi)	9.8	1.2	8.6	7.5	3.6	3.9
Ave Speed (mph)	24.6	14.2	27.4	19.5	25.6	16.0
Peak Speed (mph)	67.2	41.1	67.2	56.7	56.7	34.3
Max Accel(mph/s)	6.9	5.8	6.9	3.3	3.3	3.3
PKE (ft/ss)	1.5	2.1	1.4	1.2	1.1	1.2

Table 2.2. Comparison of FTP and Unified Cycle. Positive Kinetic Energy (PKE) is a measure of acceleration work.

The FTP bag emission rates for the 165 vehicles varied dramatically from vehicle to vehicle, ranging from within FTP standards to more than 10 times the FTP standards. Table 2.3 gives the emission multipliers of FTP standards for these vehicles, by the 10th, 25th, 50th, 75th and 90th percentile. The 100th percentile numbers represent the maximum values. From Table 2.3, one can see that the emissions increase almost evenly from the 10th to 90th percentile, but rise dramatically from the 90th to the 100th percentile. This strongly suggests that the highest emitting 10% of the vehicle population behaves differently from the other 90% of the vehicles. Based on the above arguments, we believe they represent malfunctioning vehicles. The assumption of 10% M-cars is consistent with other studies (e.g., [Bishop et al., 1994; Stephens, 1992]). For the purposes of analysis, we choose cut-points that correspond to the 90th percentile FTP multipliers, i.e., 3.2 x FTP for CO, 4.3 x FTP for HC and 2.6 x FTP for NOx when classifying M-cars.

	x FTP CO	x FTP HC	x FTP NOx
10th	0.3	0.5	0.4
25th	0.5	0.7	0.6
50th	0.9	1.2	1.0
75th	1.5	2.4	1.7
90th	3.2	4.3	2.6
100th	14.7	10.2	9.1

Table 2.3. Percentile Table of the 165 Cars

It follows that to define D-cars, emission rates will be between 1 to 3.2 times the FTP standard for CO, 1 to 4.3 times the FTP for HC and 1 to 2.6 times the FTP for NOx, as shown in Table 2.4. The emission rates for R-Cars are taken to be the average emission values for the entire 165-vehicle sample set.

	x FTP CO	x FTP HC	x FTP NOx	Average Mileage	>50,000 miles
P-Cars	< 1.0	< 1.0	< 1.0	51,000	40%
D-Cars	1 - 3.2	1 - 4.3	1 - 2.6	89,500	85%
M-Cars	> 3.2	> 4.3	> 2.6	99,200	95%
R-Cars	1.5	2.0	1.4	71,300	70%

Table 2.4. Summary Table for P-, D- M- and R- Cars

Table 2.4 also gives the average mileages and the percentages of vehicles from the LDVSP-12 data set with mileage above 50,000 miles for each vehicle category. For example, the average mileage for P-cars is 51,000 miles and about 60% of P-cars have mileages below 50,000 miles. For D-Cars, the average mileage is about 90,000 miles and almost 85% of D-cars have mileages over 50,000 miles. In other words, D-cars are likely to be the vehicles with odometer readings beyond the manufacturer's guarantee mileage. Over 95% of M-cars have odometer readings larger than 50,000 miles. R-cars have similar characteristics to D-cars.

The UNIFIED driving cycle includes a portion of vehicle operation that leads to enrichment conditions that last approximately 35 seconds for typical passenger vehicles. This is approximately 2.4% of the total cycle time. This 2.4% enrichment time is roughly consistent with other studies, such as the 6-parameter instrumented car studies conducted by the US EPA [Markey, 1992; Kishan et al., 1993]. Here we assume that the emissions which occurred in this period of time represent real-world enrichment emissions. Because the same vehicles were tested sequentially on both the LA4 and UNIFIED cycles, the enrichment emissions can be estimated by simply subtracting the Bag 2 emission rates of the LA4 from that of the UNIFIED cycle, adjusted by the speed correction factors and distance (for a detailed discussion see [An et al., 1995]). Note that although we refer to these as enrichment emissions, there is evidence that much of the NOx emissions may come from moderately high power under stoichiometric conditions.

Based on the above methodology, the real-world exhaust emissions from P-, M- and D- cars can be estimated. Approximately 33%, 10%, and 57% of vehicles are P-, M- and D-cars respectively. Table 2.5 gives the vehicle exhaust emissions for P-cars.

Emission Factors (g/mi)	***CO***	***HC***	***NOx***
Stabilized	1.12	0.05	0.18
Cold Start	2.34	0.26	0.12
Hot Start	0.55	0.03	0.07
High-power/Enrichment	3.50	0.10	0.20
Total	**7.50**	**0.44**	**0.57**

Table 2.5. Exhaust Emissions for P-Cars

From Table 2.5 it is apparent that if the enrichment mode were removed, the emission factors from other sources like cold/hot starts and hot stabilized running would be only about 4.0 g/mi for CO, 0.34 g/mi for HC, and 0.37 g/mi for NOx. These numbers are within FTP standards of 7.0, 0.4, and 0.7 g/mi for CO, HC, and NOx respectively. When the enrichment mode is included, emission factors for CO reaches 7.5 g/mi and 0.44 g/mi for HC, all beyond FTP standards. By these estimates, the enrichment mode contributes roughly 50% of CO, 20% of HC and 35% of NOx emissions. Table 3.5 also demonstrates that roughly 39% of CO, 66% of HC, and 33% of NOx are from cold/hot start emissions.

Table 2.6 shows that the M-car emissions from stabilized running and high power operations dominate, accounting for nearly 80% for CO and HC and 55% for NOx. The total emission rates reach about 60.0 g/mi for CO, 3.0 g/mi for HC and 4.0 g/mi for NOx, which are about 8 times those of P-cars for CO, 6 times for HC, and 7 times for NOx. Unlike the P-car, emissions from cold/hot starts contribute only about 20% of overall emissions.

Emission Factors (g/mi)	***CO***	***HC***	***NOx***
Stabilized	25.6	2.0	2.0
Cold Start	8.5	0.4	0.3
Hot Start	4.0	0.1	0.6
High-power	20.5	0.2	1.3
Total	**58.6**	**2.7**	**4.2**

Table 2.6. Exhaust Emissions for M-Cars

As previously mentioned, D-cars mostly represent vehicles with mileage above 50,000 miles and emission rates between 1 to 3-4 times of FTP standards. The D-car population is about 57% of the total. This means that most in-use cars have deteriorated, but do not have malfunctioning emission control systems. The exhaust emissions for D-cars are listed below:

Emission Factors (g/mi)	***CO***	***HC***	***NOx***
Stabilized	4.21	0.43	0.54
Cold Start	3.63	0.36	0.19
Hot Start	0.94	0.09	0.19
High-power	4.73	0.05	0.53
Total	**13.5**	**0.92**	**1.46**

Table 2.7. Exhaust Emissions for D-Cars

It can be seen that D-car emission rates are much lower than those of M-cars, but about 80-100% larger than those of P-cars for CO and HC, and 150% larger for NOx. This means that for a car whose mileage has passed the manufacturer's emission guarantee mileage of 50,000 miles, its CO and HC emissions are most likely to be doubled and NOx emission more than doubled. Emission contributions spilt nearly evenly from the stabilized running, cold/hot starts and high-power for CO and NOx. For HC, emissions from the stabilized running and cold/hot starts dominate.

The estimation of real-world vehicle (R-Car) emissions are based on the average emissions of all vehicles in the sample, and is given as:

*R-car = 33%*P-car + 10%*M-car + 57%*D-car*

Table 2.8 demonstrates that the average exhaust emission factors over a vehicle lifetime are approximately 16 g/mi for CO, 0.9 g/mi for HC, and 1.4 g/mi for NOx. An average light duty vehicle will emit roughly 2100 kg CO, 120 kg HC, and 190 kg NOx over its lifetime. For CO emissions, contributions from high power operation, stabilized running and cold/hot starts are about the same, 30- 37% each. For HC emission, contributions from stabilized running and cold start dominate with about 85% of total emissions. For NOx emissions, contributions from stabilized running and high-power operation dominate with about 75% of total emissions. This tells us that the hot-stabilized operation is the major emission source for all pollutants, while high-power is a major source for CO and NOx emissions and cold start is another major source for CO and HC emissions.

Emission Factors (g/mi)	***CO***	***HC***	***NOx***
Stabilized	5.33	0.46	0.57
Cold Start	3.69	0.34	0.18
Hot Start	1.12	0.06	0.19
High-Power/Enrichment	5.90	0.08	0.50
Total Average (g/mi)	**16.04**	**0.94**	**1.44**

Table 2.8. Exhaust Emissions for R-Cars

The R-car emissions shown in the above table are substantially lower than those of the M-car's, but close to the D-car's. For D-cars, the excessive emissions from the 10% population of M-Cars are roughly offset by the lower emissions of the 33% population of P-cars.

Table 2.8 presents emissions based on modal emission components. Real world vehicle emissions can also be presented based on contributions from each vehicle group, as shown in Table 2.9.

Emission Factors (g/mi)	***CO***	***HC***	***NOx***
P-Cars	2.48	0.15	0.19
D-Cars	7.70	0.52	0.83
M-Cars	5.86	0.27	0.42
Total Average (g/mi)	**16.0**	**0.94**	**1.44**

Table 2.9. Real-world Emissions by Vehicle Group

Table 2.9 tells us that most on-road emissions are from D-cars. The 10% vehicle population of M-cars also contributes significantly, accounting for approximately 30% of total emissions. It is important to point out that the 30% contribution from M-cars appears smaller than what has been suggested by other studies (e.g., [Bishop et al., 1994; Stephens, 1992]). This is because our analysis included emissions from all modes of operation, including cold/warm starts and high-power enrichment, instead of just the hot-stabilized mode. When only hot-stabilized running emissions are concerned, the contribution from M-cars approaches 50% for CO and 45% for HC.

2.3 EVALUATION OF CURRENT MODELS AND RECENT REVISIONS

In this section, we briefly review the modeling methodology of both EMFAC and MOBILE, and then focus our analysis on the limitations of these models, with respect to this project's modal emission model development. The recent revisions (as of late 1995) of these models are then described.

2.3.1 Conventional Model Summary

CARB's EMFAC and US EPA's MOBILE emission models use very similar methodologies to estimate emission inventories. There are some minor differences between these two models, such as the definition of emission regimes and how to estimate emissions associated with each regime, but the overall structure is very similar (only the structure of EMFAC is described below). A large amount of effort is regularly spent upgrading these emission-factor models. In their latest versions, MOBILE and EMFAC represent fairly accurately the total emissions of average vehicles in average driving, for large regional areas. A study has recently been performed that shows that remote sensing and other data for CO and HC emissions is roughly consistent with MOBILE5a predictions for 1993 cars [Ross et al., 1995]. There are, however, fundamental limitations for specific modeling scenarios which cannot be overcome by traditional marginal improvements.

California's Motor Vehicle Emission Inventory (MVEI) Modeling Suite

The California Motor Vehicle Emission Inventory Model (MVEI) includes more than just EMFAC—it consists of a group of models, as shown in Figure 2.1.

The CALIMFAC model produces base emission rates for each model year when a vehicle is new and as it accumulates mileage and the emission controls deteriorate. The WEIGHT model calculates the relative weighting each model year should be given to the total inventory, and each year's accumulated mileage. The EMFAC Model uses these pieces of information, along with correction factors and other data, to produce fleet composite emission factors. Finally, the BURDEN model combines the emission factors with county-specific activity data to produce an emission inventory [Maldonado, 1991; Maldonado, 1992].

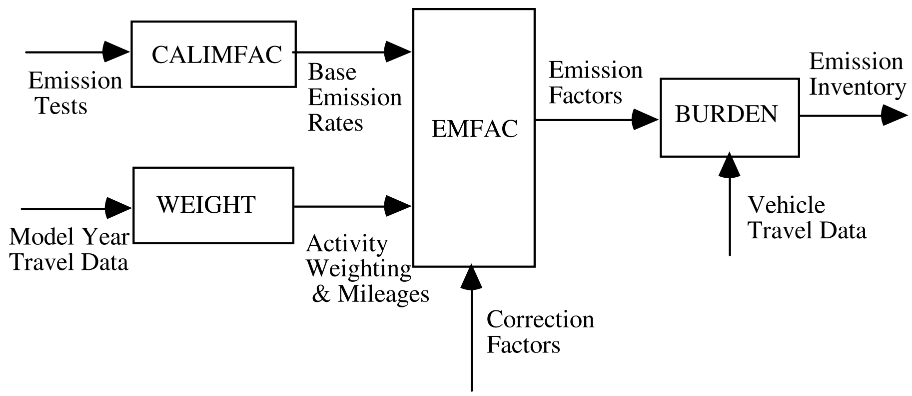

Figure 2.1. CARB's MVEI

CALIMFAC

A critical component of the MVEI modeling suite is CALIMFAC, which stands for California I/M Emission Factor Model. It calculates basic emission rates (BERs) for different I/M (Inspection/Maintenance) scenarios. Data from three testing programs are used for input data: 1) a surveillance program, 2) a random roadside program, and 3) an I/M evaluation program. CALIMFAC tracks 14 distinct technology types based on the model year group, emission control technology, and fuel delivery system. Data from vehicle manufacturers giving the relative sales by technology are used to weight the base emission rates for each model year. When a vehicle is new, its emissions are relatively small. This is called the zero mile rate. CALIMFAC determines the zero mile rate based on a standard FTP measurement. As a vehicle ages, the emissions increase due to deterioration which is measured every 10,000 miles. There are separate BERs for each vehicle class, technology, model year, pollutant, process, and I/M program.

Vehicle Classes and Technology Groups

The MVEI modeling suite provides emission estimates for seven different vehicle classes and three technology groups. The technology groups are non-catalyst (non-CAT), catalyst-equipped (CAT), and diesel (DSL)-fueled vehicles. The vehicle classes, tech groups, and the abbreviations used are listed in Table 2.10.

Abbreviation	Tech Groups	Vehicle Class
LDA	Non-CAT, CAT, DSL	Light Duty Auto
LDT	Non-CAT, CAT, DSL	Light Duty Truck
MDT	Non-CAT, CAT, DSL	Medium Duty Truck
HDGT	Non-CAT, CAT	Heavy Duty Gas Truck
HDDT	DSL	Heavy Duty Diesel Truck
UBD	DSL	Urban Transit Buses
MCY	Non-CAT	Motorcycles

Table 2.10. Vehicle Classes in EMFAC

Correction Factors

The basic emission rates produced by CALIMFAC only reflect emissions from one set of driving parameters: the FTP drive cycle, at a nominal 75 degree Fahrenheit ambient temperature. Correction factors are then introduced to estimate emissions outside of these conditions. These correction factors include: 1) Temperature Correction Factors (TCF), 2) Speed Correction Factor (SCF), 3) Fuel Correction Factor (FCF), 4) Cycle Correction Factor, and 5) High Emitter Correction Factor. The last two correction factors have been recently introduced in the 7G version of the model, described in greater detail in the next section. Among these emission correction factors, the Speed Correction Factor is the most controversial, also discussed in the next section.

EMFAC

EMFAC takes the BERs by model year from CALIMFAC together with various correction factors by model year, and applies weights to the model year rates to produce composite fleet average emission factors for each vehicle class and technology group.

MOBILE/EMFAC Limitations

Even though MOBILE and EMFAC have been constantly improved over the years, there are still some fundamental drawbacks and limitations that are difficult to overcome through marginal improvements. These limitations are inter-related and are outlined below:

1) The Speed Correction Factors used to adjust emission rates are solely based on the average trip speed, which statistically smooth the effect of accelerations and deceleration. The importance of accelerations/declarations is grossly underestimated by the models. Studies have shown that a single power acceleration can produce more CO than is emitted in the balance of a typical short (< 5 mi) trip [Groblicki, 1994]. Other events leading to high engine load can also produce high emissions. For example, vehicles traveling on significant road grades can dramatically increase emissions (see, e.g., [Cicero-Fernandez et al., 1995]), and because of the nature of the current model inputs, grades are not taken into account. This raises doubts over the validity of the SCFs methodology in assessing the impact of accelerations/declarations and grades on tailpipe emissions.

2) Both MOBILE and EMFAC are built upon pure statistical approaches, thus they are not organized according to the physical sources of emissions. This is problematic when applying the models to a wide variety of scenarios. One example is that both models do not discriminate between different makes/models of vehicles, e.g., the average emission difference between a GEO Metro and a Cadillac. In a physical model, the entire emissions process can be broken down into different components that correspond to physical phenomena associated with vehicle operation and emissions

production. Each component is then modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, and emission technology, resulting in different average emission levels.

3) Neither model is capable of predicting emissions at a micro scale level. Regulatory requirements apply both at a macro scale level (i.e., metropolitan area) and a micro scale level (e.g., highway project). Because of the inherent emissions and vehicle operation "averaging" that takes place in the conventional emission models, they offer little help for evaluating traffic operational improvements that are more micro scale in nature. State and federal air quality management plans consist of numerous traffic control measures and more sophisticated inspection/maintenance programs. Further, traffic flow improvements can be accomplished through the advent of intelligent transportation systems. Operational improvements that improve traffic flow (e.g., ramp metering, signal coordination, automated highway systems, etc.) cannot be evaluated accurately with the conventional emissions models.

4) These models can be misleading when forecasting future emissions. As mentioned earlier, they are not adequately organized according to the physical sources of emissions, and out of necessity, future scenarios are modeled with simplified assumptions. In our approach, we have constructed more convincing scenarios by relating emission factors to categories of technology.

Tunnel Studies

Over the last several years, several tunnel studies have been carried out providing data that can be used to validate these conventional emission inventory models. Initially, as part of the 1987 Southern California Air Quality Study (SCAQS), the Southwest Research Institute (SwRI) conducted a study, sponsored by the Coordinating Research Council (CRC), designed to obtain emissions factors in an on-road setting [Lawson et al., 1990]. The experimental approach was to measure air pollutant concentrations into and out of a roadway tunnel located in Van Nuys, CA. The carbon monoxide and hydrocarbon emissions factors derived by this in-situ method were far higher than those predicted by EMFAC (version 7C at the time). The average ratios of tunnel emissions factors to EMFAC7C emissions factors were: 1) 2.7 ± 0.7 for CO; 2) 4.0 ± 1.5 for HC; and 3) 1.0 ± 0.2 for NOx (nitrogen oxides). These differences between measured and modeled emissions rates raised substantial concern regarding the validity of the in-situ measurement, the vehicle emissions modeling procedure, the model inputs, the current vehicle emissions inventories, and automotive pollutant abatement strategies. Further work was undertaken to examine the general nature of discrepancies between measurements and models with the conclusion that the SCAQS Tunnel Study results were consistent with previous on-road experiments throughout the United States showing CO/NOx and HC/NOx ratios higher than dynamometer and model predictions. An additional evaluation was made of motor vehicle emissions modeling issues and it was concluded that the differences in the ratios of emitted species were due less to limitations in EMFAC and MOBILE than to limitations in the database used to construct the model input.

Since then, there have been more recent studies performed in the Fort McHenry Tunnel (Baltimore), Tuscarora Mountain Tunnel (Pennsylvania Turnpike), Cassiar Tunnel (Vancouver, BC), and Caldecott (San Francisco Bay Area) [Pierson et al., 1994; Kirchstetter et al., 1994; Gertler et al., 1995]. Results of these experiments were compared with emissions predicted by MOBLE and EMFAC. Results for the Cassiar, Fort McHenry, and Tuscarora tunnels were reported generally within +/- 50% of the model prediction. The discrepancies between the models and these recent tunnel studies are less, primarily due to improvements in the emission factor models over the years.

RECENT REVISIONS

Revisions to the EMFAC Model

In mid-December of 1995, CARB re-introduced version 7G of EMFAC, with the following key additions/changes:

- Refinement of starts and a redistribution of starts by vehicle age;
- Modification of the start emissions methodology with variable soak times;
- Adjustments for high emitting vehicles;
- Adjustments for real-world driving patterns; and
- Incorporation of recent Enhanced Inspection and Maintenance Program results.

The first two items modify the existing cold/warm start emission methodology. The third item enlarges the population of on-road gross-emitting vehicles. The fourth item modified the baseline LA4 Cycle-based emission rates based on the LA92 Unified cycle, which includes a portion of high power enrichment driving. The last item incorporates the impact of a new Enhanced Inspection and Maintenance Program. EMFAC7G tends to give higher emission inventory estimates when applied to the South Coast Air Basin. Compared to version 7F, HC emissions increase by 29% in 1990 and 5% in 2000. For CO, the increase is 82% in year 1990 and 40% in year 2000. For NOx emissions, a 41% increase in 1990 and a 10% increase in 2000 has been predicted. EMFAC7G is still based on the average trip speed, thus the methodology of using speed correction factors (SCFs) is unchanged.

The New Start Emissions Methodology

The new start emissions methodology developed by CARB has three parts: 1) variable soak fractions, 2) a new cold start emission factor methodology, and 3) variable soak time activity data. This new start emissions methodology is used for light- and medium-duty gasoline vehicles only.

> ***Variable soak fractions—***Previously, vehicles were tested for start emission factors for two time frames - after the engine had been turned off for 12 hours (cold start), and after the engine had been completely warmed up, shut off and then restarted after a 10 minute soak period (hot start). In 7G, emission factors are estimated for a variety of soak (engine-off) times. Vehicles were tested

on a special driving cycle varying only the soak time. The resultant data produced a continuum of start soak fractions which are multiplied by the cold start (12 hour soak time) emission factor.

Cold start emission factors—In previous model versions, the cold start emission factor was calculated as the emissions difference between the cold start and the (speed-corrected) hot stabilized modes of the FTP drive cycle. In 7G, the emissions from the entire FTP cold start bag 1 are multiplied by a start correction factor. The start correction factor adjusts the FTP bag 1 grams/mile to the grams from the first 100 seconds of bag 1 of the Unified Cycle. The first 100 seconds of a cold start are considered to be the significant cold start portion.

Starts activity data—Starts activity data, just as with the emission factors, were previously estimated for two modes—cold start and hot start. A trip was counted as a cold start if the engine was off for an hour or longer (for catalyst vehicles), otherwise, it was considered a hot start. The number of cold start trips was multiplied by the 12-hour cold-start emission factor, while the number of hot start trips was multiplied by the 10-minute hot start emission factor.

Under the new start emissions methodology, 12 rather than 2 distinct soak periods have been defined. This new soak activity distribution is combined with the corresponding cold start emission fractions and the new cold start emissions methodology to estimate total start emissions. Data from the EPA's Instrumented Vehicle Study were used to develop the new start activity distribution. The emissions impacts of the start emissions methodology changes on the total motor vehicle inventory in the SCAB for HC, NOx, and CO, respectively are the following: -7%, -7%, -26% in 1990; and, -10%, -3%, and -24% in 2010.

High Emitter Adjustment

CARB tested vehicles from the Inspection and Maintenance (I/M) Pilot Project on the FTP cycle, and their model year average emission rates were compared to the model year emission rates predicted in EMFAC. The fleet of over 600 vehicles that were part of this project was chosen for high emitter analysis because of the extremely high capture rate of the vehicles. The analysis showed that an emission adjustment to the model was necessary. These adjustment factors, which are used in all calendar years, apply to light- and medium-duty vehicles, both to running exhaust and start emissions. The emissions impacts on the total motor vehicle inventory in the SoCAB for ROG, NOx, and CO, respectively are the following: 15%, 13%, 65% in 1990; and, 6%, 1%, and 12% in 2010.

Cycle Correction

Although the emission rates based on the FTP are adjusted using speed correction factors, it is recognized that all types of driving may not be properly represented in this manner. In 1992, the ARB obtained data on real-world vehicle driving patterns in Southern California. Analysis of the driving patterns resulted in the development of the Unified Cycle. This one cycle was developed to represent all driving patterns in the same proportions which actually occur on the road. The Unified Cycle serves as the basis of adjustment factors referred to as Cycle Correction Factors. These factors are multiplied by the emission factor that is based on the FTP and the SCF cycles. The affected vehicle classes are light- and medium-duty gasoline vehicles. The emissions impacts on the total motor vehicle inventory in the SCAB for HC, NOx, and CO, respectively are the following: 12%, 19%, 43% in 1990; and, 4%, 18%, and 41% in 2010.

Revisions to the MOBILE Model

Since the release of "Highway Vehicle Emission Estimates" in July 1992, the EPA has extensively revised the model used to estimate average in-use emission factors for highway vehicles. The most significant changes are:

> ***Updated Basic Emission Rates*—**The BER equations describe emissions as a function of increasing mileage, for properly maintained non-tampered vehicles. Historically, data used to develop basic emission rates have been collected primarily through mail solicitation of owners selected from vehicle registration lists. In the last several years, EPA has expanded the data collection to include data from centralized inspection and maintenance program lanes, such as in

Hammond, IN, Chicago Heights, IL and Mesa, AZ. The most significant difference was an increase in estimated deterioration rates. These changes in the basic emission rates, when translated to changes in average fleet wide in-use emissions as estimated by the model, resulted in increases on the order of 20 to 30 percent for all three pollutants.

Revision to Speed Correction Factors—The speed correction factors in the model are developed for three bands of average speeds: “low” speeds, defined as average trip speeds under 19.6 mph down to 2.5 mph; “mid-range” speeds, from 19.6 to 48 mph; and “high” speeds, from 48 to 65 mph. The SCFs for mid-range and high average speeds applicable to light-duty vehicles and light-duty trucks were revised.

Fleet Characterization Data—EPA updated both the registration distributions by age and the annual mileage accumulation rates by age. The registration distribution data in MOBILE5a are based on the national fleet for calendar year 1990. The annual mileage accumulation rates have been adjusted upward by about 10%. Relative to the values used in MOBILE4, the fleet of in-use vehicles is older on average, and the vehicles of all types and ages are driven more miles than before. The net effect of both of these changes is to further increase the average in-use emission factors calculated for any given set of conditions.

There are also revisions being made in other areas, such as evaporative emission estimates and fuel effects. All of these have resulted in an increase in estimated emission factors.

MOBILE6 Plans

The US EPA has recently initiated the development of MOBILE6, the next major revision to EPA’s highway vehicle emission factor model. Revisions in MOBILE6 center on:

- *General update of some underlying data:* To further update the basic emission rate equations.

- *Effects of temperature and fuel volatility on exhaust emissions:* To revise the "high temperature and fuel volatility" exhaust emission correction factors.

- *Evaporative emissions under "real world" conditions:* The evaporative emission factors for diurnal and hot soak emissions will be updated.

- *Inspection and maintenance (I/M) program modeling:* To be able to assess the likely impacts of various "hybrid" I/M program options.

- *Trip characteristics data:* To characterize the "average trip" with new data.

- *Fuels:* To assess the impacts of various fuels on vehicle emissions.

3 Vehicle Testing

Based on the background information described in the previous chapter, we have designed a vehicle testing methodology that has provided data for developing the comprehensive modal emissions model. This vehicle testing methodology consists of several key components:

1) Defining the *vehicle/technology categories* that make up the modal emissions model;

2) Using the vehicle/technology categories for guidance, determining a *vehicle recruitment strategy*; and

3) Developing a *dynamometer test procedure* for the measurement of modal emissions.

These three components are described in the first three sections of this chapter. The fourth section describes the emissions testing that was performed. The last section of this chapter describes the data pre-processing that took place.

3.1 VEHICLE/TECHNOLOGY CATEGORIZATION

The conventional emission inventory models (California Air Resources Board's EMFAC and US EPA's MOBILE) are based on bag emissions data (FTP) collected from certification tests (using new car exhaust emission standards), surveillance programs, and inspection/maintenance programs. These large sets of emissions data provide the basis for the conventional emission inventory models. These conventional models aggregate vehicles into a few general classes (e.g., light-duty gas vehicles, light duty diesel vehicles, light duty trucks, etc.) which are then indexed by model year.

In developing a modal emission model using a physical load-based approach, we chose not to base the model on these "bag" data. Instead, it was determined that it was necessary to collect second-by-second emissions data from a sample of vehicles to build a model that predicts emissions for the national fleet.

The choice of vehicles for this sample is crucial, since only a small sample (approximately 340 vehicles) was used as the basis for the model.

Because the eventual output of the model is emissions, the vehicle/technology categories have been chosen based on a vehicle's *emissions contribution*, as opposed to a vehicle's actual population in the national fleet. Recent results from both remote sensing and surveillance studies have shown that a small population of vehicles contributes a substantial fraction of the total emissions inventory. With this approach, more emphasis is put on high emitters than if based strictly on population numbers. High emitting vehicles are not well understood, however the data and models developed in this project have gone a long way in improving our understanding of these vehicles.

In order to guide the vehicle recruitment and testing process, we have determined a vehicle/technology category set primarily driven by total emissions contribution. Early on in this study, we analyzed existing remote sensing and surveillance data to help establish the category set, as well as to determine the appropriate sample size in each category. A summary of these analyses is given below.

3.1.1 Remote Sensing Analysis

Remote sensing studies have shown that a small proportion of the vehicles studied have accounted for a large percentage of the total emissions observed. Bishop et al. [Bishop et al., 1994] found that 5% of the vehicles accounted for 50% of the total emissions while McAlinden [McAlinden, 1994] observed that 10% of the vehicles produced 60% of the emissions. Another study estimated that a single car emitting 7% CO produces 50 times more CO per mile than a vehicle in good tune emitting 0.5% CO [Lawson, 1992]. A more detailed analysis by Zhang and Stedman compared vehicle emissions between 22 fleet profiles gathered by remote sensing from around the world. For Denver, Zhang et al found that 20% of the fleet contributed 82% of the total CO emissions.

Remote sensing studies are a valuable source of data in that they represent a snapshot of a large, relatively random sample of the current vehicle fleet. There are several limitations with the older remote sensing datasets, however: only the CO emission measurements are reliable; no information on vehicle mileage or power to weight ratio are available; and problems have been noted with the decoder used to extract vehicle characteristics (such as type of catalyst and fuel system) from the vehicle identification numbers (VINs) of individual vehicles. Also, remote sensing typically does not measure vehicles during high-power episodes or during the cold-start mode of operation.

As part of an earlier study, we obtained a dataset of remote sensor readings from over 90,000 vehicles at various locations in Northern and Southern California, collected by the University of Denver for CARB in 1991 [CARB, 1994]. We grouped the vehicles into several categories of interest, and calculated average CO exhaust concentration rates. We used these data to construct average CO emission rates for candidate vehicle technology groups.

3.1.2 Surveillance Data Analysis

The California Air Resources Board regularly conducts dynamometer testing of in-use vehicles under its Light Duty Vehicle Surveillance Program (LDVSP). In our early analysis, we used data from the 1992 LDVSP-12 survey. The vehicles tested in this survey were randomly selected by stratified random sampling on vehicle model year from the South Coast Air Basin in Southern California, and brought in for testing. There are several benefits of using this data source: the vehicles were tested in the condition they were received, rather than after adjustments or repairs were made that might reduce emissions; there is extensive and accurate data on the characteristics of each vehicle, including odometer reading; and the vehicles are subject to dynamometer testing, which provides a more accurate and in-depth picture of their in-use emissions. In addition, the vehicles in LDVSP-12 were tested on CARB's UNIFIED Cycle, which was designed to be more representative of real world driving behavior than the FTP. The only limitations with the LDVSP data are that the sample size is small (only 165 cars and light duty trucks), and that no vehicles prior to MY83 were tested. The average CO emissions from Bag 2 of the UNIFIED Cycle, in grams per mile, are shown in Table 3.1. In this table, several candidate vehicle/technology categories are listed.

Vehicle Type		Emissions Distribution		
CARS	# Vehicles	within class	% of total	avg. CO
2-way/3-way catalyst equipped	23	29%	21%	19.4
3-way cat, carbureted	18	24%	17%	20.4
3-way F.I., over 50K miles	51	34%	24%	10.2 *
3-way F.I.,under 50K miles	33	13%	10%	6.2
TOTAL	125	100%	72%	12.3
TRUCKS				
2-way/3-way catalyst equipped	4	15%	4%	22.6
3-way cat, carbureted	7	19%	5%	16.7 **
3-way F.I., over 50K miles	20	57%	16%	17.0
3-way F.I., under 50K miles	9	9%	3%	6.0
TOTAL	40	100%	28%	15.0

* Excludes one MY85 limousine with 162 gpm CO   ** Excludes one truck with 466 gpm CO

Table 3.1. Emissions contributions by technology type for CARB LDVSP-12.

To estimate the contribution of the highest emitting 20% of the vehicles, the UNIFIED Cycle Bag 2 CO data were split into three groups by vehicle model year for comparison. Three age groups were chosen because roughly 50 vehicles were needed in each age group to allow for a reasonable number of vehicles in each quintile. The age groups were 83-86, 87-88, and 89-92, with 61, 56, and 48 vehicles respectively. It should be noted that the quintile groupings are not exact because the number of vehicles in each quintile was not exactly the same because of the sample size. The quintile mean CO, NOx, and HC data were plotted as well as the population emissions percentage within each age group (Figures 3.1a, and 3.1b for CO, 3.1c and 3.1d for NOx, and 3.1e and 3.1f for HC). From these plots it can be seen that the highest emitting 20% of each model year group account for about 60% of the total emissions for the group.

The remote sensing data and the CARB real-world vehicle testing results differ somewhat in estimates of just what proportion of the vehicles produce what percentage of the emissions. However, both make it clear that understanding the emissions behavior of the high emitting vehicles is critical in modeling of vehicle emissions from the on-road vehicle population. In addition to higher total emissions, the variance of the emissions from the high emitting portion of the population is much higher than the rest of the population. For example, the vehicle to vehicle variance in the UNIFIED cycle CO emissions of the highest emitting quintile was about 20 times that of the next highest emitting quintile. Thus, from a statistical sample allocation perspective, it is also important to assign more of the sample to the more variable high emitting portion of the population.

Table 3.2 shows several candidate vehicle/technology categories that were chosen early on with the data used to estimate the sample sizes. The technology-weighted travel fractions were obtained from MOBILE5a. The travel fraction for a given model year was multiplied by the distribution of fuel system and catalyst technologies for that model year. The results for each technology category were summed to obtain the travel fraction for each technology over the 25-year modeling period (MY 1976 to MY 2000). With the exception of the introduction of two-way oxidation catalysts in MY75, the shift to new fuel system and catalyst technologies occurred gradually over several years.

In order to estimate the emissions contribution of each vehicle/technology group, MOBILE5a travel fractions from the year 2000 were used in conjunction with the estimated emission rates from the LDVSP-12 data. The fleet proportions for the year 2000 were used to balance the model data collection to the intended time for its use. Categories with less than 10 vehicles were adjusted up to ten vehicles in order to keep minimum sample size at least 5 for all vehicle/technology/malfunction groups.

Table 3.2 uses the average emission rates from the LDVSP-12 for the two three-way catalyst groupings. Because the LDVSP-12 dataset contained predominately vehicles with three-way catalysts, emission rates for the no catalyst and two-way catalyst groups were estimated based on the ratio of average CO concentration from these groups to that of carbureted, three-way catalyst cars, as measured in the remote sensing data. Based on the remote sensing data, the average CO emission rate for cars without catalysts is roughly 2 times, and that for cars with two-way catalysts roughly 1.5 times, that of carbureted cars with three-way catalysts.

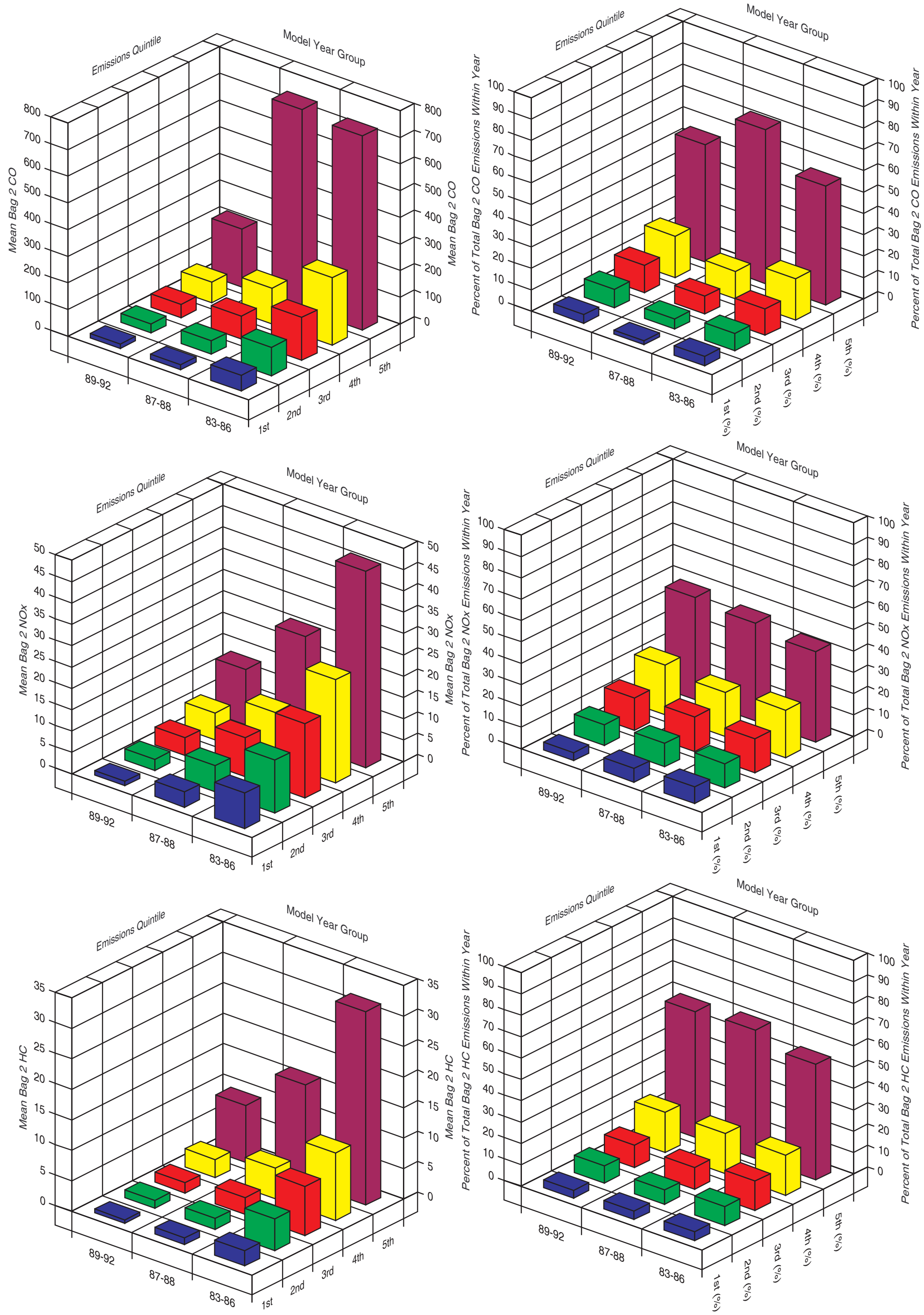

Figure 3.1. a) Mean Bag 2 CO by vehicle age group divided into quintiles, and b) Percent of Total Bag 2 CO Emissions within Year divided into quintiles c) Mean Bag 2 NOx by vehicle age group divided into quintiles, and d) Percent of Total Bag 2 NOx Emissions within Year divided into quintiles e) Mean Bag 2 HC by vehicle age group divided into quintiles, and f) Percent of Total Bag 2 HC Emissions within Year divided into quintiles.

Vehicles	**Emission Rate**	**Technology Weighted Travel Fraction**	**Score (ExM)**	**Adjusted Sample Size**	**Sample Split** (normal / high emitting)
No Catalyst	40*	.000	.00	10	.5/.5
2-way Catalyst	30**	.001	.37	10	.5/.5
3-way Catalyst, Carbureted	20.4	.051	1.03	22	.5/.5
3-way Catalyst, FI, >50K miles, Low P/W ratio	10.2			38	.5/.5
3-way Catalyst, FI, >50K miles, Med. P/W ratio	10.2	.485	4.95	38	.5/.5
3-way Catalyst, FI, >50K miles, High P/W ratio	10.2			38	.5/.5
3-way Catalyst, FI, <50K miles, Low P/W ratio	6.2			23	.8/.2
3-way Catalyst, FI, <50K miles, Med. P/W ratio	6.2	.452	2.80	23	.8/.2
3-way Catalyst, FI, <50K miles, High P/W ratio	6.2			23	.8/.2
Auto Total				225	
Light Duty Truck, Carbureted	16.7			13	.5/.5
Light Duty Truck, Fuel Injection	13.6			63	.8/.2
Truck Total				75	

* Calculated as 2 times the 3-way Carbureted emissions rate based on Remote Sensing Proportions
** Calculated as 1.5 times the 3-way Carbureted emissions rate based on Remote Sensing Proportions

Table 3.2. Vehicle Selection Matrix.

3.1.3 Final Vehicle/Technology Categorization for Recruitment and Testing

The vehicle/technology candidate categories underwent several iterations early on in the project. Increased importance was placed on a vehicle's certification standard, in particular, whether a vehicle was a *Tier 1 certified vehicle* (MY94 on) or a "*Tier 0" certified vehicle* (non Tier 1 certified). The Tier 1 standards for cars and trucks are shown in Table 3.3. The standards for cars were phased in over a three-year period; 40% of 1994 cars sold met the standards, while all 1996 cars must meet the standards. The last previous change in federal car emissions standards occurred in 1981.

The final vehicle/technology categories used for vehicle recruitment and testing are shown in Table 3.4. There were a total of 24 categories, based on fuel and emission control technology, accumulated mileage, power to weight ratio, emission certification level, and emitter level category*.

* Note that these 24 vehicle/technology categories used for recruitment are slightly different than the vehicle/technology categories used for modeling (a total of 26 categories, see Chapter 4). The main difference lies in the high emitters. Because many of the high emitting vehicles had disparate emission results when categorized by technology group, the high emitting vehicles were re-categorized into groups with similar emission characteristics. Grouping high emitters by emission profiles produced much more homogeneous groups than grouping by technology category. The modeling vehicle/technology categories are given in Table 4.1 and are described in detail in Chapter 4.

Vehicle Type	Emissions Standard	New Car Standards, grams per mile				Standards Phase-In Schedule, Model Year				
		HC	**NMHC**	**CO**	**NOx**	**1993**	**1994**	**1995**	**1996**	**1997**
LDVs (0-6,000 GVW)										
Cars	0-3,750 LVW									
	CA	0.41	0.39	7.0	0.4	100%	60%	20%		
	Federal Tier 0	0.41		3.4	1.0	100%	60%	20%		
	Federal Tier 1		0.25	3.4	0.4		40%	80%	100%	100%
Trucks	LDT1: 0-3,750 LVW									
	CA	0.41	0.39	9.0	0.4	100%	60%	20%		
	Federal Tier 0	0.80		10.0	1.2	100%	60%	20%		
	Federal Tier 1		0.25	3.4	0.4		40%	80%	100%	100%
	LDT2: 3,751-5750 LVW									
	CA	0.50	0.50	9.0	1.0	100%	60%	20%		
	Federal Tier 0	0.80		10.0	1.7	100%	60%	20%		
	Federal Tier 1		0.32	4.4	0.7		40%	80%	100%	100%
LDTs (6,001-8,500 GVW)										
	LDT3: 3,751-5,750 ALVW									
	CA	0.50	0.50	9.0	1.0	100%	100%	100%	50%	
	Federal Tier 0	0.80		10.0	1.7	100%	100%	100%	50%	
	Federal Tier 1		0.32	4.4	0.7				50%	100%
	LDT4: Over 5,750 ALVW									
	CA	0.60	0.60	9.0	1.5	100%	100%	100%	50%	
	Federal Tier 0	0.80		10.0	1.7	100%	100%	100%	50%	
	Federal Tier 1		0.39	5.0	1.1				50%	100%

Notes:

- Standards for cars and LDT1s are identical
- 50,000 mile standards for LDT2 and LDT3 are identical; however, higher mileage standards differ slightly
- GVW = gross vehicle weight
- curb weight = unloaded weight
- LVW = loaded vehicle weight, or test weight (curb weight + 300 lbs)
- ALVW = adjusted LVW, (GVW + curb weight) / 2

Table 3.3. Vehicle Emissions Standards and Phase-Ins

In this table, it can be seen that the Tier 0, 3-way catalyst, fuel-injected (FI) cars, as well as the Tier 1 cars, are divided into subgroups based on power/weight ratio and mileage, since these vehicle categories will dominate future emissions. Power/weight ratio was chosen as a discriminating variable since it plays a large role in the on set of enrichment emissions. The dividing point between low power/weight and high power/weight was set at 0.039 hp/lb. for the 3-way catalyst, FI groups and at 0.042 hp/lb. for the Tier 1 cars. Different limits were selected to reflect the increase in vehicle power to weight ratios during the time these cars were available (see [Murrell et al, 1993]).

Vehicle Technology Category	**Number Tested (Recruitment Targets)**	
Cars	**normal-emitting**	**high-emitting**
No Catalyst	5	
2-way Catalyst	10	
3-way Catalyst, Carbureted	5	10
3-way Catalyst, FI, >50K miles, low power/weight	15	25
3-way Catalyst, FI, >50K miles, high power/weight	15	
3-way Catalyst, FI, <50K miles, low power/weight	15	
3-way Catalyst, FI, <50K miles, high power/weight	15	
Tier 1, >50K miles, low power/weight	15	5
Tier 1, >50K miles, high power/weight	15	
Tier 1, <50K miles, low power/weight	15	
Tier 1, <50K miles, high power/weight	15	
Total Cars	125	55
Trucks	**normal-emitting**	**high-emitting**
Pre-1979 (<=8500 GVW)	5	
1979 to 1983 (<=8500 GVW)	10	
1984 to 1987 (<=8500 GVW)	7	8
1988 to 1993, <=3750 LVW	15	25
1988 to 1993, >3750 LVW	15	
Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	15	5
Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	15	
Total Trucks	67	53

Table 3.4. Final Vehicle/Technology Categories used for Phase 2 recruitment and testing, shown with recruitment targets.

Unlike emissions standards for cars, the federal truck emissions standards have changed several times since 1981. These changes were substantial for all three pollutants, reducing the allowable emissions of each by almost one-half. As the emissions standards changed, so did the classification of trucks by weight; the Tier 1 standards include four separate light-duty truck standards, based on a combination of *gross vehicle weight* (GVW, which includes maximum payload) and *loaded vehicle weight* (LVW, or test weight, which is the empty or "curb" weight plus 300 lbs.)[*]. Since the Tier 1 LDT1 standards are identical

[*] Although the pre-1979 truck standards apply only to trucks up to 6,000 lbs. GVW, we expanded this technology group to include trucks up to 8,500 lbs. GVW, since most of the pre-79 trucks still in use exceed 6,000 lbs. GVW.

to those for cars, these trucks (up to 3,750 GVW) are included in the car Tier 1 categories. The LDT2 and LDT3 standards are nearly identical, so these categories also are combined.

During the course of vehicle testing, the recruitment targets for high-emitting Tier 1 vehicles were revised downward (from 15 to 5 each for cars and trucks), due to the difficulty of obtaining these type of vehicles.

Towards the end of the project (i.e., Phase 4), it was determined that additional vehicle/technology categories should be incorporated into the model, in order to better estimate emission inventories into future years. We analyzed the high-growth vehicle markets which were not given enough emphasis during the initial categorization in Phase 1 (carried out in 1996). A total of four additional groups have been identified for testing and modeling:

Gas-powered LDTs, >8500 GVW

Both gasoline and diesel light duty trucks in the heavier categories (e.g., greater than 8500 lbs. gross vehicle weight) have experienced tremendous growth in the last few years. None of these type of vehicles were tested in Phase 3. This category was added in Phase 4.

Diesel-powered LDTs, >8500 GVW

During the previous Phase 3 testing, there weren't any diesel-powered vehicles tested. As an initial formation of a diesel modal model, we added a category for light duty trucks greater than 8500 lbs. gross vehicle weight. It is important to note that it is a major undertaking to develop a complete *diesel* modal emission model. Only a preliminary diesel modal model has been developed which hopefully can be developed more fully in the future.

Tier 1, High Mileage (>100K miles) Vehicles

During the Phase 3 testing, it was nearly impossible to find high mileage Tier 1 vehicles, because of the recent introduction of the Tier 1 standards when the testing was performed. There simply hasn't been enough elapsed time to find those type of vehicles with high mileage. As a result, several Tier 1 high mileage (>100,000 accumulated miles) vehicles were tested in Phase 4, making up this new category.

1995-1999 High Emitting Vehicles

During Phase 3 testing, it was extremely difficult to recruit and test high-emitting, newer vehicles (MY 1995 on). As a result, the high emitting categories developed in Phase 2 did not include these newer vehicles. During Phase 4, additional recent model year (MY 1995 on) vehicles that are high emitters were tested. These vehicles were included in the established high emitter categories.

3.2 TEST VEHICLE RECRUITMENT PROCEDURE

Given the recruitment targets set forth in Table 3.4, vehicles were recruited throughout California's South Coast Air Basin, with a small subset brought in from other states. Particular care was given to target 49-state certified vehicles as well as California certified vehicles, as discussed below. To prevent bias and to ensure the broad applicability of the testing results, to the best extent possible, vehicles were sampled randomly within each vehicle/technology category of Table 3.4. It was particularly challenging recruiting high-emitting vehicles and 49-state vehicles, so several additional databases were used to assist in the recruitment:

- ***DMV Database*—**California's Department of Motor Vehicles provided a database of local vehicle registrations, and gave permission to use the database for research purposes. This database provides license plate numbers, vehicle identification numbers (VINs), and driver information (e.g., address).

- ***High Emitter List*—**In order to identify late model vehicles that tend to be high emitters, we have developed a database of average failure rates by vehicle model. Over 300,000 vehicle test results have been analyzed from the 1995 Arizona I/M program to calculate average IM240 emissions and failure rates by specific engines in MY90-95 car models. The analysis was restricted to models for which there were at least 100 individual cars tested. Eleven models from MY90-93 have HC failure rates over 10% within

50,000 miles (fewer models have similarly high failure rates for CO or NOx). For most of these models, failure rates tend to increase with increasing mileage. The Arizona dataset has fewer MY94-95 models, and the cars have lower mileages; however, we were able to identify three models with a failure rate of at least 5% for at least one of the three pollutants (for MY94-95).

At the beginning of the testing phase, the majority of vehicles were randomly selected by telephone solicitation in Southern California. However, as individual categories in the recruitment matrix were filled, we used a variety of recruitment approaches, discussed below, to fill out the rest of the matrix.

Backup vehicles for use when scheduled vehicles could not be tested were randomly selected from small vehicle fleets (university employees, students, alumni, church groups, vehicles listed for sale etc.), rather than from the general Southern California vehicle population. This was done because several randomly selected vehicles were brought in late by the owners, then failed a preliminary safety inspection. This required bringing in backup vehicles on short notice to keep the testing on schedule.

3.2.1 High Emitting Vehicle Identification

The recruitment of suspected high-emitting vehicles was the most problematic. For this recruitment, the following strategies were used:

- **Remote Sensing:** Using a remote sensing van, a set of remote sensing measurements was made in the local area. Vehicles that had multiple high measurements were identified by license plate. The license plate data were then matched up with the DMV database in order to get the make and model of vehicle, as well as the address of the owner. Solicitation letters were then sent out to those targeted owners.

- **Local Car Dealers:** Several local car dealerships in the area were asked to inform customers who bring their vehicles in for emissions-related repairs about our study. Prior to having their vehicle fixed by the dealer, some vehicles were recruited for testing. It was hoped that this source would provide us with some newer model year vehicles with high emissions; however only limited success was achieved.

- **Local Rental Agencies and Used Car Dealers**: Local car rental agencies and used car dealers were also contacted to identify high mileage vehicles. Candidate vehicles were brought to the testing site and driven past a remote sensing van. Vehicles that had multiple high remote sensing readings were selected for testing.

- **High Emitter List:** Using the Arizona I/M database of vehicle models with high average failure rates, a subset of the local DMV database of potential high emitting vehicle models was produced. Specific vehicles were then selected randomly from this list. Solicitation letters were sent out to the vehicle owners requesting their participation in the study. The owners would bring their vehicles to the testing site, where they were driven past the remote sensing van. If they had consistently high emissions, they were selected for testing.

In general, the most successful high emitting recruitment strategies were using local rental agencies/used car dealers and the high emitter list. Screening the vehicles with the remote sensing van allowed us to select the cars most likely to be high emitters for further testing.

3.2.2 49-State Vehicle Identification

There are differences between California and 49-state certification levels for many of the vehicle/technology groups. California and federal standards are different for all car groups except the No Catalyst and the Tier 1 technology groups. For the trucks, the differences apply to all groups except the Pre-1979 and the Tier 1 groups.

During recruitment, vehicle owners were asked the state of origin of their vehicles; however many owners of used vehicles do not know the status of the vehicles. The differences in emission control technology between 49-state and California certified vehicles varies by year and manufacturer and in some cases can determine vehicle/technology category. For example, with some manufacturers the three-way catalyst was introduced earlier in the California certified vehicles. In this case vehicles of identical year, make, and model would be split between our two-way and three-way catalyst groups depending on state of certification.

The DMV database contains limited information on whether a vehicle is 49-state or California certified. In the entire subset list generated from the DMV database, an effort was made to also select a good sample of 49-state vehicles when possible. The certification of individual vehicles could only be determined once the vehicle was brought in for testing by looking at the emissions label under the vehicle hood. Approximately 12% of all vehicles tested (18% in categories where differences exist) were 49-state vehicles.

3.2.3 Recruitment Incentive

A varying cash incentive was used to recruit vehicles for testing. Owners of vehicles that were more difficult to recruit generally were given a higher cash incentive. The incentives ranged from nothing to $400, with an average between $150 and $200 per vehicle.

3.3 VEHICLE RECRUITMENT RESULTS

After vehicles were recruited for testing, they underwent an inspection to determine if they were safe to test. During Phase 2, a total of 415 vehicles were recruited. Out of these 415 vehicles, 89 did not pass the initial safety inspection and were rejected. During Phase 4, a total of 41 additional vehicles were recruited. Out of these vehicles, 11 did not pass the safety inspection and were rejected. The primary reason for failure was due to leaks in the vehicle's exhaust system. Because the recruited vehicles are tested in a closed chamber with a driver present, major exhaust leaks cannot be tolerated. Other reasons for rejections include bald tires, bad brakes, major leaks in the oil and radiator systems, etc. The owners of the rejected vehicles were told about the problems with their vehicles; a small percentage made repairs and brought their vehicles back for testing.

3.3.1 High Emitter Cutpoints

After the vehicles were tested, they were categorized as normal- or high-emitting based on their bag emissions values for the FTP cycle. A variety of cut-point definitions for high-emitting vehicles, proposed by several researchers, were reviewed. These emission cut-points are summarized in Table 3.5.

For this study, high-emitting Tier 0 vehicles were defined to be those vehicles having FTP emissions in excess of two times the corresponding FTP standard for CO or HC, or 4 times the corresponding FTP standard for NOx. For Tier 1 vehicles, high-emitting vehicles have FTP emissions in excess of 1.5 times the standard for any pollutant. These cutpoints are in-line with other researchers' definitions of high (rather than very high or super) emitters.

Emission Model/Study	Normal	Moderate	High	Very High	Super
ARB CALIMFAC	CO 1x** HC 1x NOx 1x	CO 1-2x HC 1-2x NOx 1-2x	CO 2-6x HC 2-5x NOx 2-3x	CO 6-10x HC 5-9x NOx 3-4x	CO >10x HC >9x NOx >4x
ARB EMFAC7G	CO 1x HC 1x NOx 1x	CO 1-2x HC 1-2x NOx 1-2x	CO 2-6x HC 2-5x NOx 2-3x	CO 6-10x HC 5-9x NOx 3-4x	CO >10x HC >9x NOx >4x
USEPA MOBILE	CO <=3x HC <=2x		CO >3x HC >2x	CO >4x HC >4x	CO >150 gpm HC >10 gpm
ARB LDVSP12	CO < 3x		CO >3x		
An et al. (1995) Life Cycle	CO 1x HC 1x NOx 1x	CO 1-3.2x HC 1-4.3x NOx 1-2.6x	CO >3.2x HC >4.3x NOx >2.6x		
Remote Sensing	RSD CO < 4% or 5% across all model years		RSD CO > 4% or 5% across all model years		
BAR High Emitting Profile	IM240 CO <2xFTP gpm		IM240 CO >2xFTP gpm		
NCHRP Tier 0	CO <2x HC <2x NOx <4x		CO >2x HC >2x NOx >4x		
NCHRP Tier 1	CO <1.5x HC <1.5x NOx <1.5x		CO > 1.5x HC > 1.5x NOx > 1.5x		

** All numbers expressed in multiples of the Model Year FTP standard unless noted otherwise.

Table 3.5. Cut points used in high-emitting vehicle identification.

3.3.2 Final Category Numbers

After a particular vehicle was tested, it was placed in the appropriate category in the vehicle/technology matrix. If a suspected high emitting vehicle turned out to be normal emitting, it was put in a normal emitting category. Conversely, if a suspected normal emitting vehicle turned out to be high emitting, it was moved to the appropriate high emitting category. Because of these types of shifts, it was difficult to fulfill the target recruitment numbers exactly.

Further, the odometer readings and power to weight ratios are not confirmed for each vehicle until the vehicle was brought in for testing. Therefore, if the maximum power value or odometer turned out to be different than what was known at the time of recruitment, the vehicle's location in the vehicle/technology matrix changed.

The final categorization of all vehicles tested in Phase 2 is given in Table 3.6. Comparing to Table 3.4, it can be seen that we came close to the initial targets in almost all of the cases. However, there are some categories that have many more vehicles than targeted. In any case, this vehicle distribution has proved to be more than adequate for modeling purposes.

A total of 357 vehicle tests were performed in this project (both in Phase 2 and 4). Out of these 357 tests, a total of 343 tests had valid, usable data which were used in developing the comprehensive modal emission model.

3.3.3 High Emitting Vehicles

Out of the 343 total valid vehicle tests, 107 vehicles, or 31% of the tested fleet, were high-emitters. This is by far the largest database of second-by-second, tailpipe and engine-out emissions of high-emitting vehicles assembled to date.

3.3.4 49-State Vehicles

Out of the 343 total valid vehicle tests, 37 vehicles were 49-state emission certified vehicles. This represents 11% of the fleet. When considering only the categories where differences exist, 19% of the fleet were 49-state emission certified vehicles.

Vehicle Technology Category	Number of Vehicles Tested	
Cars	**normal-emitting**	**high-emitting**
No Catalyst	8	
2-way Catalyst	13	
3-way Catalyst, Carbureted	5	11
3-way Catalyst, FI, >50K miles, low power/weight	23	24
3-way Catalyst, FI, >50K miles, high power/weight	17	
3-way Catalyst, FI, <50K miles, low power/weight	18	
3-way Catalyst, FI, <50K miles, high power/weight	8	
Tier 1, >50K miles, low power/weight	12	12
Tier 1, >50K miles, high power/weight	12	
Tier 1, <50K miles, low power/weight	16	
Tier 1, <50K miles, high power/weight	19	
Tier 1, >100K miles	6	
Total Cars	136	68
Trucks	**normal-emitting**	**high-emitting**
Pre-1979 (<=8500 GVW)	6	
1979 to 1983 (<=8500 GVW)	8	
1984 to 1987 (<=8500 GVW)	11	10
1988 to 1993, <=3750 LVW	25	17
1988 to 1993, >3750 LVW	11	
Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	16	5
Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	14	
gasoline-powered LDT (>8500 GVW)	9	
diesel-powered LDT (>8500 GVW)	8	
Total Trucks	94	46

Table 3.6. Vehicle/Technology categories with tested vehicle distribution.

3.3.5 Repeat Vehicles

Of the 343-vehicle fleet, six of the vehicles had repeat tests performed. These vehicles were tested at different times during the testing period, and were valuable in tracking vehicle emissions variability and any influence of time.

3.4 VEHICLE TESTING PROCEDURE

During the early stages of the project, a vehicle testing procedure was developed and applied to the recruited vehicles. This vehicle testing procedure includes the following test cycles:

1) A complete 3-bag FTP test;

2) A high-speed cycle (US06);

3) A modal emission cycle (MEC01) developed by the research team.

A complete FTP test is necessary for two reasons. First, it is the standard certification testing procedure, and provides baseline information about a vehicle's emissions which can be used as a reference to compare with existing tests of other vehicles. Second, FTP Bags 1 and 3 provide information on catalyst efficiency and light-off time during cold and warm starts, which are important components of the model. The primary reason for including the US06 in our test protocol is that EPA is planning to use the US06 as an additional Bag 4 in the supplemental FTP test. In the testing, the FTP driving cycle provides important information on the stoichiometric regime of driving. The US06, on the other hand, specifically targets high emission, non-FTP operation that is characteristic of modern driving patterns. The US06 velocity trace is shown in Figure 3.2.

Even though the US06 cycle was designed to cover off-cycle driving events, it is still not a "modal" emission cycle, i.e., it doesn't provide clear-cut modal emission results; i.e., emissions that can easily be matched to specified speeds, accelerations, or power rates. In order to capture specific modal emission events, we designed a specific modal emissions cycle, the MEC01. The MEC01, described in detail in Section 3.4.2, was developed and iteratively refined during the early stages of the testing phase. During the course of testing, the MEC01 cycle was slightly modified twice. In this project, we primarily used the FTP and MEC01 data for the modal model development and the US06 data as a validation cycle.

3.4.1 Testing Sequence

Several protocols were evaluated during the initial emission testing conducted in the testing phase. For example, a two-step testing sequence was initially used. This consisted of first measuring dilute tailpipe emission rates, followed by a repeat of the same test but time configured to measure catalyst efficiencies.

After an initial analysis of these data, it was determined that operating the test procedure as a two-step process did not provide data that were well suited for model development. In addition, there was too much variability in the modal emission data that the two runs could not be correlated to the degree of accuracy needed for the model. The emission measurement system was then configured to simultaneously measure engine-out and tailpipe emission rates. We also developed a procedure to allow for the comparison of bag and modal emission data as an internal on-going quality assurance check. The final testing sequence is illustrated in Table 3.7.

An IM240 test and a 1-minute idle were inserted between the FTP Bag 3 and the MEC01 tests, primarily for the purpose of warming up vehicles for the ensuing MEC01 cycle. This is necessary since it takes approximately 50 minutes to perform analysis of the bag emissions (30 minutes) and to purge and prepare the analyzers for the next test cycle (20 minutes). Thus, the vehicle would be soaking for roughly 50 minutes before the MEC01 test could begin. Running an IM240 test before the MEC01 ensures that the vehicle is fully warmed up for MEC01 testing. The one minute idle allows the engine to stabilize and the vehicle's brakes to cool prior to the MEC01. Emissions generated during these preconditioning cycles were not measured for analysis.

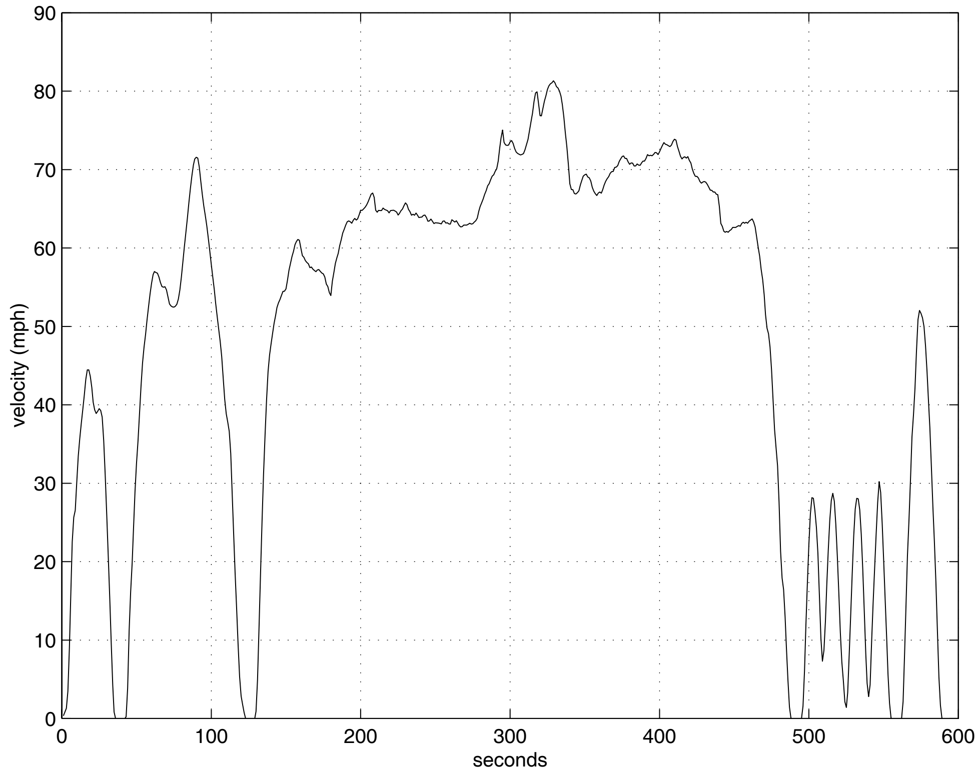

Figure 3.2. US06 velocity trace.

During the initial vehicle testing, we had a unique opportunity to evaluate the effectiveness of these test cycles and identify areas for improvement. Initially, the biggest concern was the length of the entire test procedure for each vehicle. We evaluated each segment of the test procedure to see if any were not directly useful to project goals. After careful analysis of the 30-vehicle emission data, we concluded that each segment of the test procedure has its own merit, thus only marginal modifications were possible. As shown in Table 3.7, we developed four different versions of the NCHRP test sequence in order to minimize the testing time. The particular testing sequence used for a given vehicle depends on the characteristics of that vehicle, as described below. Because the US06 has several hard acceleration and braking events, several vehicles were not able to complete the entire US06. These vehicles were typically model year 1980 and older rear-wheel drive vehicles.

Operation	**NCHRP_A (seconds)**	**NCHRP_B (seconds)**	**NCHRP_C (seconds)**	**NCHRP_D (seconds)**
12-hour soak				
equipment preparation	1,200	1,200	1,200	1,200
FTP Bag 1	505	505	505	505
FTP Bag 2	866	866	866	866
10 minute soak	600	600	600	600
FTP Bag 3	505	505	505	505
FTP bag analysis	1,800	1,800	1,800	1,800
equipment preparation	1,200	1,200	1,200	1,200
IM240 *	240	240	240	240
1 minute idle	60	60	60	60
MEC01	1,000	1,000	1,000	1,000
Repeat Hill	460	460	460	460
AC Hill	460	-	460	-
US06	600	600	-	-
US06 & MEC01 bag analysis	1,800	1,800	1,800	1,800
Total	**11,296 (188min)**	**10,836 (180min)**	**10,696 (178min)**	**10,236 (171min)**

* for vehicle preconditioning only (emissions not collected)

Table 3.7. Four NCHRP Test Sequences

Test Sequence A:

*FTP 3 bag test + IM240 + 1min idle + **MEC01 with both Repeat and AC hills + US06***

This is the default test sequence and was applied to all vehicles that both were capable of completing the US06 cycle and had air conditioners.

Test Sequence B:

*FTP 3 bag test + IM240 + 1 min idle + **MEC01 without AC hill + US06***

This test sequence was applied to all vehicles that were capable of completing the US06 cycle, but did not have operable air conditioners.

Test Sequence C:

*FTP 3 bag test + IM240 + 1min idle + **MEC01 with both Repeat and AC hills (NO US06)***

This test sequence was applied to vehicles that were not capable of completing the US06 cycle, but that did have operable air conditioners. Most of the rear-wheel drive vehicles prior to MY80 were tested under this test sequence.

Test Sequence D:

FTP 3 bag test + IM240 + 1min idle + ***MEC01 without AC hill (No US06)***

This test sequence was applied to vehicles that were not capable of completing the US06 cycle and that did not have operable air conditioners.

3.4.2 MEC01 Cycle

There are two general objectives of constructing the MEC01 cycle:

1) It should cover most speed, acceleration, and specific power ranges that span the performance envelope of most light duty vehicles; and

2) It should be composed of a series of modal events such as:

- various levels of accelerations;
- deceleration events;
- a set of constant cruise speeds;
- speed-fluctuation driving; and
- constant power driving.

Based on feedback from a number of sources, the MEC01 cycle was iteratively refined prior to any substantial vehicle testing. The first version that was used for vehicle emissions data collection was MEC01 version 5.0, shown in Figure 3.3. The MEC01 cycle consists of five different sections:

stoichiometric cruise section, *constant power section*, *constant acceleration section*, *air conditioning hill section*, and *repeat hill cruise section*.

Stoichiometric Cruise Section

This section or "hill" has been designed to measure emissions associated with cruises at eight constant speeds: 5, 35, 50, 65, 80, 75, 50, and 20 mph. Each of these events lasts approximately 20 seconds, except the 65 mph cruise which lasts 40 seconds. All of the acceleration rates in this section are below 3.3. mph/s, the maximum acceleration rate in the FTP. At four of the constant-speed plateaus, there are also "speed fluctuation" events which are common phenomena during in-use driving and may induce transient enrichment spikes. The speed fluctuation is simulated by initially coasting down for three seconds, followed by a mild acceleration back to the initial speed level. This is repeated three times.

It is important to note that there are two 50 mph cruises, one immediately preceded by an acceleration event, the other preceded by a deceleration event. Comparisons between the two have helped establish the impact that recent driving history has on emissions.

Constant Power Section

In this section there are five constant specific-power sub-cycles, with specific power (SP) ranging from 150 to 400 $(mph)^2/s$. Specific power (SP) is approximated as two times the product of velocity (v) and acceleration (a):

$$SP = 2 * v * a.$$

The units of v are mph, a is mph/s, and SP is $(mph)^2/s$. Since the specific power multiplied by the vehicle mass is the kinetic power, the specific power measures kinetic energy used during a driving episode. In the case of the FTP, the maximum SP is 192 $(mph)^2/s$. In the US06, the maximum specific-power is much greater, reaching 480 $(mph)^2/s$. During high power episodes, the kinetic power required to overcome vehicle inertia typically dominates the total power requirements. Thus during high power operation, a constant specific power approximately represents constant total power. The specific power levels from 200 to 300 $(mph)^2/s$ represent moderately high power driving, while a level of 150 is within the power range of the FTP, and a level of 400 requires wide-open-throttle (WOT) operation in most vehicles. This section allows us to detect the thresholds at which vehicles enter a power enrichment state.

Constant Acceleration Section

Five acceleration episodes are included in this section: the first goes from 0 to 25 mph with a constant acceleration rate of 3.5 mph/s; the second from 0 to 20 mph at a constant rate of 4 mph/s. These first two acceleration rates are slightly above the FTP limit of 3.3 mph/s, again intended to capture any on-set of enrichment. The third acceleration episode is from 0 to 25 mph at 4.5 mph/s, followed by two events at wide-open throttle: one from 30 to 50 mph and another from 50 to 70 mph. The last two episodes are designed to test emissions associated with the maximum enrichment level and the application of maximum power of the vehicle.

Air Conditioning Hill Section

The stoichiometric cruise section is repeated in the cycle, this time with the air conditioner on if the vehicle is so equipped. Air conditioning usage can have a drastic effect on emission rates; this section of the cycle allows direct comparison with the initial steady-state cruise section.

Repeat Hill Cruise Section

In order to determine emissions variance for each vehicle within a single test, the stoichiometric cruise section is again repeated, this time with the air conditioning turned off. This repeat hill allows us to directly compare the modal events within the hill or the composite emissions for both hills.

The time intervals between all high acceleration/deceleration modal events in the cycle are at least 30 seconds long, allowing the catalytic converter enough recovery time. Also, there are various deceleration rates in the cycle; however these rates are rather mild in order to avoid brake over-heating during the testing.

The total duration of MEC01 version 5 (including the air conditioning and repeat hills) is 1920 seconds (1160 seconds without the air conditioning and repeat hills). MEC01v5.0 was applied to the first 43 vehicles tested. After that, slight modifications were made to the cycle based on testing results and comments from the NCHRP panel.

MEC01 version 6

Version 6.0 of the MEC01 is shown in Figure 3.4, and includes the following modifications:

Constant Power Section: Among the preliminary tested vehicles, it was found that some vehicles have power enrichment thresholds below K = 150 mph^2/s, the lowest value in the constant power section. Since the major purpose of including these hills with different K-values is to detect the power enrichment threshold, we added a K = 100 mph^2/s hill in this section.

On the other hand, we found that episodes of constant power are not easily achieved due to driver and vehicle limitations. Small speed fluctuations can cause relatively large changes in the actual power demand, especial for high power episodes. Generally, the 150 and 200 mph^2/s were achieved by most vehicles with reasonable accuracy; however, some of the older vehicles had difficulty in achieving the higher power levels. These same vehicles also demonstrated more variability during the constant power episodes. Based on these concerns, as well as to avoid further lengthening of the cycle, we eliminated the K = 250 mph^2/s hill. Thus the new constant power section includes 100, 150, 200, 300 and 400 mph^2/s hills.

Acceleration Section: After much deliberation, we decided to retain this section, since it specifies some constant acceleration modal events, which may occur in real-world driving. However, we have modified the acceleration section by combining the 3 acceleration events into a single event: 0 to 60 mph in 15 seconds, at a constant acceleration rate of 4.0 mph/s. This episode is very similar to that of a vehicle entering a highway on-ramp.

Repeat & AC Hills: Our preliminary analysis showed that CO, NOx, and CO_2 emission rates with air conditioning on were significantly higher across technology groups for normally operating vehicles; however, no significant differences were observed for the malfunctioning/high-emitting vehicles. The repeat hill had significantly higher NOx emissions and lower CO and HC emissions for normally operating vehicles. Again, malfunctioning/high-emitting vehicles did not show consistent increases (or decreases) in any pollutant for the repeat hill.

This suggests that both the AC and repeat hills produce interesting results that would be valuable in modeling emission impacts of air conditioner use and driving variability. The concern is that both hills include the low power cruise section only. Thus in version 6.0, we included two moderate constant power episodes at 150 and 200 mph^2/s. In order to avoid further lengthening this section, we retained only the first half of the cruise section. The duration of each section is now 460 seconds. Unlike version 5 of the MEC01 cycle, the Repeat Hill Section will be tested prior to the AC Hill section in version 6 of the MEC01 cycle.

MEC01 version 7

A total of 82 vehicles were tested using the MEC01v6.0 cycle. Based on further recommendations from the Panel, the repeat portion of the cycle was slightly modified to better identify potential modal history effects (see Figure 3.5). The new repeat hill cycle starts with a rapid acceleration from 0 to 65 mph with a constant acceleration rate of 4.0 mph/s^2, which is a repeat of an episode in the acceleration section. It is immediately followed by a 65 mph cruise and fluctuation driving. This sequence is designed to compare 65 mph cruise driving following a mild acceleration (as in the Cruise Section) and a hard acceleration (as in this section). This event is followed by several cruise and fluctuation driving modes at 35, 5, 20, 75, 80 and 65 mph. The order of these modes has been “scrambled”: each cruise mode follows an opposite acceleration or deceleration event from the original cruise section. For example, the 65 mph cruise follows a deceleration event from the 80 mph cruise driving mode in this repeat section, while in the cruise section, it follows an acceleration event from the 50 mph cruise driving mode. The only exception is the 80 mph cruise driving mode, which is the maximum speed in this cycle, and therefore can only be approached from an acceleration event. In this section, a K = 300 mph/s^2 constant power episode was included to accelerate from 20 mph to 75 mph, which is essentially a repeat of the constant power driving in the constant power section.

In summary, this section includes a hard acceleration event (a = 4.0 mph/s^2), a constant power event (K = 300 mph/s^2), 7 cruise driving events (v = 65, 35, 5, 20, 75, and 65 mph), and 4 fluctuation driving modes (average speed = 65, 35, 20, and 65 mph). The order of these modes is “scrambled” from the original sequence. The new design of the repeat hill allowed us to analyze the history effects of the different modes.

No additional changes were made to the MEC01 cycle after these changes.

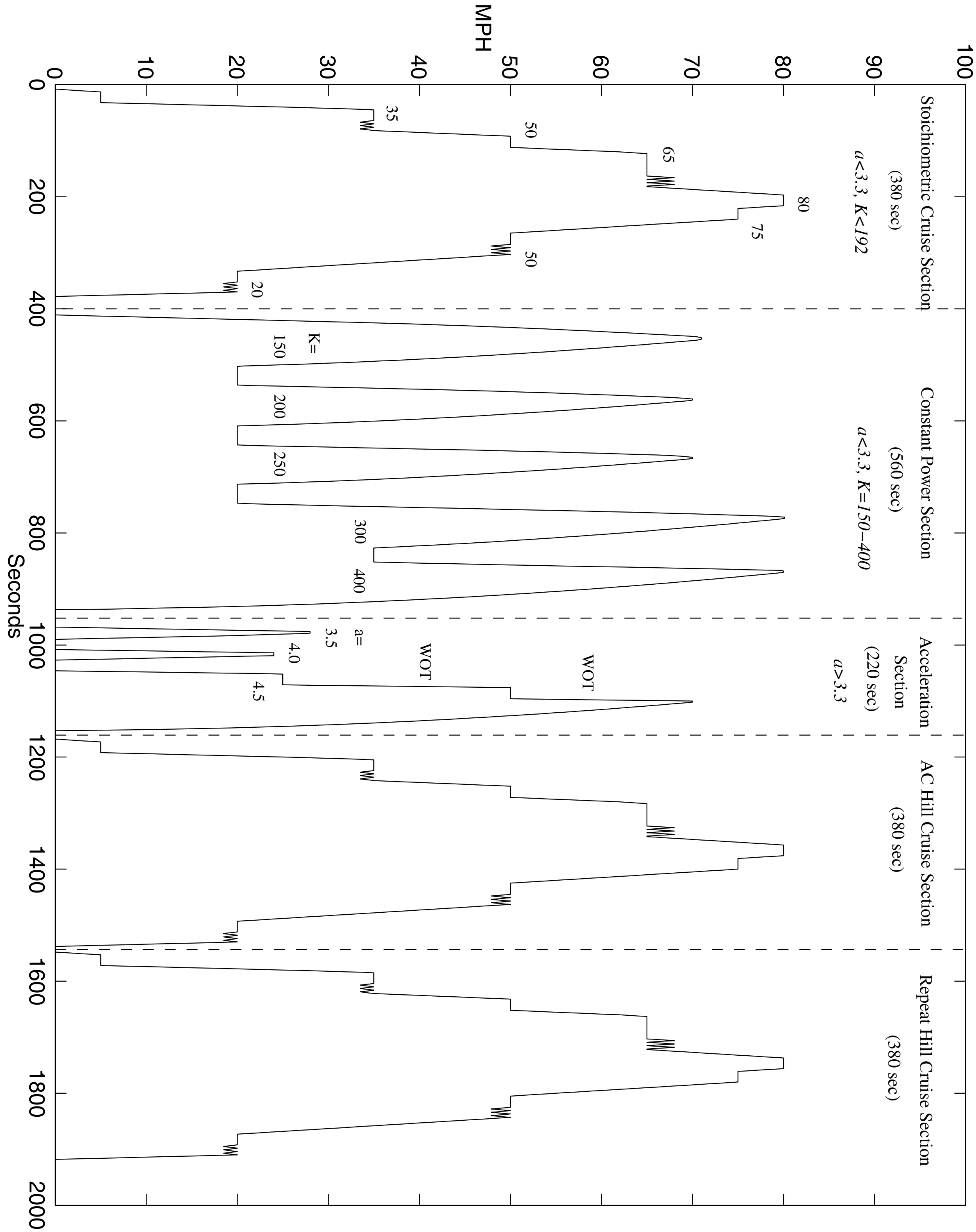

Figure 3.3. MEC01 version 5.0 modal emission cycle.

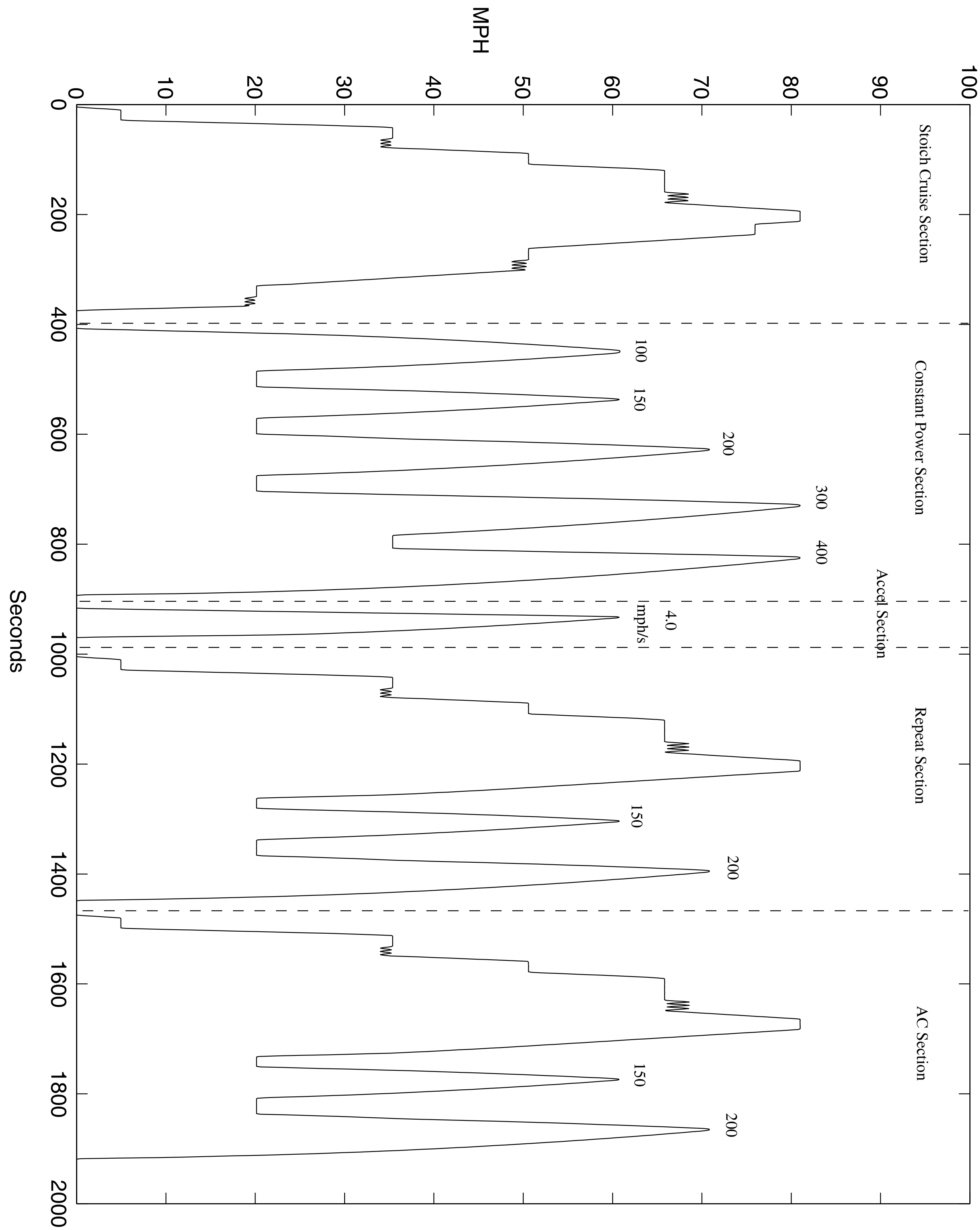

Figure 3.4. MEC01 version 6.0 modal emission cycle.

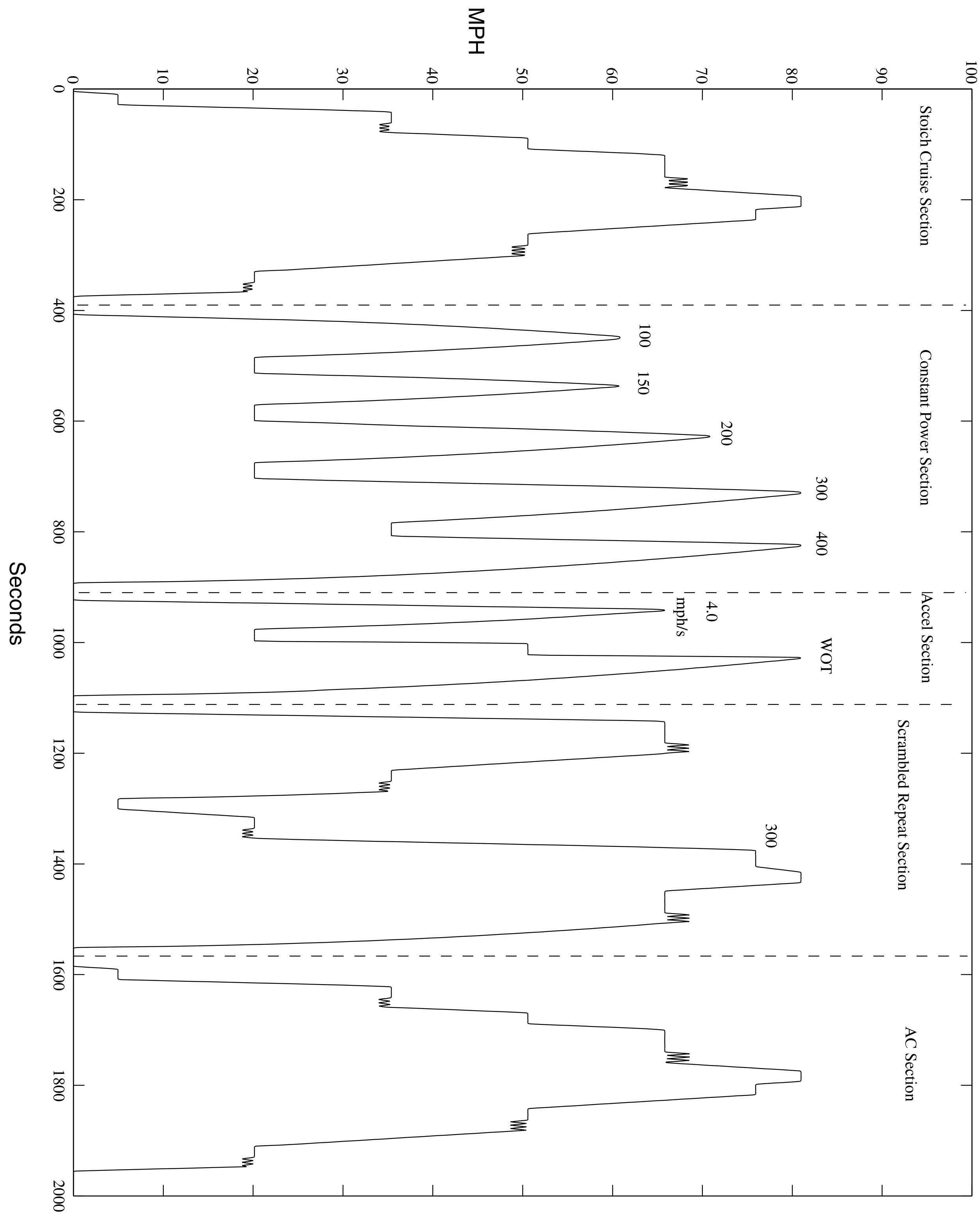

Figure 3.5. MEC01 version 7.0 modal emission cycle.

3.5 EMISSIONS TESTING PERFORMED

In total, 327 vehicle tests were performed over 18 months in Phase 2. Thirty additional vehicle tests were performed in Phase 4. Of the 357 total tests, 343 of the data sets turned out to be valid. A total of 14 tests were rejected due to a number of problems; the most common problem was that the vehicle failed at some point during the test. A vehicle failure in this case was typically an overheating problem. Although adequate ventilation was provided in the test chamber, several vehicles did not have very good cooling systems and thus overheated. When the car failed, the data up to the failure point were recovered; however, partial datasets are not useful for modeling. The other common vehicle failure was brake problems. The high-speed, aggressive US06 cycle required substantial braking of the vehicle. Even with brake assistance from the dynamometer, some vehicles' brakes were just too weak to maintain the cycle without damaging the brakes. All of the valid vehicle tests and their categories are listed in Appendix A.

3.6 DATA PRE-PROCESSING

Data generated from the vehicle emission tests are stored on magnetic/optical drives in two separate databases within CE-CERT. The raw emission data are stored on the Vehicle Emissions Research Laboratory (VERL) host computer. In addition, another complete set of data is stored on the Transportation Modeling Research Group's computer system database. Since the raw emission data must be post-processed and validated before it can be used for modeling purposes, we have developed an automated system for transfer, storing, logging and converting the emission data files. This overall process is described below.

3.6.1 Conversion

The post-processing and conversion of the emission data from VERL is straightforward, but for completeness, it is summarized here. Raw emission data from VERL are received as either concentration values or mass emission values. In March of 1997, a software upgrade on VERL's host computer made it possible for VERL to generate accurate time aligned mass emission data. Most of the emission data files after March 25, 1997 were exported as mass emission files. In a few select instances, where further post-processing was required to correct for problems such as leaks in the sample lines, concentration data was still used. This is discussed further in section 3.7.

Mass emission data are transferred from VERL's host computer to a UNIX-based database and reformatted. These data are then labeled and saved in a final refined data file along with the vehicle name, VERL's test name and the equivalent TSR name. Conversion of concentration data is more involved and is conducted as follows. First, the raw emission data are transferred from VERL into a UNIX-based database and reformatted. Then they are converted from gas concentrations in parts-per-million (ppm) to a mass emission rate in grams per second. This is done using algorithms for the dynamometer and gas analyzers which must account for parameters such as emission densities, exhaust flow rates, and differences in dry and wet gas measurements. The equations and procedure used to account for such factors are given in Appendix B. For both post-processing procedures, the post-processed modal data are appended to a log file which also includes the vehicle name, cumulative modal emission rates in grams per mile for CO_2, CO, HC, and NOx and comparable integrated emission results obtained by the bag analyses. The final step for all the test data is comparing the cumulative modal and integrated bag results as well as making visual checks to determine the need for any more post-processing of the data.

3.6.2 Time Alignment

An important part of the post-processing sequence is to time align all of the emission data. This is a necessary step since there is a time delay inherent in each of the gas analyzer response times. All emission data gathered after March 7, 1997 have been time aligned by VERL's host computer. Prior to this date, VERL's host computer was not able to perform emission data time alignment due to software limitations and it was being done by TSR. For these data, time aligning is done as part of the processing step by simply shifting the pollutant concentrations at each second an appropriate time step. The proper time shift is determined through several steps. An initial time shift for each pollutant is provided by VERL as part of the validation and calibration of the emission benches. The second step is to determine time shifts for each pollution pair via a cross correlation analysis of the second-by-second emission data. The calculated time shifts are then compared to those expected. Since time shifts may be off by less than the one-second increment at which data are collected, time shifts of plus and minus one second are also evaluated. The shifted second-by-second results are integrated and compared with measured bag results for the various pollutants. This is further discussed in Section 3.6.3. The time shift with which the integrated second-by-second results agree most closely is compared with the expected time shifts. Since the time shift is a function of the analyzer system only, it should be consistent across all tests and vehicles. This procedure ensures the accuracy of the time alignment and helps detect any differences in the modal and bag emission values.

3.6.3 Data Storage

For each test cycle, a set of two data files is received from VERL. These are copied and stored on the UNIX platform in a raw-data directory. The first file includes second-by-second data for pre- and post-catalyst emissions, actual and targeted vehicle velocity data and air/fuel ratio data. Emission data in this file are recorded as concentrations in units of ppm or percent volume and velocity data is recorded in units of mph. The second file includes information about the vehicle, test parameters, testing conditions and test results including bag results. These sets of files are backed up and renamed according to their appropriate NCHRP project name in another data directory. This procedure automatically generates a log file which matches the test original name with the NCHRP project name and the current date. In order to make the second-by-second data readily available for modeling purposes, emissions concentrations are converted to mass emission rates using a conversion procedure which is discussed in Section 3.6.1, or simply properly formatted if they already contain mass emission rate data. In addition, the emission data are time aligned as discussed in Section 3.6.2. After pre-processing of the file is complete, a refined version of the second-by-second data file is stored.

3.7 DATA QUALITY ASSURANCE AND CONTROL (QA/QC)

As mentioned above, it is critical for model development that we have confidence in the second-by-second mass emission rates. Of concern is that the dynamic dilution factor needs to coincide with the dynamic gaseous pollutant measurement. Under most conditions this is not a problem. However, during very fast transient events a slight time delay (less than one second) between the two measurements can cause errors in the modal emission rate. Most of these events are during rapid deceleration when there is a rapid decrease in dilution ratio compared to a slower response of the emission analyzer. This results in a higher emission rate for a period of one to two seconds. One way to continually validate our results and check for this problem is to aggregate the second-by-second mass emission rates in grams per second, as described in the previous section. We aggregate these numbers to get the total mass emissions in grams over the entire cycle. By dividing the total grams by the distance of the driving cycle, the emission factors in grams/mile for each bag and each cycle are able to be compared.

Under ideal conditions, bag emissions in grams/mile should agree with both the cumulative second-by-second modal emission rate and the four-mode mass emission rate. Our experience is that the consistency of the results are sensitive to both the type of pollutant and the driving cycle; e.g., the CO_2 results are more consistent than those of the other pollutants, and the FTP cycle results are more consistent than those of either the US06 or the MEC01. The comparisons have allowed us to determine most measurement and conversion problems; for example, we are able to specify any analyzer problem or calibration error, as well as time alignment problems during the sampling and measurement processes.

If any disagreement exists, we perform a visual check of the second-by-second emission profiles for each pollutant. We looked specifically at the time alignment between emissions of each pollutant and the driving trace, as well as the overall emission profile. For example, the engine out CO_2 emissions profile should be similar to that of the engine-out HC and NOx emissions. We also checked to make sure that emission rates at a given second were not unreasonably high or low.

Another method of validating the data is by performing a carbon balance check. This is done by calculating the amount of carbon in the pre- and post-catalyst lines. These two numbers should be approximately equal. Large discrepancies in pre- and post-catalyst lines may indicate a leak in the vehicle test system. In order to test a vehicle, it is necessary to drill and weld a tap for a sample probe. Such a leak could be occurring on the exhaust pipe between the two sampling taps or from one of the taps itself. A leak would cause a portion of ambient air to be drawn in with the sample diluting it, which would result in lower concentrations and, subsequently, in lower mass emission values. By comparing the pre- and post-catalyst carbon numbers, we are able to calculate a second-by-second adjustment factor which can be applied to carbon imbalance data in order to correct it.

At the end of each validation process, the percentage difference between bag and modal data is documented, as well as the problems associated with visual check of the second-by-second emissions profiles. In select cases, testing problems, such as an analyzer going off line briefly, make it difficult to generate comparable bag and integrated modal numbers. Most of the tests have differences between the bag and modal measurements which average around 2.5% for CO_2 emissions, 12.5% for CO emissions, 16% percent for HC emissions and 13.5% for NOx emissions.

3.8 MEASURED VEHICLE PARAMETER DATA

On a subset of vehicles, we were able to directly connect a datalogging tool (*Scan Gra-Fix*™) to retrieve some second-by-second engine system data for all vehicles supported by the tool when used with a 1994 and later Domestic Combination Primary cartridge, a 1993 GM Primary cartridge, or a 1992 and later Asian Import Primary cartridge. With this datalogging tool, we can obtain direct measurements of parameters such as engine speed, throttle position, etc. The collection of these data has proved to be useful in validating many of the intermediate modules of the modal emission model. Each vehicle has a different set of parameters that are reported to the scanning tool. Of the 315 vehicles tested, we recorded vehicle parameters for 87 vehicles (28%). As an example, the datalogging vehicle parameters for a 1992 Ford Taurus are shown in Table 3.8.

TIME	time mark
RPM	Engine Speed (revolutions per minute)
O2S1(mV)	Oxygen Sensor 1 (milli Volts)
O2S2(mV)	Oxygen Sensor 2 (milli Volts)
TP=TPS(V)	Throttle Position
TP MODE	Throttle Position Mode
ECT(V),	Emission Control Temperature
ECT(øF)	Emission Control Temperature
IAT=ACT(V)	Idle Air Temperature
MAF	Mass Air Flow
EPC(PSI)	Evaporative Pressure Control
INJ PW1(mS)	Injector Pulse Width 1
INJ PW2(mS)	Injector Pulse Width 2
VPWR	Vehicle Power
VREF(V)	Vehicle Reference Voltage
SPARK ADV(ø)	Spark Advance (degrees)
WAC=WOT A/C	Wide Open Throttle Air/Conditioning (on/off)
FP=FUEL PUMP	Fuel Pump (on/off)
CANP=PURGE	Canister Purge (on/off)
VEH SPEED(MPH)	Vehicle Speed (miles per hour)
PARK/NEU POS	Park Neutral Position
TR=GEAR	Gear
BOO=BRAKE SW	Brake signal
OPEN/CLSD LOOP	Open Loop
LFC=LO FAN	Low Fan (on/off)
HFC=HI FAN	High Fan (on/off)
ACCS=A/C	AC (on/off)
OCTANE ADJ	Octane Adjustment (on/off)

Table 3.8. Example Vehicle Parameter Data for 1992 Ford Taurus.

4 Modal Emission Model Development

This chapter provides a general description of the developed modal emissions model. In general, the model is a physical, power-demand model based on a parameterized analytical representation of emissions production. In this model, the emission process is broken down into different components or modules that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is then modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary based on several factors, such as vehicle/technology type, fuel delivery system, emission control technology, vehicle age, etc. Because these parameters typically correspond to physical values, many of the parameters are stated as specifications by the vehicle manufacturers, and are readily available (e.g., vehicle mass, engine size, aerodynamic drag coefficient, etc.). Other key parameters relating to vehicle operation and emissions production must be determined from a testing program, described in the model calibration procedure.

The main purpose of the comprehensive modal emission model is to predict vehicle tailpipe emissions associated with different modes of vehicle operation, such as idle, cruise, acceleration, and deceleration. These modes of operation may be very short (i.e., a few seconds) or may last for many seconds. Moreover, the model must deal with the following operating conditions:

1) variable starting conditions (e.g., cold start, warm start);

2) moderate-power driving (i.e., driving for the most part within the FTP performance envelope);

3) "off-cycle" driving (i.e., driving that falls outside the FTP performance envelope; this typically includes enrichment and enleanment events).

As discussed previously, we are concerned with a variety of in-use vehicles that vary by model, age, and condition (i.e., emissions control system deterioration or malfunction). Therefore, one needs to consider both temporal and vehicular aggregations:

Temporal Aggregation:	*second-by-second → several seconds (mode) → driving cycle or scenario*
Vehicle Aggregation:	*specific vehicle → vehicle/technology category → general vehicle mix (fleet)*

Using a bottom-up approach, the basic building block of our physical-based emissions model is the individual vehicle operating on a fine time scale (i.e., second-by-second). However, the model itself does not focus on modeling specific makes and models of vehicles. Our primary goal is the prediction of emissions in several-second modes for average, *composite vehicles* within each of the vehicle/technology categories specified in Table 4.1. Modeling at a higher level of detail is of limited value for two reasons:

1) At the second-by-second level, there can be major fluctuations in driving patterns, with large short-term emissions consequences. Major fluctuations in throttle position are common in dynamometer tests using standard driving cycles, as the driver corrects for overshooting or undershooting the target speed trace. Information on the frequency and intensity of throttle fluctuations in actual driving is not readily available, as they depend on specific road and traffic conditions. Therefore in our present view, some time-averaging process is desirable in the model.

2) It would be difficult (and outside the scope of the project) to attempt to develop a separate formalism for all vehicle models based on measured parameters describing engine and emission control system (ECS) behavior, including rates of ECS deterioration and failure for each vehicle. Instead, we are developing the generic characterization of a composite vehicle within each vehicle/technology category specified in Table 4.1. The composite vehicle (in each category) is determined based on an appropriately weighted emissions average of all vehicles tested in the category. Generic parameters are then modeled as part of the composite vehicle emissions model. Using this generic approach, one obtains good modal-emissions predictions for composite cars. Model accuracy also improves considerably with temporal aggregation.

Category #	Vehicle Technology Category
	Normal Emitting Cars
1	No Catalyst
2	2-way Catalyst
3	3-way Catalyst, Carbureted
4	3-way Catalyst, FI, >50K miles, low power/weight
5	3-way Catalyst, FI, >50K miles, high power/weight
6	3-way Catalyst, FI, <50K miles, low power/weight
7	3-way Catalyst, FI, <50K miles, high power/weight
8	Tier 1, >50K miles, low power/weight
9	Tier 1, >50K miles, high power/weight
10	Tier 1, <50K miles, low power/weight
11	Tier 1, <50K miles, high power/weight
24	Tier 1, >100K miles
	Normal Emitting Trucks
12	Pre-1979 (<=8500 GVW)
13	1979 to 1983 (<=8500 GVW)
14	1984 to 1987 (<=8500 GVW)
15	1988 to 1993, <=3750 LVW
16	1988 to 1993, >3750 LVW
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)
25	Gasoline-powered, LDT (> 8500 GVW)
40	Diesel-powered, LDT (> 8500 GVW)
	High Emitting Vehicles
19	Runs lean
20	Runs rich
21	Misfire
22	Bad catalyst
23	Runs very rich

Table 4.1. Vehicle/Technology modeled categories. Note diesel vehicles start at category 40; "blank" categories are user programmable from category #60.

Table 4.1 comes directly from the vehicle/technology categories developed and specified in Section 3.1.3 (Table 3.4), with the following exception: Because many of the high emitting vehicles had disparate emission results when categorized by technology group, the high emitting vehicles were re-categorized into groups with similar emission characteristics. Grouping high emitters by emission profiles produced much more homogeneous groups than grouping by technology category. These characteristics are described in detail in Section 4.12, and include running lean, running rich, misfiring, having a bad catalyst, and running very rich.

Separate sub-models for each vehicle/technology category listed in Table 4.1 have been created. All of these sub-models have similar structure; however the *parameters* used to calibrate each sub-model are different. Each calibrated sub-model corresponds to a composite vehicle representing the characteristics of a particular vehicle/technology category.

In developing these sub-models, it is important to strike a balance between achieving high modeling accuracy and reducing the number of model input parameters. Because the design, calibration, and in-use conditions of vehicles vary greatly, there is always the temptation to add more input parameters for special situations of different vehicles to improve modeling accuracy. In order to control the number of independent input parameters, focus has been placed on the most common emission mechanisms, rather than trying to accommodate every special vehicle case.

In the following sections, the general structure of the model is first discussed, followed by the details of each module. The parameterization of the sub-models is then addressed in detail. Finally, the high-emitting vehicle modeling is described.

4.1 GENERAL STRUCTURE OF THE MODEL

In the developed modal emissions model, second-by-second vehicle tailpipe emissions are modeled as the product of three components: fuel rate (FR), engine-out emission indices ($g_{emission}/g_{fuel}$), and time-dependent catalyst pass fraction (CPF):

$$\begin{matrix}\text{tailpipe}\\\text{emissions}\end{matrix} = FR \bullet \left(\frac{g_{emission}}{g_{fuel}}\right) \bullet CPF \qquad (1)$$

Here FR is fuel use rate in grams/s, engine-out emission index is grams of engine-out emissions per gram of fuel consumed, and CPF is the catalyst pass fraction, which is defined as the ratio of tailpipe to engine-out emissions. CPF usually is a function primarily of fuel/air ratio and engine-out emissions.

The complete modal emissions model is composed of six modules, as indicated by the six square boxes in Figure 4.1: 1) engine power demand; 2) engine speed; 3) fuel/air ratio; 4) fuel-rate; 5) engine-out emissions; and 6) catalyst pass fraction. The model as a whole requires two groups of input (rounded boxes in Figure 4.1): A) input operating variables; and B) model parameters. The output of the model is tailpipe emissions and fuel consumption.

There are also four operating conditions in the model (ovals in Figure 4.1): a) variable soak time start; b) stoichiometric operation; c) enrichment; and d) enleanment. Hot-stabilized vehicle operation encompasses conditions b) through d); the model determines in which condition the vehicle is operating at a given moment by comparing the vehicle power demand with two power demand thresholds. For example, when the vehicle power demand exceeds a power enrichment threshold, the operating condition is switched from stoichiometric to enrichment. The model does not inherently determine variable soak time; rather, the user (or integrated transportation model) must specify the time the vehicle has been stopped prior to being started. The model does determine when the operating condition switches from a cold start condition to fully warmed-up operation. Figure 4.1 also shows that the operating conditions have direct impacts on fuel/air ratio, engine-out emissions, and catalyst pass fractions.

The vehicle power demand (1) is determined based on operating variables (A) and specific vehicle parameters (B). All other modules require the input of additional vehicle parameters determined based on dynamometer measurements, as well as the engine power demand calculated by the model.

The fuel/air equivalence ratio (which is the ratio of stoichiometric air/fuel mass ratio, roughly 14.7 for gasoline) to the instantaneous air/fuel ratio), ϕ, is approximated only as a function of power, and is modeled separately in each of the four operating conditions a) through d). The core of the model is the fuel rate calculation (4). It is a function of power demand (1), engine speed (2), and fuel/air ratio (3). Engine speed is determined based on vehicle velocity, gear shift schedule and power demand.

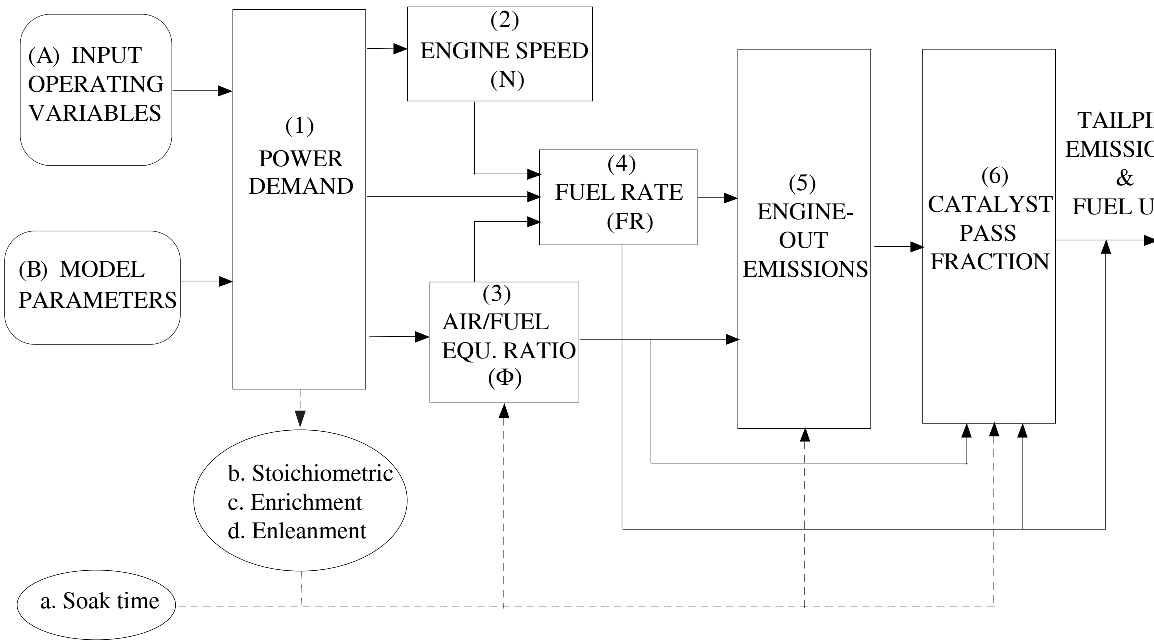

Figure 4.1. Modal Emissions Model Structure

In the next few sections, each of the six modules is described. The four operating conditions are discussed in conjunction with these six module descriptions. It is important to note that this generic model with its modules applies to the 26 different vehicle/technology categories defined in Table 4.1*. Differences between the sub-models show up only in their defining parameters.

4.2 ENGINE POWER DEMAND MODULE

The establishment of a power demand function for each vehicle is straightforward. The total tractive power requirements (in kW) placed on the vehicle (at the wheels) is given as:

$$P_{tract.} = A \cdot v + B \cdot v^2 + C \cdot v^3 + M \cdot (a \cdot 0.447 + g \cdot sin\theta) \cdot v \cdot 0.447 / 1000 \qquad (2a)$$

where *M* is the vehicle mass with appropriate inertial correction for rotating and reciprocating parts (kg), *v* is speed (miles/hour or mph), *a* is acceleration (mph/second^2), *g* is the gravitational constant (9.81

* Note that the diesel truck category uses a modified architecture, see Section 4.12.

meters/s^2), and θ is the road grade angle in degrees. Here the coefficients A, B, and C involve rolling resistance, speed-correction to rolling resistance, and air drag factors, as has been widely discussed.

If some or all of these parameters are unknown, coefficients can be obtained from coastdown data obtained in connection with the FTP and available in the EPA coastdown coefficients database [Paulina et al., 1994; SAE, 1991; USEPA, 1994]. A, B and C can be estimated based on the procedure outlined in the IM240 test procedure and using the equipment specifications developed by the US EPA [USEPA, 1994]. This procedure divides the tractive road-load horsepower at 50 mph (TRLHP@50) into the three components, which are determined by the vehicle manufacturer as specified in a SAE procedure [SAE, 1991]. In the absence of new car certification coefficients or a vehicle class designator, the following track coefficients can be used:

$$A = (0.35/50)*\text{TRLHP (hp/mph)} = 0.0052*\text{TRLHP (kW/mph)}$$

$$B = (0.10/2500)*\text{TRLHP (hp/mph}^2) = 2.9828\text{E-}05*\text{TRLHP (kW/mph}^2) \qquad (2b)$$

$$C = (0.55/125{,}000)*\text{TRLHP (hp/mph}^3) = 3.2811\text{E-}06*(\text{kW/mph}^3)$$

In this approximation, A, B, and C only rely on a single variable: TRLHP.

To translate the tractive power requirement to demanded engine power requirements, the following relationship applies:

$$P = \frac{P_{tract.}}{\varepsilon} + P_{acc} \qquad (3)$$

where P is the second-by-second engine power output in kW, ε is vehicle drivetrain efficiency, and P_{acc} is the engine power demand associated with the operation of vehicle accessories such as air conditioning usage.

4.2.1 Drivetrain Efficiency Modeling

Research has demonstrated that the torque converter and transmission efficiency are functions of engine speed and engine torque. Drivetrain efficiency drops at low engine speed range due to torque converter slippage. For older vehicles (which don't have clutch lock up) torque converter efficiency also drops in the high engine torque range. Vehicle drivetrain efficiency can be approximated as a function of speed and specific power. Specific power (SP) is defined as 2*acceleration*velocity (in mph^2/s) and is a measure of vehicle kinetic energy change. We found that the drivetrain efficiency is low at very low speeds, but increases to near its maximum at around 30 mph. The drivetrain efficiency then declines slightly as specific power increases (into a high power range, where SP > 100 mph^2/s). Thus the drivetrain efficiency ε can be modeled as follows:

$$\varepsilon = \begin{cases} \varepsilon_1 \\ \varepsilon_1 \cdot [1 - \varepsilon_2 \cdot (1 - \frac{v}{30})^2], \ldots\ldots\ldots\ldots a > 0, v < 30mph \\ \varepsilon_1 \cdot [1 - \varepsilon_3 \cdot (\frac{SP}{100} - 1)^2], \ldots\ldots\ldots\ldots SP > 100 \frac{(mph)^2}{s} \end{cases} \quad (4)$$

where ε_1 ranges from 70-93% is the maximum drivetrain efficiency, $\varepsilon_2 \approx 1.0$ is a coefficient for low speed driving, and ε_3 ranges from 0.0 – 0.2, which is a coefficient during high-power driving. Figure 4.2 illustrates a typical relationship between drivetrain efficiency and vehicle speed (ε_3 = 0.1 is assumed here). It shows that the vehicle reaches the maximum drivetrain efficiency when it cruises at speeds greater than 30 mph. Vehicle drivetrain efficiency drops both at lower speeds and at higher SP values.

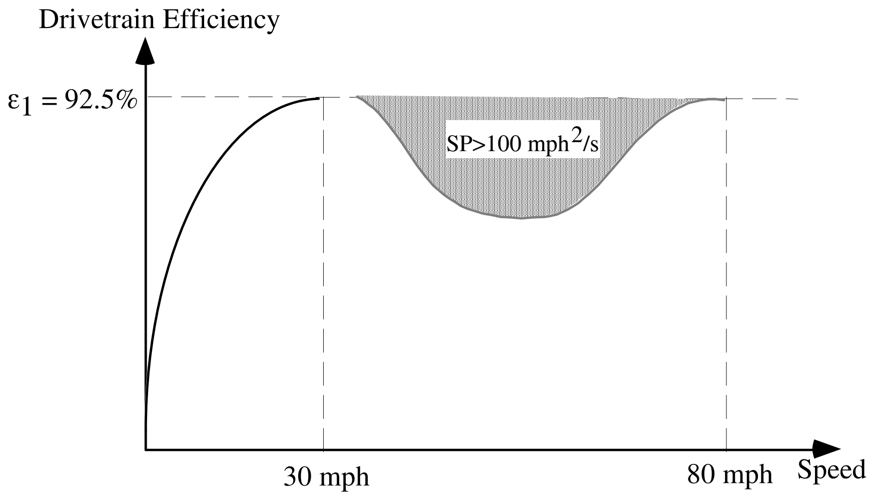

Figure 4.2. Drivetrain Efficiency vs. Speed under MEC01 cycle

Please keep in mind that Figure 4.2 is only illustrative and doesn't necessarily correspond to specific values or test cycles. Specifically, the lowest point in the figure corresponds to the highest specific power (SP) value, not any given speed value.

4.3 ENGINE SPEED MODULE

The first approximation for engine speed is to simply express it in terms of vehicle speed:

$$N(t) = S \cdot \frac{R(L)}{R(L_g)} \cdot v(t) \tag{5}$$

where: N(t) = engine speed (rpm) at time t, S is the engine-speed/vehicle-speed ratio in top gear L_g (known as N/v in units rpm/mph), R(L) is the gear ratio in L_{th} gear, L = 1,...,Lg, and v(t) is the vehicle speed (mph) at time t. Gear ratio is selected from a given set of shift schedules.

Under certain circumstances, especially for high-power events, down-shifting is required as determined by a wide-open-throttle (WOT) torque curve. The general relationship between torque and power output of the engine is:

$$Q(t) = \frac{P(t) \cdot 5252}{N(t)} \tag{6}$$

where *Q(t)* = engine torque in ft.lb at time t and *P(t)* is engine power in hp. The engine torque at any engine speed must not exceed the WOT torque, $Q_{WOT}(t)$. The latter is estimated from the following approximation based on a typical spark-ignited engine performance map:

$$Q_{WOT}(t) = Q_m[1 - 0.25 \cdot \frac{N_m - N(t)}{N_m - N_{idle}}] \qquad \text{if } N(t) \leq N_m \qquad (7a)$$

$$Q_{WOT}(t) = Q_m[1 - (1 - \frac{Q_p}{Q_m}) \cdot \frac{N(t) - N_m}{N_p - N_m}] \qquad \text{if } N(t) > N_m \qquad (7b)$$

where Q_m is the maximum torque, N_m is the engine speed at maximum torque, Q_p is the torque at maximum power, and N_p is the engine speed at maximum power. Figure 4.3 demonstrates the approximated WOT torque contour curve.

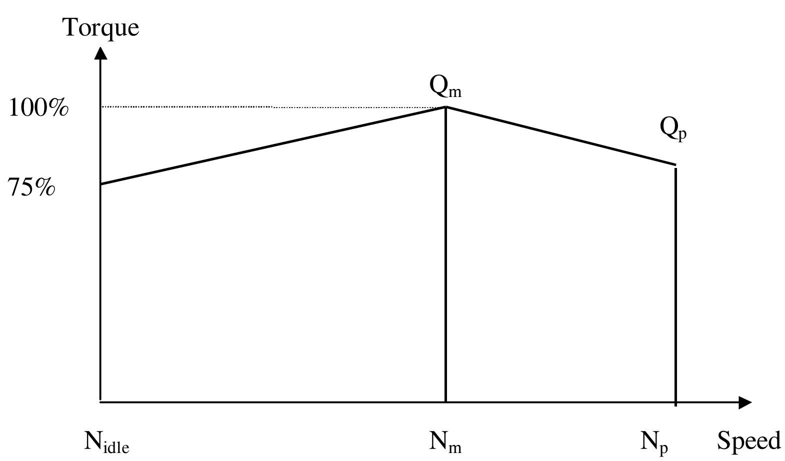

Figure 4.3. Approximation of Engine WOT Torque and Speed Relationship

When the calculated Q(t) is greater than $Q_{WOT}(t)$, the vehicle downshifts to the next lower gear. New values of engine speed, torque, and the WOT torque are calculated from the above equations. If necessary, this process is repeated (i.e., a second downshift is considered) to satisfy the operating conditions.

Engine Speed (RPM) Validation

As the model was developed, we performed intermediate variable validation with actual measurements. As discussed in Section 3.8, many second-by-second engine parameters were measured on a subset of vehicles. For engine speed modeling, our modeling results have shown satisfactory agreement on a second-by-second basis. As an example, Figure 4.4 shows the measured and modeled engine speed for a MY93 Saturn SL2 under the MEC01 cycle. In Figure 4.4, the first plot is the MEC01 cycle speed trace. The second plot is the second-by-second engine speed in RPM. The solid line represents the modeling results and the dashed line represents the measured results.

4.4 FUEL/AIR EQUIVALENCE RATIO MODULE

The fuel-air equivalence ratio domain is divided into three regions: lean, stoichiometric (roughly $0.98 < \phi < 1.02$, depending on the application), and rich. Although even small variations in fuel-air ratio within the stoichiometric region might be significant, we do not attempt to model them (the primary reason for this decision is that the uncertainty in the measured ratio must be less than 1%). In this section, we describe the fuel-air equivalence ratio modeling under enrichment, enleanment, and cold start operation conditions respectively.

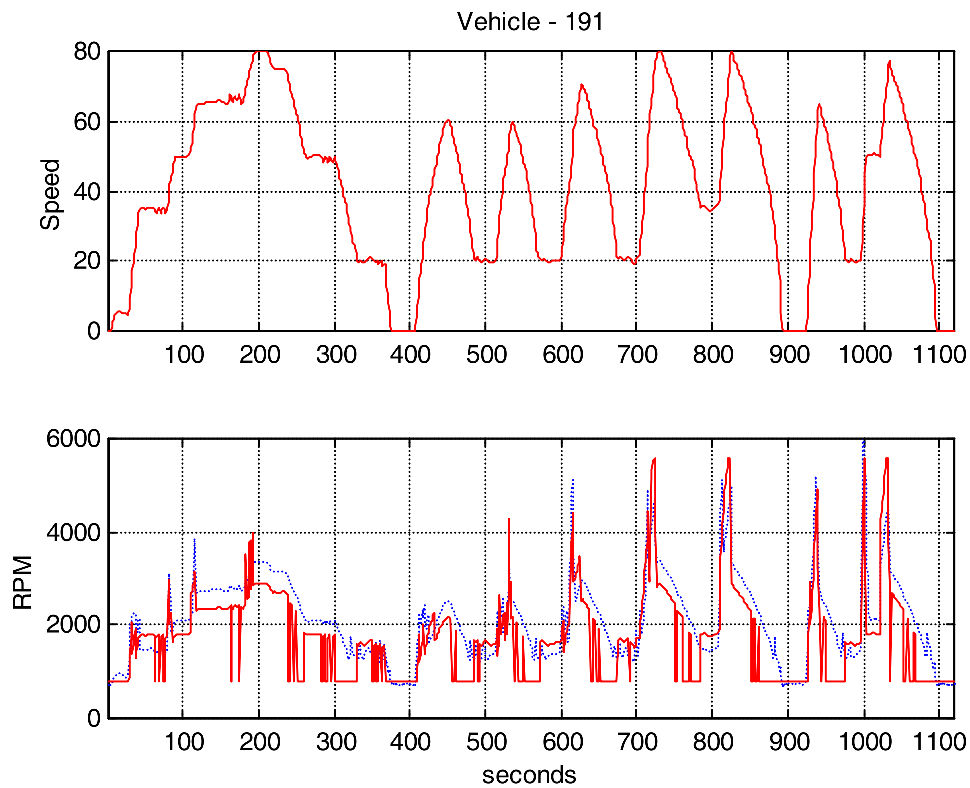

Figure 4.4. Measured and modeled second-by-second engine speeds for a MY93 Saturn SL2 under the MEC01 cycle. The solid line represents the modeling results and the dashed line represents the measured results.

4.4.1 Enrichment Operation

It is common practice to design vehicles to operate with a rich mixture under high power conditions, in effect altering emissions control principles that attempt to maintain a stoichiometric ratio (enrichment is also used during cold start operation). There are two critical issues related to estimation of enrichment. One is the threshold at which the fuel/air ratio changes from stoichiometric to rich and the other is the degree of enrichment. Based on the 350+ tested vehicles, vehicle enrichment thresholds vary widely from vehicle to vehicle. The variables used in modern computer-controlled fuel injection to determine the threshold vary as well as the thresholds themselves. In general, enrichment is primarily a function of demand power and acceleration. However, when averaging over many vehicles, we find it adequate to model enrichment in terms of a simple power or torque threshold.

The engine power or torque (P or Q) at which the equivalence ratio becomes greater than 1.02 can be taken as the enrichment threshold (P_{th} or Q_{th}). In our model, enrichment operation occurs when torque demand (Q) is larger than the corresponding enrichment threshold Q_{th}, that is:

$$\phi > 1.02\,, \quad \text{when } Q > Q_{th} = (P_{th} / 0.7457)*5252/N \tag{8a}$$

where P_{th} is the power enrichment threshold determined as:

$$P_{th} = P_{scale}*(0.5*M*SP_{max}*(0.447)^2/(1000)+ Z_{drag})/\varepsilon_1 \tag{8b}$$

where P_{scale} is a power threshold dimensionless scaling factor. It is a calibrated variable that can only be determined through measurement. SP_{max} = 192 mph^2/s is the maximum FTP specific power. M is vehicle mass is kg, Z_{drag} is power demand from air and tire drag term in kW, N is engine speed in rpm, and ε_1 is a transmission efficiency in Equation (4). SP is in mph^2/s, P is in kW and Q is in lb.ft. Above the threshold, the equivalence ratio is assumed to increase linearly with torque Q up to a maximum value ϕ_0 corresponding to a WOT torque level. Thus:

$$\phi = 1 \qquad \text{if } Q \le Q_{th}$$

$$\phi = 1 + \frac{(Q - Q_{th})}{(Q_{WOT} - Q_{th})} \bullet (\phi_0 - 1) \qquad \text{if } Q > Q_{th} \tag{9}$$

where Q_{WOT} is engine torque at WOT. ϕ_0 is the measured fuel/air equivalence ratio at WOT. The approximation of hot-stabilized fuel/air equivalence ratio as a function of engine power demand is given by Figure 4.5.

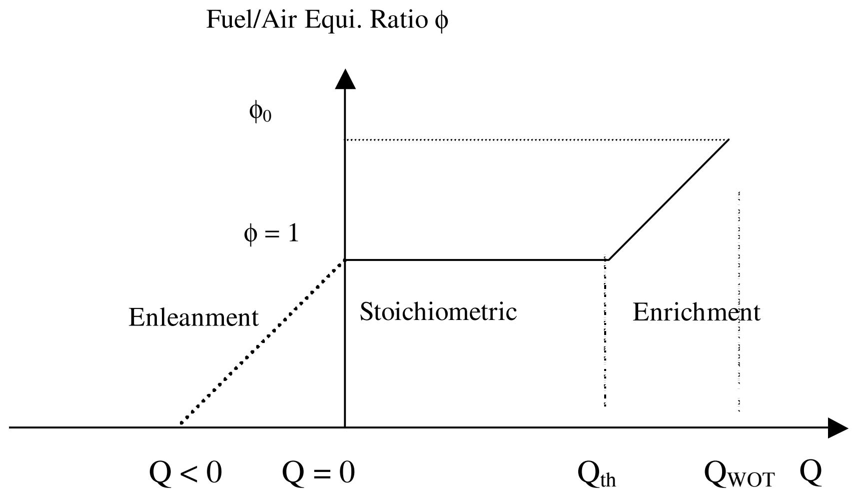

Figure 4.5. Approximation of Hot-stabilized Fuel/Air Equivalence Ratio as a Function of Engine Torque.

4.4.2 Enleanment Operation

The estimation of enleanment fuel/air ratio is not as critical as the estimation of enrichment fuel/air ratio, since only the latter is directly used in modeling vehicle emissions [An et al., 1996; An et al., 1997]. However, it is still important to determine when substantial enleanment occurs, rather than how severe the enleanment is. Our research shows that enleanment HC emissions associated with both aggressive transient and lasting deceleration episodes are significant; CO and CO_2 emissions during enleanment are negligible (for details on this analysis, see [An et al., 1998]). Enleanment HC emissions are modeled without direct involvement of fuel/air ratio, as described in Section 4.6.2 (also see [An et al., 1998]). For NO_x emissions, enleanment events usually induce several seconds of delay in catalyst efficiency recovery, resulting in an increase in NO_x emissions immediately following the enleanment events. This is discussed in Section 4.7.

4.4.3 Cold-Start Operation

During a cold-start, the engines of most vehicles operate with a rich fuel mixture. The following equations are introduced to address this phenomenon:

$$\phi(t) = \left\{1 + (\phi_{cold} - 1) \bullet \left(\frac{T_{cl} - T_{su}(t)}{T_{cl}}\right)\right\} \bullet \phi_{hot}(t) \qquad \text{if } T_{su}(t) < T_{cl} \qquad (10a)$$

$$\phi(t) = \phi_{hot}(t) \qquad \text{if } T_{su}(t) \geq T_{cl} \qquad (10b)$$

where ϕ_{hot} is the hot stabilized fuel/air equivalence ratio given by equation (9), ϕ_{cold} is the maximum value of fuel/air equivalence ratio during cold start, T_{su} is a surrogate temperature defined as:

$$T_{su}(t) = \sum_{j=1}^{t} FR(j) \qquad (11)$$

and T_{cl} is the cold-start surrogate threshold temperature when the engine reaches close-loop control. FR(j) is calculated fuel rate at the jth second. Since the engine temperature increase is directly related to the cumulative fuel consumption, the surrogate temperature is a good surrogate variable to represent the real temperature. Equation (10) states that the fuel/air mixture will be the richest during the initial second and gradually decreases to reach closed-loop control after the surrogate temperature T_{cl} is achieved, as illustrated in Figure 4.6.

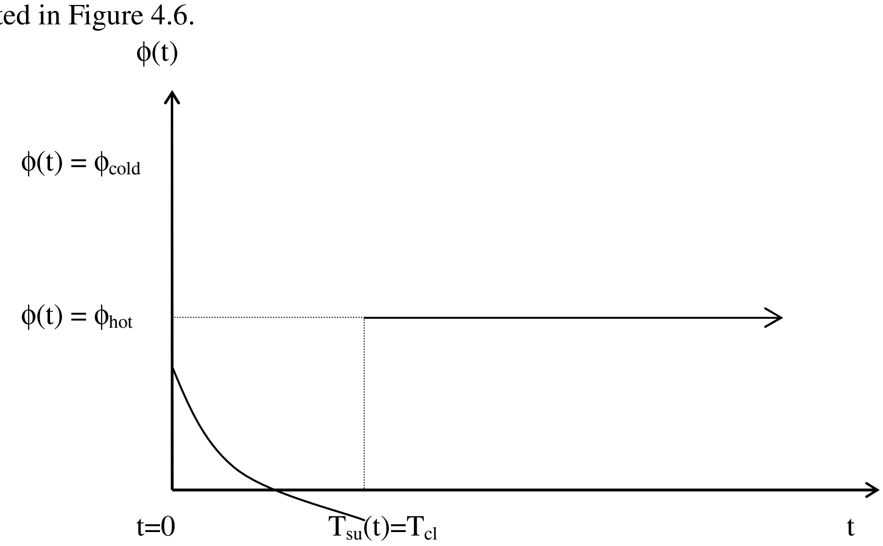

Figure 4.6. Relationship between fuel/air equivalence ratio ϕ and cold start time t.

Validation of Fuel/Air Equivalence Ratio during Hot-Stabilized Operation

As part of the intermediate variable validation, we have also compared the modeled and measured fuel/air equivalence ratio ϕ for a number of vehicles. An example is shown in Figure 4.7 for the MY93 Saturn SL2 under the MEC01 cycle. In Figure 4.7, the first plot is the MEC01 cycle speed trace. The second plot is the measured second-by-second fuel/air equivalence ratio ϕ. The solid line represents the modeling results and the dashed line represents the measured results. In general, we obtain reasonable results for most of the vehicles.

4.5 FUEL RATE MODULE

Modeling the fuel rate in any driving cycle for any vehicle has been previously discussed [An et al., 1993; Ross et al., 1993]. With the possibility of a rich mixture, this model can be expressed as:

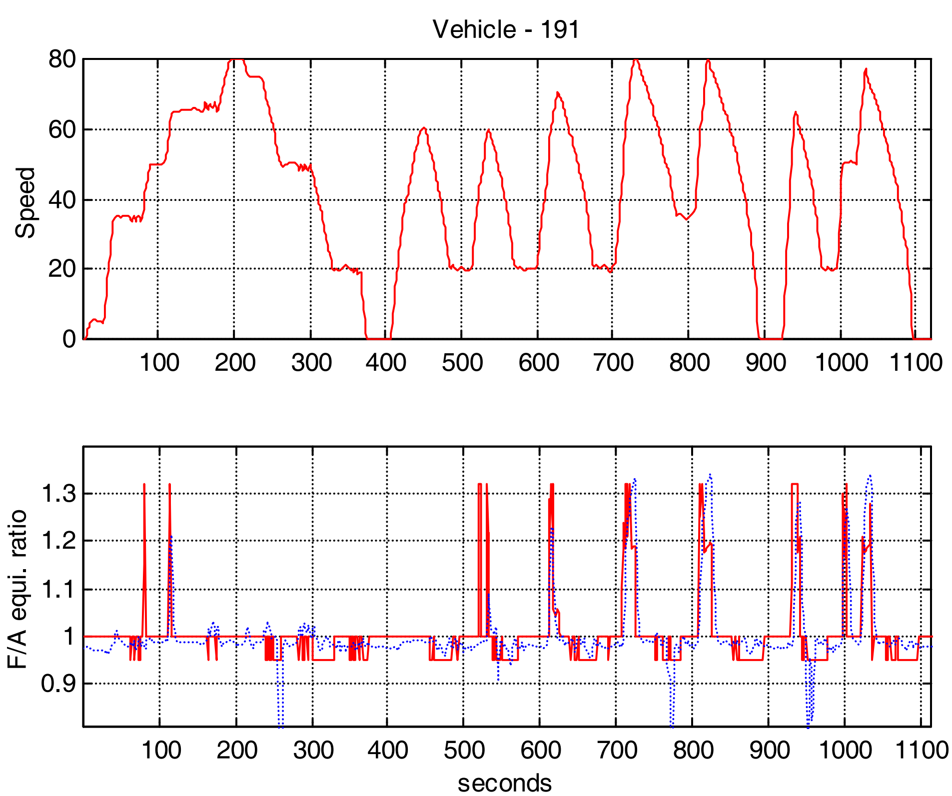

Figure 4.7. Measured and modeled second-by-second fuel/air equivalence ratio for a MY93 Saturn SL2 under the MEC01 cycle. The solid line represents the modeling results and the dashed line represents the measured results.

$$FR(t) = \phi(t) \cdot (K(t) \cdot N(t) \cdot V + \frac{P(t)}{\eta}) \cdot \frac{1}{44} \qquad \text{for P > 0} \qquad (12a)$$

$$FR(t) \ = \ K_{idle} * N_{idle} \ * V \qquad \text{for P = 0} \qquad (12b)$$

where *FR(t)* is fuel use rate in grams/second, *P(t)* is engine power output in kW, and *K(t)* is called the engine friction factor and is described below, K_{idle} is a engine friction factor during engine idling. *N(t)* is engine speed (revolutions per second), N_{idle} is idling engine speed in rps, *V* is engine displacement, and $\eta \approx 0.4$ is a measure of indicated efficiency. 44 kJ/g is the lower heating value of a typical gasoline. $\phi(t)$ is the fuel/air equivalence ratio.

For model years in the 1980s and 1990s, a satisfactory approximation is:

$$K \approx K_0 * [1 + (N(t) - 33)^2 * 10^{-4}](kJ / (rev * liter)). \qquad (13a)$$

$$K_{idle} \approx 1.5 * K_0 \qquad (13b)$$

K represents the fuel energy used to overcome engine friction per engine revolution and unit of engine displacement. For early-to mid-1990s cars, K_0 ranges from 0.19 - 0.25 kJ/(rev*liter).

4.6 ENGINE-OUT EMISSIONS MODULE

In this section, we first describe the modeling of hot-stabilized engine-out CO, HC, and NOx emissions, then the modeling of cold-start engine-out emission multipliers for these pollutants.

4.6.1 Engine-Out CO Emissions

Our analysis shows that there is a strong correlation between fuel use and engine-out emissions. The engine-out CO emission rates can be estimated as [An and Ross, 1996]:

$$ECO \approx [C_0 * (1 - \phi^{-1}) + a_{CO}]FR \qquad (14)$$

where *ECO* is the engine-out emission rate in g/s. Here C_0 is approximately 3.6, and a_{CO} is the CO emission index coefficient (emissions in g/s divided by fuel use in g/s). The first term of the above equation represents enrichment-related processes. The second term is also present at stoichiometry.

4.6.2 Engine-Out HC Emissions

HC Emissions under Stoichiometric and Enrichment Conditions

Engine-out HC emissions (EHC) are essentially proportional to fuel rate and not sensitive to the fuel/air equivalence ratio:

$$EHC_{comb} \approx a_{HC} \bullet FR + r_{HC} \tag{15}$$

where EHC is in g/s, a_{HC} is the HC emission index coefficient, and $r_{HC} \approx 0$ is a small residual value.

HC Emissions under Enleanment Conditions

We have identified two major sources of the enleanment HC emissions (HC_{lean}): transient HC emission spikes associated with speed fluctuation driving events, and enleanment HC puffs associated with long deceleration events [An et al., 1998]. We model these two events separately.

Transient Hydrocarbons Emissions Associated with the Rapid Load Changes

The transient hydrocarbons emissions are associated with rapid load reduction. After carefully analyzing the second-by-second data, we found that the severity of the HC spikes is roughly proportional to the rate of change of specific power: $\delta SP = d(SP)/dt$, where SP is defined as 2*a*v. δSP actually determines the rate of vehicle's load change. The engine-out transient HC_{lean} emissions due to rapid load reductions can be estimated as:

$$EHC_{lean\text{-}trans} = hc_{trans} * [|\delta SP| - \delta SP_{th}] \qquad \text{When } a < 0 \ \& \ |\delta SP| > \delta SP_{th} \ (mph)^2/s \tag{16}$$

where hc_{trans} is the engine-out HC_{lean} emissions (in grams) per unit of δSP, which can be directly determined through measurements. δSP_{th} is a threshold value of the specific power change rate: when δSP = δSP_{th} (mph)^2/s, $EHC_{lean-trans}$ = 0. The unit of δSP is in (mph)^2/s. We found that δSP_{th} is usually around 50 (mph)^2/s^2.

HC Emissions associated with Long Deceleration Events

In normal powered driving, the amount of condensed fuel on the walls of the intake manifold is in rough equilibrium with the addition of fresh condensate from fuel injection and the loss by evaporation into the air which is moving into the cylinders. The amount of fuel on the walls depends to some extent on the recent history of fuel injection, i.e., recent power level.

When engine power is negative, essentially during coastdown and braking events, there is still significant air flow but little or no fuel injection. The condensed fuel will be removed by evaporation over a period of seconds and pass through the cylinders. The critical fact is that during these events the fuel-air ratio is typically very lean, so lean that there is little or no combustion. In this case, the HC emissions index becomes high.

In negative power operation, built-up hydrocarbons will be released, resulting in an engine-out HC emission puff whose strength depends on the built up fuel and the rate of its release. The built-up unburned engine-out HC releases ($EHC_{lean-release}$) can be modeled as:

$$EHC_{lean-release}(t) \approx r_R \bullet (bHC - \sum^{t-1} EHC_{lean-release}(i)) \quad (17)$$

where r_R is the unburned hydrocarbons release rate in 1/second, and *bHC* is the built-up condensed fuel in the intake manifold at the start of the event. The second term in Equation (17) is the summation of released unburned hydrocarbon. Equation (17) implies that the HC_{lean} emission is proportional to the remaining volume of the built-up unburned hydrocarbons residing in the intake manifold.

From Equation (17) we can see that $EHC_{lean\text{-}release}$ has its highest value at the first second, then decays with time. From this time dependence we can measure the maximum value of $EHC_{lean\text{-}release}$, which equals $r_R * bHC$ at the first second. If we introduce the maximum value of enleanment HC puffs as hc_{max}, which can be directly measured, then we have:

$$hc_{\max} = bHC \cdot r_R \tag{18}$$

or,

$$bHC = \frac{hc_{\max}}{r_R} \tag{19}$$

Based on Equations (16) and (17), we are able to model the engine-out HC_{lean} emissions during an entire driving cycle. Three parameters require calibration: 1) hc_{trans}, the transient engine-out HC emissions per unit of dSP (Equation (16)). hc_{trans} can be determined by dividing the measured maximum transient engine-out HC emissions over the measured maximum change rate of the specific power dSP; 2) hc_{max}, the measured maximum hydrocarbon puffs associated with long deceleration (Equation (18)); and 3) r_R, the unburned hydrocarbons release rate. r_R can be determined by matching the time dependence of the modeled $EHC_{lean\text{-}release}$ of Equation (17) with the corresponding measurement values.

The total engine-out HC emission are determined as:

$$EHC = EHC_{comb} + EHC_{lean-release} + EHC_{lean-trans} \tag{20}$$

4.6.3 Engine-Out NOx Emissions

NOx emissions are very sensitive to the peak temperatures arising in the cylinder. In association with this, there is a fuel rate threshold below which the emissions are very low. Moreover, because of the cooling effect of fuel enrichment in the cylinder, enrichment NO_x emissions are typically lower than those under stoichiometric conditions.

$$ENO_x = a_{1NOx} \cdot (FR + FR_{NO1}) \qquad \text{for } \phi < 1.05$$

$$ENO_x = a_{2NOx} \cdot (FR + FR_{NO2}) \qquad \text{for } \phi \geq 1.05 \qquad (21)$$

$$ENO_x = 0 \qquad \text{for FR} < \text{FR}_{NO1}$$

where a_{1NOx} and a_{2NOx} are NO_x emission index coefficients for the stoichiometric and enrichment cases respectively, and FR_{NO1} and FR_{NO2} are fuel rate thresholds for engine-out NO_x emissions.

4.6.4 Cold-Start Engine-Out Emissions Multipliers

Vehicle engine-out emissions increase significantly during cold-start, especially CO and HC emissions. Cold-start engine-out emissions are modeled by introducing the following parameters: 1) cold-start fuel/air enrichment equivalence ratio, ϕ_{cold}; 2) cold-start surrogate threshold temperature to reach close-loop operation, T_{cl}; 3) cold-start engine-out HC emission index multiplier, CS_{HC}; and 4) cold-start engine-out NO_x emission index multiplier, CS_{NOx}.

The first two parameters ϕ_{cold} and T_{cl} determine the enrichment fuel/air equivalence ratio during cold-start based on equation (10), thus the cold start engine-out CO emissions can be determined based on equation (14).

The cold-start engine out HC and NO_x emissions can be estimated as follows:

$$EHC_{cold}(t) = \left(1 + (CS_{HC} - 1) \bullet \frac{T_{cl} - T_{su}(t)}{T_{cl}}\right) * EHC(t) \qquad \text{If } T_{su}(t) < T_{cl}$$

$$ENOx_{cold}(t) = \left(1 + (CS_{NOx} - 1) \bullet \frac{T_{cl} - T_{su}(t)}{T_{cl}}\right) * ENOx(t) \qquad \text{If } T_{su}(t) < T_{cl} \qquad (22)$$

$$EHC_{cold}(t) = EHC(t),\ \ ENOx_{cold}(t) = ENOx(t) \qquad \text{If } T_{su}(t) \geq T_{cl}$$

where $T_{su}(t)$ is the surrogate temperature defined by equation (11), and T_{cl} is defined by equation (10). The relationship presented in equation (22) is illustrated in Figure 4.8.

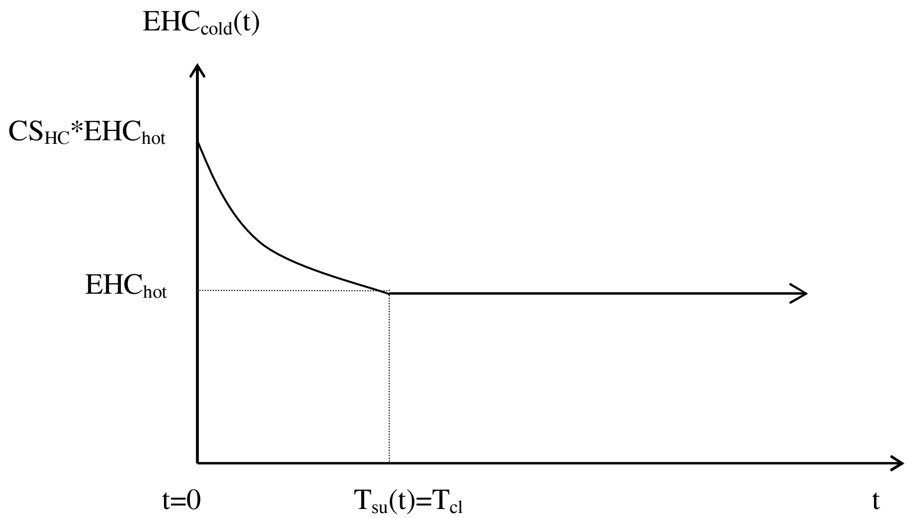

Figure 4.8. Model relationship between engine-out HC emissions and cold start time.

4.7 CATALYST PASS FRACTION MODULE

In this section, we first describe the modeling of catalyst pass fraction (CPF) under hot-stabilized conditions, then CPF modeling under cold-start conditions.

Hot-Stabilized CPF

4.7.1 CPF CO and HC

Detailed studies indicate that the CPF coefficients are sensitive to driving cycles; i.e., CPF coefficients calibrated based on high power cycles such as the MEC01 and US06 are different from the ones based on the low power FTP Bag 2 cycle. To solve this problem, we split the engine-out emissions into two parts**.** One is associated with the stoichiometric portion of emissions, i.e., directly related to fuel use. The other part is directly associated with the enriched fuel/air equivalence ratio ϕ, as shown by Equation (23):

$$CPF(i) = 1 - \Gamma_i \bullet \exp[(-b_i - c_i \cdot (1 - \phi^{-1})) \cdot FR] \tag{23}$$

where subscript i represents either CO or HC emissions, Γ_i is the maximum catalyst CO or HC efficiency, a_i represents CO or HC emission index coefficients, and FR is the fuel rate in grams/second. While b_i is the stoichiometric CPF coefficient calibrated based on the low power FTP Bag 2 cycle, c_i is the enrichment CPF coefficient calibrated based on the MEC01 cycle.

4.7.2 CPF NOx Function

The NO_x catalyst efficiency is also a function of engine-out NO_x emissions and fuel/air equivalence ratio ϕ. NO_x catalyst efficiency decreases moderately with an increase of NO_x engine-out emissions (during stoichiometric operation) and fuel/air equivalence ratio ϕ (during enrichment operation), but drops dramatically with an increase of the severity of enleanment. We have established a NO_x catalyst efficiency model as follows:

$$Cat\_Eff_{NOx} = \begin{cases} (1-b_{NO}\cdot ENO)\cdot\Gamma_{NO}, \ldots\ldots\ldots\ldots\ldots\ldots\phi = 1.0 \\ [1-b_{NO}\cdot(1-c_{NO}\cdot(1-\phi^{-1}))\cdot ENO]\cdot\Gamma_{NO}, \ldots\ldots\ldots\phi > 1.0 \\ (\Gamma_{NO}-L_{NO})/(1-\phi_{\min})\cdot(\phi-\phi_{\min})+L_{NO}, \ldots\ldots\ldots\phi < 1.0 \end{cases} \quad (24a)$$

$$CPF(NOx) = 1 - Cat\_Eff_{NOx} / 100 \quad (24b)$$

where ENO represents the engine-out NO_x emissions, b_{NO} and c_{NO} are catalyst efficiency coefficients, Γ_{NO} is the maximum measured catalyst efficiency under hot-stabilized operation conditions, ϕ is the fuel/air equivalence ratio, ϕ_{min} is the minimum measured fuel/air equivalence ratio, and L_{NO} is a dimensionless constant (≈-80).

4.7.3 Tip-in Effect of NO_x Catalyst Efficiency During Closed-Loop Operation

Simulation of the CPF during closed loop operation is more challenging due to the smaller deviations in the air-fuel ratio. We find that for most vehicles, there is a correlation between the change in (derivative of) fuel rate (ΔFR) and CPF(NOx). In order to explain this phenomena, we note that the fuel rate tends to lag slightly behind the throttle position. During accelerations the throttle opens or “tips in”, making fuel mixtures slightly lean for a short period of time [Nam et al., 1998]. The fuel injector controls lag behind this increasing intake of air, catching up only when the rate of change in air flow through the manifold lessens, at which time the A/F returns to stoichiometry. Note that the deviation from stoichiometry is small (~0.5%). This phenomenon is completely unrelated to command enrichment.

Equation (24c) gives the tip-in effect of NO_x catalyst:

$$Cat\_Eff_{NOx} = (1-\gamma)\cdot\Gamma_{NO}, ...\Delta FR > 0.05 g/s^2 \ \& \ \phi \le 1.0 \qquad (24c)$$

where γ is a tip-in coefficient and ranges from 0 to 1.0. Equation (24c) implies that, during closed-loop operation ($\phi \le 1$) and moderate acceleration ($\Delta FR > 0.05$ g/s^2) events, catalyst NO_x efficiency drops by γ*100 percent.

4.7.4 Cold-Start Catalyst Efficiency Modeling

We find that the cold-start catalyst efficiency (*Cat_Eff_cold*) can be expressed as a function of the vehicle’s cumulative fuel use:

$$Cat\_Eff_i\_cold(t) = \frac{\Gamma_i}{1+20\cdot e^{-T_{su}(t)/\beta_i}}\cdot Cat\_Eff_i\_hot(t) \qquad (25)$$

where, i = CO, HC, or NO_X, Γ_i is the maximum hot-stabilized catalyst efficiency, T_{su} is the surrogate temperature based on cumulative fuel consumption (defined by equation (11)), and β_i is a cold-start catalyst coefficient for each pollutant. $Cat\_Eff_i\_hot(t)$ is determined by equations (23)-(24). The modeled cold-start catalyst efficiency increases with cumulative fuel use as a S-curve, matching the measured cold-start catalyst profile rather well. Equation (25) doesn’t rely on any specific cold-start cycle and only requires one parameter (β_i) for each pollutant, which can be determined via a calibration process based on measurement data. Equation (25) is illustrated in Figure 4.9.

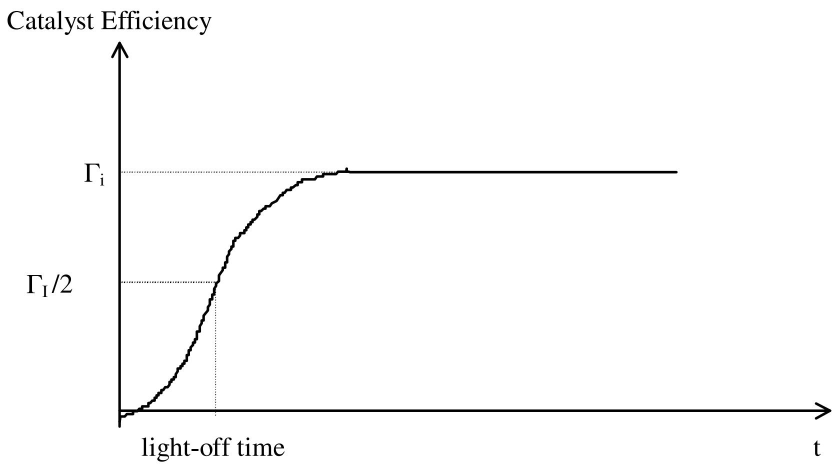

Figure 4.9. Model relationship between catalyst efficiency and cold start time.

4.8 INTERMEDIATE SOAK TIME EMISSION EFFECTS

The previous discussion of cold start emission modeling is based only on the FTP Bag 1 type test conditions. In order to handle variable soak times, we find it useful to introduce adjusted surrogate temperature ΔT_i for each pollutant as a function of soak time:

$$T_{su\_i}(T_{soak}, t) = T_{su}(\infty, t) + \Delta T_i(T_{soak}) \tag{26}$$

$$\Delta T_i\ (T_{soak}) = e^{-Tsoak/Csoak\_i} \cdot T_{cl} \tag{27}$$

where i = CO, HC and NO_x respectively, T_{soak} is a soak time for modeled vehicles, C_{soak_i} is a calibrated soak-time coefficient for each pollutant, and $T_{su}(\infty,t)$ is the surrogate temperature during full cold-start defined by equation (11). The symbol "∞" represents soak time equal to or larger than 24 hours. The relationship between ΔT_i and soak time T_{soak} is illustrated in Figure 4.10.

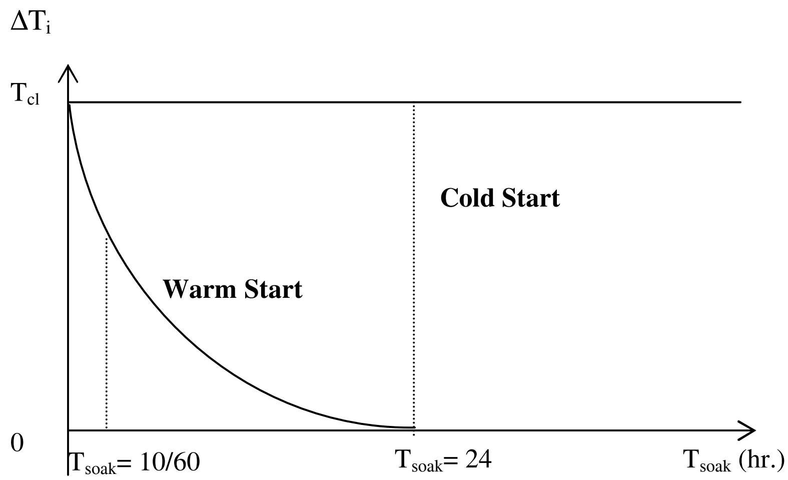

Figure 4.10. Relationship between incremental cold-start factor and soak time T_{soak}.

Thus when T_{soak} goes to 0, corresponding to hot-stabilized operation, ΔT_i tends to T_{cl}, meaning that the surrogate temperature T_{su} starts with the threshold temperature T_{cl}. When T_{soak} becomes very large, say T_{soak} = 24 hours, ΔT_i tends to 0. When T_{soak} is between 0 and 24 hours, ΔT_i is between T_{cl} and 0. This is the case for the FTP Bag 3 operational condition, where T_{soak} = 10/60 = 0.167 hours.

Thus in the soak time emission module, we simply use $T_{su}(T_{soak},t)$ defined by equation (26) to replace $T_{su}(t)$ (defined by equation (11)) to model soak time fuel/air equivalence ratio and engine-out emissions. The soak time catalyst efficiencies need to be treated slightly differently and will be introduced later.

4.8.1 Intermediate Soak Cold Start Fuel/Air Equivalence Ratio

The intermediate cold start fuel/air equivalence ratio can be modified by $T_{su\_CO}(T_{soak},t)$, based on equation (10):

$$\phi(t,T_{soak}) = \left\{ 1 + (\phi_{cold} - 1) \cdot \left(\frac{T_{cl} - T_{su\_CO}(T_{soak},t)}{T_{cl}} \right) \right\} \cdot \phi_{hot} \tag{28}$$

Thus the severity of the cold-start fuel/air equivalence ratio ϕ is a function of soak time T_{soak}, and the shorter the T_{soak}, the less severe the fuel/air equivalence ratio for the initial seconds.

4.8.2 Intermediate Soak Cold Start Engine-Out Emissions

Intermediate soak engine-out emissions can be modified based on $T_{su}(T_{soak},t)$ and equation (22) as follows:

$$EHC_{cold}(T_{soak},t) = \left(1 + (CS_{HC} - 1) \cdot \frac{T_{cl} - T_{su\_HC}(T_{soak},t)}{T_{cl}}\right) \cdot EHC(t) \qquad (29)$$

$$ENO_{cold}(T_{soak},t) = \left(1 + (CS_{NO} - 1) \cdot \frac{T_{cl} - T_{su\_NO}(T_{soak},t)}{T_{cl}}\right) \cdot ENO(t) \qquad (30)$$

The above equations show that engine-out emissions are functions of soak time as well. The shorter the T_{soak}, the lower the engine-out emissions during the initial seconds.

4.8.3 Intermediate Soak Cold Start Catalyst Efficiency

The intermediate soak cold start catalyst efficiencies need to be modified differently. The reason is that the catalyst cooldown rate differs from the engine's cooldown rate, and thus needs to be adjusted differently. Here we introduce an adjustment for catalyst surrogate temperature as follows:

$$\Delta T_{cat\_i}(T_{soak}) = e^{-T_{soak}/\beta_{cat\_i}} \cdot T_{cl} \qquad (31)$$

where β_{cat_i} are calibrated soak time coefficients for catalyst CO, HC, and NO_x emissions respectively. Equation (31) has similar behavior as equation (27).

Thus the intermediate soak cold start catalyst efficiencies can be modeled based on equations (25) and (31) as follows:

$$Cat\_Eff_i(T_{soak},t) = \frac{\Gamma_i}{1 + 20 \cdot e^{-(T_{su}(t) + \Delta T_{cat\_i}(T_{soak}))/\beta_i}} \qquad (32)$$

where Γ_i is the maximum hot-stabilized catalyst efficiency and β_i is the cold-start catalyst coefficient for each pollutant (Equation (25)). The above equation says that the initial catalyst efficiency (when $T_{su} = 0$) is a function of T_{soak}. For example, when $T_{soak} \to 0$, $Cat\_Eff(T_{soak}, 0) \to \Gamma_i$, which corresponds to a fully warmed-up situation. When $T_{soak} \to \infty$, $Cat\_Eff(T_{soak}, 0) \to 0$, which corresponds to a FTP Bag 1 cold start condition. When T_{soak} is between 0 and ∞, $Cat\_Eff_i(T_{soak},0) = \Gamma_i / (1+20e^{-\Delta Tcat(Tsoak)/\beta i}) > 0$.

4.8.4 Calibration Procedure to Determine C_{soak}

C_{soak_i} of equation (27) can be calibrated by matching measured and modeled FTP Bag 3 engine-out emissions for each pollutant, where T_{soak} = 10/60 = 0.167 hours is used. α_{soak_i} of equation (31) can be calibrated by matching measured and modeled tailpipe emissions. Thus to incorporate the intermediate soak time emissions into our model, six additional parameters C_{soak_co}, C_{soak_hc}, C_{soak_no}, and α_{soak_CO}, α_{soak_HC}, and α_{soak_NO} are used to model soak time impacts on CO, HC and NO_x emissions respectively. (Note that the soak time impact is different for CO, HC, and NO_x, and are thus modeled separately).

4.9 SUMMARY OF MODEL PARAMETERS AND VARIABLES

As discussed previously, separate sub-models for each vehicle/technology category have been created. The sub-models all have similar structure (as described in the previous section)*, however they differ primarily in their parameters.

Each sub-model uses three dynamic operating variables as input. These variables include second-by-second vehicle speed (from which acceleration can be derived; note that acceleration can be input as a separate input variable), grade, and accessory use (such as air conditioning). In many cases, grade and accessory use may be specified as static inputs or parameters.

* Note that the diesel truck category use a modified model architecture as described in Section 4.12.

In addition to these operating variables, each sub-model uses a total of 55 static parameters in order to characterize the vehicle tailpipe emissions for the appropriate vehicle/technology category. A summary list of the parameters and operating variables is given in Table 4.2. Table 4.2 gives the name and a brief definition of each parameter, as well as the associated equation number (in parentheses) in which it appears.

In Table 4.2, the model input parameters are first divided into two large categories: 13 *Readily Available Parameters* and 42 *Calibrated Parameters*. The *Readily Available Parameters* represent model input parameters which can be obtained externally from public sources (e.g., sources of automotive statistics, datasets compiled by EPA, etc.), and are further divided into *specific vehicle parameters* and *generic vehicle parameters*. The *generic vehicle parameters* are ones that may not necessarily be specified on a vehicle-by-vehicle basis, but are rather specified generically for entire vehicle classes[†].

[†] In the current model implementation, these generic vehicle parameters are programmed into the model and cannot be modified by the user (see Chapter 6).

MODEL EMISSIONS MODEL PARAMETERS AND VARIABLES		
Readily-Available Parameters	**Calibrated Parameters**	
Specific Vehicle Parameters	***(Insensitive)***	***(Sensitive)***
M - vehicle mass in lb. (2)	***Fuel Parameters***	***Cold-Start Parameters***
V - engine displacement in liter (12)	k_0 - eng. fri. factor in kJ/(lit.rev) (13)	β_{CO}, β_{HC}, β_{NOx} - cold start catalyst
N_{idle} – idle speed of engine (7)	ε_1,ε_3 - drivetrain eff. coefficients (4)	coefficients for CO, HC,
Trlhp - coastdown power in hp (2)	***Engine-out***	and NOx respectively (25)
S - eng spd./veh spd. in rpm/mph (5)	***Emission Parameters***	ϕ_{cold} - cold F/A equi. ratio (11)
Q_m - max torque in ft.lb (7)	C_0 - CO enrich. coef. (14)	T_{cl} - surrogate temp reach stoich (11)
N_m - eng spd. in rpm @ Q_m (7)	a_{CO} - EO CO index coef. (14)	CS_{HC} - cold EO HC multiplier (22)
P_{max} - max power in hp	a_{HC} - EO HC index coef. (15)	CS_{NO} - cold EO NO multiplier (22)
N_p - eng spd. in rpm @ P_{max} (7)	r_{HC} - EO HC residual value (15)	
N_g - number of gears	a_{1NOx} - NO_x stoich index (21)	***Hot Catalyst Parameters***
	a_{2NOx} - NO_x enrich index (21)	Γ_{CO}, Γ_{HC}, Γ_{NOx} - hot max CO,
Generic Vehicle Parameters	FR_{NO1}, FR_{NO2} - NO_xFR threshold (21)	HC, and NO_x catalyst
η - indicated efficiency (12)	***Enleanment Parameters***	efficiencies (23 & 24)
R(L) - gear ratio (5)	hc_{max} - max. HC_{lean} rate in g/s (18)	b_{CO}, b_{HC}, b_{NO} - hot Cat CO, HC,
	hc_{trans} - trans. HC_{lean} rate in g/SP(16)	and NOx coefficient (23 & 24)
	δSP_{th} - HC_{lean} threshold value (16)	c_{CO}, c_{HC}, c_{NO} - hot cat CO, HC
Operating Variables	r_R – HC_{lean} release rate in 1/s (17)	and NOx enrichment coefficient
	r_{O2} - ratio of O_2 and EHC (9b)	(23 & 24)
	ϕ_{min} – lean fuel/air equ. ratio (24a)	
θ - road grade (2)	***Soak-time Parameters***	γ - NOx Cat tip-in coefficient (24c)
P_{acc} - accessory power in hp (3)	C_{soak_CO}, C_{soak_HC}, C_{soak_NO}– soak time	***Enrichment Parameters***
v - speed trace in mph (2, 4, 5)	engine coef. for CO, HC, NO_x (27)	ϕ_0 - max F/A equi. ratio (9)
T_{soak} – soak time (min)	β_{cat_co}, β_{cat_hc}, β_{cat_no} – soak time	P_{scale} – Power threshold factor (8)
SH – specific humidity (grains H_20/lb)	Cat. coef. for CO, HC, NO_x (31)	

Table 4.2. Modal Emissions Model Input Parameters. The numbers in parenthesis correspond to the equations in the text in which they appear.

The *Calibrated Parameters* cannot be directly obtained from publicly available sources; rather they are deduced (i.e., calibrated) from the testing measurement data. This group of parameters is further divided into two sub-sets: an *Insensitive Set* (23 parameters) and a *Sensitive Set* (19). In the *Insensitive Set*, the model parameters are either approximately known in advance (e.g., fuel and engine-out emission parameters) or have relatively small impacts on overall vehicle emissions (e.g., enleanment parameters). The parameters in the *Sensitive Set* need to be carefully determined. There are three sub-sets of *Sensitive Parameters*:

1) *Cold-Start subset*, consisting of 7 model input parameters describing both cold-start catalyst performance and engine-out emissions;

2) *Hot Stabilized Catalyst subset*, consisting of 10 parameters that determine the relationships between catalyst efficiencies and engine-out emissions and fuel/air ratios under hot stabilized conditions; and

3) *Enrichment Parameters subset*, consisting of 2 parameters defining enrichment: the maximum enrichment fuel/air equivalence ratio ϕ_0 at wide open throttle (WOT), and the enrichment power threshold P_{scale}.

Given all of these parameters, Figure 4.11 presents a detailed flow chart of the model and where the parameters are used.

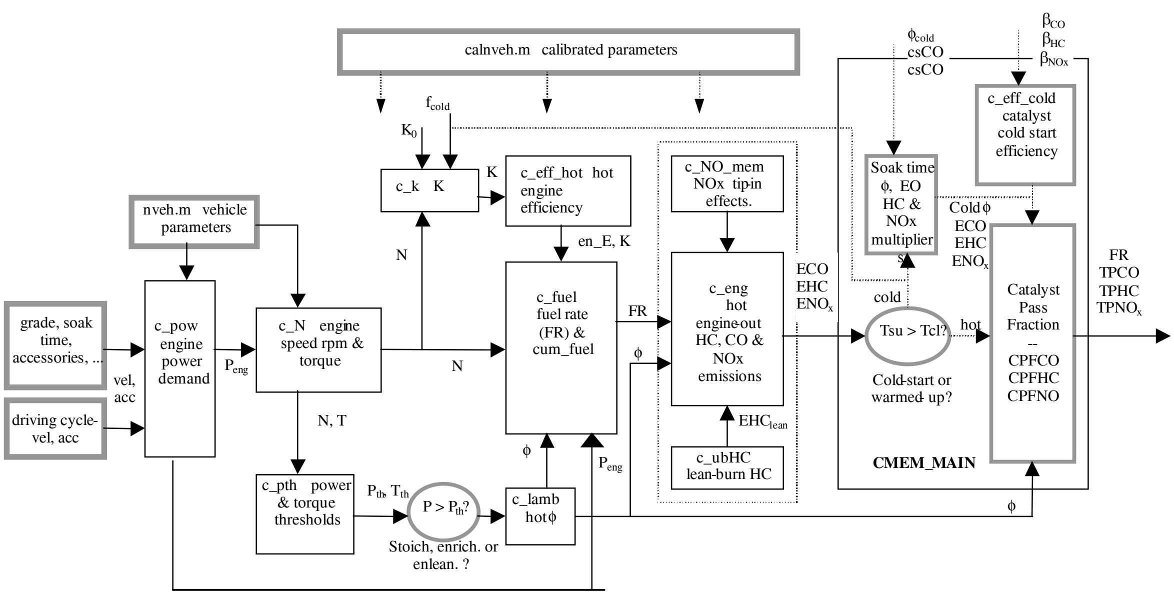

Figure 4.11. Flow chart of the Comprehensive Modal Emissions Model (CMEM)

4.10 MODEL CALIBRATION PROCESS

As the model was developed, each test vehicle was individually modeled by determining all of the parameters described in the previous section. The *Readily Available Parameters* of the test vehicles (e.g., mass, engine displacement, etc.) have been obtained for each vehicle. The *Calibration Parameters* were determined through a detailed calibration procedure, using the measured emissions results for each test vehicle. Depending on the specific parameter, the calibration values are determined either: 1) directly from measurements; 2) based on several regression equations; or 3) based on an optimization process.

4.10.1 Measurement Process

Nine parameters are determined directly from the dynamometer emission measurements:

- maximum hot-stabilized catalyst efficiencies for CO, HC, and NO_x emissions (Γ_{CO}, Γ_{HC}, and Γ_{Nox});
- maximum fuel/air equivalence ratio (ϕ_0);
- maximum lean HC emission rate during long deceleration events (hc_{max});
- maximum lean HC emission rate during transient events (hc_{trans});
- minimum fuel/air equivalence ratio (f_{min}) during enleanment operation;
- ratio of oxygen and engine-out HC emissions (r_{O2}) during enleanment operation; and
- maximum cold-start fuel/air equivalence ratio (ϕ_{cold}).

The first eight parameters are derived directly from the MEC01 cycle emissions traces. The maximum cold-start fuel/air equivalence ratio (ϕ_{cold}) is based on data from the FTP bag 1 cycle.

4.10.2 Regression Process

All seven parameters used to model engine-out emissions (C_0, a_{CO}, a_{HC}, r_{HC}, a_{1NOx}, a_{2NOx}, and FR_{NOxth}) are determined through a regression process performed on the second-by-second data. Emission measurements from the MEC01 cycle are used to determine these parameters. These parameters are determined by regressing engine-out emissions against rate of fuel use (e.g., see eqns. (14), (15), and (21)). This process was performed on the second-by-second data rather than on the operating modes which typically span several seconds. Operating at this highest time resolution insured that we captured as many (engine) operating modes as possible.

4.10.3 Optimization Processes

The remaining 26 calibration parameters are determined using an optimization process, again performed on the second-by-second data. Several optimization processes are used to calibrate the model parameters by minimizing the differences between the integrated modeled and measured emissions data. The optimization procedure is based on golden section and parabolic interpolation. During the optimization process, one parameter is optimized at a time while all remaining parameters are held constant. Parameters are optimized in a specific order such that they are dependent only on previously optimized parameters.

Table 4.3 lists the parameters that are calibrated via optimization. In Table 4.3, the modeled and measured parameters include both engine-out and tailpipe emissions for all pollutants. Variables beginning with ‘E’ represent engine-out cumulative emissions in grams per mile, whereas variables beginning with ‘T’ represent tailpipe emission factors in grams per mile. These parameters are calibrated based on measurements made under either the MEC01 (mc), the FTP Bag 1 (fc1), Bag 2 (fc2), or Bag 3 (fc3) cycles (only the first 50 seconds of the FTP Bag 3 cycle are used in the calibration process). The range in parameter values is also shown in the table.

Some variables that are initially determined based on the regression process (a_{CO}, r_{HC}, a_{1NOx} and a_{2NOx}) are further optimized here to improve the fit to the FTP Bag 2 cycle. The purpose of this optimization procedure is to get the best fit for both MEC01 and FTP bag 2 cycles. The FTP Bag 1 cycle is used to determine the cold-start parameters. The first 50 seconds of the Bag 3 cycle are used to calibrate the soak time variables. Two variables that are initially determined directly from measurements (hc_{trans} and Γ_{Nox}) are also further calibrated, and shown in Table 4.3.

4.11 VEHICLE COMPOSITING

Each of the vehicles tested during the testing phase with sufficient and acceptable data has been modeled (total of 343 vehicles), using the calibration process described above. However, the primary modeling goal is to predict detailed emissions for each average, *composite* vehicle that represents the vehicle/technology categories listed in Table 4.1. Thus, a *compositing procedure* has been developed to construct a composite vehicle to represent each of the 26 different vehicle/technology modeled categories. The compositing procedure is as follows:

Modeled	*Param.*	Min.	Max.	Cycle	Note
ECO_2gs	K_0	0	1	fc2	Engine friction factor
ECO2gs	Edt_3	0.0	0.2	mc	High-power drive train efficiency coefficient
ECO2gs	Edt_1	0.7	1.0	mc	Maximum drive train efficiency
ECOgs	a_{CO}	0	1.0	fc2	Engine-out CO emission index
ECOgs	P_{scale}	0	2	mc	Power enrichment threshold
EHCgs	r_{HC}	-0.05	0.05	mc	HC Regression coefficient
TCOgs	b_{CO}	0	10	fc2	Catalyst CO coefficient
TCOgs	c_{CO}	0	50	mc	Catalyst CO coefficient
ENOxgs	a_{1NOx}	0	1	fc2	NOx Regression coefficient, stoich.
ENOxgs	a_{2NOx}	0	0.2	mc	NOx Regression coefficient, enrich
ECOgs	T_{cold}	0	1000	fc1	Cold Start surrogate threshold temp.
ENOxgs	CS_{NO}	0	50	fc1	Cold Start engine-out CO multiplier
TCOgs	β_{CO}	0	1000	fc1	Cold Start CO catalyst coefficient
EHC_{lean}	r_R	0.01	1	mc	HC lean emission release rate
EHCgs	hc_{trans}	0	5	mc	Max. transient lean HC emission rate
EHCgs	δSP_{th}	0	100	fc2	δSP lean threshold
EHCgs	hc_{trans}	0	5	mc	Max. transient lean HC emission rate
THCgs	b_{HC}	0	1	fc2	Catalyst HC coefficient
THCgs	c_{HC}	0	50	mc	Catalyst HC coefficient
EHCgs	CS_{HC}	0	500	fc1	Cold Start engine-out HC multiplier
TNOxgs	b_{NO}	0	50	mc	Catalyst NOx coefficient
TNOxgs	γ	0	30	fc2	time delay for NOx catalyst
TNOxgs	c_{NO}	-100	50	fc2	Catalyst NOx coefficient
TNOxgs	b_{NO}	0	50	mc	Catalyst NOx coefficient
TNOxgs	Γ_{NO}	0	100	mc	Max. hot catalyst NOx efficiency
TNOxgs	β_{NO}	0	1000	fc1	Cold Start NOx catalyst coefficient
THCgs	β_{HC}	0	1000	fc1	Cold Start HC catalyst coefficient
ECOgs	C_{soak_co}	0.005	10	fc3	Soak time engine-out CO coefficient
EHCgs	C_{soak_hc}	0.005	10	fc3	Soak time engine-out HC coefficient
ENOxgs	C_{soak_no}	0.005	10	fc3	Soak time engine-out NOx coefficient
TCOgs	α_{soak_co}	0.005	30	fc3	Soak time catalyst CO coefficient
THCgs	α_{soak_hc}	0.005	30	fc3	Soak time catalyst HC coefficient
TNOxgs	α_{soak_no}	0.005	30	fc3	Soak time catalyst NOx coefficient

Table 4.3. CMEM Calibration Parameters

1. *Establish composite emission traces for each technology group*—Using the vehicles that are grouped in each vehicle/technology category, an average composite vehicle emission trace is constructed for the MEC01, FTP, and US06 cycles. This was done by averaging the second-by-second emissions over the FTP three bags, MEC01 and US06 cycles for all vehicles in each vehicle/technology category.

2. *Determine readily-available model parameters for composite vehicles*—A subset of the composite parameters are directly established based on their average values within each

vehicle/technology category, i.e., primarily the *Readily-Available Parameters*. As described in Section 4.10, the calibration process involves the use of both second-by-second engine-out and tailpipe emissions under both the FTP Bag 3 and MEC01 cycles.

3. *Establish calibrated composite parameters*—The remaining calibrated parameters for the composite vehicles are determined using the same calibration process described earlier, using the average of the calibrated parameters of the vehicles in the category as the starting point. Based on this procedure, the parameter sets of the 26 composite vehicles are given in Table 4.4.

4.12 PRELIMINARY DIESEL MODAL EMISSIONS MODEL DEVELOPMENT

As part of Phase 4 of this project, a preliminary *diesel* modal emissions sub-model for light- and medium-duty trucks (category 40) has been developed. For this sub-model, ten light- and medium-duty diesel-powered trucks were recruited and tested, providing second-by-second measurements of CO, HC and NO_x over the FTP and the modal emission cycle (MEC01). In this research, we only focused on modeling diesel emissions without any kind of engine aftertreatment (i.e., tailpipe emissions are the same as engine-out emissions). The tested vehicles include four model year 1980s Ford trucks, two model year 1990s Ford trucks and four model year 1990s Dodge trucks. All Ford models use V8 Navistar diesel engines. All Dodge models use Cummins inline six-cylinder diesel engines. Body types of the tested vehicles include regular, super, and crew cabs. Table 4.5 lists the vehicle and engine characteristics for these ten tested diesel trucks.

In Table 4.5, *Cyl*. represents number of cylinders and engine type (i.e., V8 refers to a V-8 engine and I6 refers to In-line 6 engine); *Liter* is engine size in liters; *Tran* represents transmission type; *Wt* is estimated vehicle test weight in lb.; *Odom* is vehicle's odometer reading in miles; *HC*, *CO*, and NO_x are FTP emission measurements in grams/mile; *MPG* is measured city fuel economy; *HP* is rated engine power; and N_p is the corresponding engine speed in RPM. *Tmax* is maximum engine torque and N_m is the corresponding engine speed in RPM. *Trlhp* is coastdown coefficient and *N/V* is rpm/mph in top gear.

Figure 4.12a shows the FTP emission characteristics of these tested vehicles. It shows that all these diesel trucks have relatively high NOx emissions and low CO and HC emissions. Figure 4.12b shows the measured fuel economies of these tested diesel vehicles.

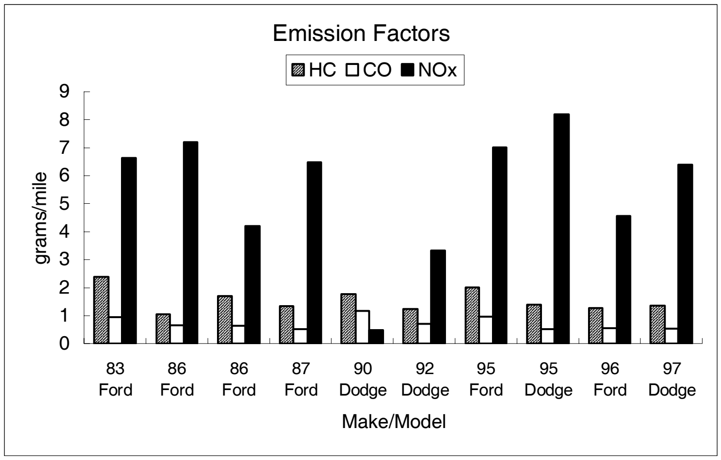

Figure 4.12a. Emission Characteristics of Tested Diesel Vehicles

	Unit	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
vehicle count	#	6	10	4	19	15	16	8	12	10	14	14	5
V	Liter	4.75	3.20	1.68	2.51	2.45	2.21	2.35	2.37	2.04	2.14	2.76	6.10
M	lb.	3000	3031	2438	3066	3158	3031	2922	3170	2913	2955	3288	4000
Trlhp	hp	13.3	12.8	11.3	11.9	12.4	12.1	12.3	11.4	11.4	11.5	12.8	18.3
S (rpm/mph)		25.39	25.4	35.4	44.6	39.3	40.9	39.6	40.0	36.2	39.6	38.2	36.8
N_m	rpm	1766	2856	3323	3307	4027	3215	4288	3619	4150	3218	3908	1286
Q_m	lb.ft	250.4	168.0	95.2	143.3	151.3	126.1	148.4	139.0	128.3	125.4	170.1	319.6
P_{max}	hp	119.6	120.0	77.1	110.8	140.1	100.5	141.0	119.6	130.0	108.2	153.5	165.6
Np	rpm	3259	4560	5261	4908	5520	4754	5650	5127	5650	5011	5404	2783
N_{idle}	rpm	967	900	950	871	880	825	900	855	900	871	846	1000
N_g	d.l.	4	4	4	4	4	4	5	4	5	4	4	3
K_0 - kJ(/rev.liter)		0.316	0.316	0.240	0.247	0.206	0.233	0.222	0.188	0.210	0.206	0.236	0.206
ε_1	d.l.	0.698	0.782	0.860	0.900	0.912	0.889	0.917	0.866	0.907	0.918	0.913	0.550
ε_3	d.l.	0.150	0.100	0.100	0.100	0.094	0.100	0.090	0.096	0.099	0.100	0.100	0.190
C_0	d.l.	3.440	3.219	3.325	3.669	3.821	3.519	3.775	3.592	3.894	3.693	3.781	3.292
a_{CO}	d.l.	0.375	0.157	0.158	0.121	0.133	0.097	0.090	0.090	0.086	0.091	0.080	0.275
a_{HC}	d.l.	0.018	0.014	0.017	0.015	0.025	0.011	0.016	0.011	0.013	0.009	0.009	0.009
r_{HC}	g/s	0.021	-0.005	0.002	0.001	0.008	0.004	0.001	0.002	0.001	0.003	0.004	0.014
a_{1NO}	d.l.	0.015	0.029	0.033	0.029	0.029	0.036	0.036	0.036	0.036	0.036	0.033	0.026
a_{2NO}	d.l.	0.033	0.022	0.014	0.038	0.035	0.035	0.035	0.040	0.034	0.033	0.037	0.040
FR_{NO1}	g/s	-0.745	-0.439	-0.215	-0.287	-0.316	-0.291	-0.277	-0.249	-0.255	-0.306	-0.272	-0.789
FR_{NO2}	g/s	0.015	0.110	0.005	0.259	0.372	0.199	0.147	0.746	0.198	0.185	0.379	0.895
hc_{max}	g/s	0.215	0.150	0.080	0.065	0.106	0.067	0.075	0.054	0.065	0.063	0.046	0.171
hc_{trans}	g.s/mph^2	2.999	1.433	0.649	0.354	4.993	4.804	0.250	0.456	0.271	4.804	4.967	4.993
r_R	1/s	0.320	0.167	0.581	0.370	0.034	0.228	0.392	0.401	0.316	0.301	0.082	0.106
ϕ_{min}	d.l.	0.891	0.691	0.402	0.314	0.232	0.373	0.175	0.320	0.161	0.123	0.288	0.969
δSP_{th}	mph^2/s	18.30	0.00	12.13	0.00	88.20	103.32	0.00	5.01	0.00	106.39	110.75	88.20
r_{O2}	d.l.	7.76	8.27	13.67	35.85	42.92	40.54	36.85	67.19	45.30	50.45	63.91	2.16
C_{soak_co}	hour	400.00	73.44	68.56	247.18	38.74	100.18	49.51	127.58	217.18	280.68	166.43	377.86
C_{soak_hc}	hour	0.38	97.21	32.81	19.26	34.66	20.65	22.68	11.30	0.38	15.12	32.22	0.01
C_{soak_no}	hour	400.00	57.50	11.75	295.09	400.00	400.00	400.00	43.34	400.00	400.00	400.00	0.38
β_{cat_CO}	1/hr	238.66	24.00	240.00	17.06	11.91	45.14	240.00	240.00	18.52	224.87	240.00	24.00
β_{cat_HC}	1/hr	0.64	11.00	240.00	12.96	38.61	114.86	240.00	240.00	240.00	240.00	40.48	24.00
β_{cat_NO}	1/hr	66.34	6.30	240.00	0.53	20.10	3.61	240.00	9.35	6.62	0.26	3.70	0.01
β_{CO}	g	499.99	0.03	24.10	18.56	18.99	24.09	23.52	34.42	39.04	9.33	16.86	0.05
β_{HC}	g	499.94	57.31	29.29	15.03	17.72	18.91	31.87	16.57	16.39	10.41	12.76	0.05
β_{NO}	g	288.20	53.60	22.02	19.34	18.26	4.83	27.69	10.43	14.21	6.21	4.47	500.00
T_{cl}	g	165.63	586.67	128.51	143.29	107.68	88.68	89.69	69.65	75.51	50.23	85.58	251.47
ϕ_{cold}	d.l.	1.26	1.21	1.21	1.18	1.21	1.17	1.19	1.11	1.14	1.15	1.19	1.25
CS_{HC}	d.l.	3.98	3.18	3.11	4.74	2.51	4.21	3.19	3.49	4.64	4.55	4.72	1.92
CS_{NO}	d.l.	1.68	1.40	0.20	2.96	3.65	4.90	1.94	3.21	1.81	4.84	4.14	0.61
Γ_{CO}	%	0.00	85.55	100.00	99.86	99.76	99.73	99.78	99.84	99.98	99.98	99.96	0.00
Γ_{HC}	%	0.00	84.25	99.67	99.91	99.78	99.88	99.90	99.86	99.93	99.83	99.95	0.00
Γ_{NO}	%	0.00	29.23	64.86	95.02	95.88	91.07	99.13	100.00	99.78	99.85	99.65	0.00
b_{CO}	1/(g/s)	0.00	0.02	0.33	0.30	0.23	0.15	0.08	0.11	0.07	0.10	0.04	0.00
c_{CO}	1/(g/s)	0.00	19.99	19.99	0.31	0.12	1.70	1.05	1.20	0.72	0.96	1.48	0.00
b_{HC}	1/(g/s)	0.00	0.00	0.08	0.09	0.04	0.04	0.05	0.02	0.02	0.02	0.01	0.00
c_{HC}	1/(g/s)	0.00	4.87	2.38	0.00	0.09	0.55	0.05	0.48	0.26	0.36	0.59	0.00
b_{NO}	1/(g/s)	0.00	4.73	2.78	1.76	1.06	1.01	1.44	0.43	0.82	0.87	0.41	0.00
c_{NO}	1/(g/s)	0.00	0.52	5.00	2.73	1.71	2.21	3.37	0.00	3.57	1.48	1.32	0.00
γ	d.l.	0.00	0.13	0.37	0.34	0.18	0.19	0.36	0.00	0.15	0.07	0.04	0.00
ϕ_0	d.l.	1.26	1.25	1.21	1.23	1.24	1.25	1.24	1.24	1.26	1.24	1.24	1.27
P_{scale}	d.l.	1.198	1.028	1.12	1.313	1.149	1.116	1.128	1.289	1.689	1.312	1.283	1.663

Table 4.4. Composite vehicle model input parameters (categories 1-12), * d.l. stands for dimensionless. See Table 4.1 for a description of the category types.

	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**40**
vehicle count	6	9	22	10	16	12	10	20	6	7	15	3	5	9
V	4.62	2.94	2.77	4.87	3.42	5.14	3.16	2.23	2.50	2.88	2.67	2.55	6.99	6.66
M	3900	3153	3351	4300	3938	4375	3643	2833	3021	3298	3054	3229	5929	6778
Trlhp	17.6	14.6	15.2	19.8	18.0	21.0	15.2	12.8	13.4	15.3	12.8	14.3	21.3	20.7
S	25.9	40.5	39.0	30.1	33.6	23.0	34.4	41.7	42.1	37.8	40.1	38.2	30.6	30.2
N_m	1959	2689	3029	2432	2953	2121	2888	3143	2867	2858	2696	3733	2543	1633
Q_m	238.2	162.8	157.8	257.6	193.8	276.3	172.0	133.6	137.6	156.8	153.7	145.3	377.9	385.6
P_{max}	143.2	118.5	128.7	175.5	150.0	182.6	130.5	107.9	104.5	122.3	106.1	122.8	244.3	186.1
Np	3607	4615	4847	3972	4603	3763	4817	5016	4854	4740	4763	4758	3914	2978
N_{idle}	920	867	895	800	850	817	886	900	967	923	914	833	829	867
N_g	3	4	4	4	4	4	4	4	4	4	4	4	4	4
K_0	0.233	0.218	0.213	0.206	0.215	0.188	0.243	0.229	0.234	0.249	0.274	0.206	0.191	0.135
ε_1	0.695	0.858	0.855	0.864	0.888	0.762	0.903	0.854	0.956	0.863	0.930	0.919	0.735	0.960
ε_3	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.000	0.100	0.000	0.100	0.100	0.200
C_0	3.735	3.548	3.718	3.911	3.765	3.857	3.751	3.402	3.713	3.607	3.401	3.899	3.580	0.002
a_{CO}	0.201	0.105	0.106	0.085	0.086	0.081	0.079	0.239	0.134	0.157	0.289	0.102	0.097	0.007
a_{HC}	0.009	0.011	0.012	0.009	0.010	0.009	0.014	0.019	0.061	0.019	0.023	0.012	0.007	0.003
r_{HC}	0.008	0.003	-0.003	-0.002	0.004	0.003	0.001	0.003	-0.005	-0.010	0.000	-0.001	0.001	0.002
a_{1NO}	0.026	0.026	0.033	0.029	0.029	0.026	0.036	0.033	0.022	0.029	0.002	0.034	0.030	0.032
a_{2NO}	0.009	0.031	0.033	0.025	0.040	0.038	0.020	0.030	0.019	0.036	0.006	0.040	0.040	0.000
FR_{NO1}	-0.672	-0.448	-0.342	-0.525	-0.407	-0.528	-0.278	-0.355	-0.306	-0.328	-0.872	-0.258	-0.805	0.002
FR_{NO2}	0.005	0.298	0.218	0.005	0.742	0.226	0.127	0.199	0.015	0.431	0.005	0.895	0.895	0.000
hc_{max}	0.119	0.088	0.082	0.066	0.069	0.048	0.063	0.138	0.178	0.128	0.156	0.087	0.152	0.008
hc_{trans}	0.395	1.095	2.075	1.746	0.654	0.045	0.516	4.993	4.993	3.293	0.989	0.955	0.382	0.010
r_R	0.685	0.339	0.114	0.123	0.542	0.621	0.245	0.157	0.010	0.126	0.446	0.142	0.215	0.233
ϕ_{min}	0.798	0.556	0.392	0.712	0.237	0.662	0.431	0.456	0.136	0.462	0.596	0.153	0.446	0.000
δSP_{th}	0.00	14.59	5.42	4.51	14.41	0.00	0.45	110.92	111.80	4.08	10.32	0.00	15.69	0.00
r_{O2}	7.14	19.08	22.82	12.23	41.60	19.66	29.85	16.31	12.53	25.87	9.75	73.65	31.22	42.28
C_{soak_co}	269.73	194.95	73.47	68.84	176.78	112.58	194.96	42.95	217.18	400.00	21.84	264.49	119.93	400.0
C_{soak_hc}	17.41	9.71	16.72	400.00	0.01	41.65	47.05	27.42	400.00	0.38	62.59	12.43	112.88	0.01
C_{soak_no}	400.00	400.00	400.00	400.00	400.00	134.87	0.01	400.00	400.00	5.78	3.06	400.00	0.38	3.30
β_{cat_CO}	0.64	14.75	12.63	35.92	30.67	18.65	0.64	240.00	0.64	0.64	24.26	0.64	240.00	0.00
β_{cat_HC}	0.01	11.23	240.00	240.00	240.00	22.26	0.64	240.00	239.97	0.01	13.87	239.97	240.00	0.00
β_{cat_NO}	24.00	14.20	13.16	240.00	7.15	5.01	239.89	83.48	0.64	0.69	4.46	240.00	240.00	0.00
β_{CO}	500.00	27.43	31.58	57.11	28.27	27.91	108.65	94.98	500.00	500.00	370.30	500.00	500.00	0.00
β_{HC}	102.49	38.38	48.83	500.00	18.88	24.47	500.00	60.98	499.99	500.00	119.59	499.99	500.00	0.00
β_{NO}	0.00	36.22	20.11	111.31	15.11	30.09	500.00	48.04	500.00	63.69	45.38	16.56	500.00	0.00
T_{cl}	261.16	332.42	143.78	202.44	100.18	151.30	109.28	167.63	77.43	248.61	853.65	50.79	250.45	191.3
ϕ_{cold}	1.29	1.12	1.14	1.12	1.11	1.11	1.12	1.31	1.17	1.23	1.37	1.17	1.14	1.00
CS_{HC}	3.71	1.90	1.94	1.69	3.98	4.12	2.68	2.85	0.00	1.24	2.90	3.86	4.63	0.98
CS_{NO}	0.00	2.01	2.44	2.39	3.99	2.54	0.39	1.17	4.70	1.73	10.50	3.57	0.92	3.53
Γ_{CO}	46.44	99.77	99.76	99.86	99.98	99.86	97.69	92.48	97.85	86.75	79.06	100.00	99.98	0.00
Γ_{HC}	53.29	98.47	99.77	99.60	99.94	99.81	96.61	92.09	97.13	87.01	74.62	99.96	99.53	0.00
Γ_{NO}	0.00	71.52	94.75	94.55	99.84	99.81	55.58	69.01	80.61	41.24	28.28	100.00	76.80	0.00
b_{CO}	0.18	0.24	0.30	0.14	0.06	0.06	0.39	0.50	0.50	0.50	0.50	0.17	0.04	0.00
c_{CO}	19.99	2.11	0.46	0.99	1.24	0.77	0.35	0.08	19.99	19.99	3.37	3.22	0.03	0.00
b_{HC}	0.08	0.08	0.10	0.07	0.02	0.02	0.15	0.39	0.19	0.51	0.98	0.05	0.02	0.00
c_{HC}	49.99	1.59	0.01	0.02	0.30	0.34	0.00	0.00	1.02	0.00	0.00	0.14	0.00	0.00
b_{NO}	10.74	2.54	1.71	2.01	0.55	0.61	5.55	4.20	5.76	5.88	20.00	0.90	1.10	0.00
c_{NO}	4.69	2.77	1.51	2.59	2.30	2.99	2.12	2.91	0.00	4.10	0.20	0.00	5.00	0.00
γ	1.00	0.60	0.16	0.26	0.12	0.17	0.37	0.81	0.00	1.00	0.10	0.00	0.63	0.00
ϕ_0	1.24	1.19	1.24	1.24	1.22	1.23	1.25	1.31	1.16	1.24	1.39	1.26	1.18	1.00
P_{scale}	1.313	1.019	1.162	1.329	1.269	1.53	1.272	1.196	0.716	1.152	0.128	1.431	1.689	-

Table 4.4. (continued) Composite vehicle model input parameters (categories 13-40). See Table 4.1 for a description of the category types.

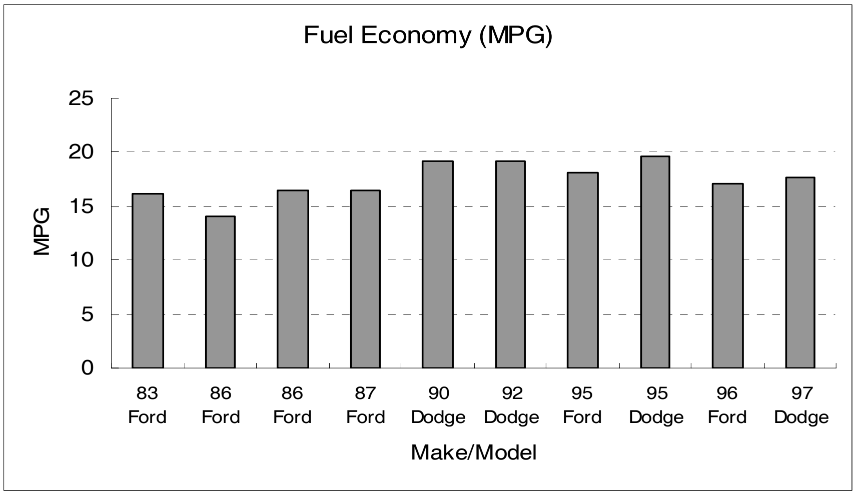

Figure 4.12b. Measured Fuel Economies of Recruited Diesel Vehicles.

MY	*Make*	*Test#*	*Model*	*Body Type*	*Engine Type*	*Cyl.*	*Liter*	*Tran*	*Wt (lb.)*	*Odom (mile)*	*HC (g/m)*	*CO (g/m)*	*NOx (g/m)*
95	Ford	400	F-350 4x4	Reg. Cab	Navistar	V8	7.3	A4	7,000	37,533	2.01	0.96	7.01
87	Ford	401	F-250 TB PU	Sup. Cab	Navistar	V8	6.9	A4	6,600	81,898	1.35	0.52	6.49
90	Dodge	402	250 PU 4x4	Reg. Cab	Cummins	I6	5.9	A4	6,900	118,557	1.77	1.17	0.49
92	Dodge	403	Ram 250 LE	Reg. Cab	Cummins	I6	5.9	A4	6,100	55,738	1.24	0.71	3.32
95	Dodge	404	Ram 2500	Reg. Cab	Cummins	I6	5.9	A4	6,100	36,603	1.40	0.51	8.19
86	Ford	405	F-250 PU	Sup. Cab	Navistar	V8	6.9	A3	6,600	61,283	1.70	0.64	4.20
97	Dodge	406	RAM 2500	Reg. Cab	Cummins	I6	5.9	A4	6,100	29,851	1.36	0.53	6.40
96	Ford	407	F-350 4x4	Crew Cab	Navistar	V8	7.3	A4	7,600	39,844	1.27	0.55	4.57
86	Ford	408	F-350 4x2	Sup. Cab	Navistar	V8	6.9	A3	7,500	72,684	1.06	0.65	7.21
83	Ford	409	F-350 4x2	Reg. Cab	Navistar	V8	6.9	A3	6,600	72,426	2.38	0.95	6.63

MY	*Make*	*Test#*	*Model*	*MPG*	*HP*	*RPM*	*Tmax*	*RPM*	*Trlhp*	*N/V*
95	Ford	400	F-350 4x4	18.1	210	3000	425	2000	21.9	31.3
87	Ford	401	F-250 TB PU	16.4	180	3300	345	1400	21.0	31.3
90	Dodge	402	250 PU 4x4	19.1	160	2500	400	1750	20.8	28
92	Dodge	403	Ram 250 LE	19.2	160	2500	400	1750	22.6	28
95	Dodge	404	Ram 2500	19.6	160	2500	400	1750	21.0	28
86	Ford	405	F-250 PU	16.5	180	3300	345	1400	18.0	31.3
97	Dodge	406	RAM 2500	17.7	215	2600	440	1600	21.0	28
96	Ford	407	F-350 4x4	17.1	210	3000	425	2000	21.9	31.3
86	Ford	408	F-350 4x2	14.1	180	3300	345	1400	21.0	31.3
83	Ford	409	F-350 4x2	16.1	180	3300	345	1400	18.0	31.3

Table 4.5. Characteristics of ten Tested Diesel Trucks.

4.12.1 Model Structure

At this preliminary stage, the diesel model development assumes that there are no emission aftertreatment components, i.e., that tailpipe emissions are the same as engine-out emissions. Since the developed diesel emissions model doesn't include these aftertreatment components (e.g., catalytic converter), the structure of the model is simpler than the gasoline counterpart. However, it uses a similar load-based physical modeling methodology that includes modules that estimate components such as power demand, engine speed, fuel rate, and engine-out (tailpipe) emissions. Due to the unique nature of diesel engines, there isn't a complex air/fuel control module as with gasoline engines.

The major differences between the diesel emissions model and the gasoline engine counterpart lie in its fuel consumption and engine-out emission modules, as well as some key engine and fuel parameters to reflect specific diesel engine/fuel properties. Both soak-time functions and enleanment HC emission modules remain the same. In summary, the key modifications from a gasoline-based vehicle emission model to a diesel-based vehicle emission model are listed as follows:

- fuel rate module was revised;
- engine-out emission module was revised
- cold-start module for CO emissions was revised;
- key engine/fuel parameters have been modified to reflect specific diesel engine/fuel properties;
- there is no air/fuel ratio module (including enrichment events); and
- there is no catalyst modeling.

Figure 4.13 shows the simplified model structure of the preliminary diesel vehicle modal emissions model.

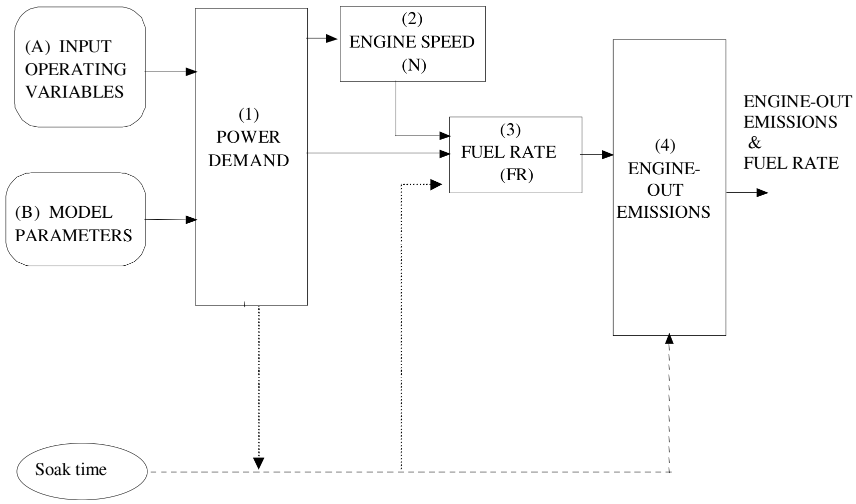

Figure 4.13. Model structure for the preliminary diesel vehicle modal emissions model

The diesel fuel consumption module was modified as follows:

$$FR \approx (k \cdot N \cdot V + \frac{P}{\eta})\frac{1}{43.2} \cdot (1 + b_1 \cdot (N - N_0)^2)$$

$$K = K_0 \cdot (1 + C \cdot (N - N_0))$$

$$N_0 \approx 30 \cdot \sqrt{\frac{3.0}{V}}$$

where *FR* is fuel use rate in grams/second, *P* is engine power output in kW, *K* is the engine friction factor, *N* is engine speed (revolutions per second), *V* is engine displacement (liter), and $\eta \approx 0.45$ is a measure of indicated efficiency for diesel engine. $b_1 \approx 10^{-4}$ and $C \approx 0.00125$ are coefficients; 43.2 kJ/g is the lower heating value of a typical diesel fuel.

Preliminary analysis had shown that there is a strong correlation between fuel use and engine-out emissions. Thus, the CO, HC, and NO_x emission rates are estimated as:

$$CO = a_{CO} * FR + C_O$$

$$HC = a_{HC}*FR + r_{HC}$$

$$NO_x = a_{NO}*FR + r_{NO}$$

where, a_{CO}, a_{HC}, a_{NO} and C_0, r_{HC}, r_{NO} are engine-out emission coefficients determined by regression and calibration procedures.

In order to determine these coefficients, a regression analysis for diesel emissions against fuel rate was performed for these diesel trucks using data from both the FTP and MEC01 cycles. Figure 4.14 shows an example regression analysis for vehicle 405 (1986 Ford F-250).

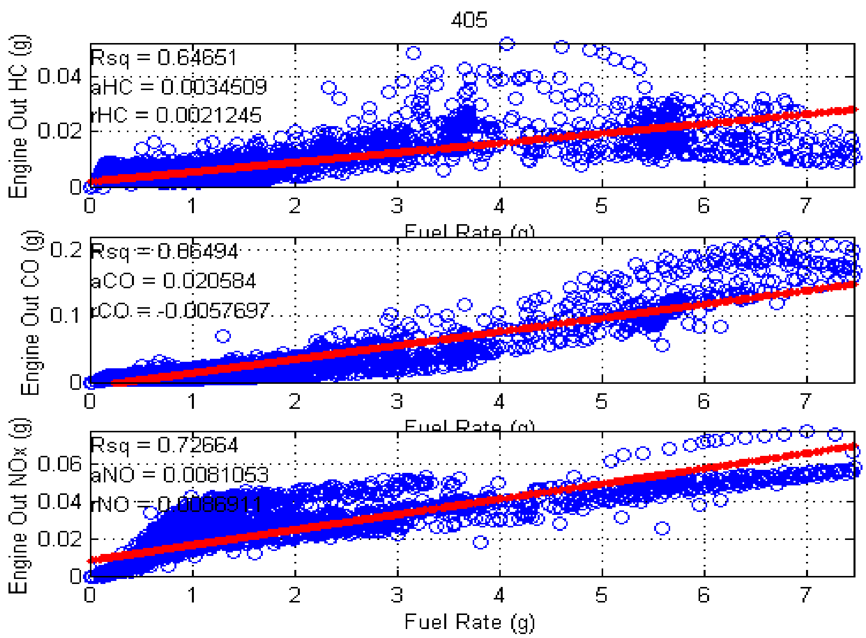

Figure 4.14. Regression Analysis for Diesel Vehicle 405 (1986 Ford F-250).

Table 4.6 summarizes the results for all tested diesel vehicles.

MY	*Make*	*Test#*	*Model*	a_{CO}	C_O	R^2_{CO}	a_{HC}	r_{HC}	R^2_{HC}	a_{NO}	r_{NO}	R^2_{NO}
95	Ford	400	F-350 4x4	0.0047	0.0039	0.1691	0.0006	0.0033	0.4516	0.0418	0.0037	0.9019
87	Ford	401	F-250 TB PU	0.0067	0.0009	0.6077	0.0026	0.0017	0.8363	0.0291	0.0082	0.8612
90	Dodge	402	250 PU 4x4	0.0045	0.0040	0.4859	0.0021	0.0038	0.4440	0.0435	-0.0111	0.8550
92	Dodge	403	Ram 250 LE	0.0023	0.0033	0.5125	0.0011	0.0023	0.5172	0.0449	-0.0040	0.8768
86	Ford	405	F-250 PU	0.0089	0.0010	0.6678	0.0035	0.0021	0.8649	0.0081	0.0087	0.7266
97	Dodge	406	RAM 2500	0.0021	0.0017	0.4300	0.0007	0.0012	0.2478	0.0319	0.0020	0.8870
96	Ford	407	F-350 4x4	0.0034	0.0027	0.1294	0.0003	0.0018	0.6692	0.0283	0.0003	0.8201
86	Ford	408	F-350 4x2	0.0063	0.0022	0.7220	0.0023	0.0022	0.4294	0.0295	0.0139	0.7478
83	Ford	409	F-350 4x2	0.0083	0.0086	0.6295	0.0027	0.0031	0.3727	0.0257	0.0072	0.7704
Average				0.0052	0.0031	0.4838	0.0018	0.0024	0.5370	0.0314	0.0032	0.8274

Table 4.6. Regression Coefficients of Tested Diesel Trucks.

Table 4.6 indicates that, generally speaking, there are strong correlations between engine-out emissions and fuel rate. This is especially true for NO_x emissions, where the correlation coefficient (R^2) values ranges from 0.75 to 0.90 for these vehicles.

Unlike gasoline vehicles, there is no enrichment during cold-start, thus the cold start engine-out CO emission (ECO) module has been modified as follows:

$$ECO_{cold}(t) = \left(1 + (CS_{CO} - 1) \bullet \frac{T_{cl} - T_{su}(t)}{T_{cl}}\right) * ECO(t) \qquad \text{If } T_{su}(t) < T_{cl}$$

where CS_{CO} is the cold-start engine-out CO emission multiplier. Cold-start engine-out HC and NO_x emissions have a similar formula.

4.12.2 Preliminary Diesel Model Results

The calibration procedure for diesel emission model is very similar to (somewhat simpler) the gasoline emission model. This is because the diesel emission model doesn't include the complicated air/fuel control and catalytic converter modules with their related parameters.

The methodology for creating a composite diesel vehicle is same as the composite gasoline vehicles. We have generated both composite emission traces and composite parameters for these ten diesel vehicles.

Table 4.7 lists the summary results of a comparison between the modeled and measured emission factors for composite diesel trucks, under FTP 3 Bag and MEC01 cycles.

Table 4.7 shows that, for the composite diesel vehicles, the percentage differences between the modeling and testing results range from -19% to +14% for all pollutants under the FTP and MEC01 cycles.

It is important to note that this preliminary diesel modal emission model is only based on ten tested vehicles; a much greater number of diesel vehicles (cars and trucks) must be tested and the model must be refined and developed further. This is a subject of future work.

	CO_2 (g/m)	***NO_x (g/m)***	***CO (g/m)***	***HC (g/m)***
FTP Bag 1				
Measured	553.5	6.34	1.78	0.68
Modeled	474.4	7.46	1.77	0.67
Diff (%)	14.3	-17.7	0.1	0.0
FTP Bag 2				
Measured	509.1	4.72	1.61	0.84
Modeled	508.3	5.63	1.59	0.85
Diff (%)	0.2	-19.3	1.2	-1.4
FTP Bag 3				
Measured	452.0	4.96	1.31	0.59
Modeled	416.0	4.62	1.22	0.61
Diff (%)	8.0	6.8	6.7	-3.4
MEC01				
Measured	472.6	4.93	1.49	0.57
Modeled	424.2	4.49	1.16	0.52
Diff (%)	10.2	8.9	22.1	9.2

Table 4.7. Results of the Modeled and Measured Emission Factors for Composite Diesel Trucks.

4.13 DEFINING TYPES OF HIGH EMITTERS*

As discussed in Chapter 1, several independent analyses have found that about half of the on-road emissions by automobiles may be from the small fraction of vehicles that are high emitters [Stedman, 1989; Lawson, 1990; Stephens, 1994; CARB, 1994]. Although there are many potential technical causes of failed or malfunctioning emissions controls, there has been relatively little study of the distribution of these technical causes in the fleet of in-use vehicles [CARB, 1996; McAlinden, 1994; Soliman, 1994]. Probably the most useful work is a comprehensive analysis of several datasets on the effectiveness of repairing specific components, which identifies components most likely to fail [Heirigs et al., 1996; API, 1996].

In the nature of investigations of high-emitters, the emphasis has been on carbureted vehicles and early-model fuel-injected vehicles. In this project, we primarily focus on newer model years, presenting information on vehicles with sophisticated computer-controlled fuel-injected engines.

4.13.1 Characterizing High Emitters

As specified in Chapter 3, suspected high-emitting vehicles were recruited and tested based on a number of different methods. Based on their FTP bag emission results, the vehicles were classified either as high emitting or normal emitting using a set of cutpoints. The high emitting vehicles were classified into different categories, based on the same approximate characteristics used in classifying normal emitters, such as emission/fuel control technology and emission certification level (e.g., Tier 0, Tier 1). However, these categories did not work well, simply because the vehicles in the groups had very different emission characteristics. It made more sense to regroup the vehicles based on the physical mechanisms of emission control system (ECS) failure. (Note that careful inspection of the tested vehicles by a professional mechanic was not a part of this NCHRP project.)

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* This section is slightly adapted from Wenzel and Ross, 1998 (SAE 981414).

To address the issue of real-world frequency of the high emitters, we categorize the several types of high emitters measured in the project according to their emissions characteristics, and make a correspondence between these types of high emitter and the distribution of high emitters with similar tailpipe-emission profiles observed in Arizona's on-going I/M program. The Arizona program covers essentially all light-duty vehicles in the Phoenix area (although the number of high emitters may be underestimated because there is a tendency for people to not register their vehicles, or register them elsewhere, if they think that they won't pass the I/M test [Stedman, 1997]). We thus determine weights to assign to the NCHRP high-emitter types which may reasonably reflect the representation of those kinds of high emitters on the road.

We focus our study on vehicles which are high emitters in low- to moderate-power driving. An example of what we call moderate power is a 50 mph cruise on a level road without unusual load, but with throttle fluctuations. Such a power level requires a fuel rate of about 0.7 grams per second for small sedans, and about twice that for large sedans and most light trucks. This power level is characteristic of the IM240 driving cycle used in the Arizona I/M program and the 505-second cycle used for bags 1 and 3 of the FTP, as shown in Table 4.8. Such moderate power modes are also found in the CE-CERT modal cycle, MEC01. The maximum fuel rates achieved in throttle fluctuations during the MEC01 are also shown in parentheses and are seen to be less than the maxima in the regulatory cycles.

mode	Average speed (mph)	Average (Maximum) Fuel Rates (g/s) small sedan	Average (Maximum) Fuel Rates (g/s) large sedan
MEC01 cycle			
low power	20, 35	0.4 (0.7)	0.6 (1.2)
mod. power	50	0.7 (1.1)	1.3 (2.0)
IM240		0.7 (2.1)	1.2 (3.5)
FTP Bag 2		0.4 (1.3)	0.8 (2.2)
FTP Bag 3		0.6 (2.1)	1.0 (3.5)

Table 4.8. Modes of the MEC01 considered

We compare emission rates in the MEC01 cycle and Arizona IM240 measurements (as well as referring to analyses of earlier FTP measurements). As seen in Table 4.8, the average and maximum power levels in FTP bag 2 are substantially less than in the IM240 cycle, while bag 3 and IM240 have similar power levels. On the other hand, bag 3 starts after a 10-minute soak which modestly increases CO and HC totals for the bag. The IM240 is supposed to begin with the vehicle hot, but there is evidence that in practice vehicles often may have cooled off somewhat or the engine block may not have been fully warmed up [Heirigs, 96]. Power levels and vehicle conditioning in the selected modes of the MEC01 shown in Table 4.8 are most comparable to those of FTP bag 3 and the IM240 cycle.

Emissions Behavior in Closed-Loop and Command Enrichment

Accurate control of the fuel-air ratio in closed-loop operation is critical to effective emissions control. It is likely that most high emitters among MY1990 and later vehicles are caused or created by some form of fuel-air ratio control problem.

In closed-loop operation with a three-way catalyst, the electronic control module manages the injection of fuel so as to essentially maintain stoichiometry (the optimum ratio of air to fuel, about 14.7:1) to maintain combustion while minimizing emissions. In vehicles with three-way catalysts, the ratio is made to swing back and forth between slightly rich and slightly lean, at about one Hz or faster, in order to automatically adjust the oxygen level on catalyst surfaces so that exhaust CO and HC are oxidized while NO is simultaneously reduced. The time dependence of the fuel-air ratio in a typical properly-functioning vehicle is schematically shown in Figure 4.15. As shown, for proper operation the fuel-air ratio oscillates around stoichiometric:

$$\left| \langle\phi\rangle - 1 \right| < \Delta\phi. \qquad (4.13.1)$$

Here, ϕ is the fuel-air ratio compared to its stoichiometric value. In fact, it should hold with substantial overlap. For many vehicles with malfunctioning ECS the fuel-air management isn't working properly, so this inequality doesn't hold, even at moderate power. In these conditions, the vehicle is likely to be a high emitter.

In Table 4.9, six emissions ratios measured in the NCHRP project are shown with typical values that have been observed for modern properly functioning vehicles in hot-stabilized operation (specifically, MY91-93 vehicles tested by manufacturers as part of the FTP Revision Project [Goodwin, 96; Goodwin, 97]). We distinguish three fuel-air ratio regions: *stoichiometric*, where equation (4.13.1) is satisfied; *rich*, where $\phi > 1$ beyond that described by Figure 4.15; and lean, where $\phi < 1$ beyond that described by Figure 4.15.

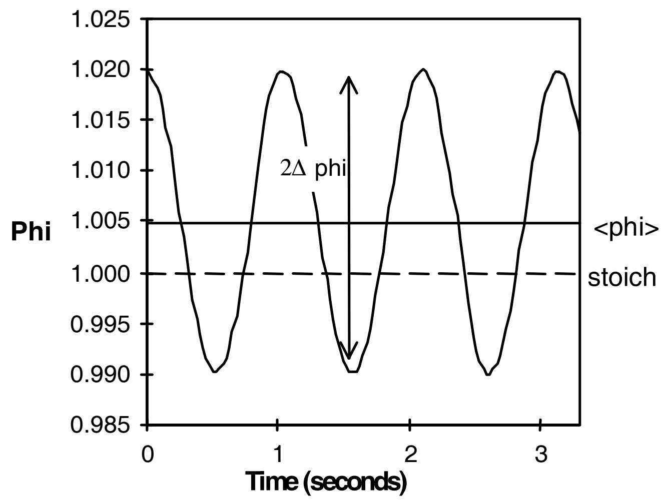

Figure 4.15. Illustrative Example of Oscillations in Fuel-Air Ratio in Closed-Loop Operation.

Variable	Stoichiometric Range	Range with Enrichment
EICO	≈ 0.08	0.1 to approx. 1.0
EIHC	≈ 0.015	≈ 0.015
EINOx	≤ 0.05, lower at low power	≤ 0.05, declines with enrichment
CPFCO	≤ 0.1	quickly → 1.0
CPFHC	≤ 0.1	gradually → approx. 0.7
CPFNOx	0.02 to 0.2	quickly → approx. 0.7

Table 4.9. Average Emission Ratios for Low-Emitting Vehicles, Stoichiometric and Rich Operations.

In stoichiometric operation one observes that:

- The CO emission index, or EICO (the ratio of mass of CO that leaves the engine to fuel input mass), varies around 0.08, from approximately 0.02 to 0.15.

- EIHC depends somewhat on details of engine design and fuel and lubricant composition, since it comes from cylinder surfaces and crevices; but it lies between 0.01 and 0.02 in rich as well as stoichiometric operation.

- EINOx, the engine-out NOx-to-fuel mass ratio, varies with power and with EGR system. The typical maximum value observed is 0.05.

- We designate catalyst activity using catalyst pass fractions, or CPFi: the mass ratio of pollutant i output from the catalyst to pollutant i input to it (i.e. the tailpipe to engine-out ratio). The three catalyst pass fractions vary considerably from one vehicle model to the next and with the details of operation.

In high-power operations, most vehicles command fuel enrichment; i.e. the fuel-air control system goes open loop and ϕ is commanded to be in a range roughly 1.05 to 1.20 (i.e. 5 to 20 percent rich). Since command enrichment results in massive increases in tailpipe CO emissions and some increase in HC, and will, moreover, be coming under regulation with the Supplemental FTP, manufacturers have begun to reduce the use of this technique.

The emissions ratios behave in predictable ways when the fuel-air ratio goes rich (right-hand column, Table 4.9):

- EICO increases strongly with enrichment (as shown by the equation 4.12.2, below); CPFCO is sensitive to even slight enrichment and increases rapidly toward 1.0 with increasing enrichment.

- EIHC is essentially independent of enrichment as such because at the high cylinder temperatures excess fuel is converted to CO and H_2; however, it increases due to other kinds of incomplete combustion, such as from cylinder misfire. CPFHC increases slowly with increasing enrichment.

- EINOx is moderately suppressed by the cooling effect of enrichment; CPFNOx may be reduced with slight enrichment, but increases rapidly with stronger enrichment in most modern vehicles (although it does decline in a few models).

In decelerations during closed-loop operation the fuel-air ratio often goes lean, often very lean in major decelerations. Lean excursions are normal, although large engine-out HC puffs may occur. If catalyst performance has deteriorated, then tailpipe HC puffs associated with these lean excursions can be substantial [An et al., 1998].

Fuel-Air Ratio Data

As suggested by Figure 4.15, ϕ (the fuel-air ratio relative to stoichiometric) would need to be known to much better than 2% accuracy to be useful for our purposes here. Fuel-air ratios based on emission measurements and chemistry are not accurate enough for this purpose. For this reason we use the emissions ratios listed in Table 4.9 as indicators of improper fuel management.

As an alternative to calculating ϕ from tailpipe measurements and chemistry, one can estimate it from a linear formula for EICO:

$$EICO \approx 0.08 + 3.6(1 - 1/\phi), \text{ or}$$

$$\phi = 1 + (EICO - 0.08)/(3.5 - EICO) \qquad (4.13.2)$$

It is likely that ϕ calculated using equation 4.13.2 is not grossly in error. Equation 4.13.2 is not however useful in lean conditions.

Definition of High and Low Emitters

For this particular analysis, we define high emitters as vehicles which exceed FTP bag 3 emissions cutpoints in grams per mile (gpm); the selected cutpoints are shown in Table 4.10 below. With the chosen cutpoints, high emitters exceed the emissions of typical properly-functioning MY 1990-1993 vehicles by more than a factor of about 2.5. These are rather low cutpoints for “high emitters”; we choose them because MY90 and later high emitters proved hard to recruit for testing.

For our analysis we also need cutpoints below which we consider a vehicle to be a low emitter. For this purpose we examine three sets of measurements, as summarized for cars in Table 4.10. The measurements are: 1) NCHRP, for MYs 90-93 measured in 1996-97 (mostly California cars). We calculate average emissions for properly-functioning cars by excluding the 10% highest emitters. 2) FTP Revision Project measurements on new MY91-94 49-state vehicles with 50,000 mile laboratory-aged catalysts [Haskew, 94]. 3) American Automobile Manufacturers Association in-use survey of MY 1991-92 cars with odometer readings from 40,000 to 60,000 miles, measured in 1995-96 [Haskew, 97]. Again, we take the average emissions of the 90% cleanest cars (sorted for each pollutant separately).

dataset	MYs	n[a]	CO	HC	NOx
NCHRP	1990-93	24	2.7	0.22	0.35
FTP-RP	1991-94	23	1.5	0.16	0.33
AAMA in-use	1991-92	57	2.5	0.21	0.22

a) number of vehicles measured in the subset considered. See text for definition of each subset

Table 4.10. Emissions from Properly-Functioning Cars at 50,000 miles in Three Studies: FTP Bag 3 (gpm).

The low cutpoints adopted are shown in Table 4.11. We regard these low cutpoints to be representative of properly functioning in-use vehicles at 50,000 miles and age 4 to 5 years. Roughly two-thirds of properly functioning vehicles will emit less than the low-emitter cutpoints chosen.

	CO	**HC**	**NOx**
Low Emitters			
cars	3	0.2	0.4
trucks	4	0.3	0.7
High Emitters			
cars	6	0.5	1.0
trucks	10	0.8	1.5

Table 4.11. Cutpoints for High and Low Emitting Vehicles in the NCHRP Project: FTP Bag 3 (gpm).

4.13.2 High-Emitter Types

Below we consider the four types of high emitters observed in NCHRP project measurements**.**

Type 1. Operates Lean at Moderate Power

In the first type of high emitter, the fuel-air ratio is chronically lean or goes lean in transient operation calling for moderate-power. An average 2% or more lean is likely to saturate the catalyst with oxygen. Examples from the NCHRP data are vehicles 103 (1993 Sundance), 202 (1997 Windstar), and 295 (1990 Chevrolet Astro).

The characteristics of the six ratios for vehicle 202 at low and moderate power are shown in Table 4.12. The effect on the CPFs is striking, while that on the engine-out emissions is slight. While vehicle 202 operates consistently lean, vehicle 103 goes lean in moderate-power transients (i.e. with throttle fluctuation). Vehicle 295 also goes lean during transients, and shows considerable catalyst deterioration as well.

Variable	**Range, Comment**
EICO	≈ 0.08 or less, normal
EIHC	≈ 0.02, normal
EINOx	≤ 0.1, slightly > normal
CPFCO	≈ 0.01, almost zero, < normal
CPFHC	≈ 0.01, almost zero, < normal
CPFNOx	roughly 0.5 to 1.0, much > normal

Table 4.12. Average Emission Ratios at Moderate Power for Type 1 (Vehicle 202).

The behavior of a high NOx emitter over a portion of the MEC (Figure 4.16a) is compared with that of a normal NOx emitter (Figure 4.16b). The tendency of vehicle 202 to run lean for long stretches is seen in Figure 4.16a. In driving at 50 and 65 mph, phi is frequently about 0.9, and the tailpipe NOx rate is high, reaching 0.1 or 0.2 grams per second. Vehicle 136, a normal NOx emitter, operates at stoichiometry during the cruise sections, resulting in very low tailpipe NOx levels. (The strong acceleration at approximately 110 to 120 seconds involves power beyond FTP levels which we do not consider here.)

The FTP bag 3 tailpipe emissions profile for these vehicles is shown in Table 4.13: very high NOx tailpipe emissions, and low CO and HC emissions, relative to emissions of clean vehicles. The profile is in the form of CO/HC/NOx levels in terms of the two cutpoints for each, with L, M and H standing for: below the low cutpoint, medium or in between, and above the high cutpoint, respectively. The low and high cutpoints for trucks are shown for comparison, from Table 4.11.

	CO	HC	NOx	profile
test vehicle 103 (car)	1.7	0.05	1.1	LLH
test vehicle 202 (truck)	0.4	0.04	2.9	LLH
test vehicle 295 (truck)	4.0	0.90	1.8	MHH
low-emitting trucks	4	0.3	0.7	
high-emitting trucks	10	0.8	1.5	

Table 4.13. FTP Bag 3 gpm Tailpipe Emissions for Type 1 Vehicles, and Truck Cutpoints.

A physical failure mechanism leading to Type 1 behavior is not so easy to pinpoint. Improper signal from the oxygen sensor or improper functioning of the electronic engine control are possibilities.

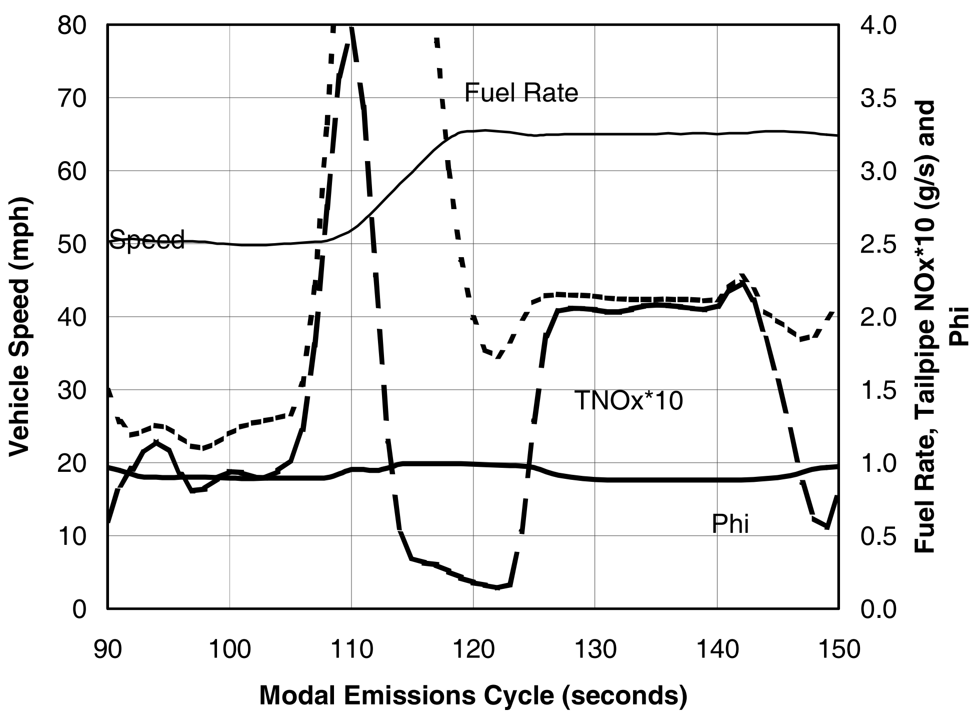

Figure 4.16a. Vehicle 202 (High NOx Emitter): Fuel Rate, Tailpipe NOx, and Phi

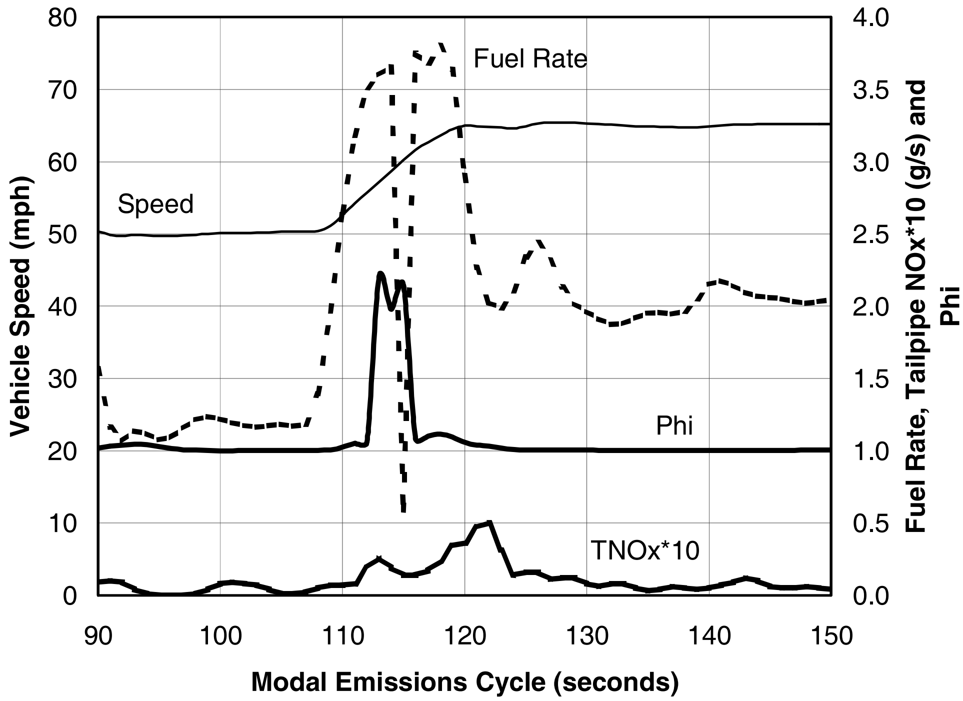

Figure 4.16b. Vehicle 136 (Normal NOx Emitter): Fuel Rate, Tailpipe NOx, and Phi

Type 2. Operates Rich at Moderate Power

In the second type of high emitter, the fuel-air ratio is chronically rich or goes rich in transient moderate-power operation. The EIHC remains normal. Under these conditions, the CO emission index and catalyst pass fraction are high, resulting in high tailpipe CO emissions. Examples from the NCHRP testing are three cars, 113 (1990 Sentra), 125 (1990 Spirit), and 136 (1993 240 SX).

The measurements on vehicle 113 at low and moderate power are summarized in Table 4.14. The high EICO and CPFCO occur in moderate-power transients (i.e. with throttle fluctuation). Relative to properly functioning vehicles, EIHC is unaffected and EINOx is slightly low. The behavior of vehicle 136 is similar. Vehicle 125 shifts from stoichiometric to steady highly-enriched operation for long periods in a manner apparently unrelated to the driving. Vehicles 43 and 277 show transient enrichment, but their strong deterioration of catalyst performance leads us to categorize them as Type 4 below.

Variable	Range, Comment
EICO EIHC EINOx	> 0.15, 2 or more times normal ≈ 0.015, normal ≈ 0.02, < normal
CPFCO CPFHC CPFNOx	roughly 0.5 to 1.0, much > normal ≈ 0.05 to 0.2, somewhat > normal ≈ 0.01, < normal

Table 4.14. Emission Ratios at Moderate Power for Type 2 (Vehicle 113)

The behavior of a high CO emitter over a portion of the MEC (Figure 4.17a) is compared with that of a normal CO emitter (Figure 4.17b). The tendency of vehicle 136 to run somewhat rich when there are throttle variations at moderate power is shown in Figure 4.17a in the 60- to 75-second segment, where EICO reaches levels of 0.2 to 0.3. The great sensitivity of CPFCO to these rich excursions is evident. A normal CO emitter, vehicle 103 (Figure 4.17b) shows much lower EICO and CPFCO in this segment of the MEC. (Again we do not focus on the strong accelerations at the beginning and end of the sequence shown.)

The FTP bag 3 tailpipe emissions profile for these vehicles is shown in Table 4.15: high CO, and low to medium HC and NOx, relative to emissions of clean vehicles. (For car 113, the CO is taken as high although the measurement comes in slightly below the high cutpoint.)

There are many possible failure mechanisms resulting in enrichment during closed loop operation; however the mechanism here must also leave the engine-out HC emissions index in its normal range of 0.01 to 0.02. Thus there can be enrichment but not misfire. One example that meets the characteristics is a leaking exhaust line which brings in oxygen before the oxygen sensor, resulting in the sensor calling for more fuel from the injectors.

	CO	HC	NOx	profile
test vehicle 113 (car)	5.9	0.21	0.24	HML
test vehicle 125 (car)	6.4	0.34	0.57	HMM
test vehicle 136 (car)	6.8	0.17	0.17	HLL

Table 4.15. FTP Bag 3 gpm Tailpipe Emissions for Type 2 Vehicles

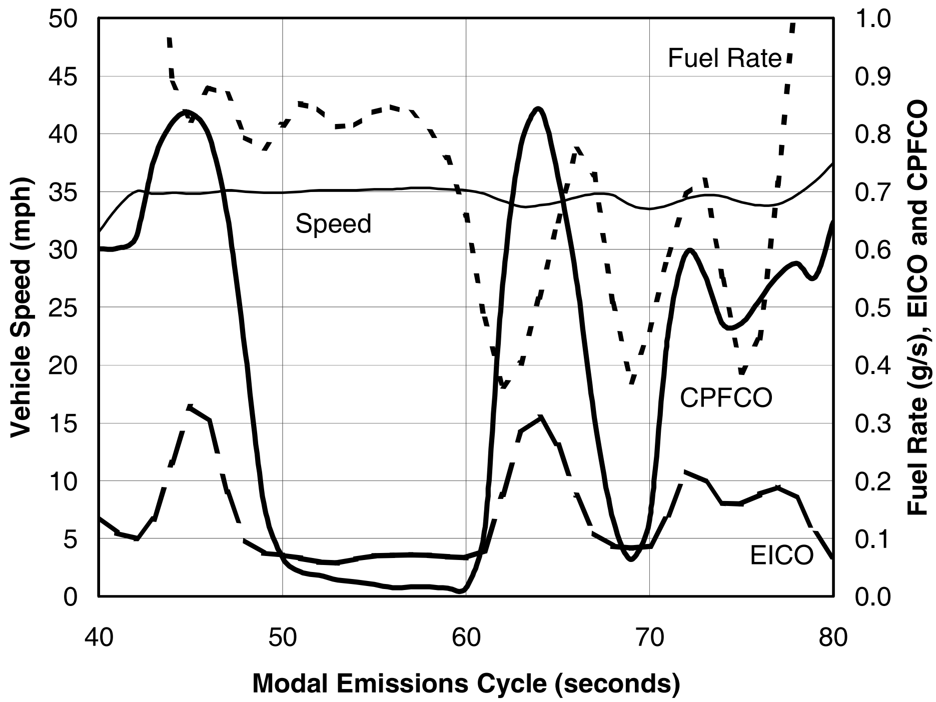

Figure 4.17a. Vehicle 136 (High CO Emitter): Fuel Rate, Engine Out CO and CO Catalyst Pass Fraction.

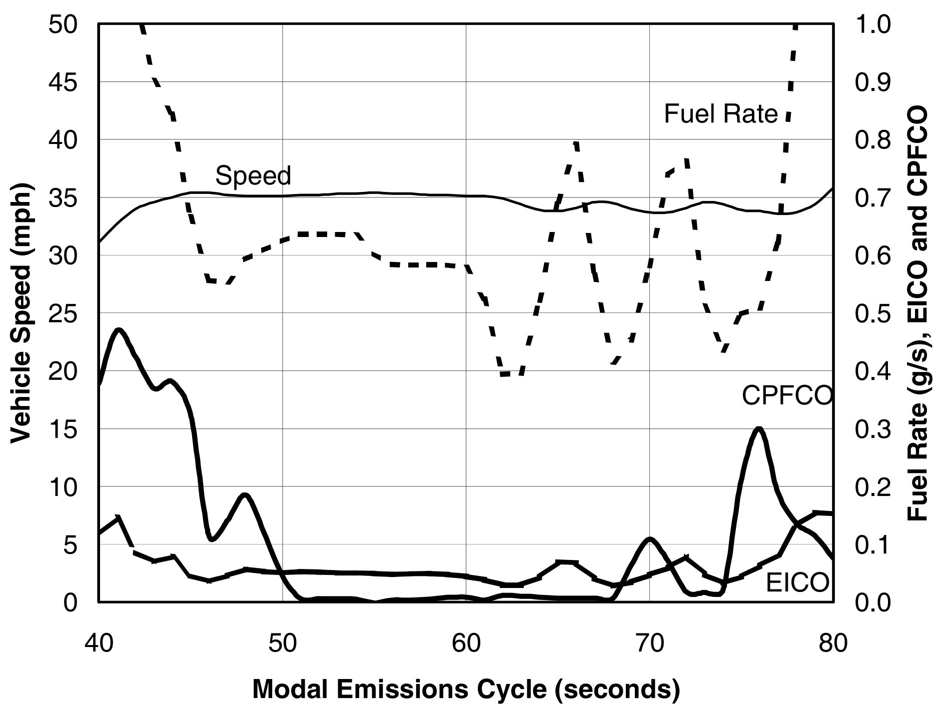

Figure 4.17b. Vehicle 103 (Normal CO Emitter): Fuel Rate, Engine Out CO and CO Catalyst Pass Fraction.

Type 3. High Engine-Out Hydrocarbon Emissions Index

The third type of high emitter involves a high engine-out emission index for HC and mild enrichment, as evidenced by high EICO and CPFCO. Catalyst performance is also poor. Examples are vehicles 178 (1992 Chevy S-10 pickup), 209 (1994 Dodge Caravan), and 273 (1992 Chevy Corsica). The characteristics of vehicle 209, whose second-by-second EIHC is consistently high, are shown in Table 4.16.

Variable	Range, Comment
EICO EIHC EINOx	> 0.15, 2 or more times normal ≈ 0.15, roughly 10 times normal ≈ 0.02, < normal
CPFCO CPFHC CPFNOx	roughly 0.5 to 1.0, much > normal ≈ 0.05 to 0.2, slightly > normal ≈ 0.01, essentially zero

Table 4.16. Emission Ratios for Type 3 (Vehicle 209)

The characteristics of vehicle 178 are shown in Table 4.17. In this case, high EIHC is a transient effect, with puffs of HC every time the fuel-air ratio declines, even in cases where it remains rich.

Variable	Range, Comment
EICO EIHC EINOx	≈ 0.15, slightly over normal ≈ 0.05, roughly 3 times normal < 0.02, < normal
CPFCO CPFHC CPFNOx	roughly 0.5, much > normal ≈ 0.1 to 0.3, > normal ≈ 0.5, much > normal

Table 4.17. Emission Ratios for Type 3 (Vehicle 178)

The behavior of a high HC emitter over a portion of the MEC (Figure 4.18a) is compared with that of a normal HC emitter (Figure 4.18b). The tendency of vehicle 178 to have HC emissions indices exceeding 0.1 at times other than major decelerations is shown in Figure 4.18a. The effect seems to be associated with throttle fluctuations between seconds 70 and 80 of the MEC (the relatively low EICO values at these times suggest that the increase in EIHC is not due to enrichment; an example of enrichment can be seen between seconds 40 and 45, at the end of an acceleration). Figure 4.18b shows that a properly-functioning engine of current technology maintains EIHC in the 0.01 to 0.02 region, except after major accelerations or decelerations. (The figure also shows small EIHC excursions above this value during transients.)

The FTP bag 3 tailpipe emissions profile for these vehicles is shown in Table 4.18: moderate to slightly-high tailpipe CO, very high HC, and moderate to low NOx relative to properly-functioning vehicles. The key aspect of the profile is the very high HC.

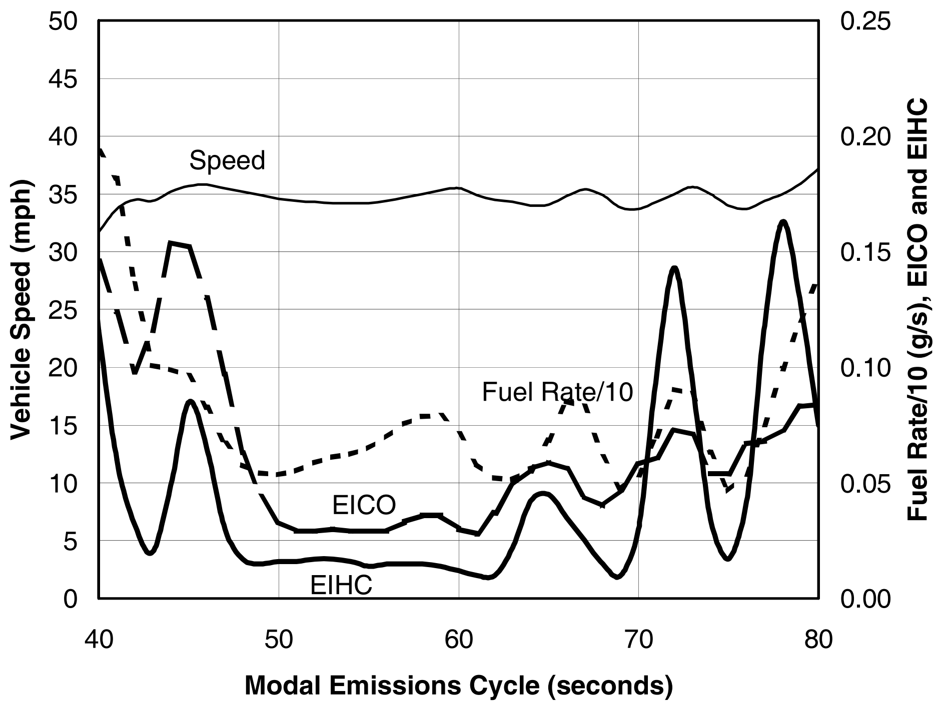

Figure 4.18a. Vehicle 178 (High HC Emitter): Fuel Rate, Engine Out CO and HC.

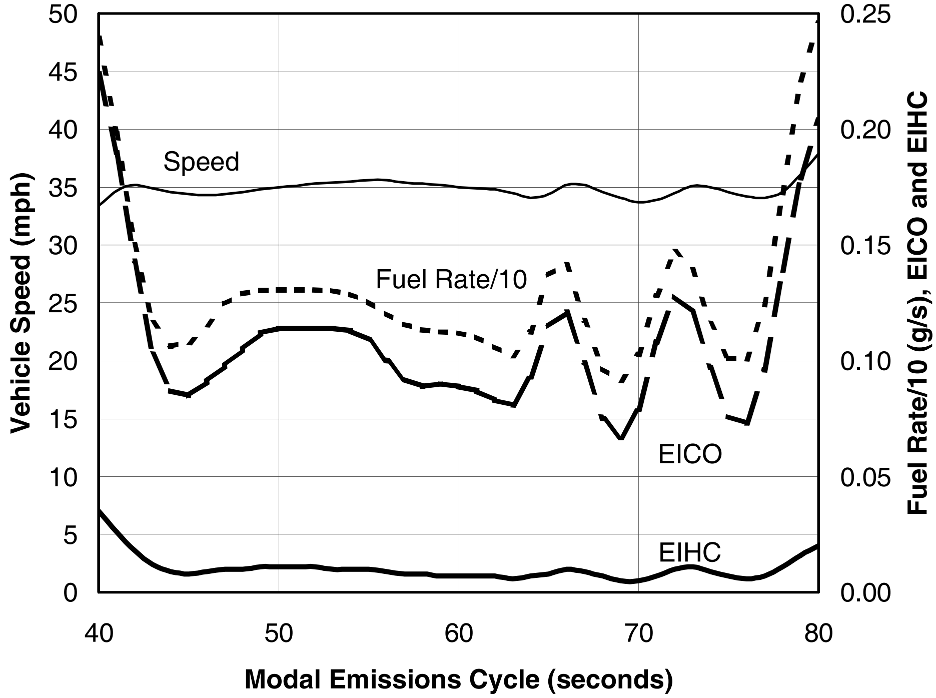

Figure 4.18b. Vehicle 295 (Normal HC Emitter): Fuel Rate, Engine Out CO and HC.

	CO	HC	NOx	profile
test vehicle 178 (truck)	4.5	1.2	0.8	MHM
test vehicle 209 (truck)	11.4	2.1	0.06	HHL
test vehicle 273 (car)	9.8	1.7	0.9	HHM

Table 4.18. FTP Bag 3 gpm Tailpipe Emissions for Type 3 Vehicles

Excess EIHC is probably caused by incomplete combustion in one or more cylinders, from a physical mechanism such as a bad spark plug or partial obstruction of an injector resulting in too little fuel injected into the cylinder. There are many possible mechanisms. Oxygen levels in the exhaust are observed to be correspondingly high (2.5 grams of excess oxygen per gram of excess engine-out fuel). Catalyst performance is also poor, and not only when EIHC is high. Perhaps the catalyst deterioration results from the history of high engine-out HC emissions.

Type 4. Poor Catalyst Performance for All Three Pollutants at Moderate Power

High tailpipe emissions of all pollutants typify Type 4 high emitters. This type involves more than one behavior, with 1) chronically poor catalyst performance, due to burned-out or missing catalyst, or 2) transiently poor catalyst performance, e.g. a catalyst pass fraction of 0.3 or more in moderate-power driving. Type 4 malfunction is distinguished from Type 3 because EIHC is normal, or only slightly high, and from Type 1 because there is no or only slight enrichment at moderate power.

We consider seven examples of this type. Two vehicles, 42 (1990 Grand Am) and 71 (1992 Corolla), have burned-out catalysts. Five, 43 and 150 (1992 Dakotas), 77 (1992 Tercel), 254 (1992 Elantra), and 277 (1992 VW Fox) are more complex examples of poor, highly-variable, catalyst performance; emissions characteristics for three of these vehicles are shown in Table 4.19. Vehicles 77 and 150 are similar in their relatively good fuel control and normal EIHC. Vehicle 43 and especially 254 and 277 have poor fuel control. Vehicle 277 could be classified as Type 2, with its considerable transient enrichment. Vehicle 254 could be classified as Type 3, being somewhat similar to 178; its EIHC is about twice normal.

Variable	**Range, Comment**
EICO	up to 0.15, normal or slightly higher
EIHC	up to 0.025, normal or slightly higher
EINOx	< 0.05, normal
CPFCO	0.3 to 0.6, well above normal
CPFHC	≈ 0.2 or 0.3, above normal
CPFNOx	0.2 to 0.6, well above normal

Table 4.19. Emission Ratios for Type 4 (Vehicles 43, 77 & 150)

The behavior of a vehicle with high emissions of all pollutants over a portion of the MEC (Figure 4.19a) is compared with that of a normal emitter (Figure 4.19b). Figure 4.19a illustrates strong if variable catalyst deterioration for vehicle 254, with CPFs of about 0.4 in moderate driving. This deterioration does not seem to be caused by excursions in phi, although we cannot be sure because the measurement of phi may not be accurate enough for this purpose. In contrast, Figure 4.19b shows that a normal emitter (vehicle 248) has CPFs of essentially zero in the same segment of the MEC (although CPFs do increase with excursions in phi).

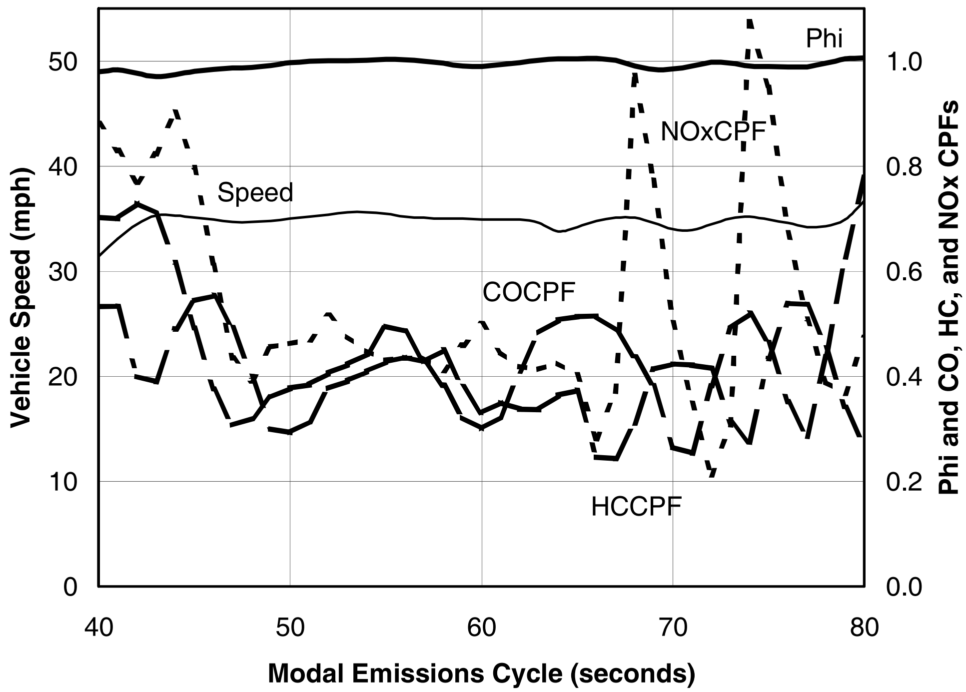

Figure 4.19a. Vehicle 254 (High CO, HC, and NOx Emitter): Phi and CO, HC, and NOx CPFs.

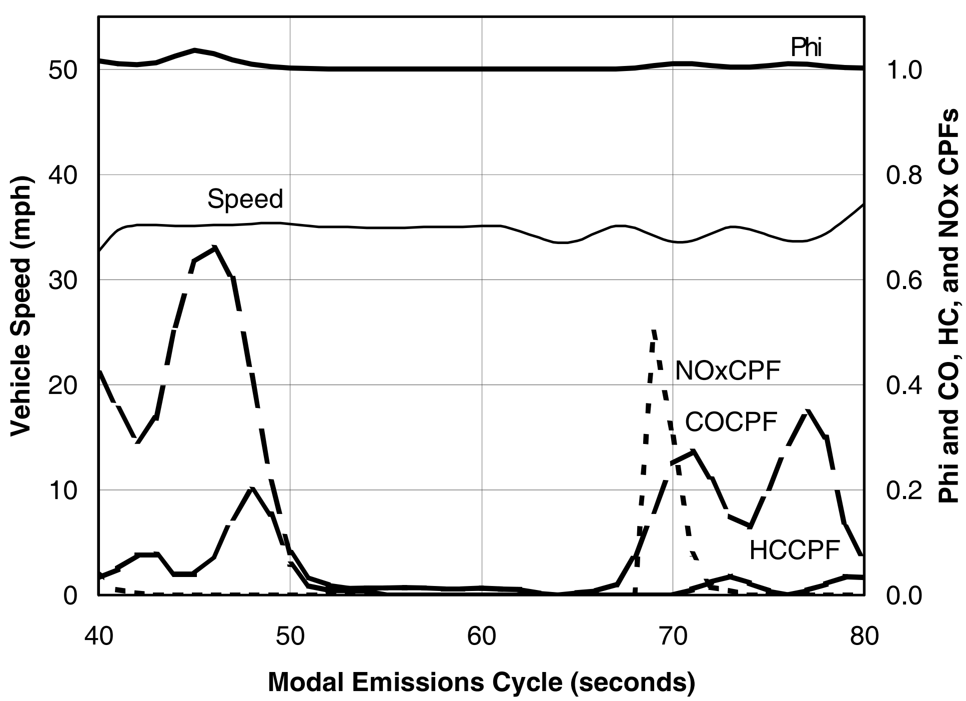

Figure 4.19b. Vehicle 248 (Normal CO, HC, and NOx Emitter): Phi and CO, HC, and NOx CPFs.

The FTP bag 3 tailpipe emissions profile for all of these vehicles is shown in Table 4.20: in almost all cases all three pollutants are high, relative to clean car levels.

	CO	HC	NOx	profile
test vehicle 42 (car)	11.6	2.1	5.4	HHH
test vehicle 43 (truck)	10.4	0.7	2.5	HMH
test vehicle 71 (car)	9.2	1.6	1.9	HHH
test vehicle 77 (car)	7.1	1.0	1.7	HHH
test vehicle 150 (truck)	8.8	1.9	2.8	MHH
test vehicle 254 (car)	11.9	1.7	3.5	HHH
test vehicle 277 (car)	24.6	1.7	1.5	HHH

Table 4.20. FTP Bag 3 GPM Tailpipe Emissions for Type 4 Vehicles.

This type of high emitter may be associated with a burned-out catalyst, as observed in two of the vehicles here; but transiently bad catalyst performance is also observed. It is difficult to distinguish between two possible basic causes of the latter. The first involves greatly deteriorated performance of the catalyst, presumably due to severe operating conditions in the past. A second possible cause is poor closed-loop control of the fuel-air ratio, such that it doesn't conform to the needed pattern but at a level of failure too detailed to be observed directly here.

Summary

The CO/HC/NOx tailpipe-emissions profiles for the high-emitters measured in the NCHRP project, using the cutpoints of Table 4.10 to define the boundaries for High, Medium and Low, are shown in Table 4.21. We include MMH vehicles as both Type 1 and Type 4 high emitters, as discussed below.

High-Emitter Type	CO/HC/NOx profile
1: lean	LLH, LMH, (MMH)
2: rich	HML, HMM
3: misfire	HHL, MHM, MHL, HHM
4: catalyst problem	HHH, MHH, (MMH)

Table 4.21. High-Emitter Types by FTP Bag 3 Profile.

An essential point is that these are general categories. Each "type" identified corresponds to more than one detailed behavior; for example, we observe both transient and chronic behavior for each type. And each type covers more than one disparate *physical* malfunction.

4.13.3 Emission Profiles in the Arizona IM240 Data

Because the number and distribution of the high emitting vehicles recruited for testing under the NCHRP project are not representative of the in-use fleet, we analyze data from the Arizona I/M program to get a sense of the prevalence of each type of high emitter.

The IM240 test was recently introduced in several non-attainment areas, including the Phoenix area, as part of an enhanced inspection and maintenance (I/M) program. The test involves a 4-minute dynamometer cycle with speeds up to 57 mph, with an average speed of 30 mph. The IM240 power levels are similar to those in FTP bag 1 or 3, and involve the same maximum specific power, as shown in Table 4.8. To reduce costs and waiting, the 240-second test is terminated early by the Arizona contractor for vehicles with relatively low or high emissions. For short tests, we calculate an adjusted gpm; our adjustment is different than that used in Arizona [Wenzel, 1997].

4.13.4 Development of Emission Profiles

Using the IM240 data, we create CO/HC/NOx profiles based on high, medium and low categories for each pollutant, as we did with FTP bag 3 measurements on the sample of NCHRP high-emitting vehicles. The profiles again depend on choice of low-emitter and high-emitter cutpoints. (Because of differences between the two measurement programs, as discussed below, these IM240 cutpoints are not the same as those for the bag 3 measurements.) We consider several alternative sets of cutpoints; two of these sets, which differ in the definition of high-emitters, are shown in Tables 4.22 and 4.23*. Among MY1990-93 cars as measured in 1995, the cutpoints of Table 4.22 yield 10% high emitters (vehicles with at least one H); almost half of the non-high emitters are classified as LLL. The cutpoints of Table 4.23 yield 25% high emitters.

Range	CO (gpm)	HC (gpm)	NOx (gpm)
high H	>20	>1.2	>2.5
medium M	6 to 20	0.4 - 1.2	1.2 - 2.5
low L	<5	<0.5	<1.2

Table 4.22. High High-Cutpoints for Profiling the IM240 High Emitters.

Range	CO (gpm)	HC (gpm)	NOx (gpm)
high H	>15	>0.8	>2.0
medium M	6 to 15	0.4 - 0.8	1.2 - 2.0
low L	<5	<0.5	<1.2

Table 4.23. Low High-Cutpoints for Profiling the IM240 High Emitters.

Almost all of the Arizona IM240 high emitters occur in eight profiles, depending on the choice of cutpoints. The profile distributions found are shown in Table 4.24. With three pollutants and three emissions levels, H, M and L, there are nineteen possible profiles of high emitters (i.e. vehicles with at least one H). Just eight in Table 4.24 have an incidence of 5% or more; only 10% of the vehicles fall in the other eleven profiles. A characteristic of most of the missing profiles is that they do not obey a tight correlation between CO and HC (independent of the NOx level).

The distribution of a sample of vehicles among the high emitter profiles is shown in Figure 4.20. The vehicles all have at least one H, i.e. with one of the pollutants high. The dashed lines mark the boundaries of the emitter profiles, using the cutpoints in Table 4.22. The lower left quadrant of the figures represents the LLx emitter profile (low CO and HC, with unspecified NOx emissions), while the upper right quadrant

* The high cutpoints shown in Table 4.22 are the cutpoints currently in use in the Arizona I/M program for MY1991 and newer cars. The high cutpoints in Table 4.23 are the final cutpoints originally proposed for the

contains cars in the HHx profile. The three levels of NOx emissions are denoted in the figures using different symbols. One sees patterns: 1) There are no HLx and few LHx vehicles; i.e. HC and CO are strongly correlated. 2) High CO is correlated with low-to-moderate NOx. 3) There is a group of vehicles with high NOx and low-to-moderate CO and HC. These general tendencies are expected, but we are surprised by their pervasiveness in a very large sample. Part of the explanation is that high CO only occurs with enrichment, which enhances HC and suppresses engine-out NOx.

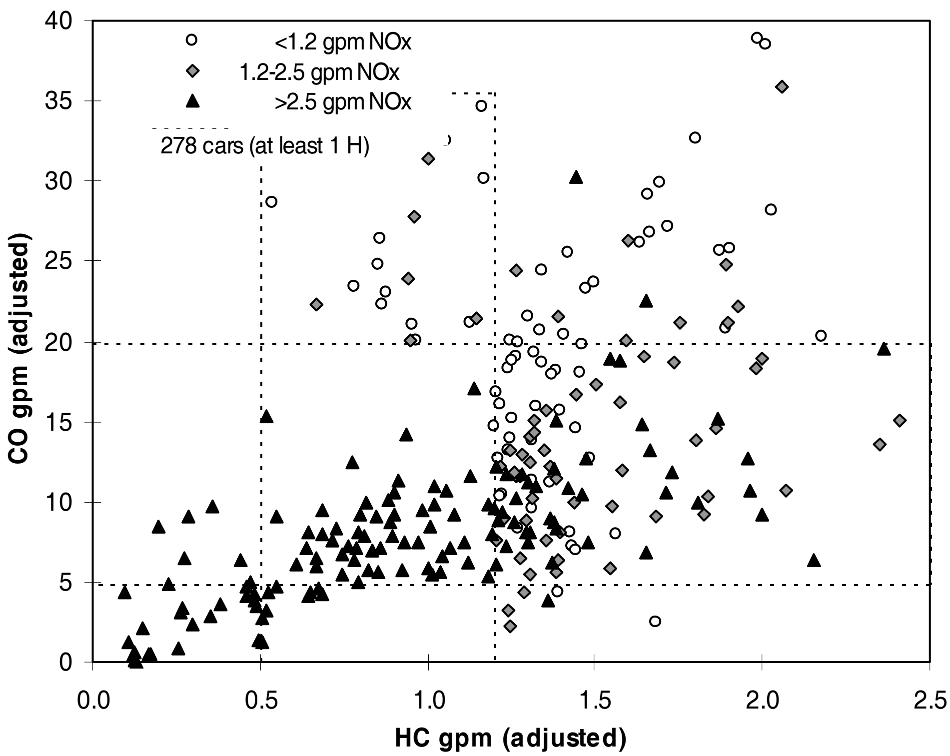

Figure 4.20. Distribution of High Emitters by Emission Profile (CO/HC/NOx), 278 Cars with at Least 1 H.

Care must be taken in interpreting the figure, since the restriction of at least one H strongly influences its appearance. Figure 4.21 is a similar scatterplot using the same cutpoints, but including vehicles with two medium-level pollutants, in order to clarify the structure near the medium-to-high transition in HC for medium CO. The distribution is smooth across this boundary. One sees, for example, that there are many

Arizona program (and not adopted due to the finding of inconsistent vehicle preconditioning [Heirigs et al, 1996]).

MML vehicles, with medium CO, but on the high side, which probably have similar malfunctions to those classified as HML, i.e. with high CO.

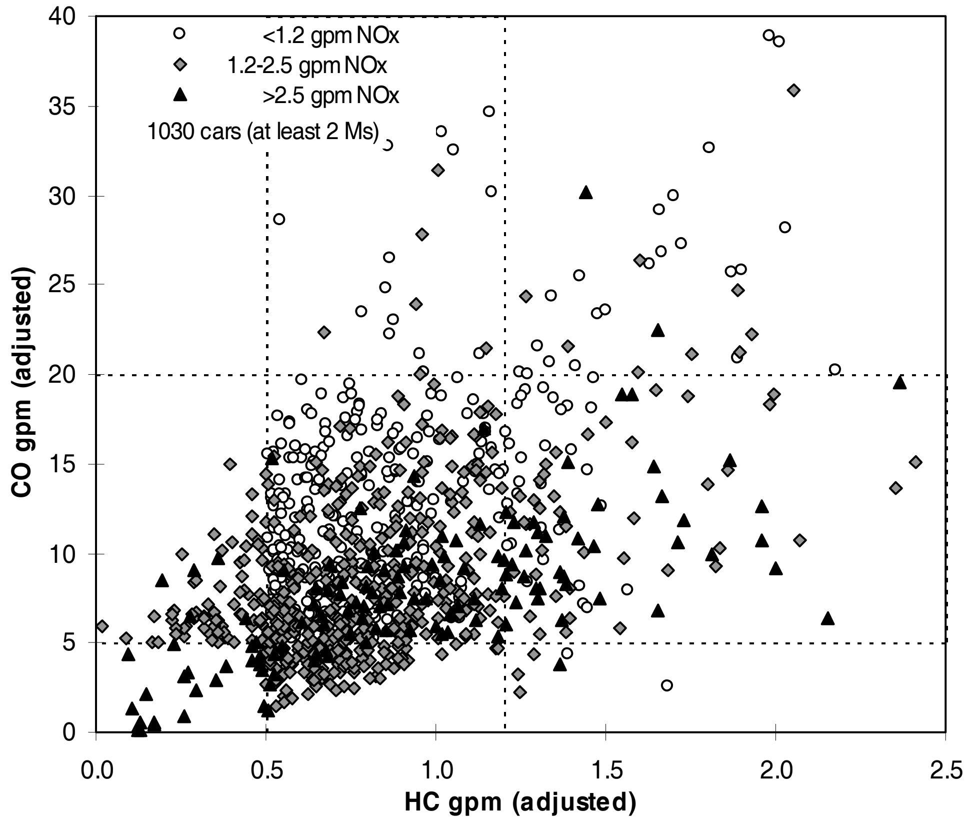

Figure 4.21. Distribution by Emission Profile (CO/HC/NOx), 1030 Cars with at Least 2 Ms.

4.13.5 Frequency of Occurrence of Types of High Emitters

All but three of the eight important IM240 profiles (Table 4.24) are included in the list of profiles identified among the NCHRP high emitters (Table 4.21); the three are MMH, LMH and MHL. The differences between the two sets of percentages in Table 4.24 show where there are sensitivities to the high cutpoints used.

High emitters from the NCHRP project (FTP bag 3) are plotted in Figure 4.22 for comparison with the sample of the Arizona IM240 high emitters in Figures 4.20 and 4.21. Figure 4.22 has the same axis scales as Figures 4.20 and 4.21, but the dashed lines reflect the lower cutpoints used for the FTP tests.

Profile: CO/HC/NOx	Percent high emitters	
	high cutpoints[b]	low cutpoints[c]
HHH	1	3
HHM	5	5
HMH	0	0
MHH	11	18
HMM	2	1
MHM	17	12
MMH	20	10
HHL	10	10
HML	11	5
HLM	0	0
MHL	6	8
MLH	2	4
LHM	1	2
LMH	4	4
HLH	0	0
LHH	0	2
HLL	0	2
LHL	0	1
LLH	7	13

a) since we base the emission profile on our adjusted gpm results from the IM240 data, some cars classified as high emitters in this analysis actually were passed by the AZ I/M contractor (were passed in Phase 2 of test).
b) b) See Table 4.22. c) See Table 4.23.

Table 4.24. Distribution of High Emitters by Profile: Arizona IM240, MY1990-1993 Corsa.

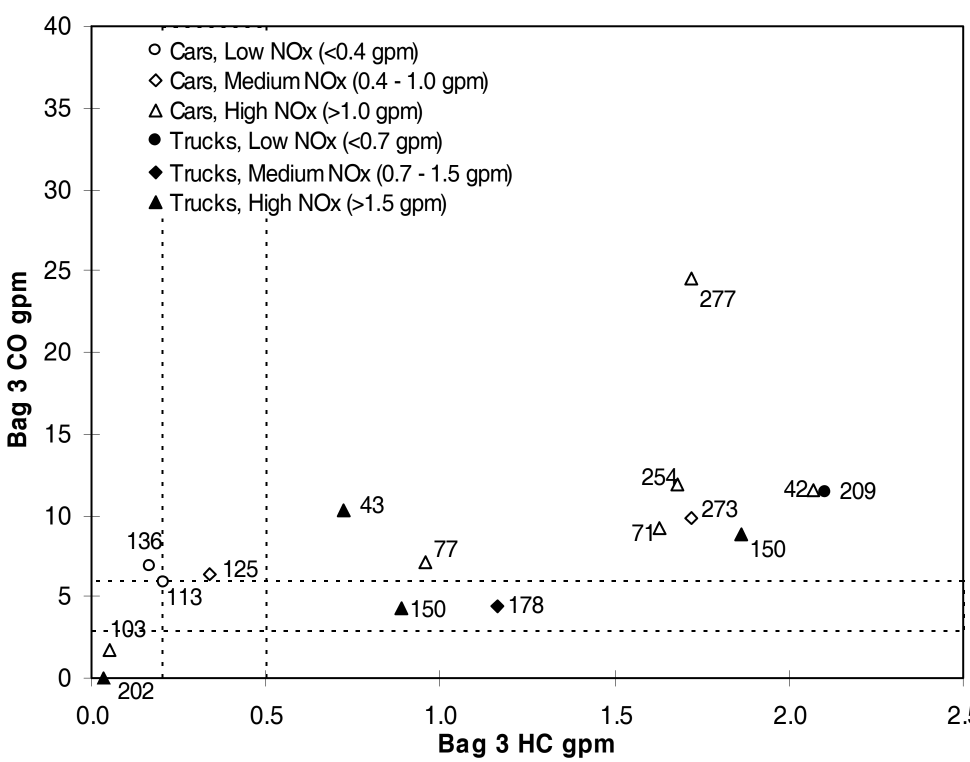

Figure 4.22. Distribution by High Emitter Type, MY90-96 Vehicles, 1996-97 NCHRP FTP.

In Figure 4.23 we present rough boundaries for the IM240 profiles for the four types of high emitter identified among the NCHRP vehicles. As seen, we assign about one-third of IM240 category MMH to Type 4 and two-thirds to Type 1, all of LMH to Type 1, and all of MHL to Type 3. The resulting frequencies as percentages of all high emitters are shown in Table 4.25.

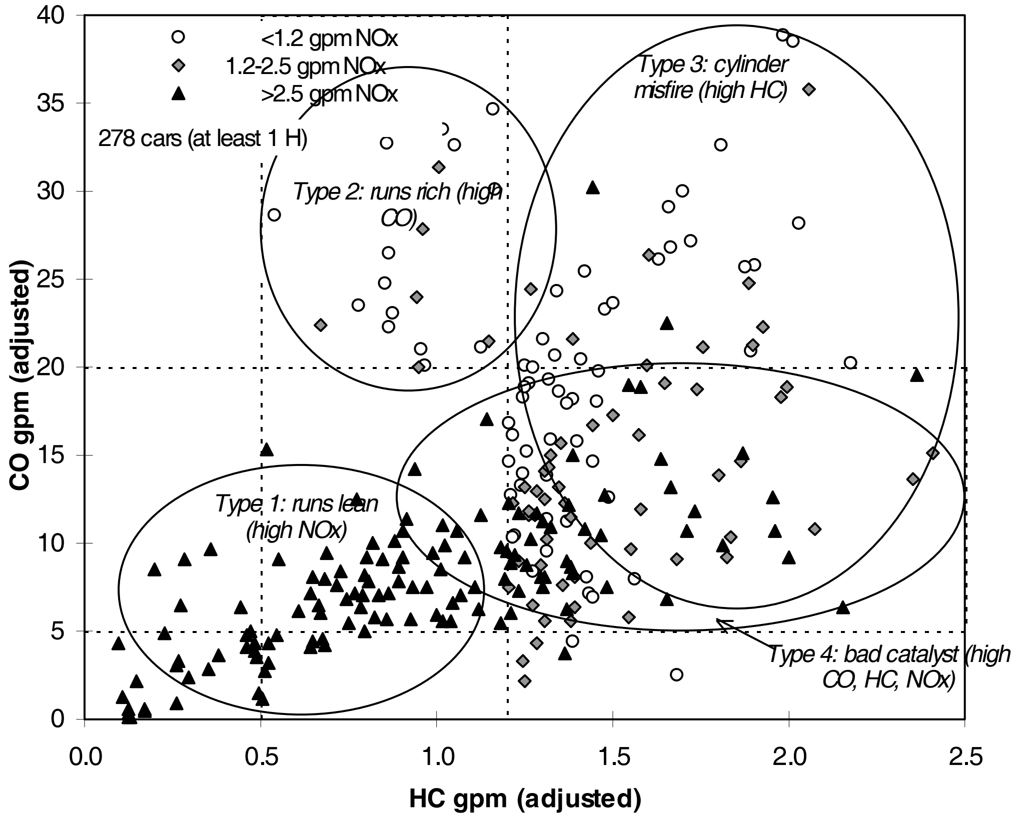

Figure 4.23. Distribution by Emission Profile and Type, MY90-93 Cars, 1995 AZ IM240.

High Emitter Type	Profile	Percent of High Emitters	Percent of All Cars
1: Runs Lean	LLH, LMH, (MMH)	24	2.4
2: Runs Rich	HML, HMM	13	1.3
3: Misfire	HHL, MHM, MHL, HHM	38	3.8
4: Bad Catalyst	HHH, MHH, (MMH)	19	1.9
Other high emitters		5	0.5

Table 4.25. Distribution of IM240 Profiles of MY90-93 Cars, Based on Cutpoints of Table 4.22.

These frequencies or weights are used in formulating the contribution of high emitters in the modal model, as discussed below in Section 4.13.

4.13.6 Caveat

There are several important differences between IM240 bag emissions as measured and those of FTP bag 3 analyzed above:

- The sample of vehicles is quite different. IM240 test results of over 135,000 MY90-93 passenger cars were analyzed; these vehicles represent roughly half of the registered vehicles in the Phoenix area (the program is a biennial program, where testing is required every two years and upon vehicle sale). These data are much more representative of the in-use fleet than the 300 vehicles tested under the NCHRP program. In addition, the Arizona data are dominated by 49-state vehicles with somewhat different emissions controls than for California vehicles. Moreover, the measurements in Arizona used here were made in 1995, while those at CE-CERT were made in 1996-97. In addition, the IM240 sample used consists of cars only, while the NCHRP data contains both cars and light trucks.

- The conditioning of the vehicles (i.e. the block and catalyst temperatures prior to testing) is somewhat different. This is probably not a big effect for high emitters. As an extreme comparison, when one compares the NCHRP FTP bag 2 and bag 3 data for high emitters one finds that bag 2 HC and CO emissions are only moderately lower, in spite of the full warm-up and lower power requirements of bag 2.

- Most important, we are comparing carefully controlled FTP measurements carried out on 300 vehicles in a laboratory setting with relatively inexpensive measurements on over one hundred thousand vehicles. The equipment and procedures are different; and we have found that it is not a routine matter, even in their laboratory setting, to obtain accurate results. We find that the Arizona IM240 measurements tend to exaggerate the emissions of low- and medium- emitting vehicles, a subject we will explore in a different report. (This does not mean that the Arizona measurements fail to satisfy their purpose, the identification of high emitters.)

- Another problem with the IM240 analysis is that about half of the IM240 tests analyzed were ended after 31 seconds of driving, because the cars met low "fast pass" emission cutpoints. And most of those tested more than 31 seconds were also given a shortened test. Only a small fraction of the tested cars were given the full IM240 test; most of these cars were randomly recruited to receive the full test. Although we make adjustments to make the shortened test emission results roughly comparable to those of a full IM240 test, these adjustments are rather simplistic and may affect our results.

All of these differences between the FTP and IM240 testing may affect the accuracy of mapping FTP high emitter types to IM240 emission profiles.

4.13.7 Discussion

Generally speaking, the four types of high emitters identified from the emission ratios are roughly equally represented in the Arizona I/M fleet. Type 1 (runs lean) occurs in 24% of high emitter vehicles while Type 2 (runs rich) occurs in only 14% of high emitter vehicles. It is possible that there has been a shift in the distribution of high emitters from high CO to high NOx emitters, as we have moved from carbureted to sophisticated computer-controlled fuel-injected vehicles. Also, earlier I/M programs using idle emissions tests virtually ignored NOx emissions, so high emitters may have been previously repaired to reduce CO and HC at the expense of NOx emissions.

For many people, the study of emissions-control malfunction concerns component malfunction. While our study does not directly address individual components, we do get some information on what components may affect the different types of high emitters. As just mentioned, we find that relatively small fuel control deviations from stoichiometry characterize about 40% of the high emitters. Another group (33%) can be roughly characterized as cylinder misfire (Type 3). Catalyst malfunction in the absence of one of the other malfunctions (Type 4) has a relatively low probability at 19%. However, catalyst malfunction is an important but subsidiary problem in many Type 2 and 3 vehicles. So the statement that replacing the catalyst will improve the emissions performance in one-half or more of vehicles is in agreement with our data. But the improvement might be temporary in many vehicles because uncorrected conditions of frequent enrichment or misfire might cause swift catalyst degradation.

In the NCHRP sample, we did not find excessive lean operation to be associated with catalyst degradation. We have not gone further in attempting to pinpoint component failures from the NCHRP data. The data are rich; we hope that others will study them to discover more.

4.13.8 Limitations

There are several analytical and measurement limitations to this study of the occurrence of high emitters. Most have been mentioned, but they are worth a reminder: a) Accurate measurement of fuel-air ratio is difficult, so much of what we conclude about this critical aspect of emissions control is inferred. b) The sample of NCHRP vehicles is small, and has been further sliced into many categories. To the extent study results are as important as we think they are, this study should be followed up by one with substantially more tests of modern high-emitters. c) Most of the measurements involved MY1990-93 vehicles, which we have treated as a group. We have not examined changes in vehicular emissions control technologies during the 1990s. d) The use of profiles involves cutpoints, with the attendant sensitivity to choice of cutpoints. We have examined a few sets of cutpoints for the IM240 data and find that the general results hold for these cutpoints. e) Verification of the accuracy of the IM240 measurements at high gpm levels needs to be improved.

4.14 INCLUSION OF HIGH EMITTERS IN THE NCHRP MODAL MODEL

The goal of this section is to determine linear-combination coefficients c_{ij} such that in the modal model the contribution of high emitters can be added to that of normal emitters. In particular, for any model-year group, j, the model combines the sub-model s_0 for a normal emitter with sub-models s_i for each of the four types of high-emitting composite vehicles, i = 1 through 4, so that the modal model with normal emitter and corresponding high emitters is

$$\Sigma_i\, c_{ij}\, s_i$$

with i summed from 0 to 5. The normal-emitter weight is one corrected for the fraction of high emitters:

$$c_{0j} = (1 - F_{Hj})$$

The weight for each corresponding high-emitter composite vehicle i is F_{Hij}, the fraction of vehicles that are high emitters in the group:

$$c_{ij} = F_{Hij}$$

Here $\Sigma_i\, c_{ij} = 1$, and $\Sigma_i\, F_{Hij} = F_{Hj}$. This is a simplified description of the model. The actual calculation is somewhat more complicated because the role of high emitters depends on the variation within model-year of average emissions as well as F_H, and the sample from the NCHRP study is not large enough to represent both variations.

4.14.1 Two Elements of Deterioration

Two different processes account for the increase of gpm emissions over new-vehicle levels during the life of a vehicle fleet:

1) degradation (typically gradual) of emissions control system (ECS) components

2) increasing fraction of vehicles with malfunctioning or failed ECS

Degradation characterizes “normal emitters”. Degradation is an ongoing process with moderate consequences for the individual vehicle.

Unlike normal emitters, “high-emitters” arise probabilistically, i.e. a vehicle may become a high emitter at some point in its history. It is believed that high emitters are associated with poor maintenance (both neglect of maintenance and incompetent repairs) and with less-robust emissions controls.

All kinds of malfunction/failure occur with rather different emissions consequences. As discussed above in 4.12.5, the four different types (runs lean, runs rich, misfire and catalyst failure) have comparable probabilities.

The tool used for the analysis is the “cumulative vehicle probability distribution” (VPD), as shown in Figure 4.24. The VPD describes the fraction of vehicles (on the y-axis) with emissions above a given level on the x-axis; for example, in Figure 4.24, about 20% of the vehicles have HC emissions greater than about 0.3 grams per mile, while 1% of the vehicles have HC emissions greater than 2 grams per mile. With degradation, the average gpm of normal emitters increases, as shown in Figure 4.25. That is, the upper/left part of the distribution shifts to the right. The high-emitter contribution increases with the increasing fraction of high emitters and increasing average emission; i.e., the lower/right segment of the distribution shifts upward and becomes flatter. An illustrative cutpoint at 0.5 gpm is shown in Figure 4.25; only above it do we call a vehicle a high emitter.

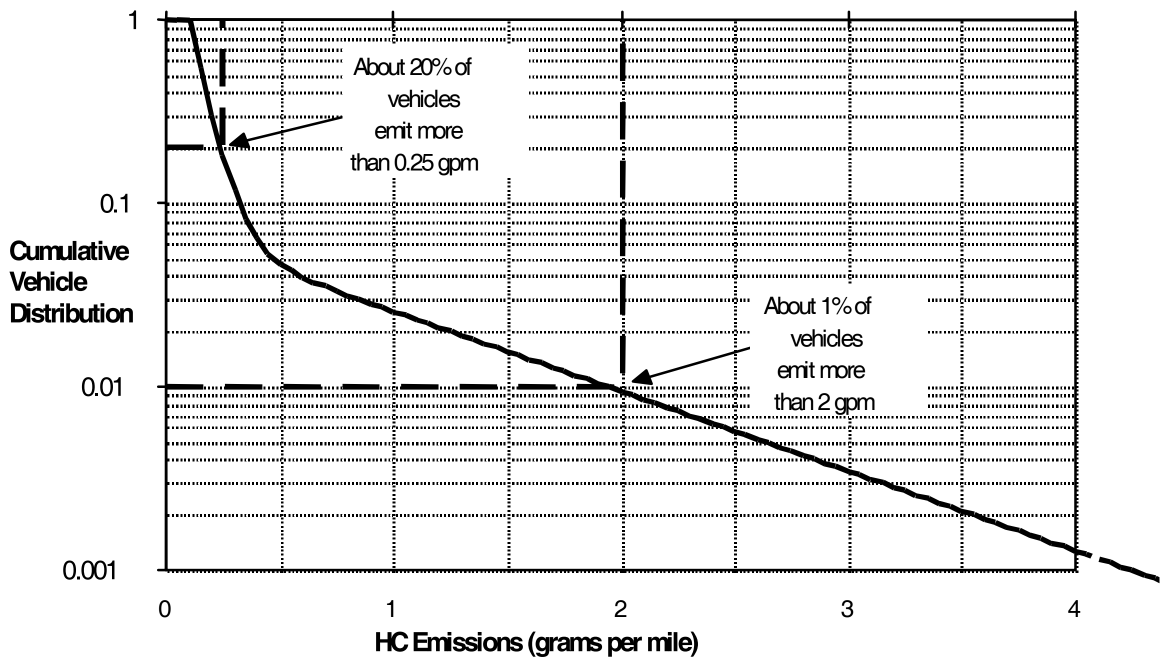

Figure 4.24. Sample Vehicle Probability Distribution, HC; MY91 Cars, 1996 AZ IM240.

4.14.2 The Data Analyzed

The NCHRP project was not designed to obtain numbers of vehicles in each vehicle-technology category that represent the occurrence of vehicles of that category, as registered or on the road. In this analysis, we use FTP and IM240 data from a variety of sources to construct the entire distribution of both normal and high-emitting vehicles expected in the in-use fleet. The distribution of normal-emitters is taken from FTP measurements of in-use vehicles conducted by the AAMA and CARB (LDVSP 13). Because these measurements were made in laboratory settings under carefully controlled conditions, they are considered to be accurate. However, the FTP datasets are not large enough to include a representative sample of vehicles with high emissions. Moreover, recruitment of representative numbers of high emitters is difficult. The distribution of high-emitters is primarily based on Arizona IM240 program measurements of passenger cars, which involves essentially the entire light-duty vehicle fleet in the Phoenix area. The IM240 measurements are used to determine the weights to be given high emitters in the modal model. (Although the AZ IM240 is a mandatory program, some recruitment bias may still be present, in that not all vehicles in the area are legally registered, and not all registered vehicles are brought in for emissions testing.)

We compare IM240 emissions with FTP Bag 3 emissions, rather than composite emissions, since the IM240 cycle was constructed based on the FTP Bag 3 cycle. (Any differences between the FTP Bag 3 and the IM240 speed sequences are minor from the perspective of this study.) We examine two sets of AZ IM240 measurements: 1) the random 2% sample of vehicles tested over the full IM240 cycle by the Arizona IM240 contractor, Gordon-Darby, in 1996; and 2) all vehicles tested by Gordon-Darby in 1995. Since the majority of vehicles in set (2) either fast-pass or fast-fail before the full 240-second test is completed, we adjust fast-pass/fast-fail IM240 test results to their estimated full-test equivalents. We examine, in addition, two other IM240 datasets: 3) full IM240s conducted for EPA by Automotive Testing Laboratory (ATL) between 1992 and 1994, and 4) adjusted Colorado IM240 measurements in 1996. Because the latter have fast pass but no fast fail, they may be more accurate for high emitters than set (2), the adjusted AZ IM240.

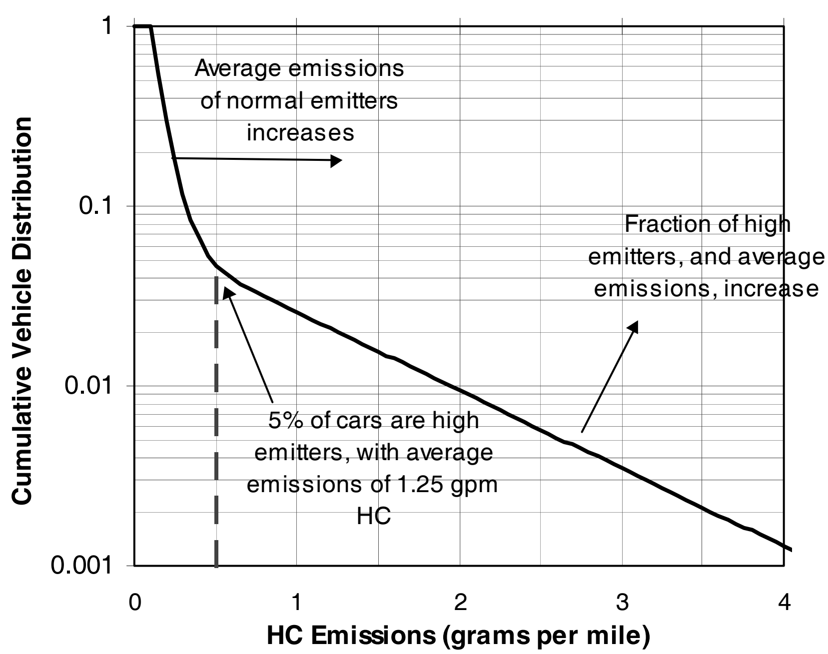

Figure 4.25. Trends in Vehicle Distributions as Age and Mileage Increase, HC; MY91 Cars, 1996 AZ IM240.

The ATL measurements were made in the same lanes with the same equipment as the AZ IM240, but with somewhat more careful procedures, especially preconditioning. The difference between the ATL and AZ IM240 (2% random) distributions can be attributed to the effect of inconsistent preconditioning, as well as possible recruitment biases, especially for high emitters. The difference between the random 2% and full sample AZ IM240 distributions are most likely to be attributed to our adjustments to the fast-pass/fast-fail results.

Unfortunately, the AZ IM240 measurements are not as reliable at low gpm as they presumably are at high gpm; the gpm emissions of the cleanest vehicles are much higher than in FTP surveys. We believe the AZ IM240 data sets tend to overestimate emissions for normal-emitters because less care is taken to control environmental conditions that affect emissions. (We are not criticizing the AZ IM240 contractor, since his responsibility does not extend to accurate measurements on normal emitters.) Others have demonstrated that a large number of vehicles are not adequately preconditioned (i.e., fully warmed-up prior to testing) in the AZ IM240 datasets [Heirigs and Gordon, SAE 962091]. In addition, our method to extrapolate fast-pass/fast-fail IM240 emissions to full-IM240 equivalent emissions may add a bias.

We develop weights for three groups of vehicle model years: MY81-86, MY87-90, and MY91-93. The VPDs from different test programs are shown in Figures 4.26a, 4.26b, and 4.26c for MY91-93 passenger cars with 60-100 thousand miles, for CO, HC and NOx, respectively. (We restrict the analysis to vehicles within a mileage range to minimize the effect of vehicle age when comparing data from different test years. We do not include vehicles with low odometer readings or in a range spanning 100 thousand miles to avoid the problem of misread or rolled over odometers, which is a serious problem in the Arizona IM240 data.) The FTP data, presumably correct at low gpm, shows 90% of vehicles with emissions less than the low-gpm boundary shown in Table 4.26. The table also shows the emissions levels at which the high emitter tails of the AZ IM240 distributions roughly begin, and the cutpoints above which we define vehicles to be high emitters.

	"low" gpm FTP bag 3	"high" gpm, AZ IM240	cutpoints for high emitters (gpm)
CO	<5	>15	10
HC	<0.4	>0.8	0.5
NOx	<1.0	>2.0	1.5[a]

a) The high-emitter cutpoints for MY81-86 are chosen to be larger. See Table 4.27 below.

Table 4.26. Approximate Boundaries for IM240 and FTP Bag 3 Series.

Consider first the normal emitters, i.e. the peaks at upper left of each distribution. For CO (Figure 4.26a) and NOx (Figure 4.26c), the ATL gpms are substantially higher than the FTP for the cleanest 90-95% vehicles, while the AZ IM240 gpms are two or more times the FTP emissions. For HC (Figure 4.26b) the ATL measurements are fairly close to the FTP data for the best 90%. The random 2% AZ IM240 are also much closer to FTP data at low gpm than the full sample.

In Figures 4.26a, 4.26b, and 4.26c we see, on the one hand, that relatively low-statistics FTP surveys run out of vehicles or representative recruitment where the high emitter "tail" begins; on the other hand, the high-statistics IM240 measurements appear to overestimate emissions of the normal emitters. The approach then is to connect the two distributions, using only FTP at low gpm and only IM240 at high gpm. The connections have to span the regions between by the boundaries listed in Table 4.26.

4.14.3 Combined FTP-IM240 Distributions

The way we choose to connect these distributions is also shown for MYs 91-93 in Figures 4.26a, 4.26b, and 4.26c. These are simply straight-line extrapolations on the semi-log graphs of the tails of the IM240 distributions, down to the low emissions defined by the FTP series. After considering the strengths and weaknesses of the four IM240 series, we have chosen to base the straight-line extrapolations primarily on the 2%-random full-test data from Arizona, with guidance from the slopes of the Colorado data at large gpm. At small gpm we make use of hints that maybe found in the LDVSP and AAMA FTP data. We refer to these as combined FTP-IM240 distributions.

The combined FTP-IM240 distributions are highly uncertain in the region of extrapolation, between the low gpm boundary (upper edge of FTP data) and the high gpm boundary (lower edge of the IM240 data).

That is, the extrapolations could be either steeper or flatter. However, the corresponding emissions of the high emitters are somewhat less uncertain. For example, in Figure 4.26a a reasonable high extrapolation for CO is shown. It corresponds to the average CO gpm of high-emitters being 20% greater than the chosen extrapolation. The extrapolation is shakier in the case of HC and not much more than guess work in the case of NOx.

The combined FTP-IM240 distributions for MY87-90 and MY81-86 are shown in Figures 4.27a through 4.27c and 4.28a through 4.28c, respectively. The extrapolations for MY87-90 are more convincing than for MY91-93. The same cutpoints are used as for the MY91-93 analysis. Unfortunately, the extrapolations for MY81-86 HC and NOx are essentially dependent on assumed cutpoints rather than being indicated directly by the data, and MY87-90 is the most important contributor of high emissions in 1996, although the group's role is now declining. In response to the lack a break in the combined VFTP-IM240 distributions, we choose the cutpoints for MY 81-86 large enough to clearly distinguish high from normal emitters. (See Table 4.27 below.)

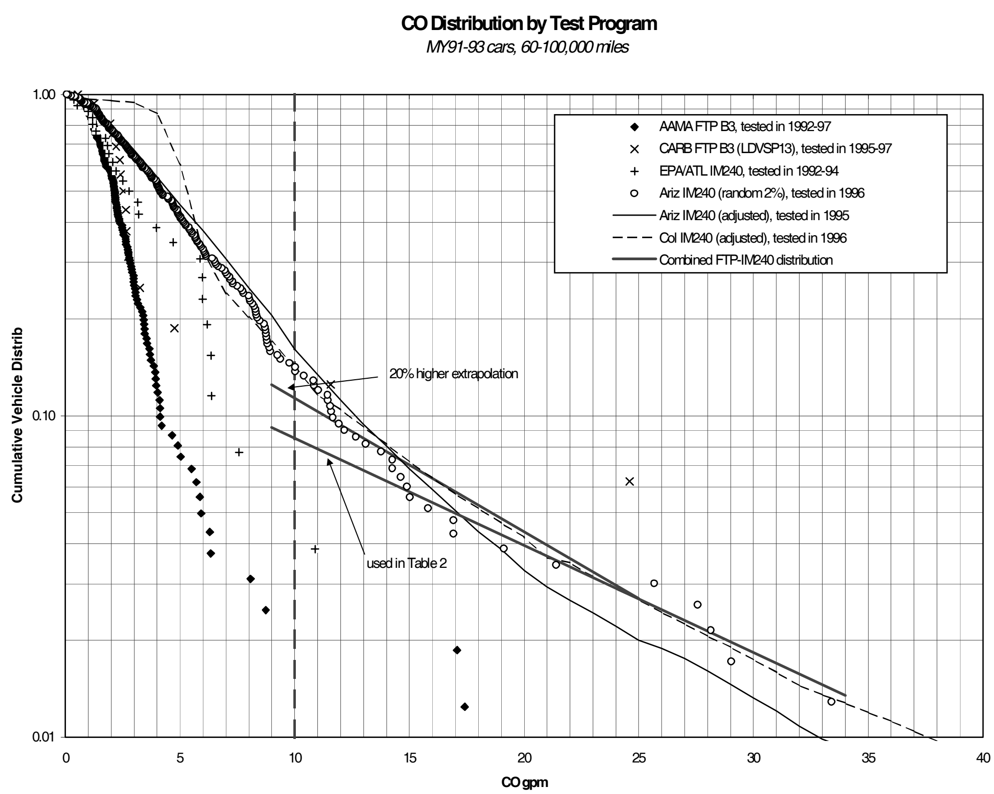

Figure 4.26a. CO distribution by test program, MY 91-93 vehicles, 60 – 100000 miles.

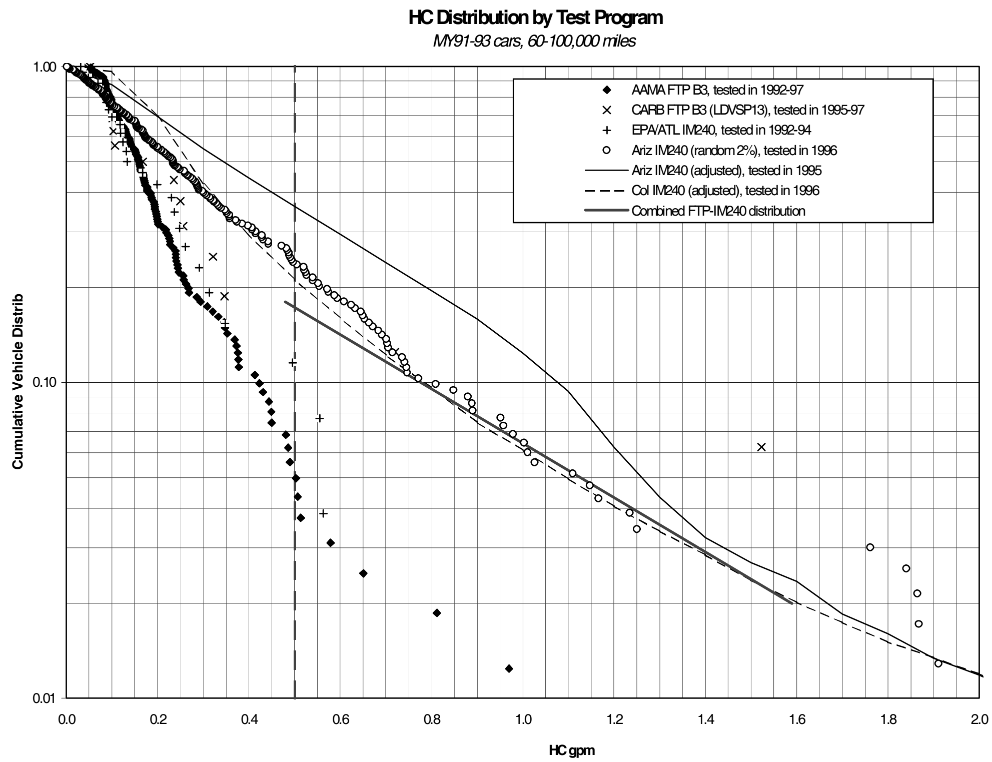

Figure 4.26b. HC distribution by test program, MY 91-93 vehicles, 60 – 100000 miles.

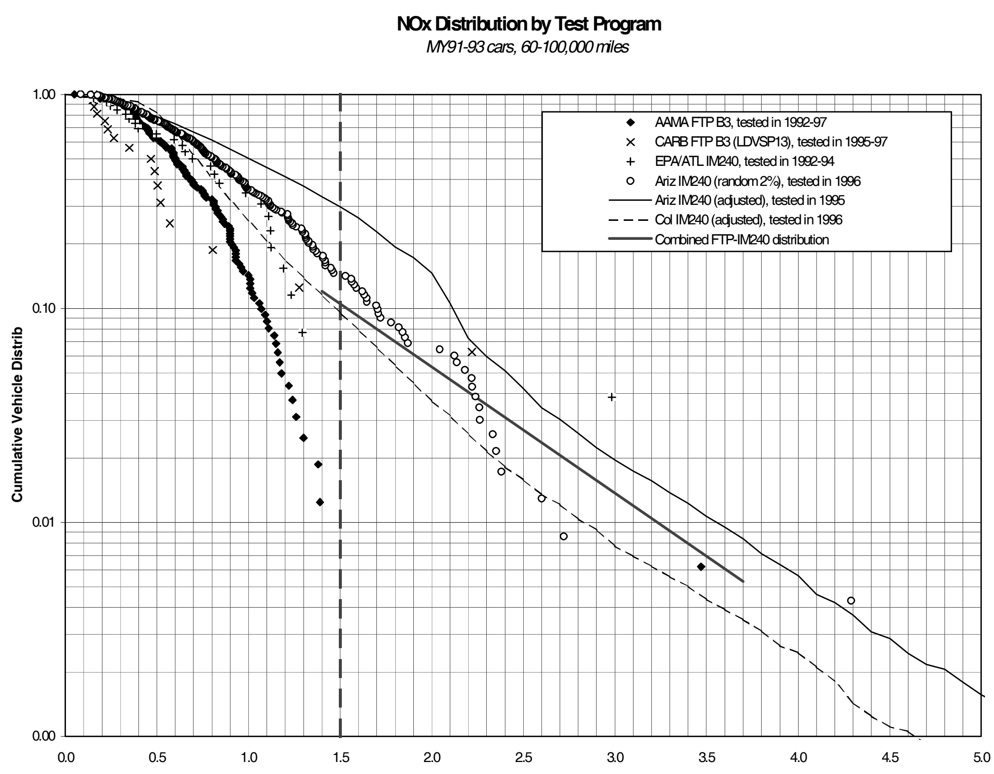

Figure 4.26c. NOx distribution by test program, MY 91-93 vehicles, 60 – 100000 miles.

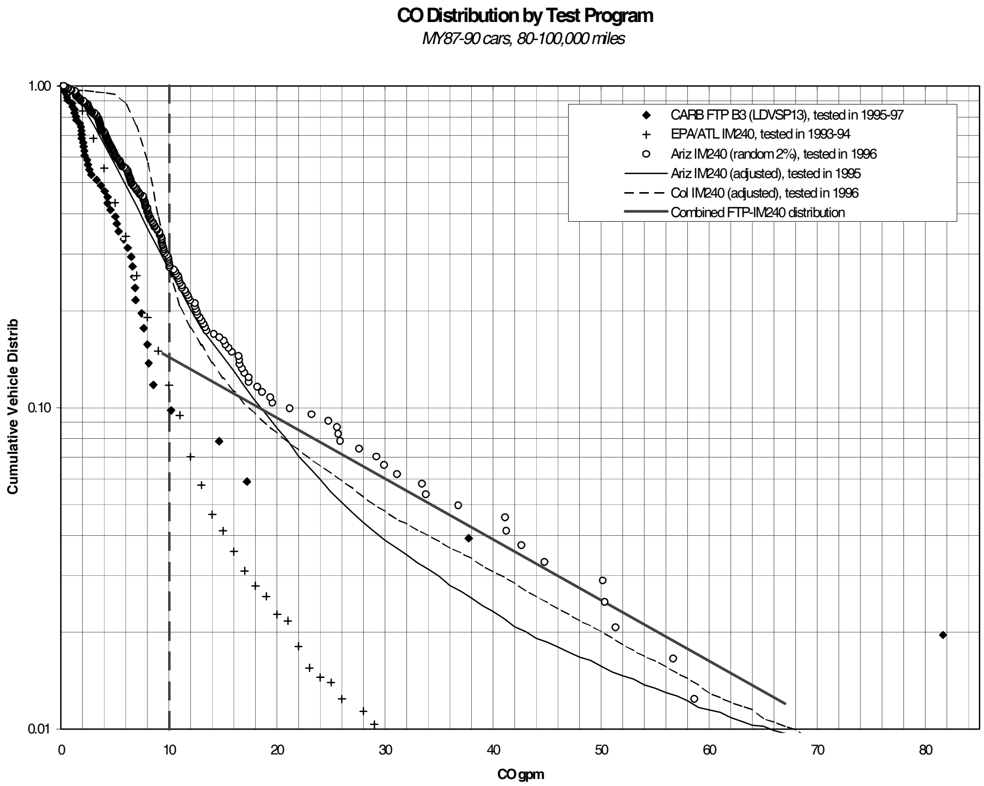

Figure 4.27a. CO distribution by test program, MY87-90 vehicles, 80-100000 miles.

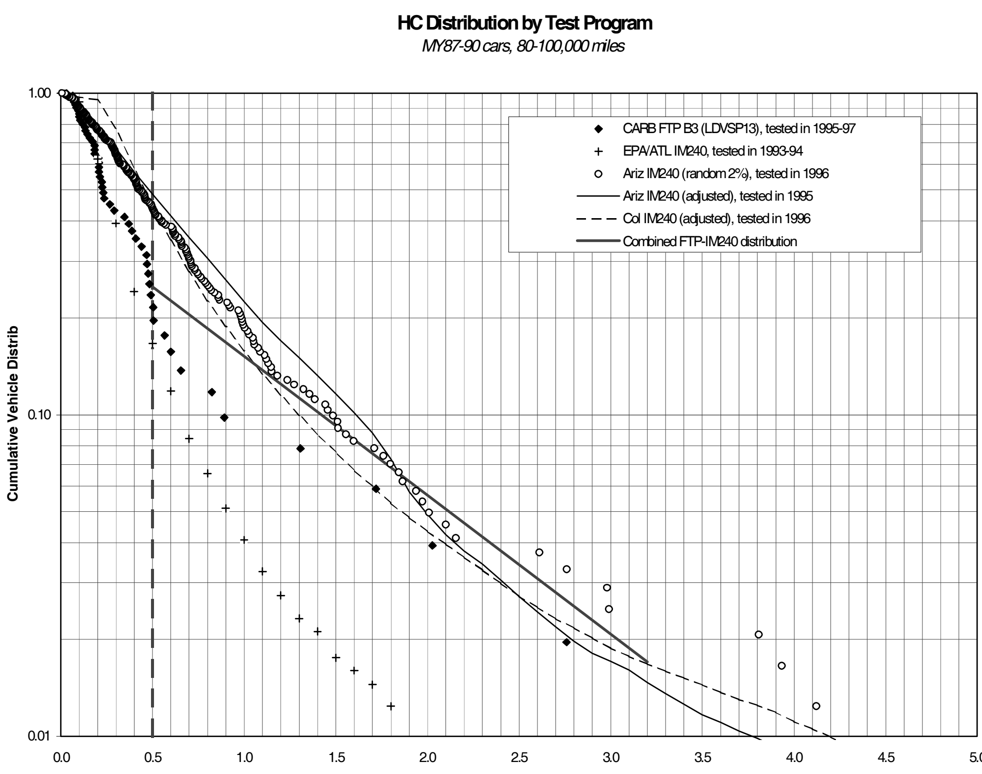

Figure 4.27b. HC distribution by test program, MY87-90 vehicles, 80-100000 miles.

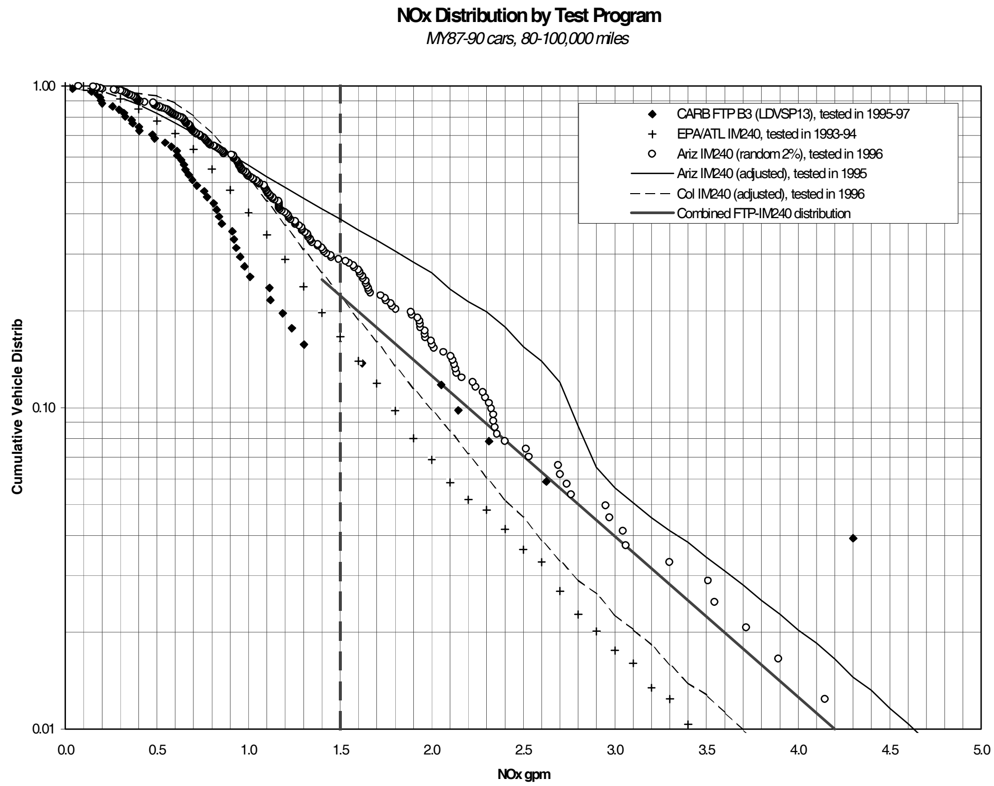

Figure 4.27c. NOx distribution by test program, MY87-90 vehicles, 80-100000 miles.

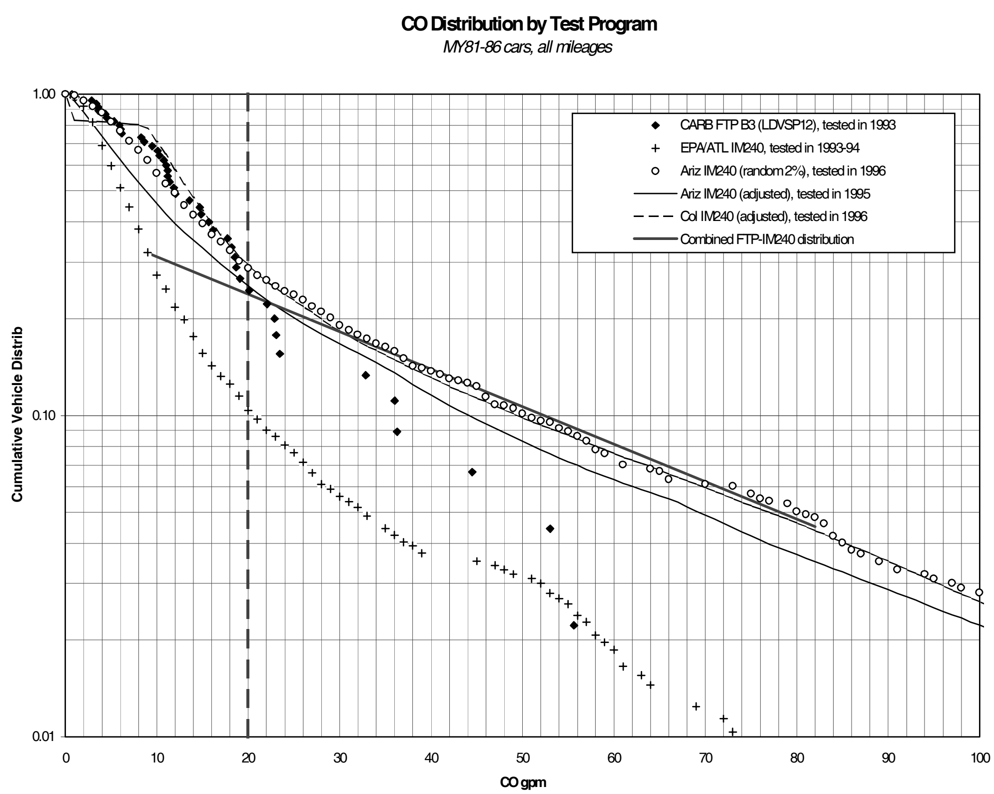

Figure 4.28a. CO distribution by test program, MY81-86 vehicles, all mileages.

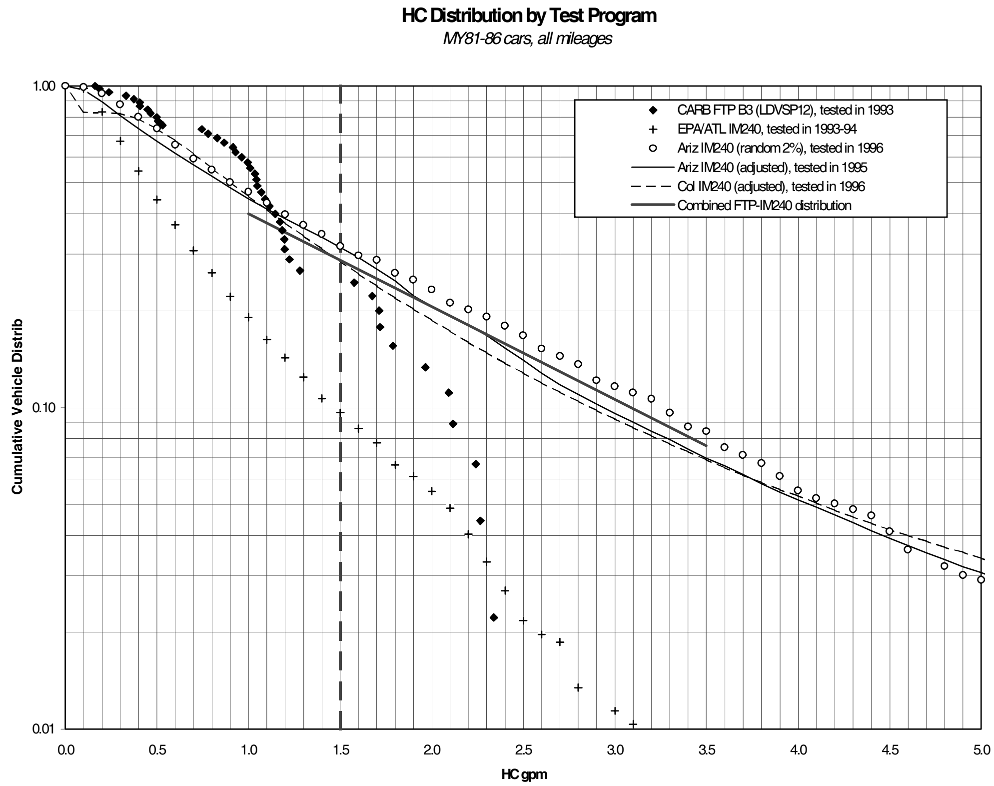

Figure 4.28b. HC distribution by test program, MY81-86 vehicles, all mileages.

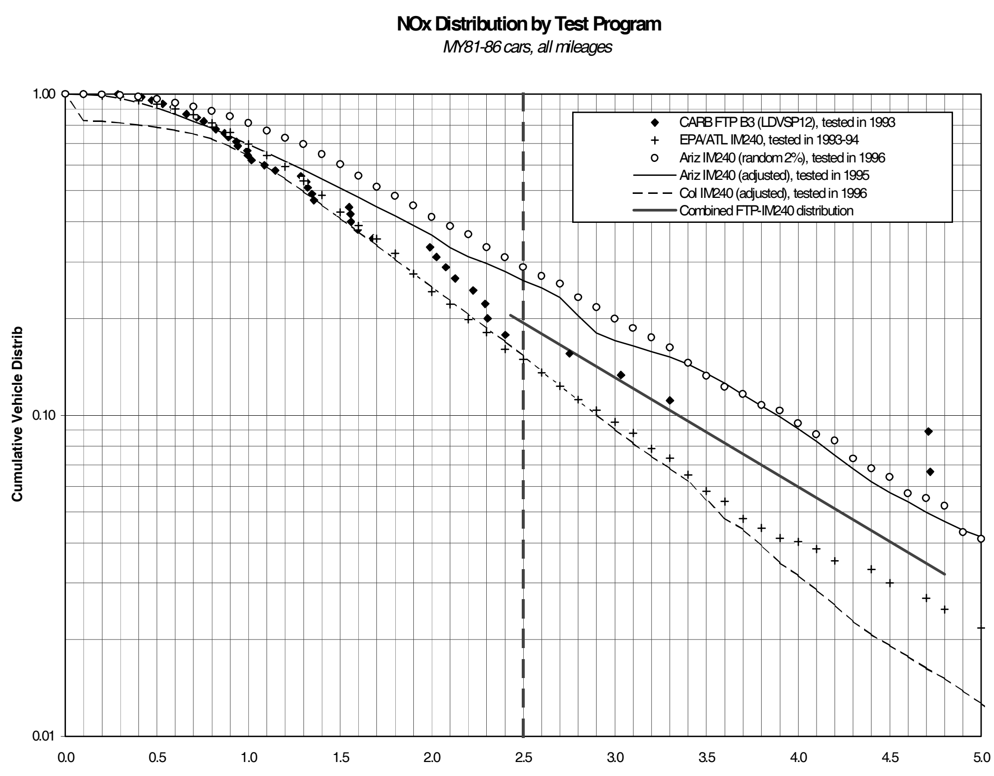

Figure 4.28c. NOx distribution by test program, MY81-86 vehicles, all mileages.

4.14.4 High-Emitter Terminology

Let HEC be the "high-emitter contribution", the product of the high-emitter average gpm, $\langle gpm \rangle_H$, and the fraction of high emitters, (F_H), among a set group of vehicles:

$$HEC = \langle gpm \rangle_H \bullet F_H \qquad (4.14.1)$$

The fraction of high emitters is the cumulative fraction of vehicles at the cutpoint, as illustrated in Figure 4.29.

NEC is the normal-emitter contribution, i.e.

$$NEC = \langle gpm \rangle_N \bullet (1 - F_H) \qquad (4.14.2)$$

Since F_H is typically << 1, it's not important to know F_H accurately in determining NEC in Eq(4.14.2). The total gpm emission of the average vehicle is:

$$\langle gpm \rangle = HEC + NEC = \langle gpm \rangle_H \bullet F_H + (1 - F_H) \bullet \langle gpm \rangle_N \qquad (4.14.3)$$

4.14.5 HEC Dependence on MY and Mileage

The high emitter contribution to the emissions of a modal-emissions model category of vehicles (cars and light trucks combined), defined by MY (but not technology, such as carbureted versus fuel injected), is determined in a sequence of steps. A regression analysis was conducted on tailpipe emissions against model year, technology group, and odometer mileage. The single most important variable was model year. When technology group was added to the regression, it did not significantly improve the regression.

It simplifies the discussion to know that emissions by a given model year are determined primarily by vehicle mileage, and not by vehicle age as such. The evidence for this is illustrated in Figure 4.29. The figure shows that, holding vehicle MY and mileage constant, emissions are quite similar as vehicles age.

Vehicle age alone, therefore, has little impact on emissions; on the other hand, emissions decrease with newer MYs (as shown in Figure 4.29) and lower mileages (shown in Figure 4.30 below). Thus, of the three independent variables MY, mileage and age, we will neglect age in the following discussion. The sequence of steps, then, is to first examine the gpm dependence, then the mileage dependence, and then the MY dependence of the emissions.

High-emitter contribution—from combined FTP-IM240 distributions the fraction of high emitters and average gpm, and thus the HECs, are determined for each of three MY groups: MY91-93 (Figures 4.26a through 4.26c), MY87-90 (Figures 4.27a through 4.27c), and MY81-86 (Figures 4.28a through 4.28c). This analysis is carried out for a selected mileage group for the two groups of recent models, and for all mileages together for the oldest group of models. Results are shown in Table 4.27.

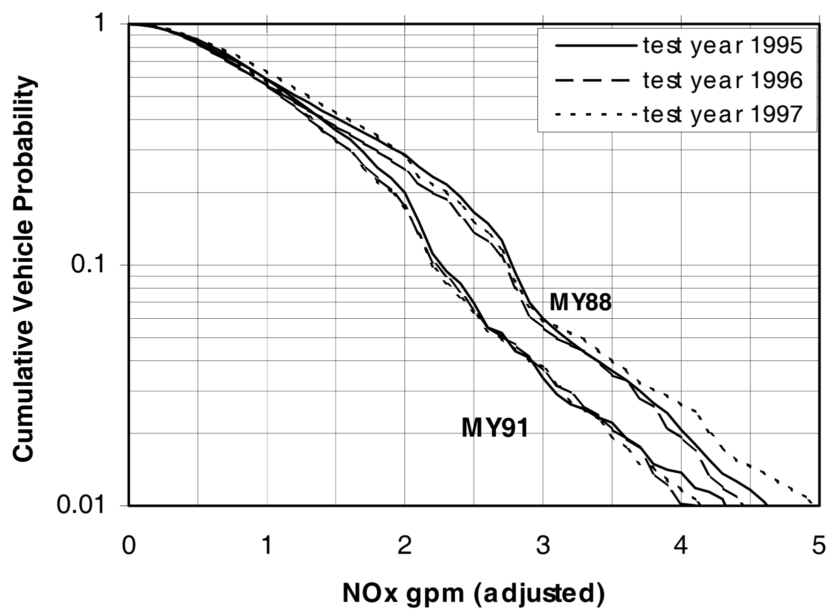

Figure 4.29. NOx Emissions Distribution by MY and Test Year; MY88 and MY91 Cars, 80-100,000 miles, Arizona IM240.

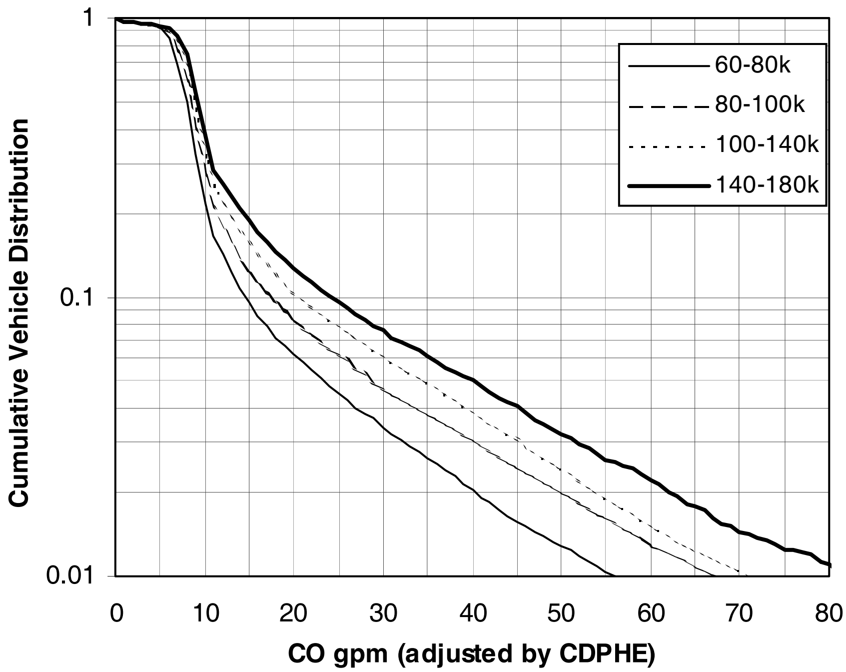

Figure 4.30. CO Emissions Distribution by Odometer Group; MY87-90 Cars, 1996 Colorado IM240

	odometer group & cutpoints[a]	F_H	$<gpm>_H$	HEC (gpm)	B (gpm/10,000mi)
MY81-86	all miles				
CO	20	25%	55	14	1.15
HC	1.5	~29%	3.0	~0.87	~0.07
NOx	2.0	~27%	3.4	~0.92	~0.08
MY87-90	80-100k				
CO	10	15%	31	4.6	0.51
HC	0.5	25%	1.5	0.38	0.042
NOx	1.5	23%	2.3	~0.5	~0.06
MY91-94	60-100k				
CO	10	8.5%	23	2.0	0.25
HC	0.5	18%	1.0	0.18	0.024
NOx	1.5	10%	2.2	~0.2	~0.03

Table 4.27. High-Emitter Contributions for Test Year 1996, Selected Model-Year and Odometer Groups
a) odometer group in 1000 miles and high-emitter cutpoints in gpm.

Mileage dependence—let the HEC shown in Table 4.27 be denoted by $HEC(MY_0, m_0)$, where m_i stands for a mileage (odometer) interval. The HEC for all mileages for a given MY and test year (TY) is determined by first adopting a simple proportionality to describe the increase in HEC with mileage:

$$HEC(MY, m) = B_{MY} \cdot m \quad (4.14.4)$$

Here m is odometer mileage in units of 10,000 miles and the coefficient B is in gpm per 10,000 miles. This form is supported by the trends in HEC with mileage group. A typical example of the odometer dependence is shown in Figure 4.30. (Here we use Colorado IM240 data for foreign car models, which appear to be relatively unaffected by misread vehicle odometers.) Simple proportionality to the mileage appears to be a good approximation. B is different for each pollutant and MY group, as shown in the right-hand column of Table 4.27, with B increasing for earlier MY groups.

Define $n_A(m_i)$ as the odometer distribution (by 10,000 miles) for each vehicle age, A (years). n is the fraction of registered vehicles in each odometer group m_i, with $\Sigma_{mi}\, n_A(m_i) = 1$, for each age, and

$$\Sigma_{mi}\, n_A(m_i) \bullet m_i \int <m>_A$$

is the average odometer miles of vehicles of age A. Let N_A be the fraction of all registered vehicles of age A, with $\Sigma_A N_A = 1$. The odometer averages by age and the fraction of vehicles of each age, determined from Colorado IM240 1996 tests and used here, are shown in Table 4.28. This corresponds to registration, not on-road, frequency.

Age	N_A (%)	$<m>_A$ (10,000 miles)
1	5.7	1.4
2	8.5	2.4
3	7.4	3.8
4	7.4	5.1
5	6.9	6.2
6	7.2	7.5
7	7.3	8.5
8	8.0	9.7
9	8.1	10.4
10	7.7	11.4
11	7.5	11.9
12	6.6	12.9
13	5.6	13.2
14	3.6	13.8
15	2.7	13.4

Table 4.28. Age and Odometer Distributions.

Model-year dependence—in Figure 4.31, the results from Table 4.27 for B_{MY} are shown vs. MY. One finds that simple proportionality on the age of the vehicles when tested the MY dependence yields a reasonable description of the data:

$$C = B_{MY} / (TY - MY) \qquad (4.14.5)$$

(There is little data on high emitters from recent MYs, so Eq(4.14.5) is not to be extended to model years newer than 1993.) The slopes of the lines in Figure 4.31 are the values of C shown in Table 4.29. The units of C are gpm / (years ï 10,000 miles).

	MY group	C
CO	81-86	0.10
CO	87-93	0.07
HC	81-93	0.006
NOx	81-93	0.007

Table 4.29. Model-Year Coefficient C.

The coefficient for CO before MY81-86 is taken to be different because of evidence of a major change in control of enrichment in MY1987, presumably associated with the move from carburetors to fuel injection.

Thus, the high-emitter contribution of MY81-93 vehicles in calendar year CY is the sum, over model years for each MY group j, of the products:

$$HEC_{CY,j} = \Sigma_{MY,j}\ C_{MY}\ (TY - MY)\ N_A <m>_A \qquad (4.14.6)$$

with the condition A = CY - MY.

Note that the CY dependence applies to existing model years whose high emitters have been adequately studied in this project, i.e. MY81-93.

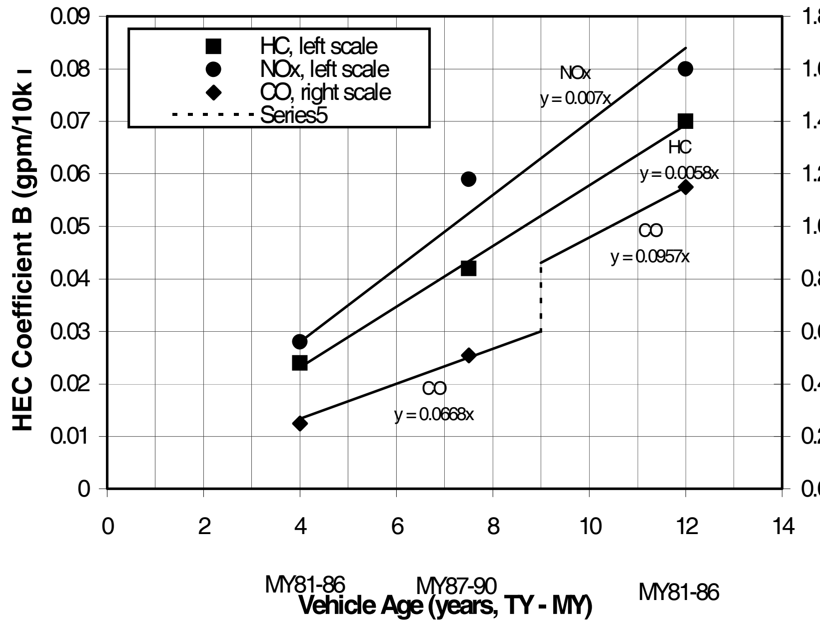

Figure 4.31. Coefficient B by Model Year.

For CY 1997, $HEC_{CY,j}$ is shown in Table 4.30.

MY Group (j)	CO	HC	NOx
MY81-86	5.9	0.32	0.43
MY86-90	2.4	0.21	0.27
MY91-93	0.6	0.05	0.07

Table 4.30. HEC_{CY} for 1997 by Pollutant and Model-Year Group (gpm)

4.14.6 Linear Combination Coefficients for the High Emitters

The NCHRP high emitters are categorized by five broad high-emitter types i (runs lean, runs rich - two subtypes, misfire and catalyst failure), taken over the whole sample for MY81-93 and for both cars and trucks, and not by MY (or technology). Let j index the three MY groups: 1981-1986, 1987-1990, and 1991-1993, with cars and trucks together. Let a_{ij} be the weight of high-emitter type i in the model year group j, with $\Sigma_i a_{ij} = 1$. The high-emitter emissions for MY group j, are found as a weighted sum over the emissions of composite high-emitter vehicles i. The average emissions of high emitters in category j are:

$$<gpm>_{NCHRP,j} = \Sigma_i a_{ij} <gpm>_{NCHRP,i} \qquad (4.14.7)$$

and the weight for MY-category j is

$$w_j = HEC_{CY,j} / \Sigma_i a_{ij} \langle gpm \rangle_{NCHRP,i} \qquad (4.14.8)$$

where $HEC_{CY,j}$ is the HEC of the combined FTP-IM240 distribution corresponding to MY group j (shown in Table 4.30).

The FTP bag 3 emissions for the 5 high-emitter composite vehicles, $\langle gpm \rangle_{NCHRP,i}$, are shown in Table 4.31.

High Emitter Type (i)	CO	HC	NOx
Type 1: lean	4.4	0.68	2.11
Type 2: rich	19.5	1.28	0.99
Type 3: misfire	8.4	1.45	0.75
Type 4: bad catalyst	13.4	2.05	2.89
Type 5: very rich	96.7	3.60	0.41

Table 4.31. FTP Bag 3 Emissions, $\langle gpm \rangle_{NCHRP,i}$, for the Five Composite High-Emitters Measured in the NCHRP Project

In the modal model then, for MYs 1981-93, the weight for the sub-model representing a normal-emitter composite vehicle j is given by Eq(4.14.9):

$$(1 - F_H)_j \qquad (4.14.9)$$

The weight for each corresponding high-emitter composite vehicle of type i is:

$$c_{ij} = w_j \bullet a_{ij} \qquad (4.14.10)$$

Note that the equations do not refer to pollutant. Reasonable results should be roughly the same independent of pollutant, since the pollutant mix a_{ij} is obtained from the IM240 data.

Relative weights of the five types—it remains to specify the weights a_{ij}. This is based on the HLM profiles for tailpipe emissions of the three pollutants as measured in the adjusted AZ IM240 dataset for 1996. As discussed in detail above in 4.12.5, the high-medium-low profiles depend on the choice of cutpoints. The high-emitter cutpoints chosen here are the "start-up" IM240 cutpoints for HC and NOx and one-half of those cutpoints for CO. (The low cutpoints are a fraction of those.) Results for the fraction a_{ij} of vehicles in the four high-emitter types for each of three MY groups are shown in Figure 4.32 and Table 4.32. There are actually five types: Type 2 is the highly-rich CO emitter for MY81-86, as well as the moderately rich CO emitter for MY86-93. For the calculation the relative weights are renormalized omitting the "other" category.

High Emitter Type (i)	MY81-86	MY86-90	MY91-93
Type 1: lean	11%	15%	10%
Type 2 or 5: rich or very rich	25%[b]	34%[b]	48%[b]
Type 3: misfire	39%	24%	15%
Type 4: bad catalyst	11%	9%	7%
Others	13%	18%	20%
Total	100%	100%	100%

a) i is the type of high emitter and j is the MY group. b) Type 5 for MY81-86 and Type 2 for MY87-93

Table 4.32. Relative Weights, a_{ij}, of the Five Types of High Emitter[a]

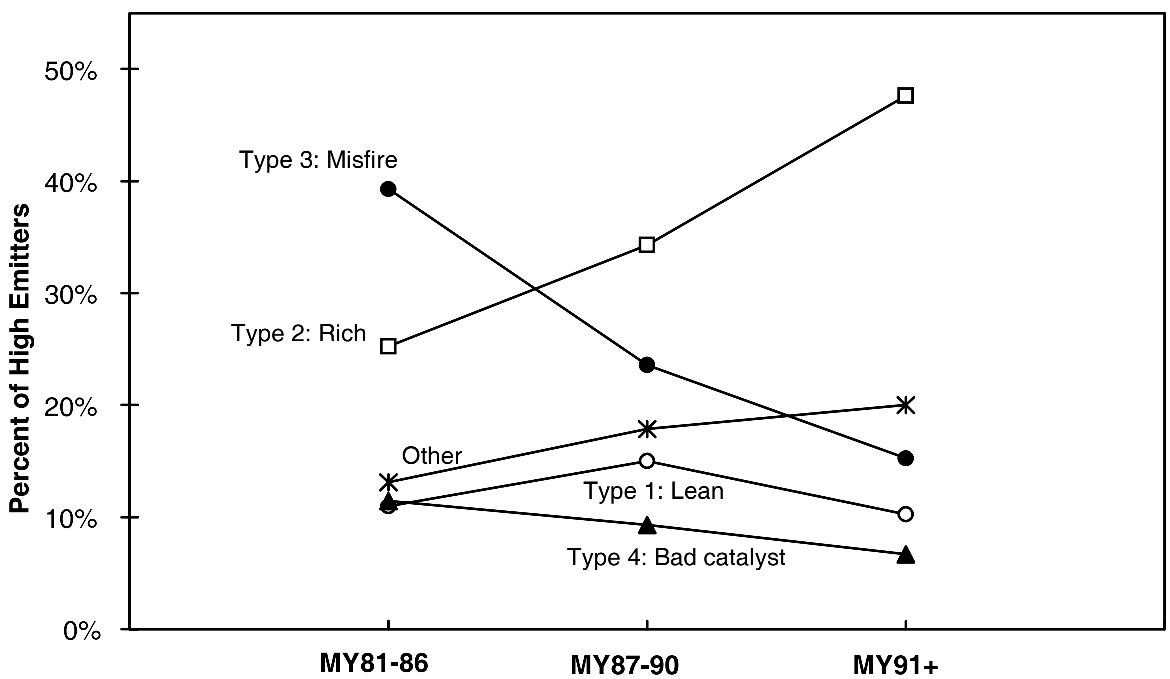

Figure 4.32. Distribution of High Emitter Types by MY Group, All Vehicle Types. Start-up HC and NOx, Start-up*0.5 CO Cutpoints, 1996 Arizona IM240

4.14.7 Weights for High Emitters

Table 4.33 shows the weights for each MY group, w_j, as defined in Eq(4.14.8). Tables 4.34a through 4.34c show the weights for each high-emitter composite vehicle, c_{ij}, as defined in Eq(4.14.10), for each pollutant. The weights in Tables 4.34a through 4.34c vary slightly by pollutant.

	Weighted Average (gpm)			MY Group Weights (w_j)		
MY Group	CO	HC	NOx	CO	HC	NOx
MY81-86	34.2	2.05	1.10	0.173	0.156	0.391
MY87-90	12.8	1.30	1.33	0.187	0.161	0.203
MY91-93	15.0	1.30	1.25	0.040	0.038	0.056

Table 4.33. Average gpm and Weights by MY Group.

High Emitter	CO Weights (c_{ij})		
Composite	MY81-86	MY87-90	MY91-93
Type 1: lean	0.022	0.034	0.005
Type 2 or 5: rich or very rich	0.050	0.078	0.024
Type 3: misfire	0.078	0.055	0.008
Type 4: bad catalyst	0.022	0.021	0.004
Total	0.173	0.187	0.040

Table 4.34a. CO MY Group Weights for each High Emitter Composite Vehicle.

High Emitter	HC Weights (c_{ij})		
Composite Vehicle	MY81-86	MY87-90	MY91-93
Type 1: lean	0.020	0.029	0.005
Type 2 or 5: rich or very rich	0.045	0.067	0.023
Type 3: misfire	0.071	0.047	0.007
Type 4: bad catalyst	0.020	0.018	0.003
Total	0.156	0.161	0.038

Table 4.34b. HC MY Group Weights for each High Emitter Composite Vehicle.

High Emitter	NOx Weights (c_{ij})		
Composite	MY81-86	MY87-90	MY91-93
Type 1: lean	0.050	0.037	0.007
Type 2 or 5: rich or very rich	0.114	0.084	0.034
Type 3: misfire	0.177	0.059	0.010
Type 4: bad catalyst	0.050	0.022	0.005
Total	0.391	0.203	0.056

Table 4.34c. NOx MY Group Weights for each High Emitter Composite Vehicle.

5 Model Validation, Uncertainty, and Sensitivity

An essential step in the modeling process is performing *model validation*, examining the *model uncertainty*, and analyzing *model sensitivity*. This chapter addresses these three topics. In addition, a large amount of analysis has been performed on emissions data to support many of the model categories and the development of specific model components.

Model Validation

Model validation is the assessment of how well the model performs on independent input data, when compared to some ground truth data. For model validation, the key question to answer is whether or not the model predicts with reasonable accuracy and precision. These general questions lead to several other questions, such as what statistics or functions will properly describe accuracy and precision. Large-scale CMEM validation has been conducted by comparing composite vehicle bag numbers for CO_2, CO, HC, and NO_x for the FTP, MEC, and US06 test cycles using linear regression. Of these, the FTP Bag 3 (excluding the first 100 seconds) and the US06 are the most important because they were not used in model development and thus provide independent test data. For this validation, we use the slope and intercept of the regression of observed values against predicted values to measure model accuracy. Precision is measured using the r-square of the regression. High r-square values alone do not indicate a good model, because a consistent but highly biased model is not good for prediction. This model validation is addressed in Section 5.1.

A second validation was conducted on measured and modeled second-by-second CO_2, CO, HC, and NO_x emissions for individual vehicles. The model was not intended for use as a second-by-second model for prediction of individual vehicles, however the second-by-second evaluation provides insight into bias and variability of the model. In this validation case, bias was measured by taking the mean observed value minus the mean predicted value over the entire distribution of vehicles. Variability was assessed using standard Mean Square Error (MSE) and the Normalized Mean Square Error (NMSE) measures. This model validation is addressed in Section 5.2.

Model Uncertainty

Computer emission models, when given identical inputs, produce identical outputs. However, several sources of variability go into any model developed from measured data. Variation, acknowledged or not, exists as part of the model development process and needs to be addressed to assess the validity of the model results. In a vehicle emissions model, some of the main sources of variation are:

- ***Emissions Measurement Variability*** – Emissions measurement is subject to instrument variability.
- ***Vehicle Driving Variability*** – Small differences in driving a trace are inevitable with human testing.
- ***Vehicle Operation Variability*** – Vehicle engines, particularly in privately owned and operated vehicles, do not function identically from one day to the next.
- ***Vehicle Sampling Variability*** – Privately owned and operated vehicles are subject to differing operation, maintenance, fuel etc. resulting in considerable vehicle to vehicle differences, even in identical vehicles.
- ***Parameter Estimation Variability*** – Model structure and in particular model parameters are estimated from vehicle test data that has small test-to-test differences which affect parameter estimates.

The model uncertainty is addressed in Section 5.3.

Model Sensitivity

In order to estimate parameter sensitivity of the model, a variety of parameter sets were applied to the model and the emission results were analyzed. The parameter sets and resulting model emissions estimates were used in a stepwise multiple regression to identify the parameters that have the largest effect on the model output. These results are based on the range and variability of parameter values found on the vehicles used in the model development and provide an estimate of model parameter sensitivity for emissions in the range observed in our test fleet. This sensitivity analysis is described in Section 5.4.

Data Analysis

In order to support the model development, a good deal of data analysis has taken place. Much of this data analysis is lengthy and outside the scope of the model development and is therefore not included in this final report. However, some important analysis work has been included in Section 5.5.

5.1 COMPOSITE VEHICLE VALIDATION

The emissions of tailpipe CO_2, CO, HC, and NO_x for the 26 composite vehicles were calculated for the three bags of the FTP, the MEC, and the US06 test cycles. As described in Chapter 4, the composite vehicle model parameters were determined using composited vehicle driving and emissions traces. These composited vehicle driving and measured emission traces are used in this validation for comparison to the modeled results. The measured values of emissions serve as the *observed* data set (plotted on the X-axis) and the modeled emission values serve as the *predicted* data set (plotted on the Y-axis). A regression was run comparing the predicted results against the observed results for each emission and driving trace. The plots of the regressions appear in Figures 5.1-5.5. A joint statistical test [Draper and Smith, 1966] was used to test the joint hypothesis that the intercept equals zero and the slope equals one. Significant p-values ($p < 0.01$) indicate that there is a significant bias in the model for the regression being tested. If the model were perfect, the slope would be one and the intercept would be zero and all points would fall on the line (r-squared = 1.0). It should be noted that for high r-squared values (low variability about the regression), the joint probability test is sensitive to smaller slope and intercept differences. The slope, r-squared, and Y-intercept values are summarized in Table 5.1.

Overall, the composite vehicle validation results are very good. The engine-out emissions are included for completeness, but the tailpipe emissions are the ones directly related to the utility of the model. Several conclusions from the analysis of the composite car results can be summarized:

- The tailpipe emissions for the independent FTP Bag 3 results (Figure 5.3) show no significant bias in HC ($p > 0.01$) and a significant bias for CO_2, CO, and NO_x (primarily due to one or two high emitting categories).

- The tailpipe emissions for the independent US06 results (Figure 5.5) show no significant bias in HC ($p > 0.01$) and a significant bias for CO_2, CO, and NO_x.

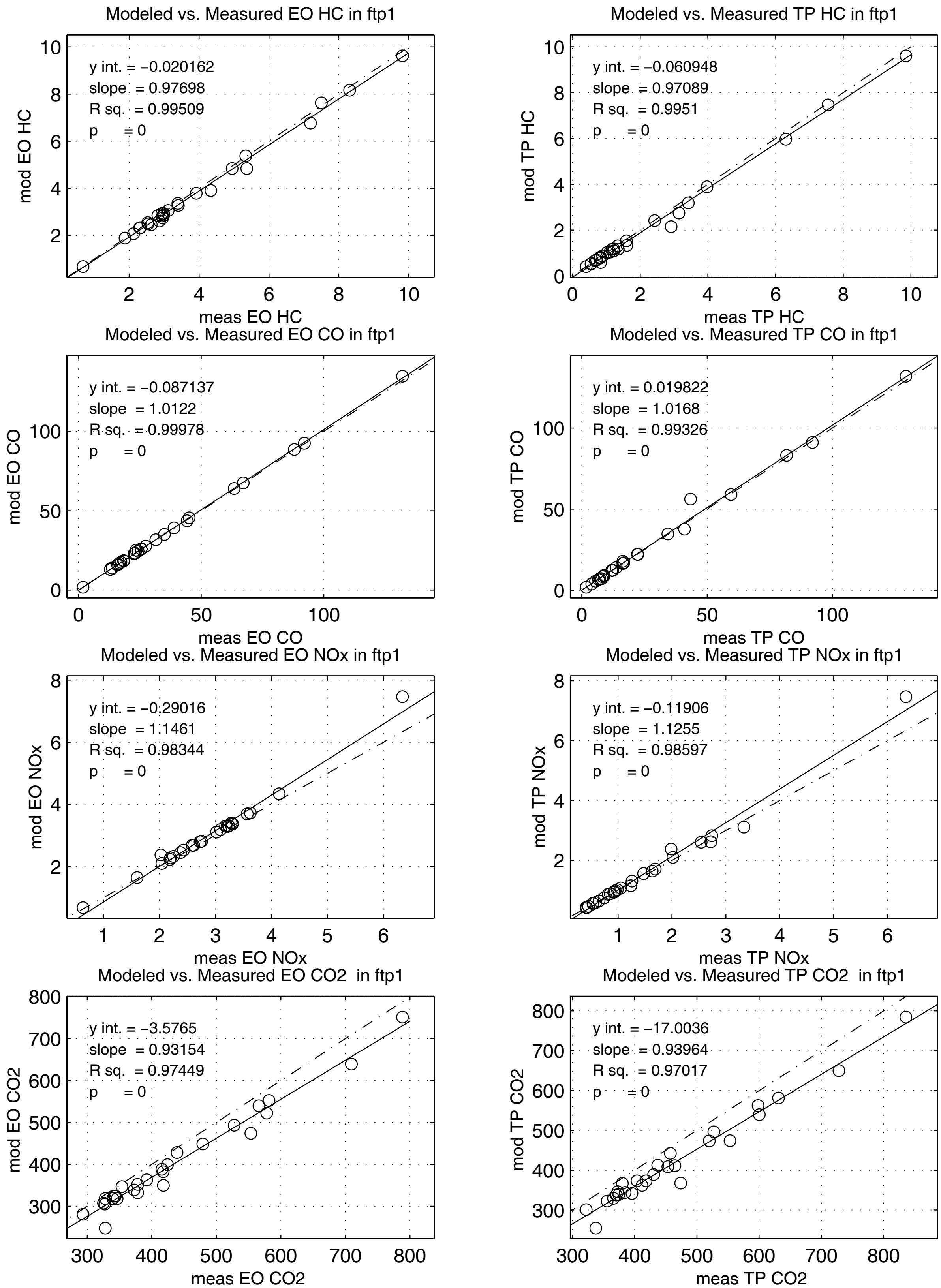

Figure 5.1. FTP Bag 1 Validation Plots for a), HC b) CO, c) NO_x, and d) CO_2.

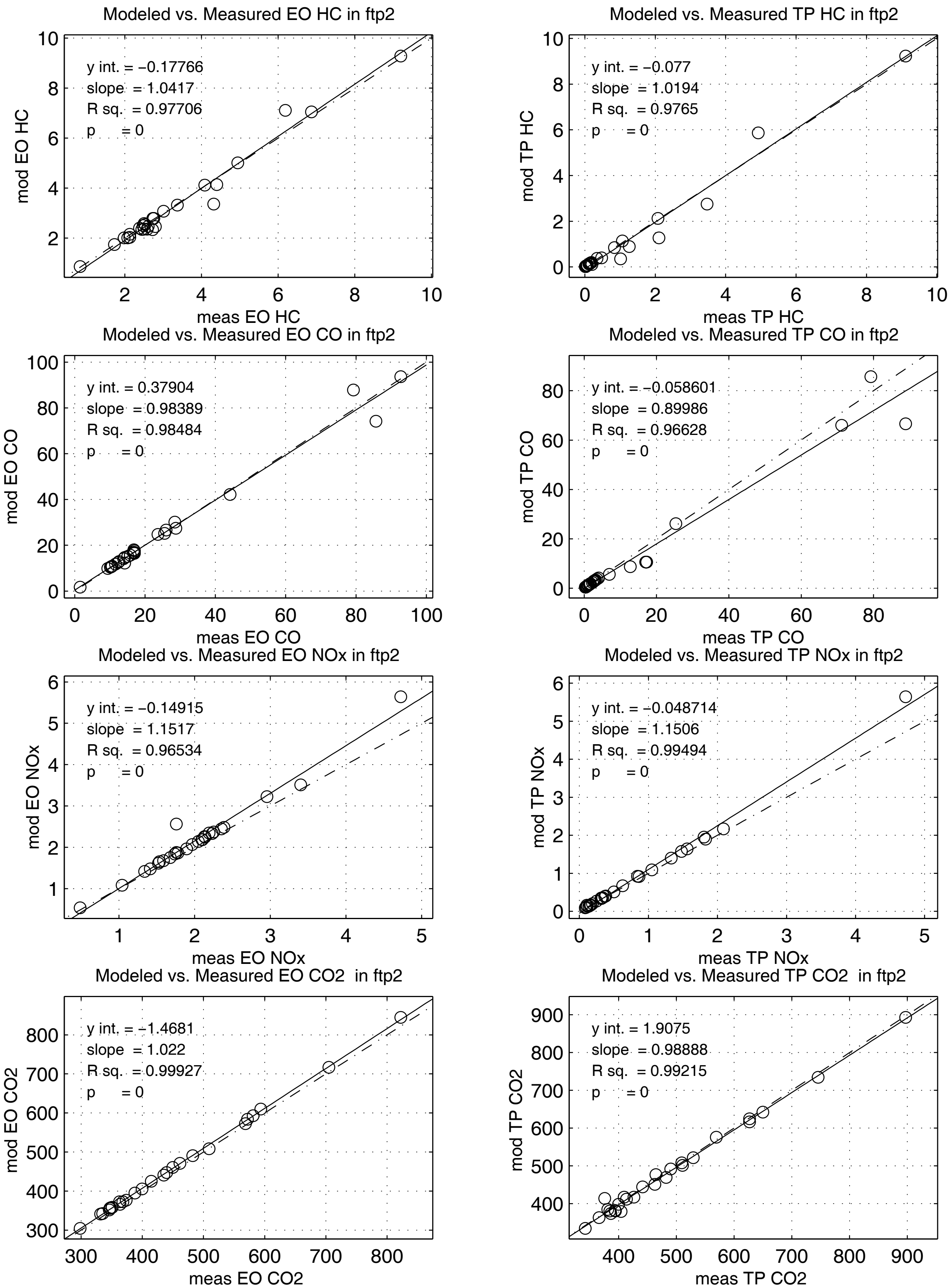

Figure 5.2. FTP Bag 2 Validation Plots for a) HC, b), CO c) NO_x, and d) CO_2.

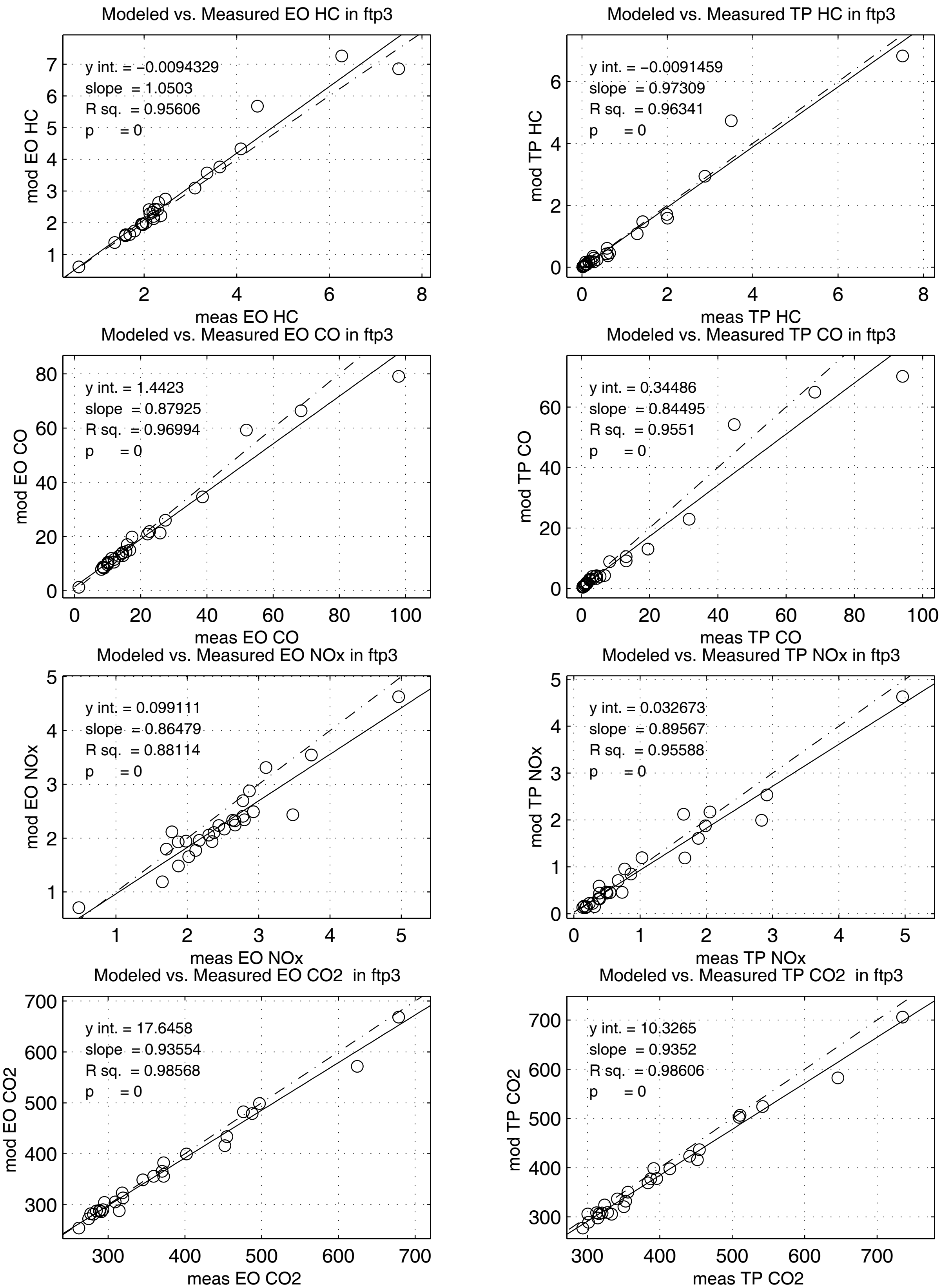

Figure 5.3. FTP Bag 3 Validation Plots for a), HC b) CO, c) NO_x, and d) CO_2.

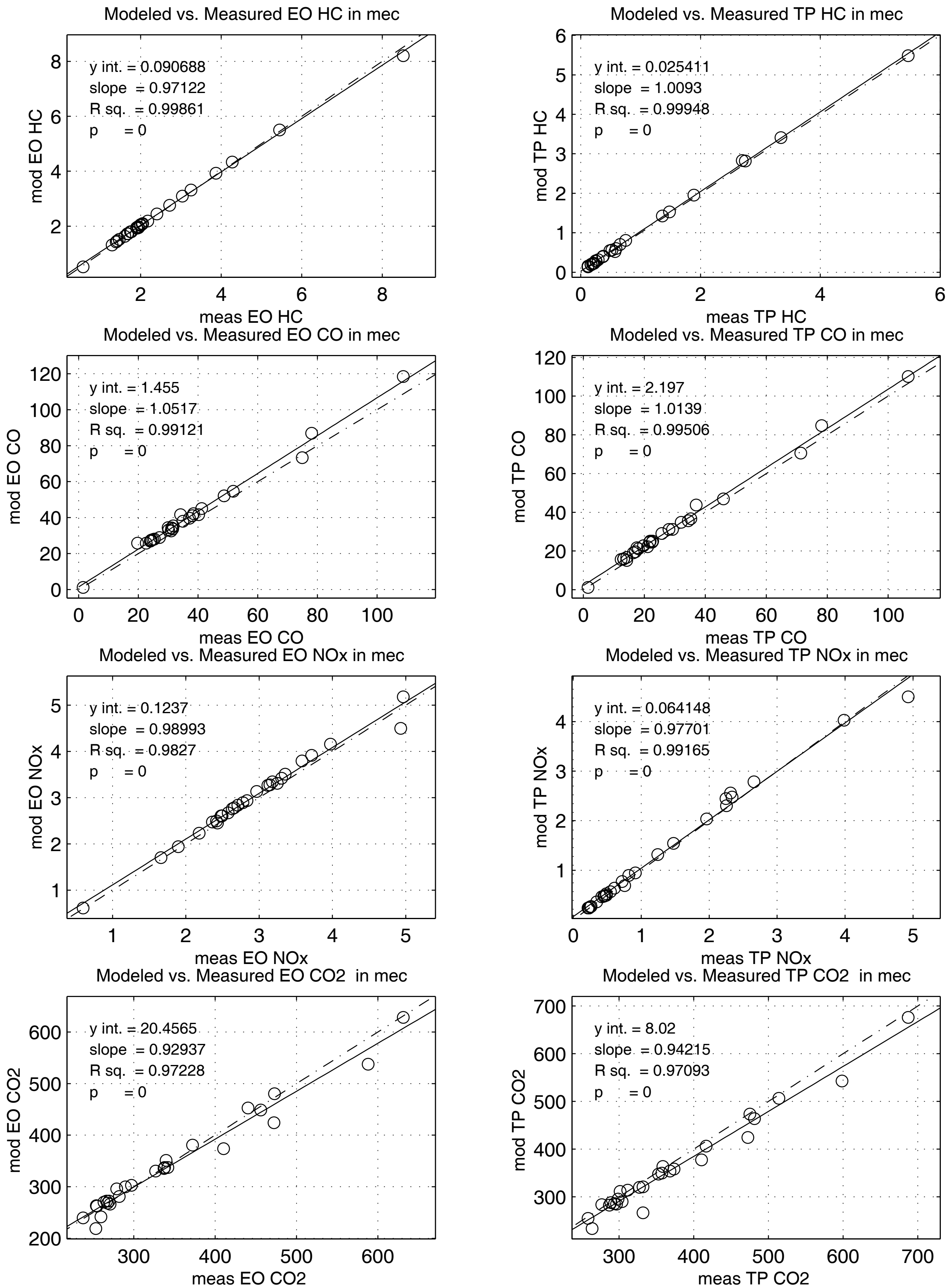

Figure 5.4. MEC Validation Plots for a), HC b) CO, c) NO_x, and d) CO_2.

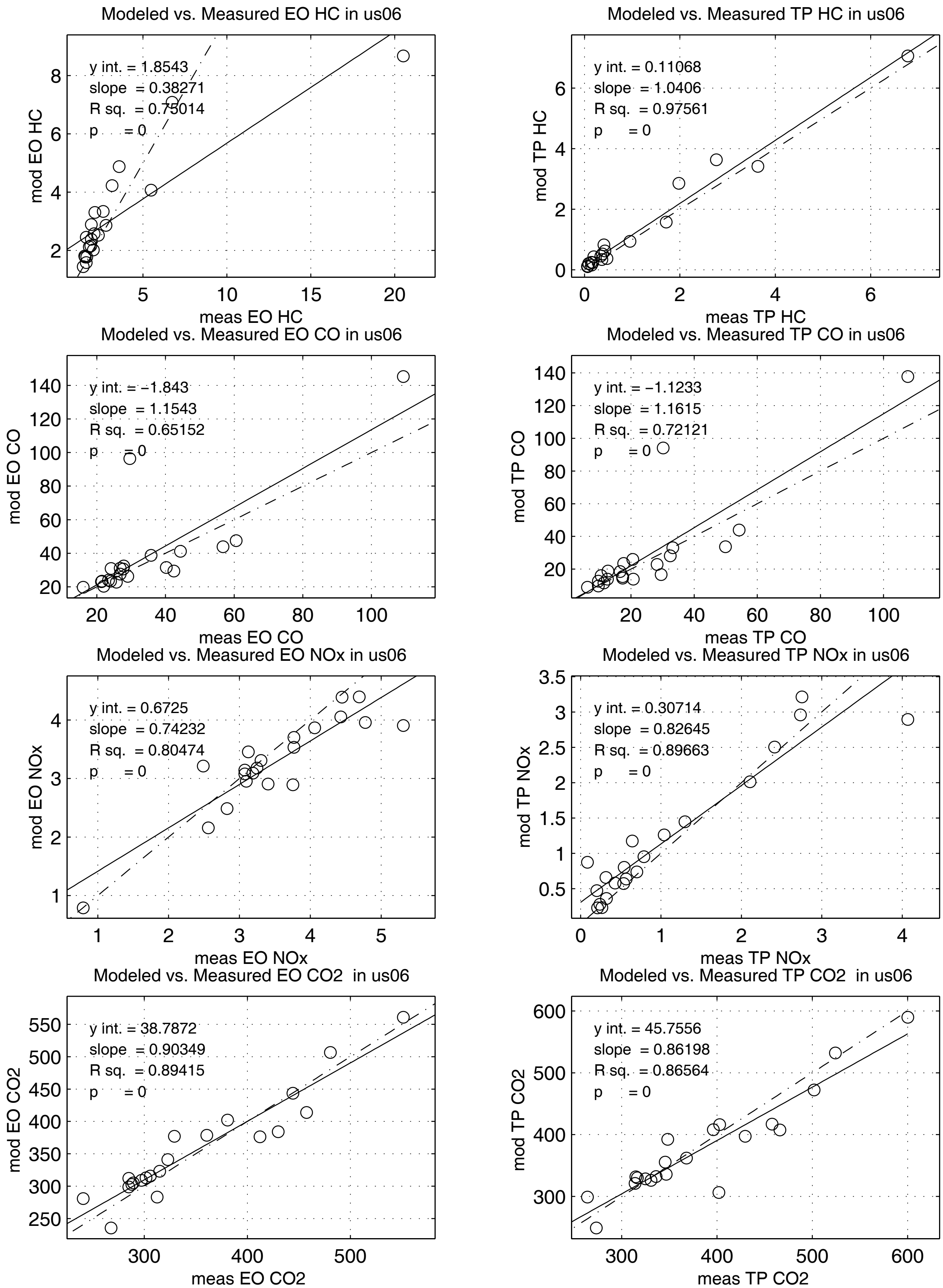

Figure 5.5. US06 Validation Plots for a HC), b) CO, c) NO_x, and d) CO_2.

- The tailpipe emission results for FTP Bag 1 (Figure 5.1) are excellent for HC and CO, having no significant bias and very low variability. There is a significant bias in the NO_x results, primarily due to five high emitting groups. The results are biased for CO_2 but with low variability.

- The tailpipe emission results for FTP Bag 2 (Figure 5.2) are excellent for HC and CO_2, having no significant bias and very low variability. There is a significant bias in the NO_x results, with low variability. The results are biased for CO primarily due to three high emitter groups.

- With the exception of an occasional individual composite vehicle, the engine-out results have either no significant bias or very small bias for FTP Bag 1 except for CO_2 which is predicted low, FTP bag 2 except for NO_x, FTP Bag 3 except for NO_x the MEC except for NO_x which has one problem category, and the US06 test cycle except for HC and NO_x.

Cycle	Emission	Slope	Y-Intercept	R-Squared
FTP Bag 1	TP CO	1.017	0.019822	0.993
	TP HC	0.971	-0.060948	0.995
	TP NOx	1.126	-0.119060	0.986
	TP CO2	0.940	-17.0036	0.970
FTP Bag 2	TP CO	0.900	-0.058601	0.966
	TP HC	1.019	-0.077000	0.977
	TP NOx	1.151	-0.048714	0.995
	TP CO2	0.989	1.907500	0.992
FTP Bag 3	***TP CO***	***0.845***	***0.344860***	***0.955***
	TP HC	***0.973***	***-0.009146***	***0.963***
	TP NOx	***0.896***	***0.032673***	***0.956***
	TP CO2	***0.935***	***10.3265***	***0.986***
MEC	TP CO	1.014	2.19700	0.995
	TP HC	1.009	0.025411	0.999
	TP NOx	0.977	0.064148	0.992
	TP CO2	0.942	8.02000	0.971
US06	***TP CO***	***1.162***	***0.11068***	***0.721***
	TP HC	***1.041***	***-1.12330***	***0.976***
	TP NOx	***0.826***	***0.30714***	***0.897***
	TP CO2	***0.862***	***45.7556***	***0.866***

FTP Bag 3 and US06 Are Independent Test Cycles; TP is tailpipe.

Table 5.1. Summary of composite vehicle validation regression slope, Y-intercept, and R-Squared values.

5.2 SECOND-BY-SECOND VALIDATION

As previously mentioned, second-by-second individual vehicle CO_2, CO, HC, and NO_x emissions were analyzed as a whole for determining bias and variability. For this analysis, bootstrap re-sampling was used (see [Efron and Tibshirani, 1986]). Individual vehicles were used for this analysis to ensure that the population used for bootstrapping was sufficiently large. Bootstrapping on a small population such as the 26 composite vehicles can cause problems in the results.

Bias in this case is defined as:

Bias(i) = Observed Concentration at Time i(O_i) – Predicted Concentration at Time i (P_i).

Variability was assessed using measures of mean square error and normalized mean square error defined as (see, e.g., [Bornstein and Anderson, 1979]; [Hanna and Heinold, 1985]; and [Hanna, 1988]):

Mean Square Error = Sum $(O_i - P_i)^2/n-1$

Normalized Mean Square Error = (Sum $(O_i - P_i)^2/n$*)/(Mean Observed Concentration * Mean Predicted Concentration)*

Bootstrap resampling is a statistical technique useful for constructing confidence limits in varied applications [Efron and Tibshirani, 1986; Gart and Nam, 1988; Cook, 1990]. The following is a short description of why it is applied. We want to generate plots of bias vs. time, MSE vs. time, and NMSE vs. time, where time is the second-by-second time range over a given cycle for a particular emission. For each second, point estimates are helpful, but of more use would be 95% confidence intervals for the appropriate statistics, since they indicate how variable the estimates are. However, it is not really known if this data is normal, and so the distributions of bias, MSE and NMSE are not known. In short, the usual confidence intervals may not be appropriate. However, the bootstrap method will result in confidence limits for the statistics of interest (bias, MSE, NMSE) that do not depend on the form of the distribution.

The bootstrap procedure is applied to the normal emitting and high emitting vehicles separately to identify possible differences in model performance.

The following is an example of how the bootstrap was applied to the entire data set to generate a bias confidence interval for a particular second in time. First, a random sample of size 20 is chosen from the 340 vehicles. From this sample, the bias estimate is calculated. Then the sampled values are replaced. A second sample is taken of size 20, and a new bias estimate is calculated. The sample values are again replaced. This process is repeated until you have 100 estimates from the samples. Now from these 100 estimates, a confidence interval can be calculated in two ways. First, the interval can be calculated by the theoretically-derived bootstrap confidence interval formula, or secondly by using the 97.5 percentile value as the upper limit and the 2.5 percentile value as the lower limit. If the bias confidence interval contains zero, then there is no significant bias in the model at this particular second in time. If zero is not in the interval, then the model is significantly overpredicting across vehicles (if bias is negative) or underpredicting (if bias is positive) at that second in time. Similar intervals can be found for MSE and NMSE to better understand the variability of the model over the driving cycle. Overall, these confidence interval plots provide feedback to see where in the cycle the model is performing well, and where it is not performing well.

The second-by-second bias, MSE, and NMSE were calculated for the FTP Bag 3 and US06 test cycles for this model validation. The first 100 seconds of data were left out of the validation for the FTP Bag 3 cycle because the data were used in model development. The remainder of the FTP Bag 3 cycle provides an independent data set with mild driving conditions. The US06 cycle was used because it also is not used in the development of the model, and is a difficult test cycle for model prediction. For these calculations, the confidence limits were determined using the percentiles of the bootstrapped results, which do not require any assumptions about the distribution of the second-by-second emissions. The MSE and NMSE results were similar to the bias results and are not presented graphically.

As an example of bias for a single set of emissions traces, the modeled and observed second-by-second FTP Bag 3 emissions of the category 5 composite vehicle (3-way catalyst, fuel injected, greater than 50,000 miles, high power to weight ratio) are presented in Figure 5.6. The difference between the observed (solid) line and the predicted (dashed) line at each second is the bias at that particular second. For the bootstrap analysis, the second-by-second average bias is the average bias across all vehicles that are in the analysis.

The bootstrap analysis for normal emitting vehicles for the FTP Bag 3 cycle are presented in Figure 5.7. The bias at each second, calculated across all high emitting vehicles, is presented in Figure 5.8. For all of these bootstrap figures, the upper and lower limits of the confidence bands are plotted using a (+) and the actual observed average across all vehicles is presented as a (o).

The second-by-second US06 emissions of the category 5 composite vehicle are presented in Figure 5.9 as an example. The difference between the observed (solid) line and the predicted (dashed) line at each second is the bias at that second. The bootstrap analysis for normal emitting vehicles for the US06 cycle are presented in Figure 5.10 The bias at each second, calculated across all high emitting vehicles, is presented in Figure 5.11. The Mean Square Error (MSE) is the error at each second and represents the variability in bias across the driving trace. The MSE across all vehicles is presented in Figure 5.12. The NMSE is the normalized mean square error at each second, calculated across all vehicles (Figure 5.13). The average emissions and bias results are presented in Table 5.2.

Cycle	Emission	Average g/sec.	Average Bias	Maximum Bias	Minimum Bias
FTP Bag 3	CO_2	3.5146	0.5298	2.9049	-1.6718
	CO	0.0732	0.0186	0.1538	-0.5111
	HC	0.0053	0.0015	0.0136	-0.7750
	NO_x	0.0069	0.0025	0.0199	-0.0077
US06	CO_2	5.0568	0.2156	4.3302	-3.1592
	CO	0.2809	0.0027	1.4295	-1.6395
	HC	0.0081	0.0016	0.0250	-0.0272
	NO_x	0.0136	0.0048	0.0136	-0.579

Table 5.2. Average emissions, average bias, maximum bias, and minimum bias for FTP Bag 3 and US06 driving cycles, across all vehicles.

The second-by-second model validation bias results in brief are:

- Tighter confidence limits (lower vehicle-to-vehicle variability in bias) are found on the decelerations and the cruise events for both normal emitters and high emitters;
- Second-by-second bias results show the majority of the seconds of the FTP Bag 3 cycle and the US06 cycle to have no significant bias for normally operating vehicles;
- Normally operating vehicles do show a pattern of overprediction of emissions at the start of acceleration events followed by underprediction of emissions at the end of acceleration events. This results in low bias for the acceleration mode on average;
- Second-by-second bias results show a tendency to underpredict NOx emissions slightly on the cruise sections of both driving cycles for high emitting vehicles;

The second-by-second model validation MSE and NMSE results in brief are:

- Second-by-second model MSE on the US06 test cycle is highest on the acceleration events;
- Second-by-second model NMSE is lower for CO_2 than for CO, HC, and NO_x;
- Second-by-second model NMSE is higher on the deceleration events for CO, HC, and NO_x and higher on the acceleration events for CO_2.

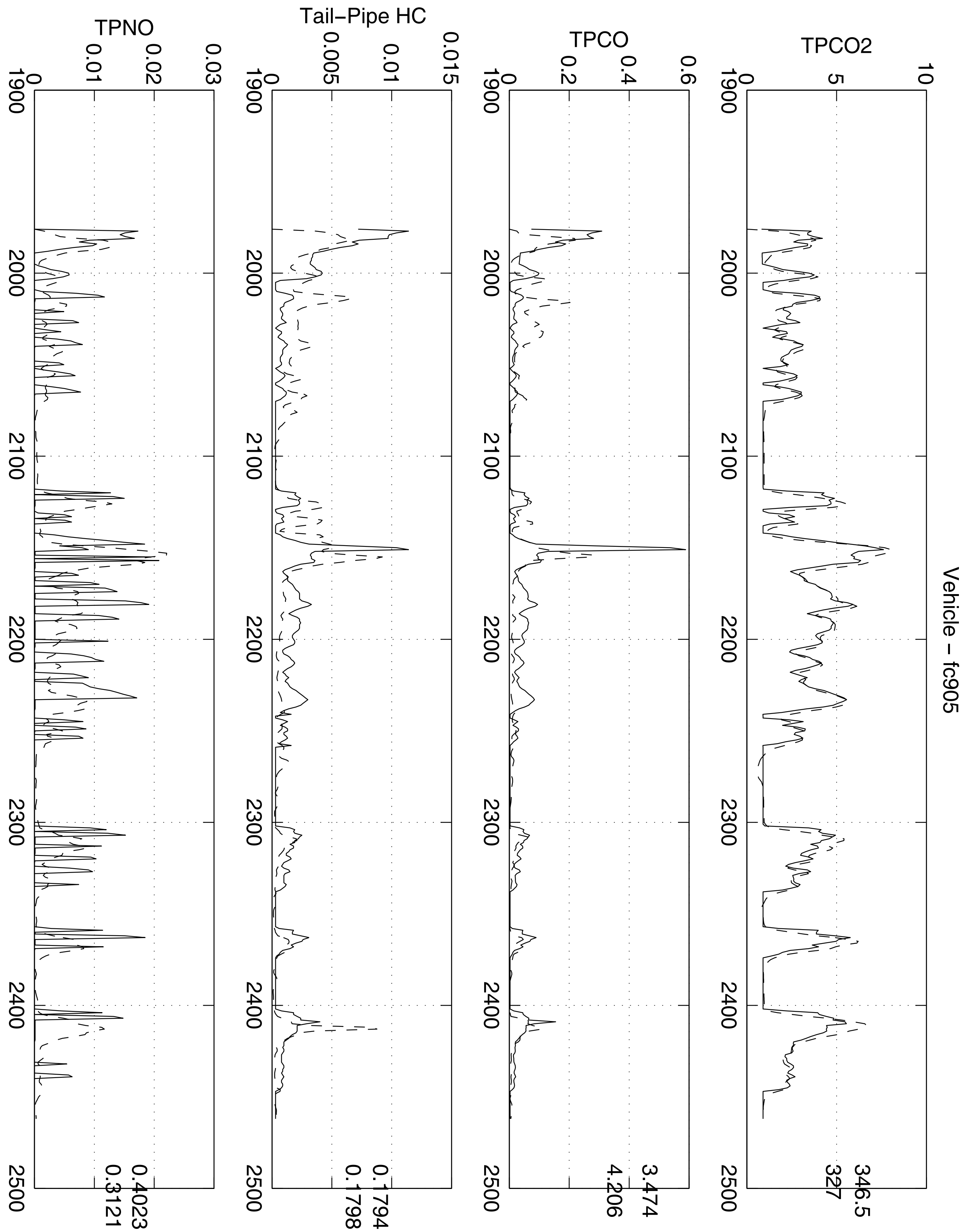

Figure 5.6. Second-by-second plot of FTP Bag 3 observed (solid line) and modeled (dashed line) emissions for a) CO_2, b) CO, c) HC, and d) NO_x for composite category 5 vehicle.

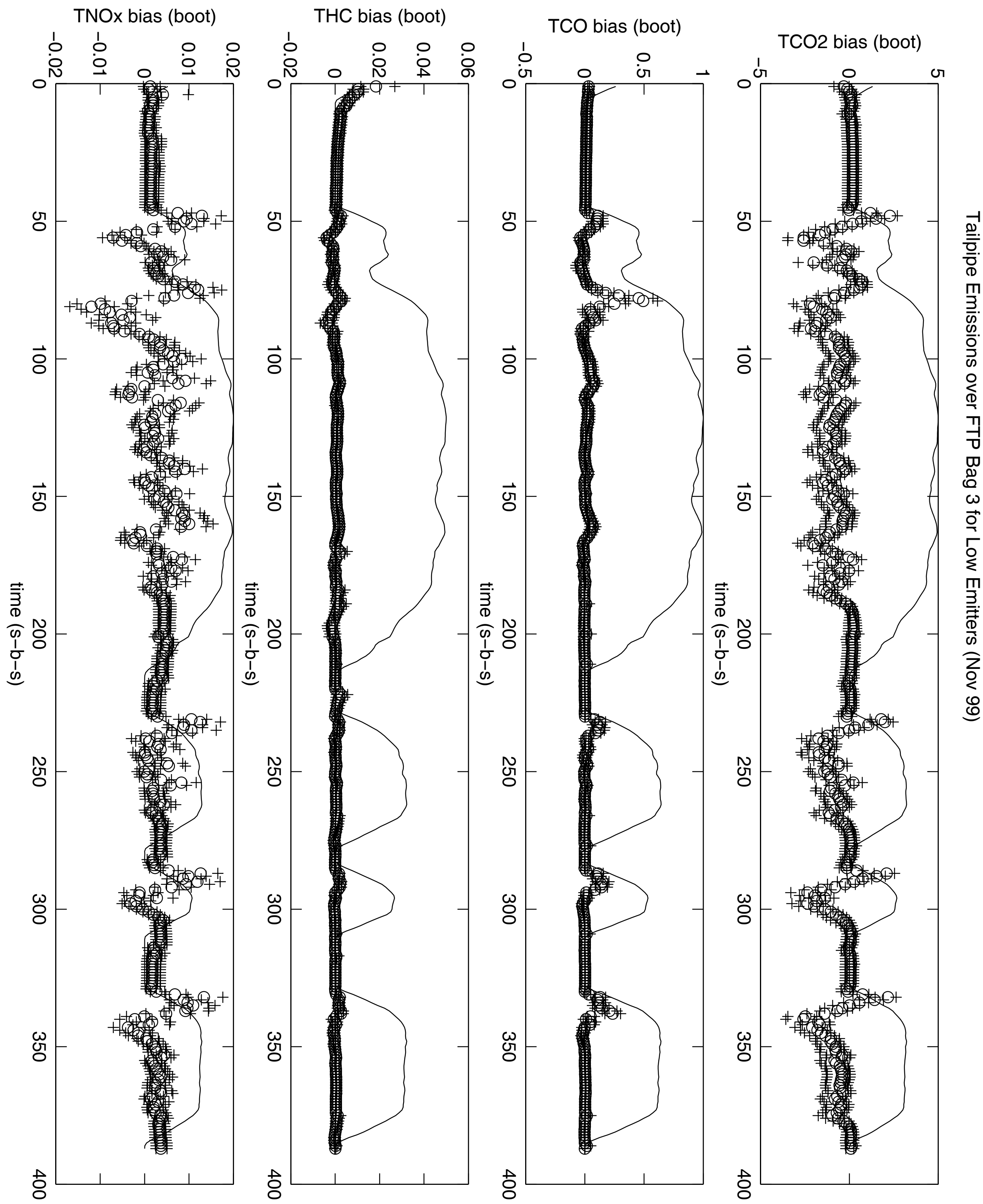

Figure 5.7. Normal emitting vehicle second-by-second speed and model bias (o) on the FTP Bag 3 test cycle with upper and lower 95% confidence limits (+) for a) CO_2, b) CO, c) HC, and d) NO_x.

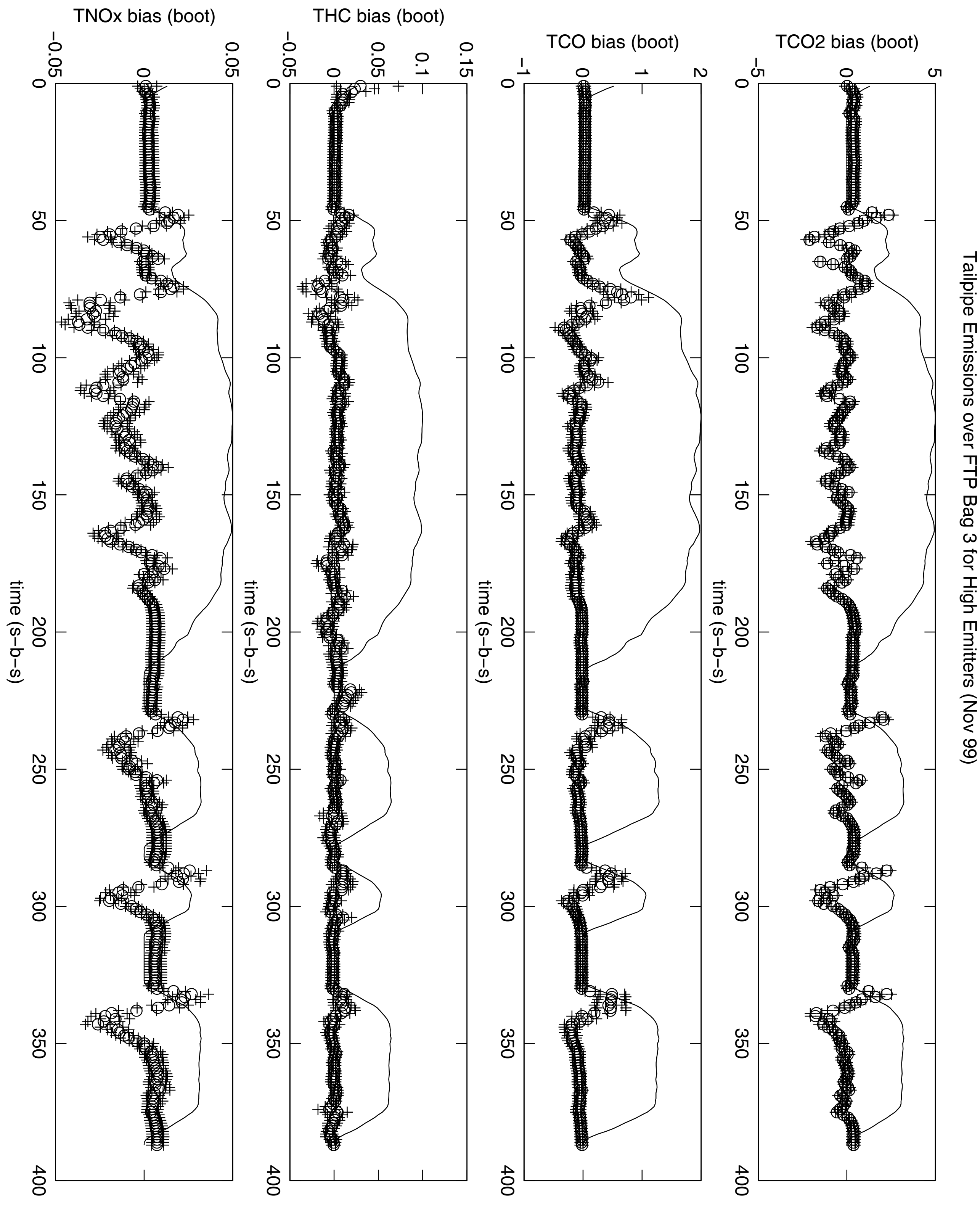

Figure 5.8. High emitting vehicle second-by-second speed and model bias (o) on the FTP Bag 3 test cycle with upper and lower 95% confidence limits (+) for a) CO_2, b) CO, c) HC, and d) NO_x.

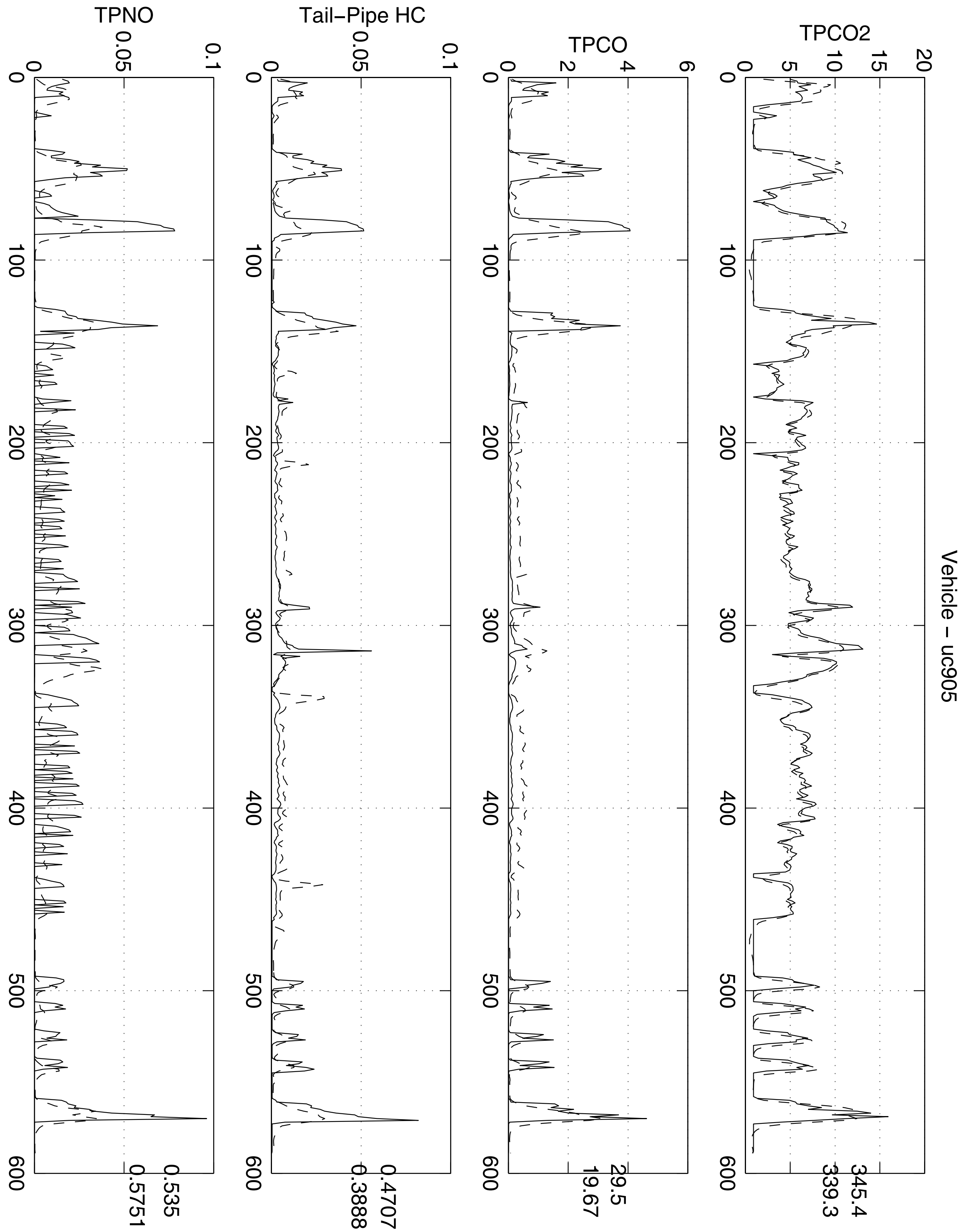

Figure 5.9. Second-by-second plot of US06 observed (solid line) and modeled (dashed line) emissions for a) CO_2, b) CO, c) HC, and d) NO_x for composite category 5 vehicle.

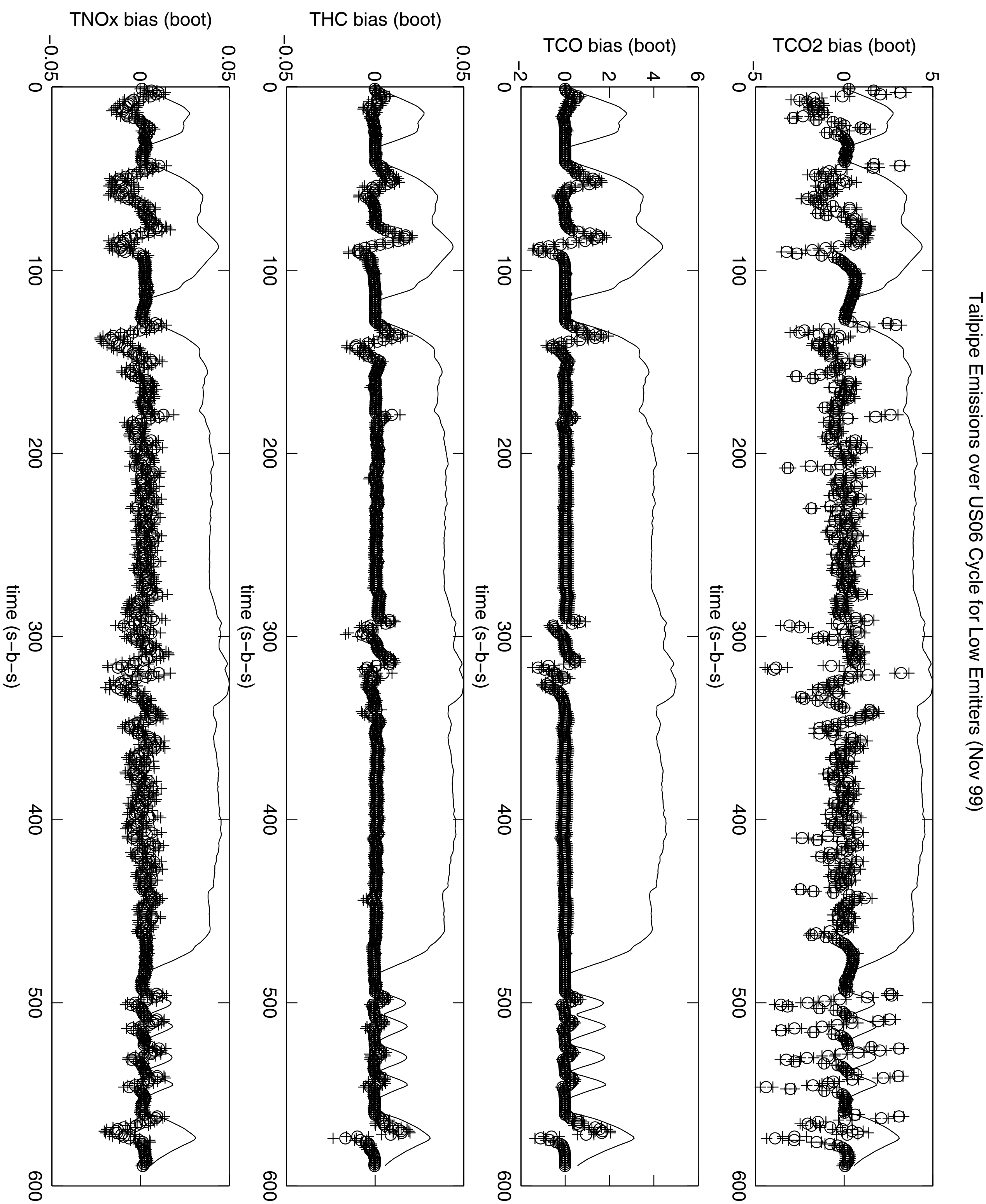

Figure 5.10. Normal emitting vehicle second-by-second speed and model bias (o) on the US06 test cycle with upper and lower 95% confidence limits (+) for a) CO_2, b) CO, c) HC, and d) NO_x.

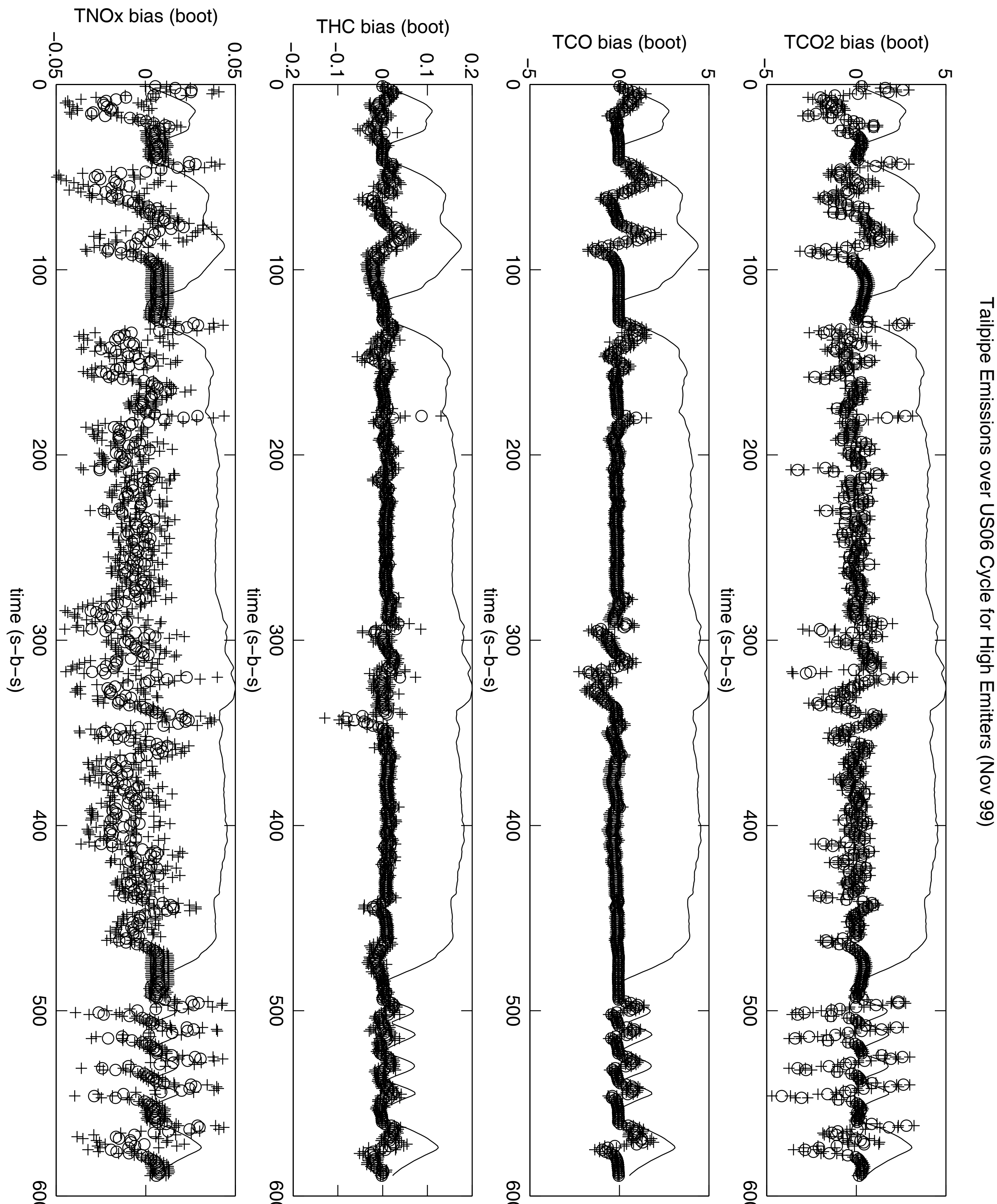

Figure 5.11. High emitting vehicle second-by-second speed and model bias (o) on the US06 test cycle with upper and lower 95% confidence limits (+) for a) CO_2, b) CO, c) HC, and d) NO_x.

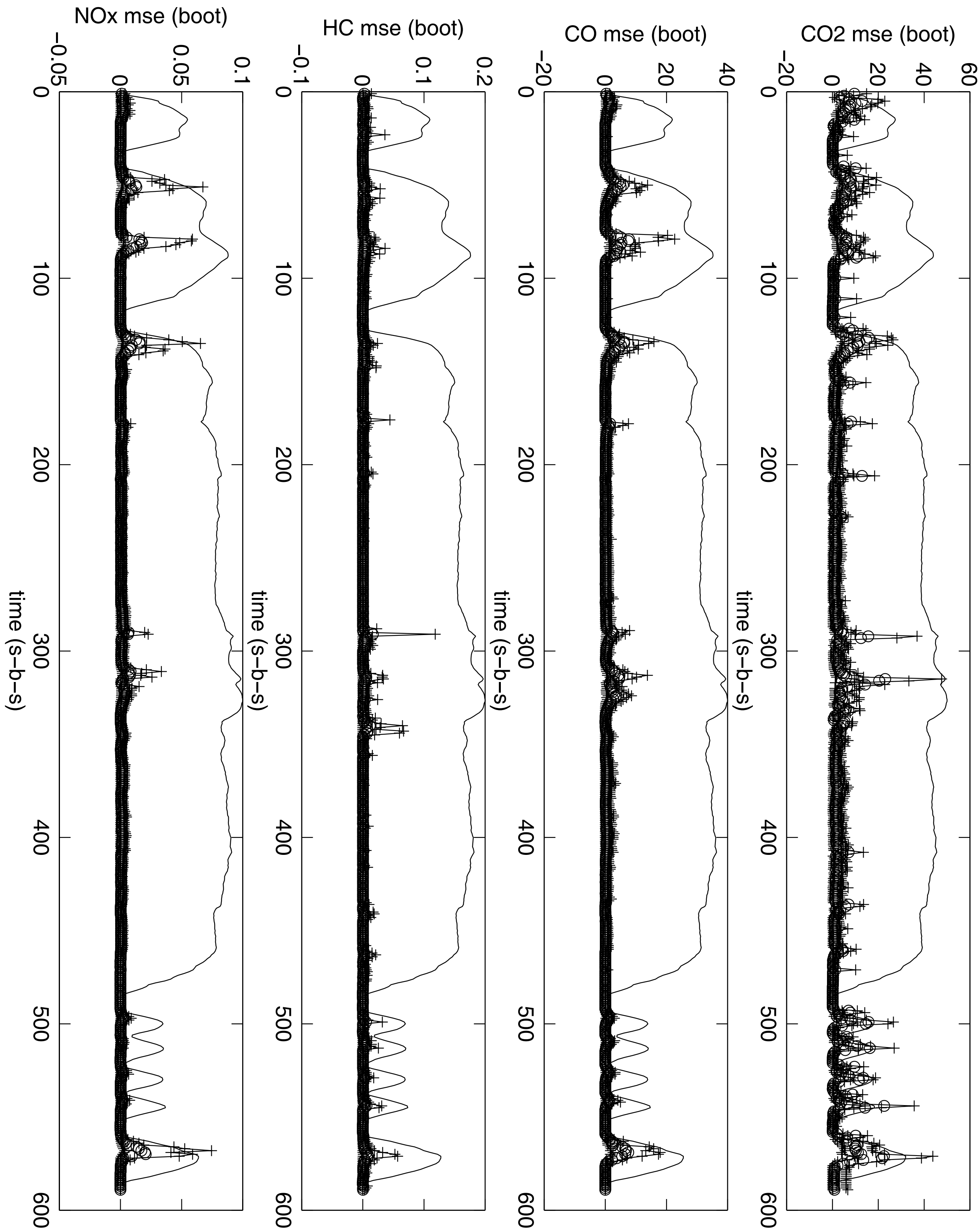

Figure 5.12. All vehicles second-by-second speed and model MSE (o) on the US06 test cycle with upper and lower 95% confidence limits (+) for a) CO_2, b) CO, c) HC, and d) NO_x.

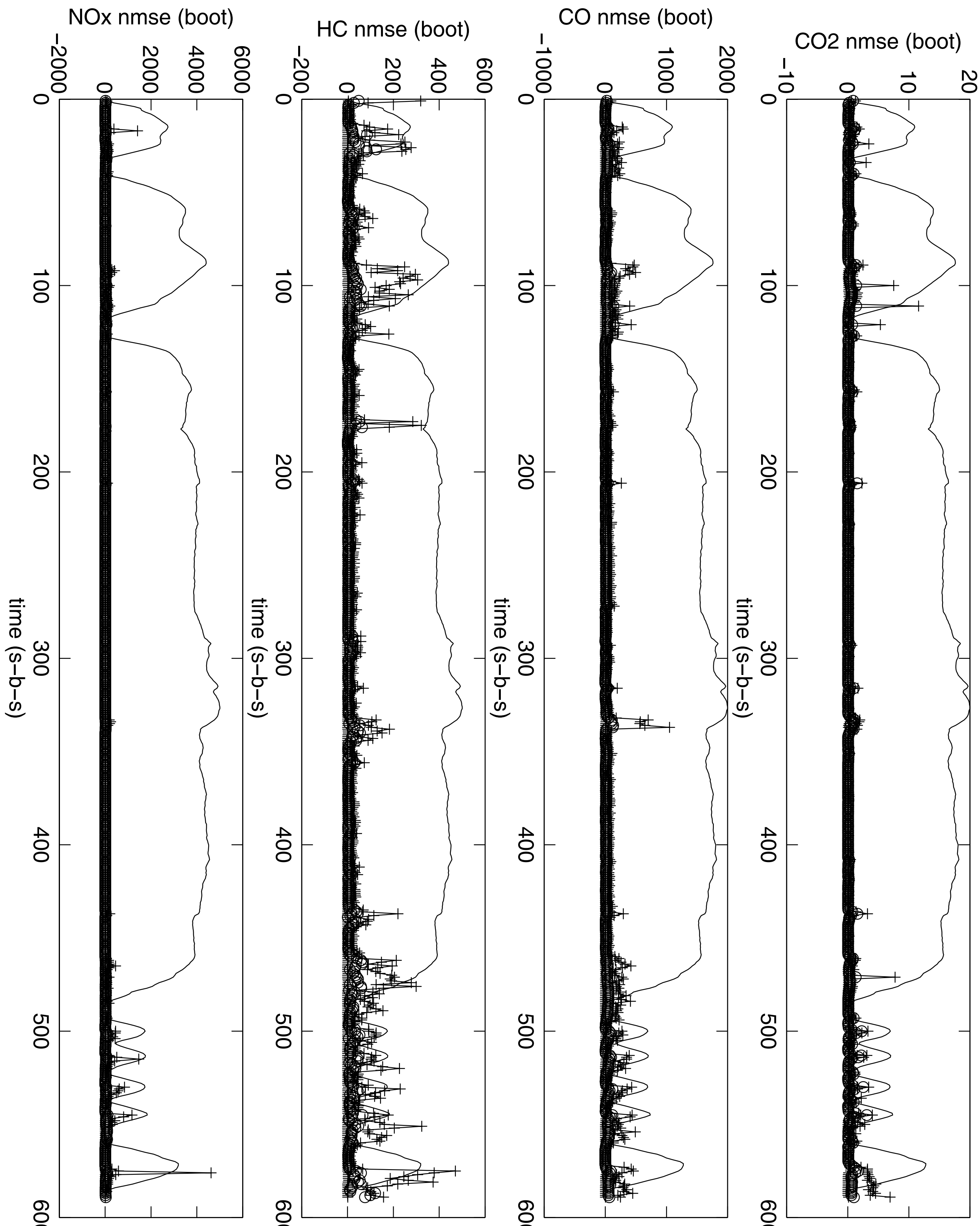

Figure 5.13. All vehicles second-by-second speed and model NMSE (o) on the US06 test cycle with upper and lower 95% confidence limits (+) for a) CO_2, b) CO, c) HC, and d) NO_x.

5.3 MODEL UNCERTAINTY

As previously described, there are several sources of model uncertainty. The main sources of variation analyzed include *emission measurement variability* (Section 5.3.1), *vehicle driving and operation variability* (Section 5.3.2), *vehicle sampling variability* (Section 5.3.3), *parameter estimate variability* (Section 5.3.4), and *model output variability* (Section 5.3.5).

5.3.1 Emissions Measurement Variability

On one of the test runs for vehicle #154 (1965 Mustang) in the No Catalyst/Carbureted group (Category #1), sample lines were purposefully placed into the exhaust system in "pre" and "post" catalyst positions. Since the vehicle has no catalyst, the samples drawn are identical except for very small time and exhaust mixture differences. The total grams measured by each instrument for each of the steady-state cruise sections of the first cruise hill of the MEC01 cycle were calculated. The steady-state cruises were selected to make comparison with vehicle-to-vehicle and run-to-run results possible and to eliminate possible variability that could result from hard driving.

To calculate the instrument variability, it was first necessary to calculate the relative bias of the instruments. The difference ($D_{Instrument}$) in average grams/second between the two instruments at each speed was calculated and tested for correlation with speed. No significant correlation between speed and instrument difference was found ($p > 0.05$). The average CO_2 (g/s) was around 5.719 with an average between-instrument bias of 0.017 (g/s). For CO, HC, and NO_x, the respective averages (g/s) were 0.178, 0.054, and 0.031 with between-instrument biases of 0.008, 0.002, and 0.002 respectively.

The variance of $D_{Instrument}$ is the sum of the variances of the two instruments so *precision* can be calculated as:

$$\textit{within instrument precision} = (\text{Standard Deviation } (D_{Instrument}))/\sqrt{2}$$

These results are summarized in Table 5.3.

	CO_2	CO	HC	NOx
S.D. $D_{Instrument}$ (grams/s)	0.0493	0.0078	0.0036	0.0067
Precision $D_{Instrument}$	0.0246	0.0039	0.0018	0.0034
Average (grams/s)	5.719	0.178	0.054	0.031
Precision $D_{Instrument}$(%)	0.43%	4.38%	7.20%	10.97%

Table 5.3. Standard Deviation and Precision of $D_{Instrument}$. and Precision $D_{Instrument}$(%).

5.3.2 Vehicle Driving/Operation Variability

Small differences in following the driving trace induce emissions differences in the same vehicle on identical test cycles. Motor vehicles emissions vary from day to day, even when driven on the same driving trace. Simple things such as changing the oil, changing air filters, tune ups, and different blends of gasoline can affect vehicle operation and emissions. A vehicle test is a snapshot in time, with the emissions characteristics of the vehicle likely to change over time. Several vehicles were re-tested during the course of this project and can be used to calculate a range of emissions for the same vehicle on separate tests. An analysis of covariance (ANCOVA) was run on vehicles having more than one test run, with difference in power as the covariate. The ANCOVA tests for differences between groups, first run and second run in this case, in the presence of covariates.

An examination of the results found that the inclusion of power as a covariate removed too much variability. This occurred because speed and power are positively correlated, but unlike speed, power has a significant correlation with emissions. For this analysis the repeated vehicles were screened for significant power difference effects. No significant power effects were found. The four repeated vehicles were a 1965 Ford Mustang (vehicle test #154, #314), 1991 Dodge Dakota Pickup (vehicle test #315, #321), 1991 Dodge Spirit (vehicle test #102, #199), and a 1991 Geo Metro (vehicle test #303, #306).

The average grams/second emissions for each of the tests were calculated for each steady state speed event in the first hill of the MEC01 cycle. The average emissions and the average difference in emissions are presented in Table 5.4.

Vehicle	Mean CO2 (g/s)	Mean CO2 Difference	Mean CO (g/s)	Mean CO Difference	Mean HC (g/s)	Mean HC Difference	Mean NOx (g/s)	Mean NOx Difference
1991 Geo	2.822	0.106	0.270	0.021	0.007	0.0006	0.032	0.005
1991 Spirit	3.928	0.040	0.001	-.0003	0.0002	-0.0002	0.008	-0.0002
1991 Dakota	4.193	0.226	0.198	-0.226	0.008	-0.0064	0.021	-0.0016
1965 Mustang	5.719	-0.038	0.178	0.0314	0.054	-0.0243	0.031	-0.0104

Table 5.4. Mean and Mean Difference For Steady-State Cruise Events for Repeat Tests.

The difference in CO_2 from run to run was less than 5% of the mean for all four vehicles. For CO the differences ranged from less than 10% to 30%. HC differences ranging from less than 10% to over 80%, while the average NO_x difference ranged from less than 5% to approximately 30%. From these results it can be seen that on average, CO_2 and NO_x were very repeatable across all four vehicles. The repeatability of CO and HC was quite variable from vehicle to vehicle.

5.3.3 Vehicle Sampling Variability

Variability exists between vehicles within the different vehicle technology groups. Identically manufactured vehicles will not exhibit identical emissions behavior, particularly after different ownership. Similar vehicles were selected from the test data and given the same comparison as the re-tested vehicles in Section 5.3.2. Vehicles exhibiting significant covariance were again excluded from the analysis. The eight pairs of similar vehicles were two 1985 Honda Accords (vehicle tests #27, #62), 1985 Toyota Pickups (vehicle tests #98, #131), 1986 Ford F150 Pickups (vehicle tests #64, #158), 1988 Toyota Pickups (vehicle tests #145, #159), 1990 Nissan Pickups (vehicle tests #160, #180), 1994 Ford Aerostars (vehicle tests #60, #90), 1994 Honda Civics (vehicle tests #163, #314), and 1995 Honda Civics (vehicle tests #37, #45).

The repeatability of CO_2 from similar vehicles (Table 5.5), while not as quite as good as for the same-vehicles-repeated, was still quite good. The average difference in NO_x emissions ranged from 10% to

150%, not as repeatable as the same vehicles. For many of the similar vehicles, the HC data was repeatable with average differences at 10-30% of the mean emission rate, while for other vehicles the differences were up to 500%. The CO average differences were at or above 100% for the majority of the vehicles. Overall, some of the similar vehicles were as repeatable as the re-tests of the same vehicles. However, some similar vehicles had quite different emission rates across the speeds.

Vehicle	Mean CO2 (g/s)	Mean CO2 Difference	Mean CO (g/s)	Mean CO Difference	Mean HC (g/s)	Mean HC Difference	Mean NOx (g/s)	Mean NOx Difference
1985 Accord	3.174	0.036	0.740	-1.052	0.014	-0.018	0.010	0.008
1985 Toyota	4.551	-0.505	0.136	-.204	0.003	-0.002	0.024	0.026
1986 Ford	6.931	0.798	0.014	0.028	0.002	0.0004	0.041	0.047
1988 Toyota	4.062	0.094	0.224	0.381	0.008	0.011	0.021	-0.020
1990 Nissan	4.104	-0.679	0.240	0.338	0.005	0.006	0.016	0.009
1994 Ford	5.417	0.199	0.043	0.053	0.001	0.005	0.011	-0.007
1994 Honda	3.246	-0.064	0.024	-0.003	0.001	0.0001	0.003	0.0003
1995 Honda	2.688	0.427	0.051	-0.048	0.001	-0.0003	0.004	-0.006

Table 5.5. Mean and Mean Difference For Steady-State Cruise Events for Repeat Tests on Similar Vehicles.

5.3.4 Parameter Estimation Variability

The model parameters are calibrated for each vehicle from the emissions data. These calibrated parameters represent estimates of the “true” parameters for the individual vehicles and are subject to error from small driving differences, vehicle operational differences, as well as parameter estimation differences. The sources of variation listed above will have some effect on the estimates of the parameters for individual vehicles that lead to different model predictions for the same vehicle. With random selection, it is expected that all these effects will average out and the composite vehicles will provide model vehicles representative of their group.

As part of the NCHRP testing, the CE-CERT instrumented vehicle (1991 Ford Taurus) was run on the same test cycles three separate times within one month. The test data were used to calculate three sets of parameter values for the vehicle from the three test runs. The parameter values and the mean, standard deviation, and coefficient of variation (SD/Mean) for the parameters are listed in Table 5.6. Overall, the coefficient of variations (CVs) were less than 0.5, indicating low variation of the parameter estimates relative to their means. There are seven parameters with CVs over 0.5: hc_{jk}, *r_R, spd_th, HCB1,* $Csoak_{no}$, $Bcat_{co}$, *and* $Bcat_{hc}$. These parameters were variable from run to run, but did not exhibit single outliers, indicating that parameter estimation is variable but not failing to converge.

Parameter	Test 1	Test 2	Test 3	Mean	St. Deviation	St.Dev/Mean
K_0	0.253	0.240	0.240	0.244	0.007	0.030
ε_3	0.097	0.100	0.100	0.099	0.002	0.018
$\mathbf{C_0}$	3.909	3.902	3.852	3.888	0.031	0.008
a_{CO}	0.089	0.086	0.086	0.087	0.002	0.019
a_{HC}	0.012	0.012	0.011	0.012	0.001	0.052
$\mathbf{r_{HC}}$	0.004	0.005	0.004	0.004	0.000	0.058
a_{1NO}	0.034	0.033	0.034	0.033	0.000	0.012
a_{2NO}	0.017	0.021	0.021	0.020	0.002	0.126
FR_{NO1}	-0.449	-0.454	-0.462	-0.455	0.007	-0.015
FR_{NO2}	0.005	0.005	0.005	0.005	0.000	0.000
Γ_{CO}	99.594	99.097	99.460	99.384	0.257	0.003
Γ_{HC}	98.750	98.733	98.636	98.706	0.061	0.001
Γ_{NO}	99.270	99.177	99.081	99.176	0.095	0.001
b_{CO}	0.105	0.096	0.049	0.083	0.030	0.359
c_{CO}	1.524	1.660	1.699	1.628	0.092	0.056
b_{HC}	0.022	0.020	0.015	0.019	0.004	0.208
c_{HC}	0.897	0.892	1.142	0.977	0.143	0.146
b_{NO}	1.983	1.694	1.762	1.813	0.151	0.083
c_{NO}	2.580	2.164	3.186	2.643	0.514	0.194
ϕ_0	1.279	1.284	1.274	1.279	0.005	0.004
ϕ_{min}	0.972	0.964	0.973	0.970	0.005	0.005
P_{scale}	1.121	1.126	1.249	1.165	0.073	0.062
hc_{max}	0.059	0.066	0.056	0.060	0.005	0.091
hc_{trans}	4.625	4.993	0.519	3.379	2.484	0.735
r_R	0.086	0.031	0.044	0.054	0.028	0.531
δSP_{th}	111.800	161.798	46.609	106.736	57.761	0.541
r_{O2}	4.722	4.607	4.812	4.713	0.103	0.022
β_{CO}	34.071	28.981	30.392	31.148	2.628	0.084
β_{HC}	33.633	500.000	20.820	184.818	273.031	1.477
β_{NO}	8.118	13.542	9.580	10.413	2.806	0.270
ϕ_{cold}	1.298	1.262	1.294	1.284	0.020	0.015
CS_{HC}	4.014	2.798	4.855	3.889	1.034	0.266
CS_{NO}	5.226	7.061	5.446	5.911	1.002	0.170
T_{cl}	129.932	110.258	115.190	118.460	10.237	0.086
γ	0.243	0.301	0.303	0.282	0.034	0.122
C_{soak_co}	130.482	280.687	399.996	270.388	135.052	0.499
C_{soak_hc}	49.059	17.184	41.801	36.015	16.706	0.464
C_{soak_no}	59.069	3.184	5.425	22.559	31.638	1.402
β_{cat_CO}	4.659	0.011	0.329	1.666	2.597	1.558
β_{cat_HC}	10.892	0.641	0.453	3.995	5.973	1.495
β_{cat_NO}	4.403	7.378	5.882	5.888	1.488	0.253
ε_1	0.870	0.845	0.868	0.861	0.014	0.016

Table 5.6. 1991 Taurus Model Parameter Estimates, Mean, S.D. and Coefficient of Variation.

5.3.5 Single Vehicle Model Output Variability

The Taurus repeat run results from the Section 5.3.4 were used to construct approximate confidence limits on the model output for one vehicle by generating 1,000 random sets of Taurus parameters using the parameter means and variances found in Table 5.6 (from previous section). The parameters were generated as independent Normal random variables. The parameter sets and resulting model emissions estimates were then used to calculate the standard deviation of the estimated CO_2, CO, HC, and NO_x (Table 5.7). These results are based on the range and variability of parameter values found on the instrumented vehicle runs assuming independence of the model parameters. The actual standard deviation of the observed US06 test data are presented in Table 5.7 along with the standard deviation for the 1,000 random vehicle model results.

Emission	Observed St. Deviation	Modeled St. Deviation
CO_2	5.282	5.960
CO	7.281	2.929
HC	0.082	0.054
NOx	0.062	0.060

Table 5.7. Taurus Instrumented Vehicle US06 Test Standard Deviation and Modeled 1,000 Random Vehicle Standard Deviation for CO_2, CO, HC, and NO_x.

The variability of the modeled CO_2, CO, HC and NO_x results are somewhat lower than the observed variability of the three tests. While three tests are minimally sufficient to estimate test-to-test variability, these results do not provide any indication that the model estimation process is introducing additional variability into the results.

5.3.6 Composite Vehicle Model Output Variability

The results of Section 5.3.5 apply to model output for a single vehicle, however the modal model is based on composite vehicles where the random errors which apply to individual vehicles average out within a category. The variance of a composite vehicle can then be estimated as:

$$\text{Composite Vehicle Variance} = \text{Single Vehicle Variance} / \sqrt{n}$$

The composite vehicle corresponding to the 91 Ford Taurus (Category 5) had 15 vehicles averaged into the composite trace so the estimated variance is equal to the variance of the single vehicle divided by $\sqrt{15}$. The estimated emissions for the composite vehicle and estimated 95% confidence limits using this estimate of the composite vehicle variance are presented in Table 5.8.

Emission	Modeled Composite Vehicle US06 Mean	Estimated S.D. of Mean Composite	95% Lower Confidence Limit	95% Upper Confidence Limit
CO_2	377.4	3.029	375.7	379.1
CO	30.28	1.488	29.46	31.10
HC	0.438	0.084	0.392	0.484
NOx	0.630	0.030	0.625	0.635

Table 5.8. Mean Modeled US06 Total CO_2, CO, HC, and NO_x With 95% Confidence Limits For A Single Composite Vehicle.

Thus, based on the model output mean and variability of the instrumented Ford Taurus, the 95% confidence limits for the 3-way catalyst, FI, >50K mi., high power/wt. composite vehicle for CO_2 are 375.7 to 379.1. As a percent, the modeled CO_2 is 377.4 ± 0.4%. Similarly, CO, HC, and NO_x are respectively: 30.28 ± 2.7%, 0.438± 10.5%, and 0.630 ± 0.8%.

These results are dependent upon several assumptions; the instrumented Ford Taurus has test-to-test variability representative of the vehicles included in the composite, the model output errors are Normally distributed, and the generation of independent model parameters produces representative results in the range of parameters observed here. The confidence limits were expressed as the next higher whole percent because of these uncertainties.

If the instrumented Ford Taurus is representative, the composite vehicles made up of higher numbers of vehicles will have smaller confidence limits and those made up of fewer vehicles will have larger confidence limits. A more exact analysis of the variability of the composite vehicles would require using the bootstrap re-sampling technique and is beyond the scope of this project at this time. These confidence limits are provided to give estimates of the model confidence limits based on observed test data using our optimization and modeling methods.

5.3.6 Variability Summary

- Differences in emissions for steady-state driving modes between the same vehicle driven on repeat days are smaller than differences between similar vehicles;

- Model parameter estimates for the same vehicle from three test runs were very stable for 35 of the 43 model parameters;

- Model parameter estimates for four parameters had coefficients of variation over 1, but did not exhibit convergence problems;

- Parameter estimation variability did not substantially increase model output variability beyond that observed in the actual data for the three replicate runs;

- Composite vehicle model output variability from all sources was estimated at ± 0.4% for CO_2, ± 2.7%, for CO, ± 10.5% for HC, and ± 0.8% for NO_x.

5.4 MODEL SENSITIVITY

The results from the parameter estimation for the 343 vehicles were used to conduct a model parameter sensitivity analysis. The parameter sets and resulting model emissions estimates were used in a stepwise multiple regression to identify the parameters that have the largest effect on the model output. These results are based on the range and variability of parameter values found on the vehicles used in the model development and provide an estimate of model parameter sensitivity for emissions in the range observed in our test fleet.

The stepwise multiple regression [Draper and Smith, 1966] is a statistical method which selects the single variable which best improves the prediction of the dependent variable at each step of the regression. The first step includes the single variable that is the best predictor. Each additional step includes the variable which best improves the regression. At each step, the program checks to see if any of the variables in the regression no longer significantly improve the regression. Variables that no longer have a significant *F-to-remove* measure are removed from the regression prior to continuing on to the next step. When no variables significantly improve the regression, the procedure is halted. In this case the predictors are the parameter values of the individual vehicles and the dependent variables are the US06 emissions results for the same vehicles. Parameters that are highly correlated with each other will not all be included in the regression. For example Γ_{CO}, Γ_{HC}, and Γ_{NO} are all highly correlated and only one is likely to be included in the regression. Small random differences in the parameter values can lead to the inclusion of any of the three in a particular regression.

The model parameters that best predict the US06 CO_2 model results are listed in Table 5.9. The single most important variable as measured by the *f-to-remove* is FR_{N01}, followed by b_{hc} and a_{CO}. The 10 model parameters listed accounted for 56% of the variability observed in the modeled CO_2 US06 results.

Variables In Model

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	204.211	24.889	204.211	67.320
Edt3	369.463	121.440	.126	9.256
aCO	-336.319	71.519	-.207	22.114
aNO1	1644.010	487.451	.157	11.375
FRNO1	-330.920	29.534	-.532	125.547
cCO	-2.137	.830	-.124	6.638
bHC	-118.541	25.099	-.269	22.306
bNO	4.623	1.001	.245	21.323
lam_m	48.215	15.513	.137	9.660
r_R	43.200	17.923	.098	5.809
Tlamb	.063	.022	.131	8.289

Table 5.9. Final CO_2 stepwise regression parameters for the US06 cycle

For CO, 10 model parameters significantly improved the regression. B_{NO}, Γ_{NO}, and a_{NO1} were the most important variables in the regression. Overall, the 10 model parameter values were able to account for 48% of the observed variability in the US06 model results.

Variables In Model

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	-1076.947	113.041	-1076.947	90.764
Edt3	-1625.203	447.220	-.162	13.206
aNO1	12090.445	2109.323	.338	32.855
FRNO1	-340.261	105.462	-.160	10.410
FRNO2	-132.777	53.363	-.117	6.191
MAXNO	5.276	.812	.389	42.266
bNO	39.589	3.884	.613	103.884
COB1	-.326	.087	-.172	13.900
csHC	29.114	6.185	.215	22.158
csNO	5.836	2.550	.111	5.237
Tlamb	.368	.085	.224	18.490

Table 5.10. Final CO stepwise regression Parameters for the US06 cycle

For HC, a total of 6 model parameters significantly improved the regression. The best parameter for prediction of US06 HC is a_{HC}. The 6 variables account for 53% of the observed variability in US06 HC model results.

Variables In Model

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	1.633	.465	1.633	12.355
aHC	27.442	3.960	.308	48.022
MAXCO	-.020	.004	-.228	21.755
bHC	1.779	.335	.304	28.216
bNO	.036	.013	.143	7.793
lam_m	.417	.199	.089	4.416
maxhc	2.249	1.033	.102	4.745

Table 5.11. Final HC stepwise regression Parameters for the US06 cycle

For NO_x, 10 model parameters were able to account for 66% of the variability in the modeled US06 results. Model NO_x results are most sensitive to the b_{NO}, MAXNO.2, and a_{1NOx}(aNO1) parameters.

Variables In Model

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	1.638	.368	1.638	19.850
aHC	-7.222	2.732	-.095	6.990
aNO1	35.327	4.547	.297	60.354
aNO2	18.199	5.153	.145	12.473
MAXNO.2	-.026	.003	-.338	71.763
cHC	-.015	.004	-.162	14.508
bNO	.100	.010	.466	94.991
rO2	-.007	.002	-.163	19.128
HCB1	.001	2.403E-4	.114	8.666
id	1.157	.163	.311	50.509
Bcat_hc	-.001	4.918E-4	-.087	4.988

Table 5.12. Final NO_x stepwise regression Parameters for the US06 cycle

Several conclusions can be drawn from this analysis which apply to the model output with model parameters in the range observed in our test fleet:

- For the hard driving US06 cycle, 48% to 66% of the observed variability in modeled CO_2, CO, HC, and NO_x emissions can be accounted for with 6 to 1 model parameters;
- For CO_2, modeled emissions are most sensitive to the NO_x fuel rate enrichment threshold (FRNO1), b_{hc} and a_{CO};
- For CO, modeled emissions are most sensitive to b_{NO}, Γ_{NO}, and a_{NO1};
- For HC, modeled emissions are most sensitive to aHC, Γ_{HC} (which is highly correlated with Γ_{HC}), and b_{HC};
- For NO_x, modeled emissions are most sensitive to b_{NO}, Γ_{NO}, and a_{1NOx}.

5.5 SUPPORTING DATA ANALYSIS

Throughout the testing and modeling building, numerous analyses have taken place on the acquired data. These analyses have helped validate the choices of vehicle/technology categories and the development of specific model components. Much of this data analysis is lengthy and outside the scope of this report. However, some of the analyses are presented below.

Data analysis was conducted on three areas that support the model development: 1) Estimation of the power necessary for running of the AC compressor, 2) Testing for a hysteresis effect on steady-state cruise emissions; and 3) studying model parameter differences between vehicle/technology categories.

5.5.1 Air Conditioning Power Estimation

In the CME model, AC compressor effects are included as an increased load on the engine. The MEC cycle contains an air conditioning (AC) hill. For part of the cycle the AC was turned off (hill 1). The exact same portion of the cycle was then repeated with the AC turned on (hill 2). The emissions data for the two hills was extracted from each tested vehicle. CO_2, CO, HC, and NOx emissions in grams were summed over the AC hill and the non-AC hill. Using the equations below, the fuel rate was calculated for both hills for each vehicle.

$$C = (12/28)*ECOgs + (12/44)*ECO_2gs + (12/13)EHCgs$$

$$fuel\_rate = C*(13.87/12)$$

Where ECOgs is the engine out CO emissions in grams per second, ECO_2gs is the engine out CO_2 emissions in grams per second, and EHCgs is the engine out HC emissions in grams per second. The C should be carbon and the units of fuel rate should be grams per second.

The average percent increase in fuel rate with the air conditioner activated was calculated for each vehicle category (Table 5.13). No data was available for vehicle category 1 (No Catalyst cars) or 12 (Pre-1979 Trucks) where all of the vehicles tested either had no functioning air conditioner or failed to complete the AC portion of the test. The percent differences ranged from a low of 1.82% fuel rate increase for category 13 (1979-1983 Trucks) to a high of 21.16% fuel rate increase for category 9 (Tier 1, >50K miles, high p/w). The change in fuel rate was then used to interpolate the percent increase in horsepower that would be needed to compensate for the increase in fuel use.

An analysis of covariance (ANCOVA) was conducted to test the hypothesis that the observed differences could be accounted for by differences in driving trace. The ratio of calculated power for the AC-hill over the non-AC hill was used as the covariate in an ANCOVA on Fuel Rate difference between technology groups. The interaction term between the group variable and the power ratio covariate was not significant, indicating that the effect of power differences on Fuel Rate ratio was not different between groups. The ANCOVA was then re-run without the interaction term. The covariate was not significant (Table 5.14, p=0.1644), indicating that there was no significant effect of power differences on the Fuel Rate results.

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Vehicle Category	21	.236	.011	2.427	.0009	50.958	.997
power AC/power No AC	1	.009	.009	1.950	.1644	1.950	.268
Residual	175	.811	.005				

Table 5.14. Analysis of Covariance of Fuel Rate by Vehicle/Technology Category.

Category	% Fuel Rate Increase	Sload (hp)
1	11.60*	3.23
2	11.60	3.23
3	18.05	3.58
4	18.54	4.52
5	14.14	3.58
6	15.46	3.69
7	13.70	3.02
8	18.91	4.62
9	21.16	4.40
10	14.68	3.42
11	18.47	4.77
12	1.82*	0.86
13	1.82	0.86
14	9.82	2.78
15	12.13	3.43
16	15.84	6.06
17	18.46	5.97
18	8.65	3.76
19	11.39	2.64
20	6.76	0.83
21	8.86	4.94

22	8.86	3.48
23	3.22	4.33
24	19.96	3.47
25	13.72	1.67
26	17.33	2.19
40	4.48	1.19

*** No test data available. Value estimated using nearest category.**

Table 5.13. Average percent increase in fuel rate with AC activated.

The significant ($p = 0.0009$) Vehicle Category effect indicates that the observed differences in percent increase in Fuel Rate emissions between vehicle/technology groups are not random. This result indicates that the modal model should include different size AC effects for the different vehicle/technology categories. The averages presented in Table 5.13 are the current best estimate of the size of the AC effect on Fuel Rate for each category.

5.5.2 Steady-State Hysteresis

Repeating the steady-state cruise hill at the end of the test cycle tested repeatability within cycles with different prior history, an important assumption built into the model. The third version of the MEC test cycle contained a repeat of the steady-state cruise hill with speeds scrambled so that cruise sections which are entered from an acceleration event are entered from a deceleration event and cruise sections which are entered from a deceleration event are entered from an acceleration event. The speeds which were preceded by an acceleration from one hill and a deceleration on the other hill were 5 mph, 20 mph, 35 mph, and 65 mph. For this analysis, test data from 112 vehicles were used.

A two-way ANOVA was run on CO_2, CO, HC, and NO_x to test for differences in emission rate for speed, Acceleration/Deceleration, and the interaction of speed and A/D. The four ANOVA's are summarized in Table 5.15.

Source	Degrees of Freedom	CO_2 p-value	CO p-value	HC p-value	NOx p-value
Speed	3	**<u><.0001</u>**	**<.0001**	**<.0001**	**<.0001**
A/D	1	0.5743	0.0982	0.0911	0.2486
Speed*A/D	3	0.1907	0.0821	0.6956	0.5202

Table 5.15. Acceleration/Deceleration ANOVA Summary.

Significant differences in emission rates were observed between steady-state cruise speeds as expected. No significant difference in emission rates was observed between steady-state cruises entered from acceleration vs. entered from a deceleration. No significant interaction was found.

These results indicate that there is no significant history effect on emission rates for steady-state cruises. However, the vehicle-to-vehicle variability in emissions is rather high relative to the observed emission rates, which lowers the power of this test to detect differences. CO and HC are significant at the 10% ($p < 0.10$) level commonly used for screening results for additional analysis. A more detailed analysis to test for a hysteresis effect within our individual vehicle/technology groups is beyond the scope of this project.

5.5.3 Calibrated Parameter Analysis

In Chapter 4, Table 4.4 lists every model parameter for all 26 vehicle/technology categories. In this section, several selected calibrated parameters in selected vehicle/technology categories are compared, showing how these parameters differ from each other from category to category.

Seven calibrated parameters are selected for this analysis:

K_0 - Engine friction factor in kJ/(lit.rev)

a_{CO} – Engine-Out CO emission index coefficient

a_{HC} – Engine-Out HC emission index coefficient

a_{1NOx} - Engine-Out NO_x emission index coefficient

b_{CO}, b_{HC}, b_{NO} - hot Catalyst CO, HC, and NOx coefficients

Twelve composite vehicle categories are used, given in Table 5.15.

Categories 2, 3, and 13 represent older cars and trucks (MY 70s and early 80s). Categories 4, 8, 15, and 17 represent newer technology cars and trucks (MY late 80s and 90s). Categories 19-23 represent high-emitting vehicles.

Figure 5.14 shows a comparison between the K_0 values among these vehicle categories. It clearly shows that the older and high-emitting vehicle categories have higher values of K_0, which represents the engine friction energy loss (in kJ) per unit of engine revolution (in rps) and engine displacement (in liters). For older technology vehicles (categories 2, 3, and 13), $K_0 \approx 0.25$ kJ/(rev.liter); for high emitting vehicles, K_0 ranges from 0.23 to 0.27 kJ/(rev.liter). For newer technology vehicles (categories 4, 8, 15, and 17), $K_0 \sim$ 0.20-0.22 kJ/(rev.liter).

Category #	Vehicle Technology Category
Normal Emitting Cars	
2	2-way Catalyst
3	3-way Catalyst, Carbureted
4	3-way Catalyst, FI, >50K miles, low power/weight
8	Tier 1, >50K miles, low power/weight
Normal Emitting Trucks	
13	1979 to 1983 (<=8500 GVW)
15	1988 to 1993, <=3750 LVW
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)
High Emitting Vehicles	
19	Runs lean
20	Runs rich
21	Misfire
22	Bad catalyst
23	Runs very rich

Table 5.16. Vehicle categories selected for comparison.

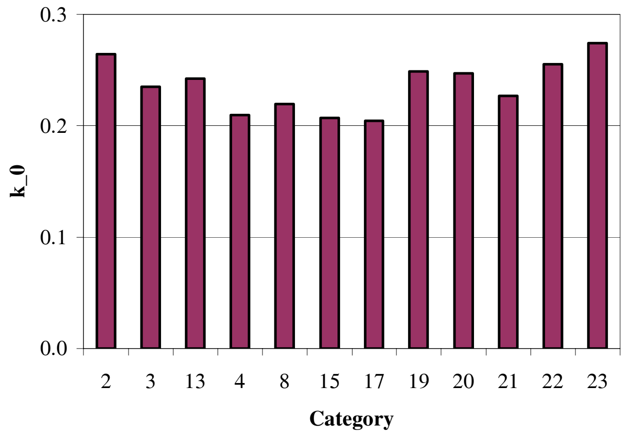

Figure 5.14. K_0 (in kJ/(rev.liter)) and vehicle categories.

Figures 5.15 – 5.17 compare the engine-out emission indexes values – a_{CO}, a_{HC} and a_{NOx}, among these vehicle categories.

Figure 5.15 illustrates that the older vehicle categories have higher values of a_{CO}, which represents the engine-out emissions (in gram) per unit of fuel consumption (in gram). For older technology vehicles (categories 2, 3, and 13), a_{CO} ~ 0.18–0.20; For newer technology vehicles (categories 4, 8, 15, and 17), a_{CO} ~ 0.08-0.10 (g-CO/g-fuel). There are large variations in high-emitting categories, for categories 19 (lean) and 21 (misfire), a_{CO} values are quite low, only about 0.08-0.09. But for categories 20 (runs rich), 22 (bad catalyst), and 23 (runs very rich), a_{CO} values are extremely high, ranging from 0.19 to 0.29 (g-CO/g-fuel).

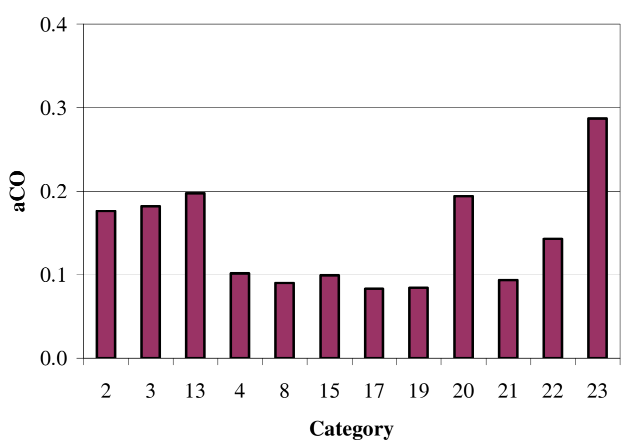

Figure 5.15. a_{CO} (g-CO/g-fuel) and vehicle categories.

Figure 5.16 shows that the high-emitting vehicles have much higher a_{HC} values than the normal emitting vehicles. For normal emitting vehicles, a_{HC} ranges from 0.01 to 0.02; but for high emitting categories, a_{HC} ranges from 0.01 (category 19) to 0.07 (category 21). Category 21 represents the engine misfire case, that is why it has an extremely high engine-out HC emission index value.

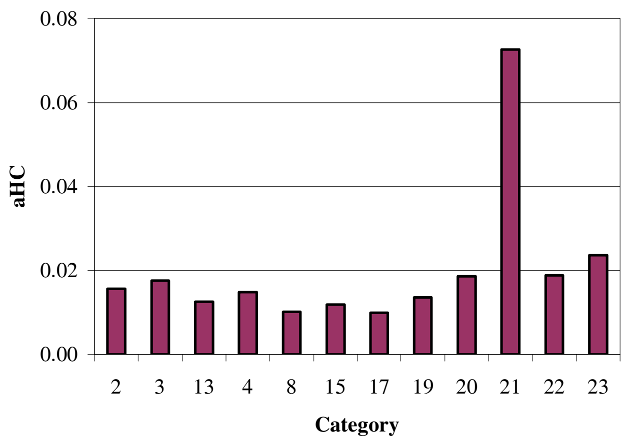

Figure 5.16. a_{HC} (g-HC/g-fuel) and vehicle categories.

Figure 5.17 shows that some high CO and HC emitting vehicle categories have lower a_{NO} values (category 23 (run very rich) has a value < 0.01). But a_{NO} reaches the highest value (~ 0.03) in category 19 (runs lean) and category 22 (bad catalyst).

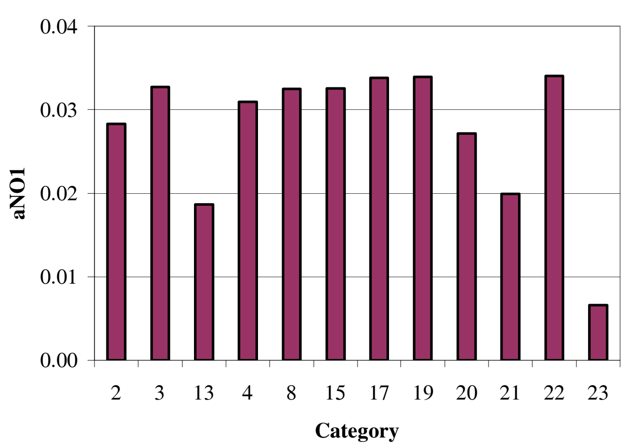

Figure 5.17. a_{NOx} (g-NOx/g-fuel) and vehicle categories.

Figures 5.18 – 5.20 compare the hot-stabilized catalyst coefficients – b_{CO}, b_{HC} and b_{NOx}, among the selected vehicle categories. Generally speaking, the higher b_{CO}, b_{HC} and b_{NOx} values imply that the catalysts are more sensitive to the engine-out emissions, and are thus less efficient.

Figure 5.18 shows that the high-emitting vehicles have much higher b_{CO} values than the normal emitting vehicles. For normal emitting vehicles, b_{CO} ranges from 0.10 to 0.3; but for high emitting categories, b_{CO} ranges from 0.32 (category 21 – misfire case) to 0.47 (categories 20 and 22). Categories 20 represent the engine rich operation case, and category 22 represents a bad catalyst case.

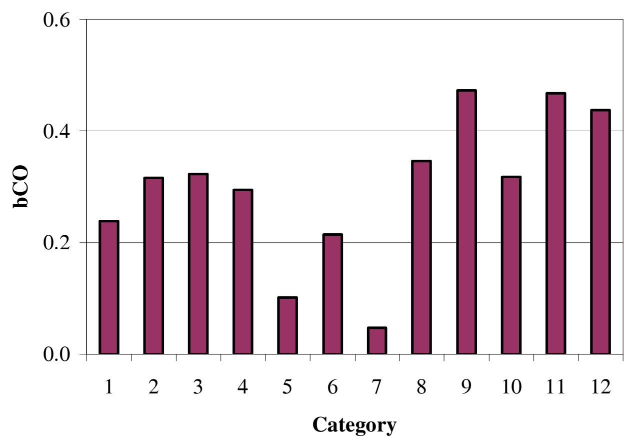

Figure 5.18. b_{CO} (1/(g/s)) and vehicle categories.

The trend is very similar for the HC catalyst case. Figure 5.19 illustrates that the high-emitting vehicles have, in general, higher b_{HC} values than the normal emitting vehicles. For normal emitting vehicles, b_{HC} ranges from 0.01 to 0.48; But for high emitting categories, b_{HC} ranges from 0.23 (category 19 – runs lean) to as high as 0.98 (category 23 – runs very rich case).

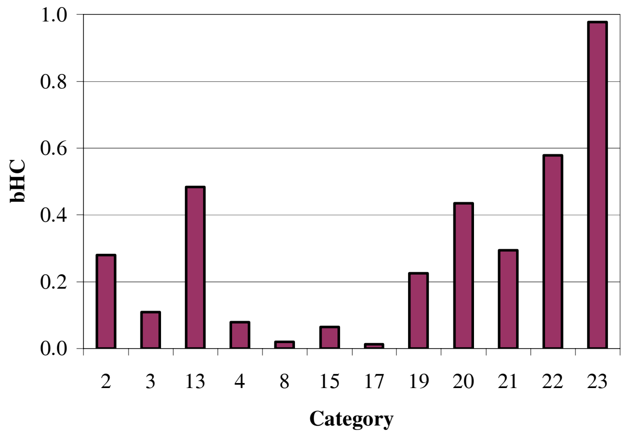

Figure 5.19. b_{HC} (1/(g/s)) and vehicle categories.

It is more complicated for NO_x catalyst efficiency. Figure 5.20 shows that the older technology vehicles have much higher b_{NO} values than the newer technology vehicles. For the older technology vehicles (categories 2, 3, and 13), b_{NO} ranges from 8 to 13; while for newer technology vehicles (categories 4, 8, 15 and 17), b_{NO} only ranges from 0.5 to 3. For high emitting categories, b_{NO} are high for vehicle categories 19-23.

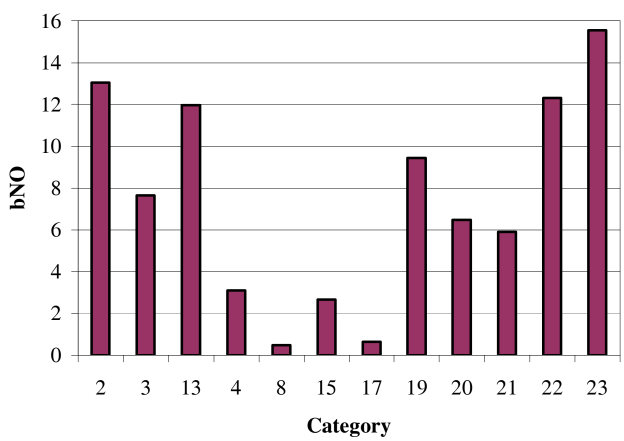

Figure 5.20. b_{NOx} (1/(g/s)) and vehicle categories.

The above discussion demonstrates that most calibrated parameters do have a definite physical meaning and correlate well with different definitions of composite vehicle categories.

6 Transportation/Emission Model Integration

The comprehensive modal emissions model was designed so that it can interface with a wide variety of transportation models and/or transportation data sets in order to produce an emissions inventory. As shown in Figure 6.1, these transportation models/data vary in terms of their inherent temporal resolution. For example, at the lowest level, microscopic transportation models typically produce second-by-second vehicle trajectories (location, speed, acceleration). Driving cycles used for vehicle testing are also specified on a second-by-second basis (speed vs. time). In addition, there are other types of transportation models/data sets that aggregate with respect to time, producing traffic statistics such as average speed on a roadway facility type basis. Similar acceleration statistics may also be produced by these models. At the highest level, total vehicle volume and average speed over an entire regional network may be all that is provided.

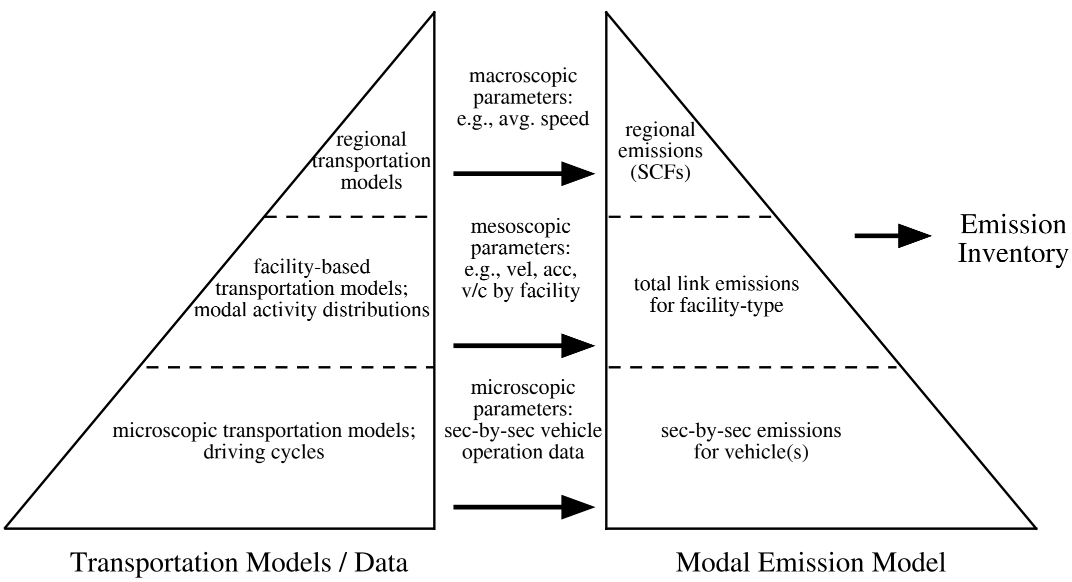

Figure 6.1. Transportation/Emission Model Interface

In order for the modal emission model to be closely integrated with these different types of transportation models (with varying levels of temporal and vehicle resolution), it must be able to operate at various temporal resolutions. The model has been developed in a bottom-up fashion, concentrating first at a high temporal resolution (i.e., on the order of a few seconds) and then aggregating upwards. As illustrated in

Table 6.1, emissions can be predicted second-by-second, by vehicle operating mode, or aggregate emissions can be given for a specific driving cycle (i.e., velocity profile).

Temporal Aggregation:	*second-by-second → several seconds mode → driving cycle or scenario*
Vehicle Aggregation:	*specific vehicle → vehicle/technology category → general vehicle mix*

Table 6.1. Temporal and vehicle aggregation.

In addition to temporal aggregation, vehicle aggregation must also be considered. Given an appropriate parameter set, CMEM is capable of predicting emissions for individual vehicles. However, our ultimate goal is the prediction of detailed emissions for an average *composite* vehicle within each vehicle/technology category. This composite vehicle approach is somewhat different from the approach used by traditional emission factor models. At the highest level of vehicle aggregation, the model outputs from each vehicle/technology category (i.e., composite vehicle) can be combined appropriately to represent emissions from the general vehicle population.

When considering the interface between transportation and emission models, there are primarily two key components that must be considered: 1) the vehicle fleet distribution, and 2) the vehicle operation.

Vehicle Fleet Distribution

As previously discussed, a vehicle fleet may consist of just a single specific vehicle. More than likely, however, the vehicle fleet will consist of a mixture of different vehicles. Transportation models typically aggregate similar types of vehicles into groups, based on how they operate within a transportation or traffic simulation model. In addition to the obvious divisions of vehicle types (i.e., motorcycles, passenger cars, buses, heavy-duty trucks), categories are often made based on vehicle performance (e.g., high-performance cars, low-performance cars) that can be closely related to traffic simulation parameters. For heavy-duty trucks, transportation models/datasets typically categorize their vehicles based on their configuration and number of axles. In all cases, a straightforward approach to handling the transportation/emissions model interface is to create an appropriate *mapping* between the vehicle types defined in the transportation model, and the vehicle types defined in the emission model. This is usually represented as a matrix which specifies the different categories and the percentage of each vehicle class.

Vehicle Operation

The parameters that define how vehicles operate in a transportation modeling framework are highly dependent on the fidelity level of the model. For microscopic transportation simulation models, typical vehicle operating parameters include second-by-second velocity, acceleration (which can be differentiated from velocity), and position (from which road grade can be deduced) for each individual vehicle. Other secondary variables that may be given at this fine level of resolution include load-producing accessory use (e.g., air conditioning) and front and rear vehicle spacing (which may play a role with aerodynamic drag reduction if sufficiently small).

For mesoscopic transportation models (e.g., models that still consider individual vehicles but not their dynamic operation), the vehicle/traffic operating parameters may include average velocity by roadway facility type, volume/capacity by roadway facility type, and average energy or work parameters such as Positive Kinetic Energy (PKE), or Total Absolute Acceleration Differences (TAD). For macroscopic models, the parameters average speed and VMT are typically provided.

This chapter discusses these transportation/emission modeling issues. In the first section, a short description is given on the user interface of the core, second-by-second modal emission model. A more detailed description of how to use the model is provided in the "CMEM User Guide", a companion document to this report. The next section describes another form of the model, also occurring at the microscopic level. In this form, the model is represented as velocity/acceleration-indexed emissions/fuel lookup tables. In the third section of this chapter, mesoscale-level emission factors are given based on predetermined roadway facility/congestion-based driving cycles. The fourth section of this chapter discusses a detailed methodology on how to generate the appropriate weights for the CMEM categories given a vehicle registration database. The final section describes vehicle category mappings that have been made between the conventional EMFAC/MOBILE models and CMEM's vehicle/technology categories.

6.1 USER INTERFACE FOR CORE MODAL EMISSIONS MODEL

During development, the comprehensive modal emissions model was carried out in a research environment, using MATLAB modeling/analysis tools [Mathworks, 1998]. In order to use the model outside the development environment, executable code was created from the finalized source code. For this executable code a command line user interface was developed. The command-line code has been developed for both the PC environment (running from a DOS command line) and the UNIX environment (compiled for both SUN and SGI workstations). Running from the command line, the executable code reads in specific input files and produces specific output files, as described below.

The CMEM executable code takes on two forms:

Core Model—the core executable code allows the user to obtain emission data for a single specified vehicle category and a given vehicle activity file. As illustrated in Figure 6.2, the core model uses two input files and outputs two emission files. One input file is used to control the parameters of the model, the other input is a second-by-second vehicle activity file. One resulting output file provides tailpipe emissions and fuel consumption on a second-by-second basis. The other output file is a vehicle summary file. The control input file specifies the vehicle category to be modeled and the soak time prior to the model run. Default parameters to the model can be overridden with specific entries in the control input file. The vehicle activity file consists of column-oriented data vectors. The minimum vectors that are required are time (in seconds) and vehicle velocity (in MPH or KPH depending on control file). Optional data vectors in the vehicle activity input file include acceleration (if directly measured and not derived from velocity differentiation), grade, and secondary load activity (such as AC use). The emissions output file also consists of column-oriented data vectors, including time, velocity, HC, CO, NOx, and fuel use.

Other second-by-second parameters (e.g., CO_2, fuel/air ratio, etc.) can also be selected for output via the control file.

Batch Model—the batch executable code allows the user to obtain emission data for multiple vehicles (from a variety of categories) with different trajectories specified in the vehicle activity file. As illustrated in Figure 6.3, the batch model requires three input files: a parameter control file, a soak-time file, and a time-ordered vehicle activity file. Two output files are available: a second-by-second, time-ordered vehicle emissions file, and a vehicle integrated emissions file. The control file is similar to that described above, however it also includes a matrix correlating vehicle ID (*vehid* of the activity file) and the vehicle type (*vehtyp*). The control file also specifies whether a soak time file exists. An optional soak time file specifies how long each vehicle has been stopped prior to the model application. The vehicle activity file is similar to that described above, except it has an additional column vector specifying particular vehicles (*vehid*). Several transportation models output vehicle trajectories in this format. The second-by-second time-ordered vehicle emissions file is similar to that used in the core model, except again it has an added column specifying vehicle ID. The vehicle integrated emissions file provides the integrated emission results of the velocity patterns for each vehicle.

In addition to the command line version of the code, a more friendly graphical user interface for CMEM has been implemented in Microsoft ACCESS. ACCESS is a separate database management program sold by Microsoft, and is often bundled with Microsoft Office software. ACCESS runs on Windows 95, 98, and NT platforms. It is possible to cut, copy, and paste data from any Windows application to and from ACCESS. Because ACCESS is part of the Microsoft Office software, it is also possible to link and embed various software objects between the Office suite of software.

ACCESS is a database management system that stores and retrieves data, presents information, and automates repetitive tasks. The user can also create various input forms and create reports. It is also possible to develop code in Visual Basic and embed the code within individual ACCESS databases. That is how CMEM is implemented.

For more details on how to run CMEM either through the command line interface or through the ACCESS graphical user interface, please refer to the companion document, "CMEM Users Guide".

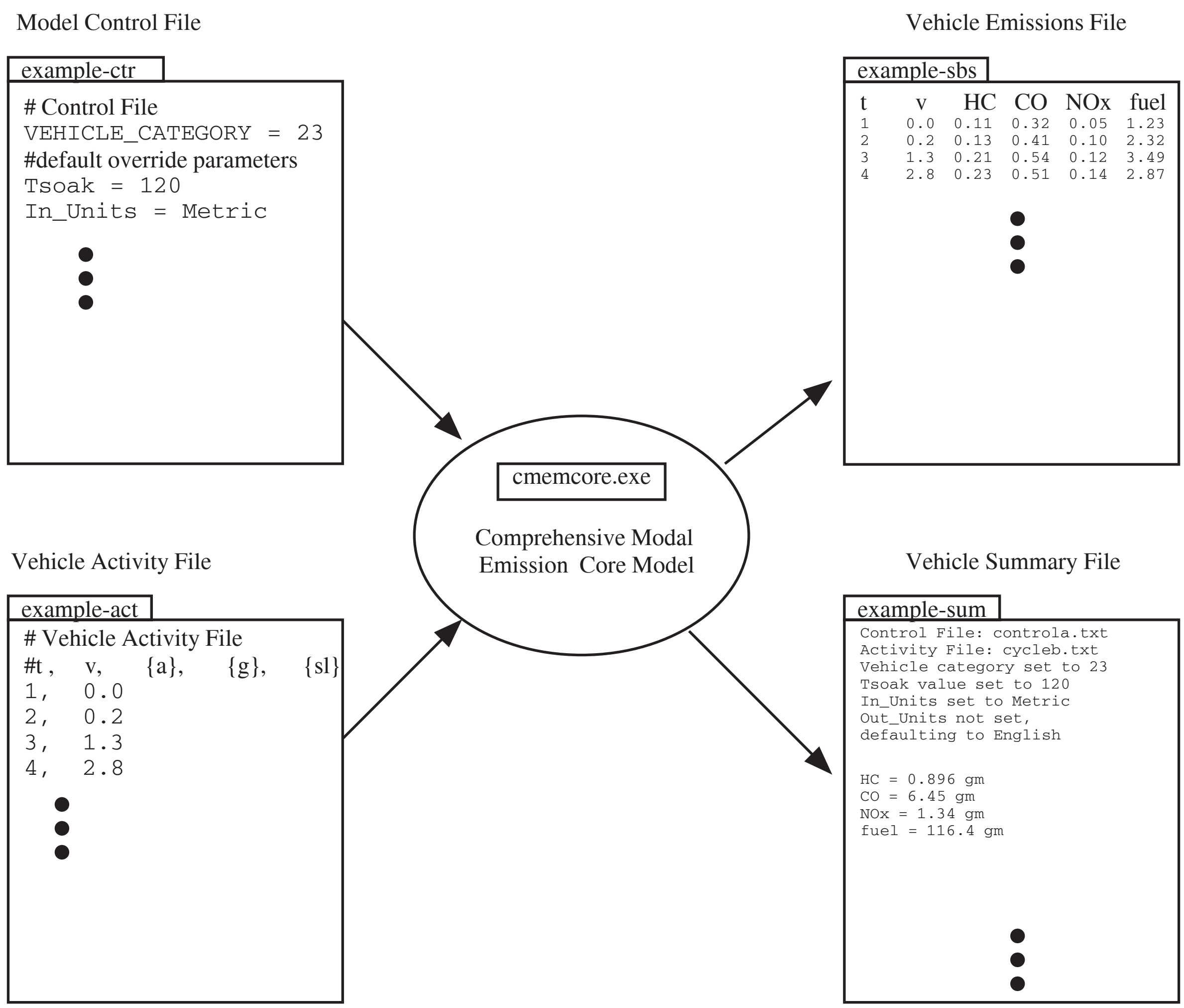

Figure 6.2. Core form of the modal emission model executable.

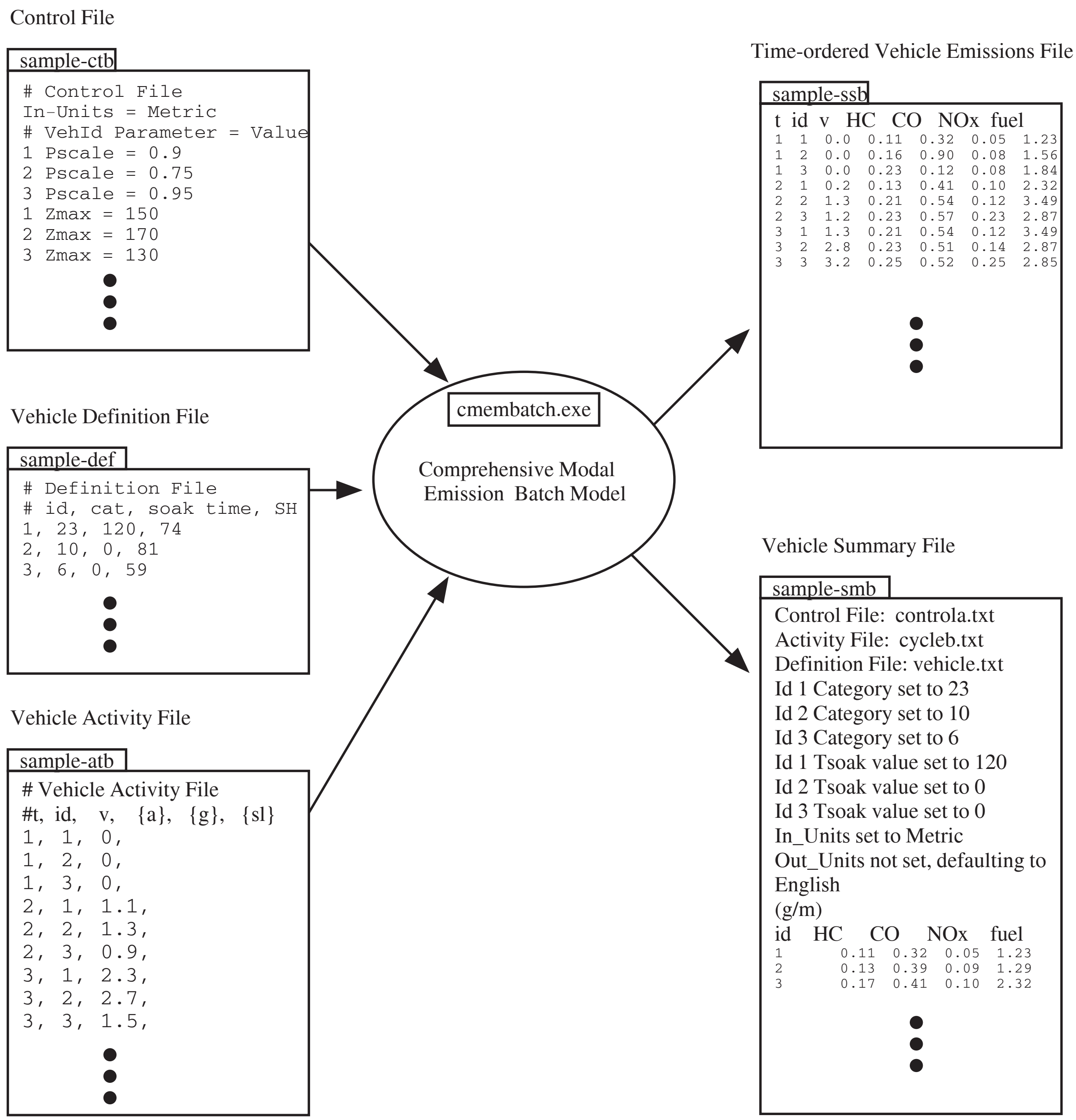

Figure 6.3. Batch form of the modal emission model executable.

6.2 VELOCITY/ACCELERATION-INDEXED EMISSION/FUEL LOOKUP TABLES

Interfacing transportation and emission models at the microscopic level is straightforward, as shown in Figure 6.4. Second-by-second vehicle operation data is generated on the transportation/data side and transferred straight across to the modal emissions model. The emissions data can then be integrated to provide an emissions inventory. Another technique that can be used is to generate velocity/acceleration-indexed lookup tables of emission values and directly integrate those with the microscopic traffic simulation model. FHWA's suite of microscopic models (i.e., FRESIM, NETSIM, CORSIM) are capable of estimating emissions using this technique.

It is straightforward to generate these lookup tables from our basic core modal emissions model. All the different combinations of velocity and acceleration are input into the model and an emissions "mesh" is created as output. When inputting different sets of velocity and acceleration, the core modal emissions model also evaluates whether the input is outside the performance envelope of the vehicle. For example, if you ask a low-powered vehicle to undertake a hard acceleration at high speed, the vehicle will not be able to meet this performance demand. When vehicle operation inputs are beyond the performance envelope, emissions and fuel consumption are predicted for the maximum performance at the given speed.

The velocity/acceleration-indexed lookup tables have been generated for the 26 different composite vehicles representing the 26 modeled vehicle/technology categories. These lookup tables are illustrated in Appendix D, where fuel, CO, HC, and NOx are shown for each composite vehicle. For the majority of these vehicles, it is readily apparent that the emissions and fuel consumption are fairly low at low power; emissions then increase tremendously in a "cliff"-like fashion when the enrichment threshold is exceeded. The emissions levels in the enrichment region can be several orders of magnitude greater than those in the low-powered stoichiometric region. Because of this, little detail is seen at the lower emission levels. In order to see these lower emission details, it is possible to plot these velocity/acceleration-indexed graphs on a semi-log basis.

The lookup table-based emission model form is straightforward to implement, and the computational costs are very low. However there is a serious potential problem with this form of model. Using instantaneous lookup tables assumes that there is no time dependence in the emissions response to the vehicle operation. This assumption is not true for many vehicle types where vehicle operating history (i.e., the last several seconds of vehicle operation) can play a significant role in an instantaneous emissions value (e.g., the use of a timer to delay command enrichment, and oxygen storage in the catalytic converter). Further, there is no convenient way to introduce other load-producing effects on emissions such as road grade, or accessory use (e.g., air conditioning), other than introducing numerous other lookup tables, or perhaps a applying a set of corrections.

6.3 ROADWAY FACILITY/CONGESTION-BASED EMISSION FACTORS

Interfacing transportation and emissions models at the mesoscopic level is somewhat more complicated than at the microscopic level. However, one of the key advantages of the microscopic modal emissions model is that one can estimate emissions (and fuel consumption) for any given driving cycle, without the trouble of performing expensive dynamometer testing. Therefore, it is possible to create mesoscopic emission factors as illustrated in Figure 6.5. Driving cycles can be generated for different roadway facility types and different congestion levels (step 1 in Figure 6.5). These driving cycles can then be applied to the modal emissions model (step 2) and the resulting emissions output can be integrated to provide facility-based emission factors (step 3).

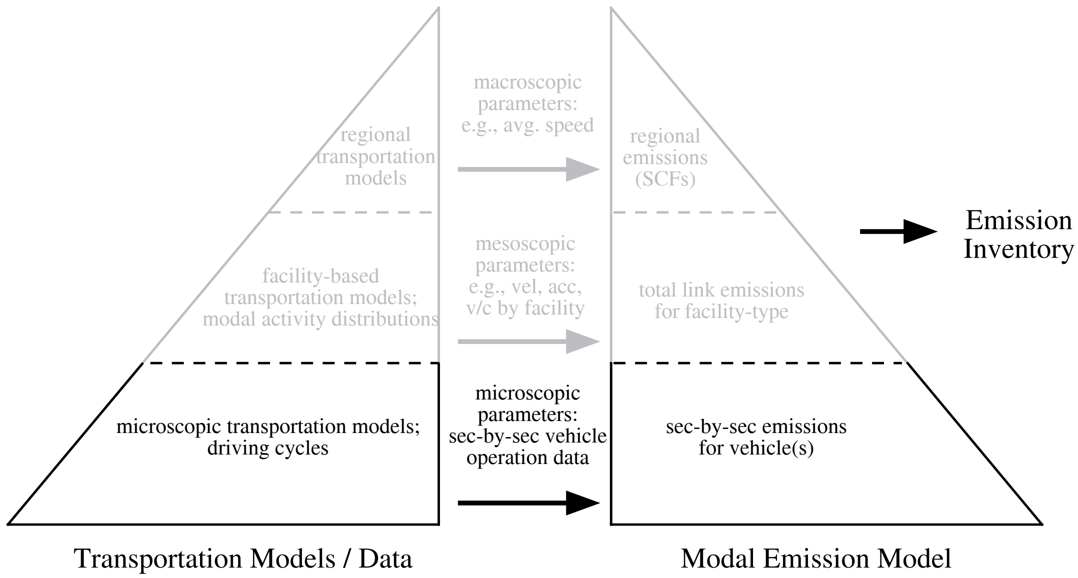

Figure 6.4. Interfacing transportation and emission models at the microscopic level-of-detail.

Current conventional emission models have no mechanism to produce facility-specific emissions inventories, i.e., emissions for specific roadway facilities such as highways, highway ramps, main arterials, residential roads, etc. This is a critical issue, since driving patterns vary greatly depending on road type. Two "trips" that have the same average speed can have drastically different emission results depending on whether the trip was made on free-flowing arterials or on a congested freeway.

To address these problems, the U.S. EPA is introducing into its latest version of MOBILE (MOBILE6, to be released at the end of 2000) a new modeling methodology that uses facility-specific driving cycles for inventory development. Under contract to the EPA, Sierra Research [Sierra-Research, 1997] has created several facility-specific driving cycles based on matching speed-acceleration frequency distributions for a wide range of roadway types and congestion levels. These cycles have been developed based on a large amount of "chase car" and instrumented vehicle data collected in the cities of Spokane, Baltimore, Atlanta, and Los Angeles. The congestion level was recorded as different "Levels-Of-Service" (LOS) values based on the LOS measures developed by the Transportation Research Board (TRB, see [TRB, 1994]). FHWA currently employs these LOS measures for congestion. For freeways (i.e., non-interrupted flow), LOS is a function of both average vehicle speed and traffic flow rate. Primarily due to inter-vehicle interaction at higher levels of congestion (corresponding to LOS values of B, C, D, E, and F), vehicles will have substantially different velocity profiles under different LOS conditions. Under LOS A, vehicles will typically travel near the highway's free flow speed, with little acceleration/deceleration perturbations. As LOS conditions get progressively worse (i.e., LOS B, C, D, E, and F), vehicles will encounter lower average speeds with a greater number of acceleration/deceleration events.

Six driving cycles have been developed for freeway driving. These cycles range from high-speed driving (LOS A+, where vehicles have little or no interaction with other vehicles) to driving in near gridlock conditions (LOS F-). Cycle length ranges from 4 to 12 minutes and the cycles were constructed to optimally match the observed speed-acceleration and specific power frequency distributions of the on-road vehicle data [Sierra-Research, 1997]. These cycles are shown in Figure 6.6. General characteristics of these cycles are given in Table 6.2. The cycle characteristics include average speed (mph), maximum speed (mph), maximum acceleration rate (mph/second), cycle length in terms of time (seconds) and distance (miles), and *Kmax*, the maximum specific energy (defined as 2 * velocity * acceleration, in units of mph^2/second).

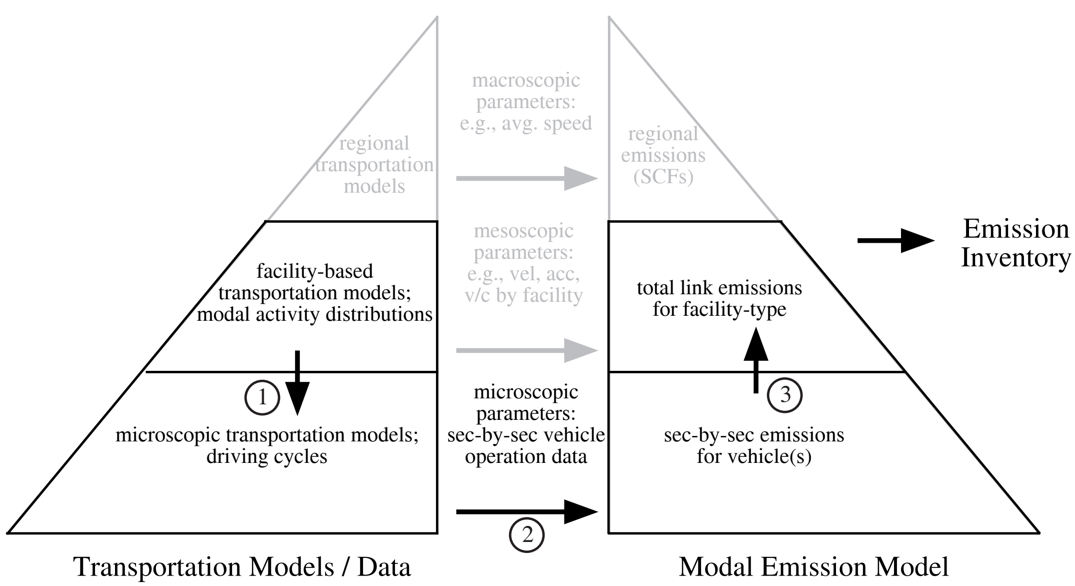

Figure 6.5. Interfacing transportation and emission models at the mesoscale level-of-detail.

Other driving cycles have been developed for arterial driving patterns, shown in Figure 6.7. The general characteristics of these cycles are given in Table 6.3. Similar to the developed freeway cycles, arterial driving is characterized for different LOS conditions. ART-AB is arterial driving under LOS A-B, ART-CD is arterial driving under LOS C-D, and ART-EF is arterial driving under LOS E-F. In addition to these arterial cycles, a cycle was created for freeway ramps. Also, a cycle was created representing local roadways (LOCAL). Lastly, a general non-freeway cycle (NON-FR) was created representing vehicle operation on arterials, collectors, and local roadways.

Cycle	Avg Speed (mph)	Max Speed (mph)	Max Accel (mph/s)	Length (seconds)	Length (miles)	Kmax (mph^2/s)
LOS A+	63.2	74.7	2.7	610	10.72	357
LOS A-C	59.7	73.1	3.4	516	8.55	307
LOS D	52.9	70.6	2.3	406	5.96	233
LOS E	30.5	63.0	5.3	456	3.86	227
LOS F	18.6	49.9	6.9	442	2.29	215
LOS F-	13.1	35.7	3.8	390	1.42	99

Table 6.2. Freeway congestion cycle characteristics (Kmax is the maximum specific energy, defined as 2 * velocity * acceleration).

In order to create facility/congestion-based emission factors, these driving cycles were applied to each modal emission composite vehicle. The resulting emission and fuel factors are given in Appendix E. An example of these emission/fuel factors for Freeway LOS A-C conditions are given in Table 6.4.

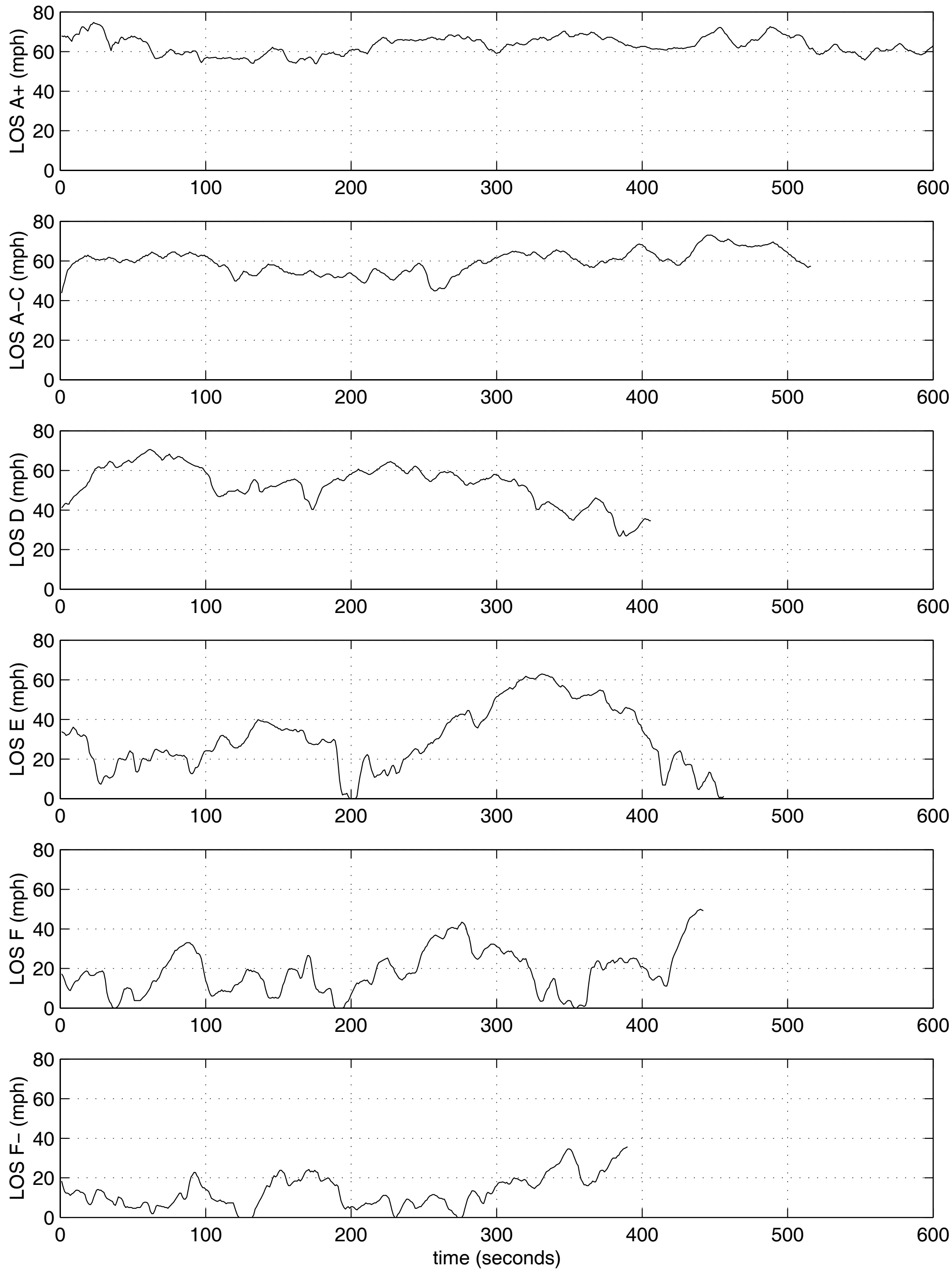

Figure 6.6. Freeway congestion cycles.

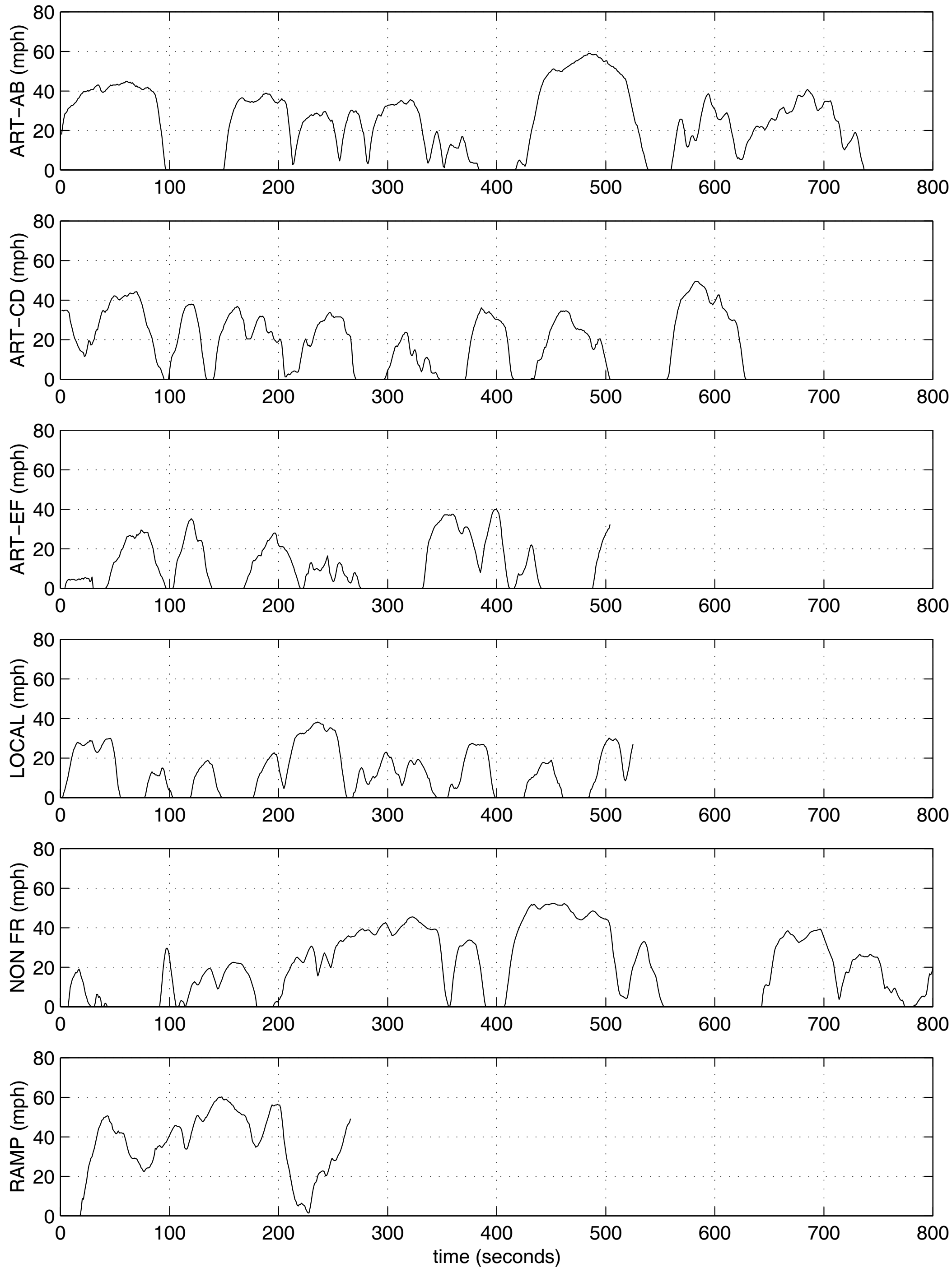

Figure 6.7. Arterial cycles.

Cycle	Avg Speed (mph)	Max Speed (mph)	Max Accel (mph/s)	Length (seconds)	Length (miles)	Kmax (mph^2/s)
ART AB	24.7	58.9	5.0	737	5.07	193
ART CD	19.2	49.5	5.7	629	3.36	195
ART EF	11.5	39.9	5.8	504	1.62	180
LOCAL	12.8	38.3	3.7	525	1.87	132
NON FR	19.3	52.3	6.4	1348	7.25	206
RAMP	34.6	60.2	5.7	266	2.55	222

Table 6.3. Arterial cycle characteristics (Kmax is the maximum specific energy, defined as 2 * v * a).

#	Freeway, LOS A-C cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	137.2	54.87	7.35	1.60
2	2-way Catalyst	108.9	11.37	0.70	1.87
3	3-way Catalyst, Carbureted	82.0	10.13	0.34	1.12
4	3-way Catalyst, FI, >50K miles, low power/weight	84.7	6.92	0.23	0.57
5	3-way Catalyst, FI, >50K miles, high power/weight	91.0	7.74	0.24	0.39
6	3-way Catalyst, FI, <50K miles, low power/weight	85.3	6.38	0.13	0.55
7	3-way Catalyst, FI, <50K miles, high power/weight	82.2	3.77	0.13	0.57
8	Tier 1, >50K miles, low power/weight	81.9	4.58	0.07	0.10
9	Tier 1, >50K miles, high power/weight	77.4	2.94	0.05	0.27
10	Tier 1, <50K miles, low power/weight	80.5	3.93	0.06	0.19
11	Tier 1, <50K miles, high power/weight	89.5	3.83	0.04	0.14
24	Tier 1, >100K miles	93.1	6.40	0.18	0.19
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	184.6	50.33	3.29	3.45
13	1979 to 1983 (<=8500 GVW)	147.1	25.49	1.39	2.64
14	1984 to 1987 (<=8500 GVW)	109.1	11.12	0.45	1.22
15	1988 to 1993, <=3750 LVW	107.3	10.43	0.47	0.65
16	1988 to 1993, >3750 LVW	137.6	9.06	0.40	0.90
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	119.2	5.83	0.11	0.30
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	146.9	6.18	0.13	0.40
25	Gasoline-powered, LDT (> 8500 GVW)	181.4	4.30	0.14	2.23
40	Diesel-powered, LDT (> 8500 GVW)	112.0	0.95	0.42	3.72
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	108.3	9.41	0.60	2.32
20	Runs rich	93.7	20.67	1.69	1.33
21	Misfire	102.1	23.61	2.31	0.56
22	Bad catalyst	112.9	18.70	3.13	2.41
23	Runs very rich	119.6	101.1	3.34	0.51

Table 6.4. Facility/congestion-based emissions/fuel factors for the different vehicle/technology categories (Freeway LOS A-C cycle).

Again, these factors can be applied at the mesoscale level of transportation/emissions modeling. If a transportation model predicts the amount of traffic flow and congestion conditions for the different roadway segments (freeway, arterial, collector, ramp), then these factors can be appropriately applied and summed together to create an emissions inventory.

6.4 CATEGORIZATION FROM A VEHICLE REGISTRATION DATABASE

In order to use the modal emissions model for estimating an inventory for a vehicle fleet, it is necessary to take a given vehicle database and determine the appropriate CMEM category for each vehicle. A common vehicle database will typically come from a state's department of motor vehicles (DMV) or a national database such as that assembled by the R.L. Polk & Company. A DMV vehicle registration database contains information about each registered vehicle, and with that information, each vehicle can be categorized into the appropriate CMEM vehicle/technology group. A state's entire vehicle registration database can be used, but more commonly, *regional subsets* of the database are applied. These regional subsets could be at the county level, city level, or even at the zip-code level.

A subset of a vehicle registration database can also be determined using license plate monitoring. If a set of license plate numbers are observed and recorded, the license plate numbers can be used as a filter set applied to the vehicle registration database. This is similar to creating a regional subset (by county, city, zip-code, etc.), however the license plate number is used as the filter field. Many states now use remote sensing equipment for monitoring instantaneous emissions of vehicles as they pass a particular spot on the road. With these emission measurements, the license plate is typically imaged with a video camera and registered with the measurement database.

As an example of a methodology for going from a vehicle registration database to the CMEM vehicle/technology categories, we have developed a *categorization program*, described below. This categorization program uses certain fields from a vehicle registration database and classifies each individual vehicle. Please note that this categorization program serves as an example for the local

Riverside California area only and should not be applied elsewhere without changing some of its assumptions.

The categorization process is illustrated in Figure 6.8. Several fields are extracted from the database, and a *decision tree* is used when categorizing each vehicle. In addition to the information provided from the vehicle registration database, additional information is necessary. For example, in order to classify a vehicle as either a high- or normal-emitter, high emitter probability distributions are necessary.

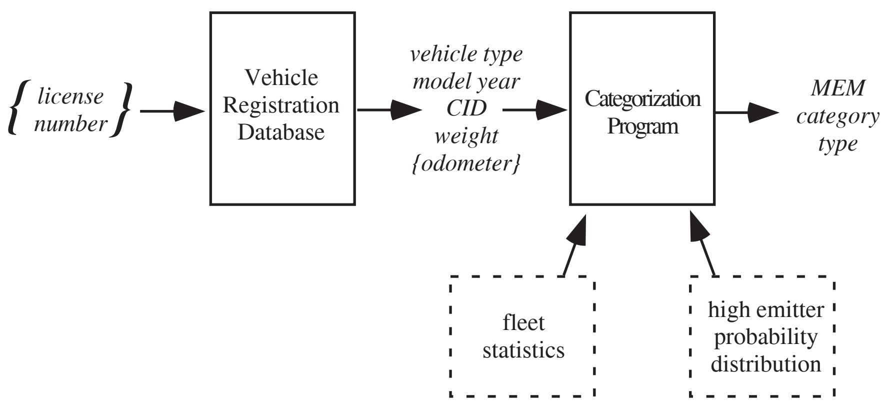

Figure 6.8. Registration Database to CMEM category type.

6.4.1 Vehicle Registration Database Fields

There are many fields in a typical vehicle registration database for each vehicle, several of which are used by the categorization program. Fields of a typical vehicle registration database are described below:

Owner Information

The owner's name, address, and zip-code are almost always included in a vehicle registration database. The address and zip-code information can be used to filter larger databases into smaller areas of interest.

Vehicle Type

A parameter is often given specifying what the type of vehicle. Common parameters include symbols for motorcycles, passenger vehicles, trucks, and miscellaneous.

Registration Information

Information of registration is typically included in the form of registration status, expiration date, year-first-sold, and purchase price. The *year-first-sold* data field is typically the same as the *model year* field, which is a critical piece of information when categorizing vehicles.

Vehicle Make, Model

The vehicle make and model information is included, along with information on body style.

Fuel Type

Another important field for categorization is the type of fuel a vehicle uses. Common parameters include symbols for gas, flex fuel, electric, natural gas, diesel, and propane.

Vehicle Identification Number (VIN)

A vehicle registration database almost always contains the Vehicle Identification Number (VIN) for each vehicle. This VIN is a unique alphanumeric character set for each vehicle. Encoded in the VIN is a wealth of information such as make, model, vehicle creation date, manufacturing plant, engine and emission control equipment specifications, etc. It is a difficult task to decode VINs, since vehicle manufacturers use different formats. Commercial VIN decoders exist, however they are often incomplete and expensive. If it were possible to decode each vehicle's VIN, then the categorization process could be done nearly deterministically (rather than stochastically, as described below). Due to its complexity, we did not attempt to perform VIN decoding in our categorization program.

Cubic Inch Displacement (CID)

The vehicle's engine size is given as CID, and this is usually included in the VIN information. In California's vehicle registration database, CID is given as a separate field in the registration data.

Vehicle Weight

Similar to CID, the vehicle weight is another key field in the database. Weight is particularly important in the truck classifications. Also, both CID (which can be related to horsepower) and weight are used to calculate the power-to-weight ratio of each vehicle. This is important in the CMEM automobile classification system.

Odometer

In most vehicle registration databases, there is a field for the odometer. The odometer information of most vehicle databases is only updated when a vehicle is sold or transferred. Recently, there have been efforts made to update the odometer information on a yearly basis using updated registration documents or by cross referencing to yearly smog check data or mileage surveys. However, the odometer data in California's current database is highly suspect and unreliable. For this reason, we use estimated mileage accrual rates (indexed by year) to determine the average mileage of a vehicle. In the categorization program, we assume a normal distribution around this average mileage, and use a stochastic random variable to estimate each vehicle's mileage.

6.4.2 Categorization Program

The categorization program is essentially a decision tree, illustrated in Figure 6.9a and 6.9b. The fields of the vehicle registration database that are used include vehicle type (car or truck), fuel type, model year, vehicle weight, and vehicle CID. The fuel type field is used to differentiate between gasoline and diesel powered vehicles. The first decision point in the program is determining whether the vehicle is a car or a truck. The car decision tree flow diagram is shown in Figure 6.9a, the truck decision tree flow diagram is shown in Figure 6.9b.

Car Categorization

As discussed in previous chapters, there are a total of twelve separate car categories, and five shared high-emitter categories. Model-year information is used throughout the decision tree as a proxy for vehicle technology (e.g., emission certification standard, emission control system, fuel system, etc.). If the year is 1974 or older, then these vehicles are classified into CMEM category 1 (non-catalyst cars). If the model-year is in the range of 1975-1980, then the vehicle is classified into CMEM category 2 (2-way catalyst cars).

After 1980, the vehicles can potentially fall into a high emitter category*. As specified in Chapter 4, an approximate high-emitter distribution was developed based on the Arizona I/M program dataset. This distribution will likely be different for different parts of the country. This example distribution is shown in Table 6.5.

MY Group	Normal Emitter	HE Type 1: runs lean (19)	HE Type 2 or 5: runs rich (20,23)	HE Type 3: misfire (21)	HE Type 4: bad catalyst (22)
MY 81-86	33%	10.5%	7.6%	28.4%	20.4%
MY 87-90	65%	6.8%	6.2%	13.1%	8.7%
MY 91-93	91%	2.1%	2.2%	2.7%	1.6%
MY 94-97**	98%	0.6%	0.8%	0.5%	0.3%

Table 6.5. Estimated high emitter distribution in fleet.

* Please note that vehicles older than 1980 can be high emitters, however their emission characteristics do not differ substantially from a normal emitting 1980 and older vehicle and are therefore not distinguished.

** Our analysis of high emitters was limited to MY97 and older vehicles; further research is necessary to estimate the distribution of high emitters among newer vehicles in the fleet (although preliminary evidence has shown that MY97 and newer vehicles have a very small high emitter fraction).

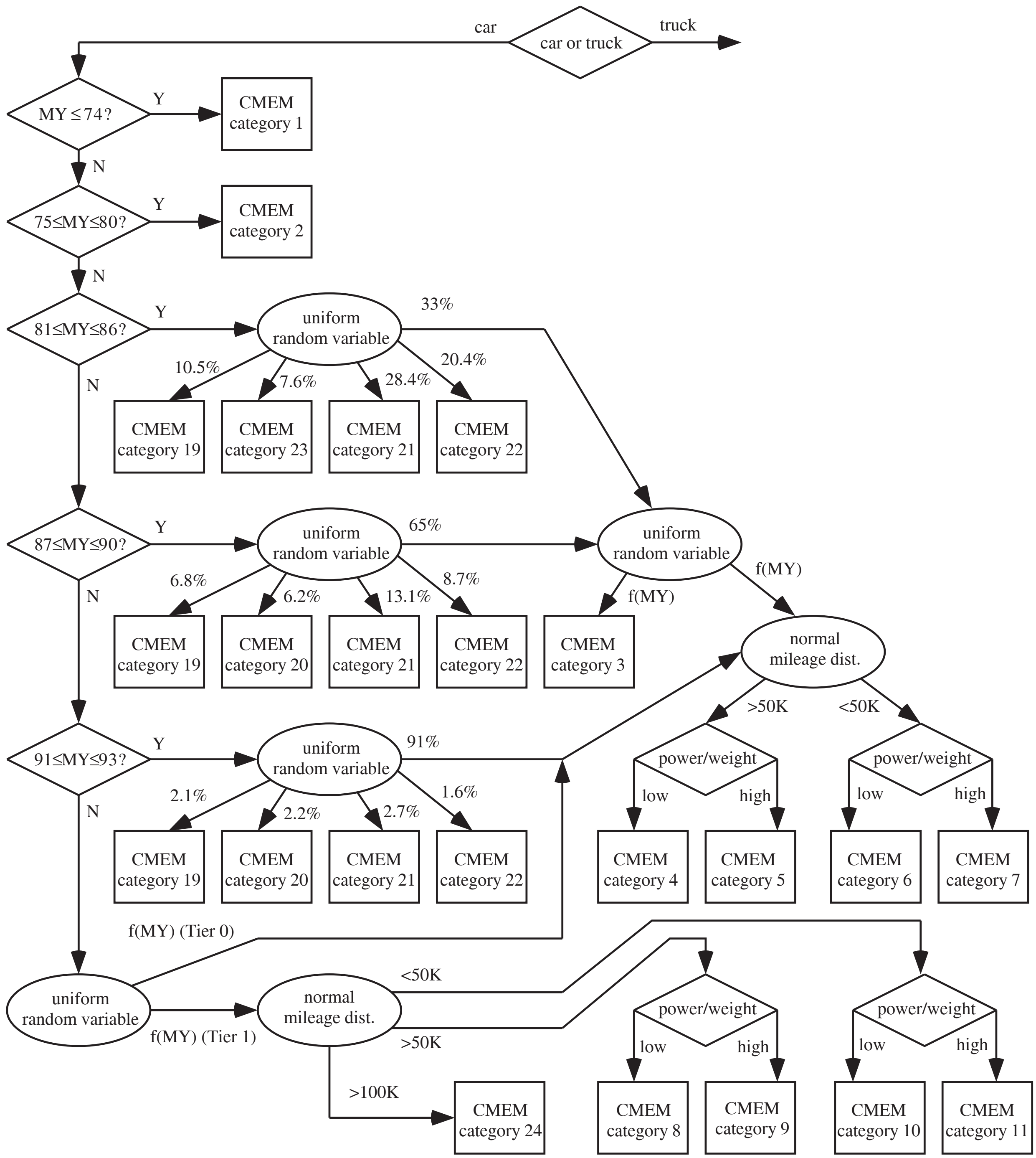

Figure 6.9a. Categorization decision tree for light duty automobiles.

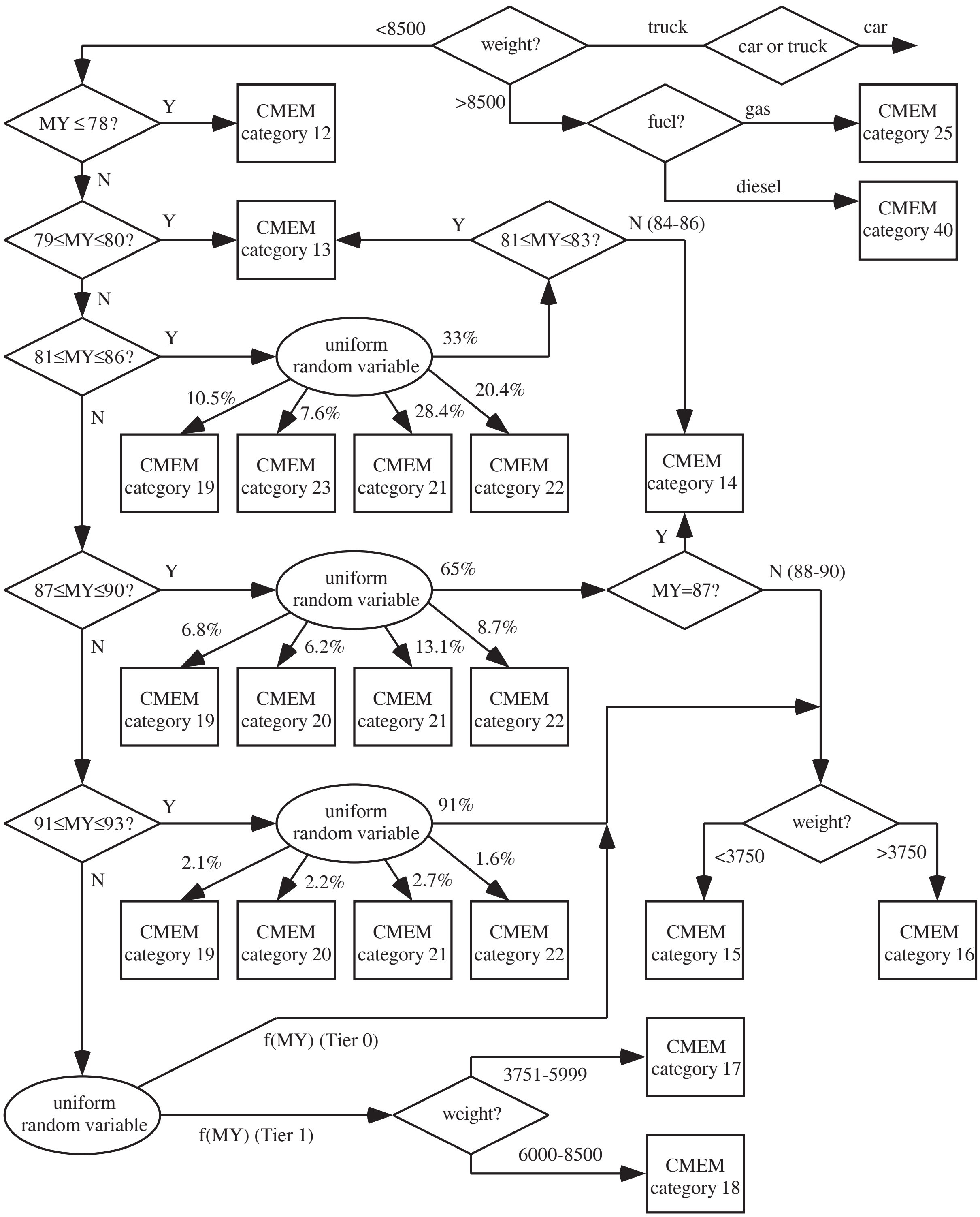

Figure 6.9b. Categorization decision tree for light duty trucks.

Since it is impossible to determine whether a vehicle is a high emitter (let alone what type of high emitter) directly from the vehicle database fields, the categorization is handled stochastically. A uniform random variable is generated, and the category decision is based on the high emitter distributions. If the vehicle is categorized to be a normal emitter, further processing is done on the vehicle information. Note that the percentages in Table 6.5 is only a "snapshot" in time, based on 1998 data.

Beginning in 1981, fuel-injection technology started penetrating the vehicle fleet. In the CMEM categorization, a distinction is made between carbureted vehicles versus fuel injected vehicles. From 1981 (all vehicles have 3-way catalytic converters) the percent of the fleet with carburetors slowly decreases over the years. The approximate 3-way catalyst, carbureted vehicle distribution is shown in Table 6.6.

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
% carbureted veh.	91%	83%	73%	61%	49%	32%	26%	10%	13%	2%	0%

Table 6.6. Distribution of carbureted vehicles by model year.

Given this distribution of carbureted vehicles, again a uniform random variable is used to properly allocated vehicles to CMEM category 3. Vehicles that are not categorized as carbureted vehicles for model year time frame 1981-1986 go on for further processing into other CMEM categories.

Accumulated Mileage

The next decision for the vehicles is based on accumulated mileage. Remember that in some cases the CMEM categorization differentiates between whether a vehicle has fewer than or greater than 50,000 accumulated miles. As discussed above, odometer information that may appear as a variable field in a vehicle registration database is often unreliable. The odometer information in these databases is not updated frequently enough, and also suffers from mis-readings of odometers that have rolled over. For these reasons, we determine accumulated mileage stochastically. Mileage accumulation rates by year have been compiled by both CARB and the US EPA based on various sources (e.g., odometer surveys, R.L.

Polk & Company, etc. [US EPA, 1998]). For our Riverside California example case, we used the same mileage accumulation rates that CARB's MVEI modeling suite uses [CARB, 1996].

By summing the mileage accumulation rate for each year, it is possible to determine the average mileage for each vehicle year. For example, to determine a 1981's average mileage, we simply sum the mileage accumulation rates for 1997, 1996, 1995, …, and 1981. The average mileage for each vehicle year (determined for the base year 1998) is given in Table 6.7.

Year			**1997**	**1996**	**1995**	**1994**	**1993**	**1992**	**1991**	**1990**
Average mileage			14169	27732	40688	53037	64779	75914	86442	96363
Year	**1989**	**1988**	**1987**	**1986**	**1985**	**1984**	**1983**	**1982**	**1981**	**1980**
Average mileage	105677	114384	122485	130082	137246	144034	150491	156705	162776	168716
Year	**1979**	**1978**	**1977**	**1976**	**1975**	**1974**	**1973**	**1972**		
Average mileage	174535	180242	185845	191350	196764	202092	207339	212509		

Table 6.7. Average accumulated mileage by model year (relative to base year 1998).

We make an important assumption in mileage accumulation, i.e., that the mileage for a given model year is normally distributed around the average accumulated mileage. This says that given all the vehicles for a specific model year, the average accumulated mileage will be the center of the normal distribution, which tails off symmetrically in both directions (i.e., some vehicles will have higher mileage, others will have lower mileage). Further, we assume that the standard deviation of this normal distribution is approximately one third of the average accumulated mileage (if it is found that these assumptions are not true, substitute distributions can be used). The categorization program then uses a cumulative density function that predicts the probability a vehicle will have mileage greater than or less than the specified 50,000 mile cut point.

This is demonstrated in Figure 6.10, which shows the normal distributions for a 1981 vehicle (solid line) and a 1991 vehicle (dashed line). The probability that these vehicles have less than 50,000 miles is given based on the area under the curves up to the cut point with respect to the total area. For the 1981 vehicle, only a small portion of the distribution curve falls below the 50,000 mile cut point (approximately 1.7%). This says that approximately 1.7% of 1981 vehicles have less than 50,000 miles. Similarly, for the 1991 vehicles, roughly 10% of them have accumulated less than 50,000 miles. The cumulative density functions have been calculated for each model year, giving the above 50K/below 50K probabilities as illustrated in Table 6.8.

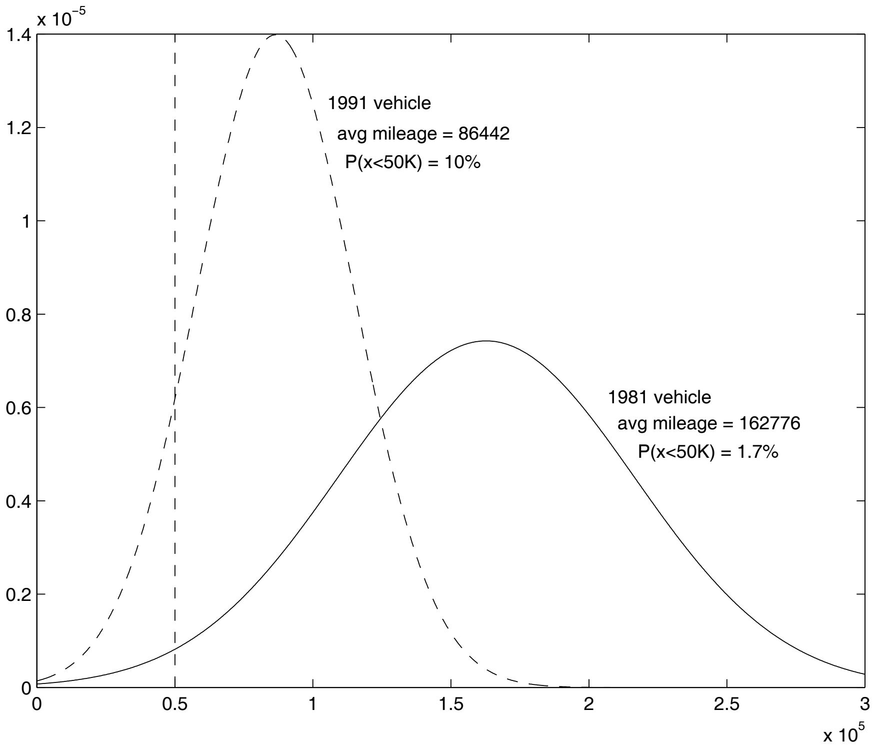

Figure 6.10. Example of normal cumulative density functions for 1981 and 1991 vehicles.

Year			**1997**	**1996**	**1995**	**1994**	**1993**	**1992**	**1991**	**1990**
prob(x<50K)			100%	99.25%	75.60%	43.11%	24.47%	15.05%	10.07%	7.24%
Year	**1989**	**1988**	**1987**	**1986**	**1985**	**1984**	**1983**	**1982**	**1981**	**1980**
prob(x<50K)	5.52%	4.40%	3.65%	3.11%	2.70%	2.39%	2.15%	1.95%	1.79%	1.65%
Year	**1979**	**1978**	**1977**	**1976**	**1975**	**1974**	**1973**	**1972**		
prob(x<50K)	1.53%	1.43%	1.34%	1.26%	1.19%	1.13%	1.07%	1.02%		

Table 6.8. Probability of mileage less than 50,000 miles by model year (relative to base year 1998).

In the categorization program, the normal distributions are set up for each vehicle year, and a random sample is taken from the distribution. The random sample value is then used to calculate the mileage which is then simply compared to the 50,000 mile cut point to determine which branch of the decision tree it falls in.

Power/Weight Ratio

After the mileage determination in the decision tree, the power/weight ratio is used next as a decision split. In the categorization program, the power/weight ratio can usually be calculated deterministically. The fields *CID* and *weight* are both used from the vehicle registration database. In order to calculate approximate horsepower of the engine, we rely on an empirical relationship between CID (cubic inch displacement) and horsepower, indexed by model year. Based on [Murrell, 1993], this approximate linear relationship is given as:

$$HP \approx (0.02 * year - 1) * CID, \text{ for years ranging from '74 to '93}$$

It is important to note that this relationship is approximately correct for the model year range of 1974 – 1993. Thus given CID from the database, HP can be calculated. Power to weight ratio is then simply calculated as HP/weight, where weight is determined directly from the vehicle registration database.

Once power/weight is calculated, it is compared to the cutpoints determined previously (see Chapter 3). For Tier 0 vehicles, the cut point is approximately 0.039. For Tier 1 vehicles, the cut point is approximately 0.415 (the average power/weight of new vehicles has gradually increased over the years). Once the power/weight decision is made, the vehicles fall into their final categorization, as seen in Figure 6.9a.

Further down in the decision tree, different high emitter distributions are used depending on the model year grouping. At the bottom of the tree, the remaining vehicles are Tier 1 vehicles, which are then divided into their appropriate categories depending again on mileage and power/weight. For the Tier 1 vehicles, a uniform random variable is used to approximate the penetration by model year. For 1994 vehicles, 40% of the cars are Tier 1 certified. For 1995, approximately 80% are Tier 1 certified. For 1996 and beyond, all cars are Tier 1 certified.

Truck Categorization

The categorization for trucks is similar to that of cars, although somewhat less complicated. Referring to Figure 6.9b, the first decision is whether the truck is greater than 8500 GVW. If it is, then another decision is made based on its fuel type. If it is gasoline, then it is category 25. If it is diesel fueled, then it is category 40. If the truck is less than 8500 GVW, then the model year of the vehicle is used to determine the path in the decision tree. If the model year is less than or equal to 1978, the truck is classified as CMEM category 12. If the truck model year ranges from 1979 to 1980, the truck is classified as CMEM category 13. From 1981 on, high-emitter probability distributions again come into play. Similar to the car decision tree, a uniform random variable is used to predict whether a truck is normal emitting, or a specific type of high emitter. If it is normal emitting and is in the model year range 1981-1983, then it is classified as CMEM category 13. If it is in the model year range 1984-1986, then it is classified as CMEM category 14.

For the model year grouping 1987-1990, a different high emitter distribution is used. If the vehicle is predicted to be normal emitting and model year 1987, it is classified as CMEM category 14. The remaining model years (1988-1990) are further differentiated by vehicle weight. If the weight (given directly by the vehicle registration database weight field) is less than 3750 lbs, then it is classified as CMEM category 15. If it is greater than 3750 lbs, it is a CMEM category 16.

For the model year grouping 1991 – 1993, again a different high emitter distribution is used. As before, if the vehicle is determined to be normal emitting, then it is further differentiated by weight. Similar to the car decision tree, a uniform random variable is used to determine if a truck is a Tier 1 vehicle in the later model years. In 1994, 10% of the trucks are Tier 1 certified. In 1995, 21% are Tier 1 certified. In 1996, 45% are Tier 1 certified. In subsequent years, all trucks are Tier 1 certified. The Tier 1 trucks are then differentiated by weight in the CMEM categorization.

6.4.3 Program Application

As an example, the categorization program was applied to the Riverside, California area. California's Department of Motor Vehicle's 1996 vehicle registration database was first pre-filtered to all of the zip-codes within Riverside's city limits. This subset contained approximately 179,000 vehicles. A second area was also defined to contain the zip-codes within Riverside's city limits as well as other outlying areas. This particular subset contained approximately 301,000 vehicles. When these subset databases were created, a large number of the irrelevant fields were eliminated to reduce the size of the data files. An example of the database input is shown in Figure 6.11.

```
,VIN,,,MKNAME,,MY,,YFSA,,,MODEL,,,FUEL,,CID,CLASS,WEIGHT
,2G37T3Z110630,,,PONTIAC,,73,,CA,,,LEMANS,,,G,,400,0,3799
,WBABF4323REK13579,,,BMW,,94,,CA,,,325IS,,,G,,152,0,3164
,1G4NV5537RC255985,,,BUICK,,94,,CA,,,SKYLARK,,,G,,138,0,2791
,4S2CG58V6S4333292,,,ISUZU,,95,,CA,,,RODEO,,,G,,195,0,3755
,JN6FD06S0EW001142,,,NISSAN,,84,,OS,,,720,,,G,,120,1,2836
,1P4GH44R2PX756692,,,PLYMOUTH,,93,,CA,,,VOYAGER,,,G,,201,0,3476
,1G2NE12T8TM508920,,,PONTIAC,,96,,CA,,,GRAND AM,,,G,,146,0,2662
,JB7FP5475DY800133,,,DODGE,,83,,CA,,,D50,,,G,,155,1,2630
,3GCCW80HXHS914471,,,CHEVROLET,,87,,CA,,,ELCAMINO,,,G,,305,0,3106
,JT5RN75TXJ0021701,,,TOYOTA,,88,,CA,,,CAB/CHASSIS,,,G,,144,1,2796
,2GCEC19H9R1196498,,,CHEVROLET,,94,,CA,,,GMT-400,,,G,,305,2,4210
,1FTCR14X7LPA49501,,,FORD,,90,,CA,,,RANGER,,,G,,245,1,3085
,YV1AX8854J1786521,,,VOLVO,,88,,CA,,,245,,,G,,141,0,3034
,1GNGR26K9HF129704,,,CHEVROLET,,87,,OS,,,R20 CONV,,,G,,350,2,5058
,JHMSM3421BC120156,,,HONDA,,81,,CA,,,ACCORD,,,G,,107,0,2249
,JHMAD5433FC029833,,,HONDA,,85,,CA,,,ACCORD,,,G,,112,0,2277
,1FMEU15G6CLA00315,,,FORD,,82,,CA,,,BRONCO,,,G,,351,0,4079
,1FALP62W2RH216207,,,FORD,,94,,CA,,,THUNDERBIRD,,,G,,281,0,3570
,1FMDU34X6RUB35970,,,FORD,,94,,CA,,,EXPLORER,,,G,,245,0,4053
,2MEBM79F4JX618498,,,MERCURY,,88,,CA,,,MARQUIS,,,G,,302,0,4025
```

Figure 6.11. Example database input into the categorization program. The fields are comma delimited, with a number of fields eliminated to save space.

The categorization program was applied to both of these database subsets. The results are shown in Table 6.9. It can be seen that the majority of the vehicles in the local Riverside registered fleet are Tier 0 certified vehicles, with mileage greater than 50,000 miles. It can be seen that adding vehicles in the outlying area results in a slightly newer vehicle fleet.

#	Vehicle Technology Category	Categorization Results (%)	
	Normal Emitting Cars	Riverside proper	Riverside region
1	No Catalyst	5.18%	4.68%
2	2-way Catalyst	7.68%	7.41%
3	3-way Catalyst, Carbureted	5.12%	5.16%
4	3-way Catalyst, FI, >50K miles, low power/weight	10.51%	10.99%
5	3-way Catalyst, FI, >50K miles, high power/weight	14.16%	14.12%
6	3-way Catalyst, FI, <50K miles, low power/weight	1.08%	1.16%
7	3-way Catalyst, FI, <50K miles, high power/weight	1.68%	1.67%
8	Tier 1, >50K miles, low power/weight	1.45%	1.54%
9	Tier 1, >50K miles, high power/weight	2.67%	2.65%
10	Tier 1, <50K miles, low power/weight	1.30%	1.44%
11	Tier 1, <50K miles, high power/weight	2.68%	4.68%
24	Tier 1, >100K miles	0.09%	0.10%
	Normal Emitting Trucks		
12	Pre-1979 (<=8500 GVW)	5.24%	4.96%
13	1979 to 1983 (<=8500 GVW)	2.01%	1.96%
14	1984 to 1987 (<=8500 GVW)	2.62%	2.60%
15	1988 to 1993, <=3750 LVW	3.87%	3.96%
16	1988 to 1993, >3750 LVW	3.64%	3.52%
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	0.29%	0.30%
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	0.43%	0.43%
25	Gasoline-powered, LDT (> 8500 GVW)	1.79%	1.86%
40	Diesel-powered, LDT (> 8500 GVW)	0.07%	0.06%
	High Emitting Vehicles		
19	Runs lean	4.88%	4.90%
20	Runs rich	1.82%	1.83%
21	Misfire	10.45%	10.53%
22	Bad catalyst	7.40%	7.46%
23	Runs very rich	1.89%	1.91%

Table 6.9. Vehicle/Technology categorization results for the Riverside area.

6.5 CATEGORIZATION FROM MOBILE/EMFAC MAPPINGS

As an alternative to characterizing the vehicle fleet through a registration database, it is possible to use the fleet characteristics many states have already calculated for their region using the conventional regional emission inventory models MOBILE (US EPA, for the 49 states) and EMFAC (CARB, for California). In order to calculate these emission inventory estimates, vehicle fleet percentages and/or vehicle populations have to be determined for the region in question. These vehicle fleet percentages and/or vehicle populations have been calculated for the gross vehicle categories of the regional models. For MOBILE, these categories consist of light duty gas vehicle (LDGV), light duty diesel vehicle (LDDV), light-duty gasoline trucks (LDGT), light-duty diesel trucks (LDDT), and a variety of different heavy-duty truck categories.

Since the current version of CMEM only addresses light-duty vehicles, we are only concerned at this point with LDGVs, LDGTs, and LDDTs. For each of these categories, MOBILE also specifies the vehicle fleet fraction by model year.

For CARB's MVEI model suite (i.e., EMFAC), the categories are very similar, with a bit more disaggregation for the light duty vehicle technologies. The categories include light duty automobiles (LDA) which are split into gasoline fueled with no catalytic converter (LDA-NOCAT), those with catalytic converter (LDA-CAT), and those that are diesel fueled (LDA-diesel). Similarly with light duty trucks (LDT), there are LDT-NOCAT, LDT-CAT, and LDT-diesel. CARB also has a wide range of medium- and heavy-duty truck categories, which are currently outside the scope of this project. Similar to MOBILE, CARB's MVEI model also specifies the vehicle fleet fraction by model year.

Vehicle fleet percentages and vehicle populations have already been determined for many regions, therefore it makes sense to take advantage of this information in determining vehicle fleet percentages and/or populations for the CMEM vehicle categories. For this reason, *mappings* have been created between CARB's and EPA's vehicle category types and CMEM's vehicle categories. Using these mappings, states can take existing vehicle distributions based on the current CARB/EPA models and translate them for input into CMEM. This mapping procedure is illustrated in Figure 6.12.

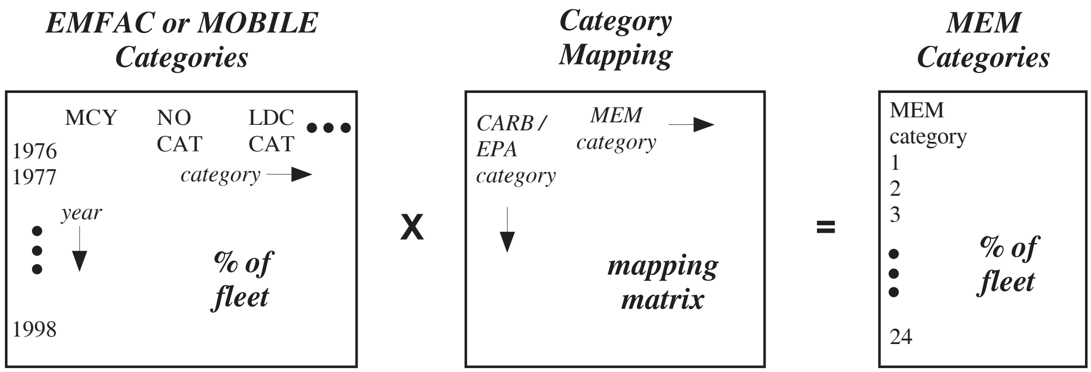

Figure 6.12. EMFAC/MOBILE to CMEM category mapping procedure.

In this illustration, the gross vehicle categories of MOBILE or MVEI are given across the top of a matrix, while the model year index runs along the side. The category mapping simply gives the percentage distribution for each category/year bin that corresponds to the appropriate CMEM category. These mappings can be created using knowledge of what vehicle model years correspond to the different CMEM categories. For example, model year 1974 and older automobiles do not have catalytic converters, therefore all of these vehicles can be categorized into CMEM category 1 (CMEM category 12 for LDTs). Information that was used in creating the decision trees of the previous section is also used here in determining the weights of the mappings.

As an example of a mapping for a 1998 base year, we have taken the CMEM categories and produced mappings for LDGVs, as shown in Table 6.10. Because this mapping was created for light duty automobiles only, all of the truck categories have zero weights. An example mapping for LDGTs is given in Table 6.11. Similarly, since this mapping applies to trucks only, the automobile categories have zero weights. These tables can also be used directly for CARB's LDA-CAT and LDA-NOCAT categories. The LDT-NOCAT will correspond directly to CMEM category 1. The LDGV table can be used for CARB's LDA-CAT category, ignoring CMEM category 1. Similarly for LDT-CAT and LDT-NOCAT: the CMEM category 12 can be used for LDT-NOCAT, and the remaining portion of the LDGT table can be used for LDT-CAT.

LDGV									CMEM CATEGORY																	
MY	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**24**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**25**	**40**	**19**	**20**	**21**	**22**	**23**	**sum**
1972	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1973	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1974	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1975	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1976	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1977	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1978	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1979	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1980	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1981	0.0%	0.0%	30.1%	1.5%	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.5%	0.0%	28.4%	20.4%	7.6%	100%
1982	0.0%	0.0%	27.5%	2.9%	2.9%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.5%	0.0%	28.4%	20.4%	7.6%	100%
1983	0.0%	0.0%	24.2%	4.4%	4.4%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.5%	0.0%	28.4%	20.4%	7.6%	100%
1984	0.0%	0.0%	20.2%	6.3%	6.3%	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.5%	0.0%	28.4%	20.4%	7.6%	100%
1985	0.0%	0.0%	16.2%	8.3%	8.3%	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.5%	0.0%	28.4%	20.4%	7.6%	100%
1986	0.0%	0.0%	10.6%	11.1%	11.1%	0.4%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.5%	0.0%	28.4%	20.4%	7.6%	100%
1987	0.0%	0.0%	17.0%	23.1%	23.1%	0.9%	0.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.8%	6.2%	13.1%	8.7%	0.0%	100%
1988	0.0%	0.0%	6.5%	28.2%	28.2%	1.3%	1.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.8%	6.2%	13.1%	8.7%	0.0%	100%
1989	0.0%	0.0%	8.5%	26.9%	26.9%	1.6%	1.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.8%	6.2%	13.1%	8.7%	0.0%	100%
1990	0.0%	0.0%	1.3%	29.7%	29.7%	2.3%	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.8%	6.2%	13.1%	8.7%	0.0%	100%
1991	0.0%	0.0%	0.0%	40.9%	40.9%	4.6%	4.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.1%	2.2%	2.7%	1.6%	0.0%	100%
1992	0.0%	0.0%	0.0%	38.7%	38.7%	6.8%	6.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.1%	2.2%	2.7%	1.6%	0.0%	100%
1993	0.0%	0.0%	0.0%	34.4%	34.4%	11.1%	11.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.1%	2.2%	2.7%	1.6%	0.0%	100%
1994	0.0%	0.0%	0.0%	17.1%	17.1%	12.9%	12.9%	11.4%	11.4%	8.6%	8.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1995	0.0%	0.0%	0.0%	2.4%	2.4%	7.6%	7.6%	9.8%	9.8%	30.2%	30.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1996	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.4%	49.6%	49.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1997	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%	50.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%

Table 6.10. LDGV -> CMEM category mapping.

LDGT	CMEM CATEGORY																										
MY	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**24**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**25**	**40**	**19**	**20**	**21**	**22**	**23**	**sum**
1972	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1973	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1974	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1975	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1976	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1977	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1978	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1979	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1980	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1981	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	73.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.5%	0.0%	12.2%	3.5%	7.8%	100%
1982	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	73.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.5%	0.0%	12.2%	3.5%	7.8%	100%
1983	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	73.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.5%	0.0%	12.2%	3.5%	7.8%	100%
1984	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	73.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.5%	0.0%	12.2%	3.5%	7.8%	100%
1985	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	73.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.5%	0.0%	12.2%	3.5%	7.8%	100%
1986	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	73.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.5%	0.0%	12.2%	3.5%	7.8%	100%
1987	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	79.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.9%	8.7%	6.1%	2.3%	0.0%	100%
1988	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	36.3%	42.7%	0.0%	0.0%	0.0%	0.0%	3.9%	8.7%	6.1%	2.3%	0.0%	100%
1989	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	32.4%	46.6%	0.0%	0.0%	0.0%	0.0%	3.9%	8.7%	6.1%	2.3%	0.0%	100%
1990	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	25.3%	53.7%	0.0%	0.0%	0.0%	0.0%	3.9%	8.7%	6.1%	2.3%	0.0%	100%
1991	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	29.0%	59.0%	0.0%	0.0%	0.0%	0.0%	1.5%	7.1%	2.3%	1.1%	0.0%	100%
1992	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	23.8%	64.2%	0.0%	0.0%	0.0%	0.0%	1.5%	7.1%	2.3%	1.1%	0.0%	100%
1993	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	24.6%	63.4%	0.0%	0.0%	0.0%	0.0%	1.5%	7.1%	2.3%	1.1%	0.0%	100%
1994	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	25.0%	65.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1995	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	22.0%	57.0%	21.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1996	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	12.2%	32.9%	31.7%	23.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%
1997	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	41.3%	58.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100%

Table 6.11. LDGT -> CMEM category mapping.

7 Conclusions and Recommendations

7.1 SUMMARY OF WORK

After four years of research and development, a comprehensive modal emissions model (CMEM) was created for light duty vehicles. The model is capable of predicting second-by-second tailpipe emissions and fuel consumption for 26 different vehicle/technology categories. During the course of this research and development, a number of important tasks were accomplished:

- ***literature review—***a literature review was performed focusing on vehicle operating factors that affect emissions;
- ***database development—***a wide variety of data sets were collected pertaining to vehicle emissions and activity;
- ***emission modeling review—***the current conventional emission models were reviewed and evaluated in light of this modal emissions model development;
- ***modal emissions testing procedure development—***a testing procedure was designed for the development of the modal emissions model;
- ***vehicle testing—***a total of 357 detailed vehicle dynamometer tests were performed to collect data for the model development;
- ***composite vehicles—***26 different composite vehicle models were developed representing a wide variety of vehicle/technology categories of light duty vehicles.
- ***validation—***the 26 composite vehicle models were extensively validated using independent test data.

- ***core emissions model*—**executable code has been produced to predict second-by-second emissions given an activity file for a *single* vehicle type. The operation and output of the model can be adjusted using a control file.

- ***batch emissions model*—**executable code has been produced to predict second-by-second emissions given an activity file for an entire *fleet* of vehicles. The operation and output of the model can be adjusted using a control file.

- ***graphical user interface*—**the model has also been implemented to run from Microsoft Access with an easy-to-use graphical user interface.

- ***velocity/acceleration-indexed emissions/fuel tables*—**lookup tables have been developed for each composite vehicle model. Many microscopic transportation models can directly use these tables.

- ***roadway facility/congestion-based emission factors*—**emission factors were created using EPA's latest facility/congestion cycles.

- ***vehicle category generation methodology*—**given a vehicle registration database, a procedure was developed to categorize each vehicle into the appropriate vehicle/technology category; and

- ***vehicle category mappings*—**mappings were created between EMFAC/MOBILE vehicle categories and the modal emission model categories.

7.2 RECOMMENDED FUTURE WORK

In developing this comprehensive modal emission model, many modeling issues were considered, such as different vehicle/technology categories, variable soak time starts, enrichment and enleanment behavior, and high-emitter characteristics. When developing the model, we attempted to capture many of the important aspects of vehicle operation and its effect on tailpipe emissions. However, because the production of vehicle emissions is a complex process and dependent on may variables, it was impossible to model every aspect at a high level of detail. In addition, CMEM is a "living" model: it needs to be updated periodically to properly represent the current vehicles in any given fleet. Future vehicle fleets will surely include new technologies that are not represented in this first version of the model. The following future work is recommended:

Incorporation of New Vehicle/Technology Categories—In order to better estimate emission inventories into future years (e.g., 2010, 2020), additional vehicle/technology categories must be incorporated into the model.

Improved Enrichment Behavior—Most modern vehicles have very low emission rates when they are in a hot stabilized operating mode, operating under low- to medium-loads. However, when the load is sufficiently high (e.g., high acceleration, high speed, going up a grade, etc.) many vehicles operate with a rich mixture and their resulting emission levels are several orders of magnitude greater than when under controlled, stoichiometric conditions. The current modal emissions model simulates these enrichment events based primarily on using a power threshold. When the power demand on the engine passes this threshold, the model switches to simulate enrichment mode. Because enrichment emissions are so much greater than stoichiometric emissions, even a few very short enrichment events can quickly dominate the total emissions produced on a vehicle trip. It is therefore critical to characterize enrichment operation to a high level of detail. Thus far in the comprehensive modal emissions model, a rather simplistic enrichment model has been used. Enrichment conditions should continue to be analyzed to better improve this critical component of the model.

Improved Catalyst Pass Fraction Module—Significant emission decreases have come about by closely controlling the vehicle's air/fuel ratio and using catalytic converters. When the air/fuel ratio is controlled precisely around the proper stoichiometric ratio and the catalytic converter is operating properly, large reductions in emissions are achieved. Similar to the reasoning stated above, the modal emission model uses a straightforward module and estimates the catalyst efficiency reasonably well. However to better improve this critical component of the model, catalyst efficiency measurements should continue to be made and analyzed. The catalyst pass fraction module should continue to be updated as new catalyst technology is developed.

Variable Soak Time Starts—The variable soak time starts described in Chapter 4 are based on several curves that represent emission-control behavior and catalyst cooling. However, this part of the model is based on only three emission “starts”: a hot start (FTP Bag 2 or MEC01 or US06), a 10-minute soak warm start (FTP Bag 3), and a 24-hour soak cold start (FTP Bag 1). The equations that predict variable soak time start emissions can be vastly improved with additional start emissions data. A test program should be developed to measure emissions from a wide range of soak-times. Further, the cycles should be varied after these soak times since the catalyst light-off times depend on the aggressiveness of the testing cycle.

Secondary Load Power Estimation—The default air conditioning power estimation in the model is based on a single temperature/humidity combination. Under in-use conditions, the load from AC operation varies widely, based upon temperature, humidity, and sun load. Users should be aware of this factor and attempt to provide appropriate AC load factors for their specific operating conditions.

Ambient Temperature—The model is calibrated for an ambient temperature of 75 degrees F. While hot, stabilized emissions are not greatly affected by ambient temperature, cold start emissions are. Therefore, the model is not well suited for ambient temperatures below 50 degrees without modification to account for longer cold start periods.

High Emitting Vehicles—In this NCHRP project, an initial characterization of high emitters has been made, and high emitting vehicle models have been developed. In order to improve high emitting vehicle modeling, many more high emitting vehicles need to be tested, and the cause of their high emissions needs to be better investigated. In addition, data sets from many more inspection/maintenance programs need to be analyzed to determine the vehicle activity component of high emitters (e.g., vehicle fleet distribution). In the model development to date, high emitting vehicles have been characterized through 1997. Recent evidence has shown that the more modern vehicles have very low probabilities of being high emitters, however additional activity and emission data need to be collected to improve this part of the model.

Future Vehicle Model Prediction—As described previously, CMEM has been developed using a physical, power-demand approach based on a parameterized analytical representation of emissions production. Each component is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, emission technology, and level of deterioration. One distinct advantage of this physical approach is that it is possible to adjust many of these physical parameters in order to predict emissions of future vehicle models. Although it is difficult to predict with any degree of certainty what the technology mix of vehicles will be in the future, some projections of future emission control systems and engine technology can be made. As an example, it is likely that the enrichment "power-threshold" for many vehicles will tend to increase as the emission control systems become more robust, and more vigorous certification testing (e.g., SFTP) takes place. The emission effects of other changes can be predicted, such as engines with lighter materials, breathing enhancements, variable displacement, variable compression ratios, pre-heated catalyst systems, lean-burn NOx catalysts, etc. It is recommended that a study be performed with CMEM to predict the emission characteristics of future vehicle/technology categories. This can be accomplished by adjusting many of the parameters of the physical component modules in a way that makes sense based on technology trends. Simple examples of this are to look at increasing enrichment thresholds of more recent model vehicles, shorter catalyst light off times, etc. The resulting emission factors of future vehicle/technology categories can then be used in estimating inventories well into the next millennium.

CMEM Integration into Transportation Frameworks—In Phase 3 of this project, much effort was spent in identifying how CMEM can be integrated into various transportation modeling environments. The core and batch executable models have been developed in a flexible fashion so that they can easily be incorporated into various frameworks. In addition, velocity/acceleration-index emission/fuel lookup tables were created, which can be integrated into many existing microscopic transportation simulation models (e.g., CORSIM, NETSIM, etc.). This integration work should continue with other types of transportation data and/or models, getting the maximum utility out of CMEM.

***CMEM Comparison to MOBILE*—**CMEM has been validated using independent driving cycles and measured emissions. However, it would be a worthwhile exercise to compare the newer generation (microscopic) transportation/emission models (e.g., TRANSIMS/CMEM) with today's traditional macroscopic transportation/emissions model (i.e., regional model/MOBILE). When the newer generation transportation/emission models are sufficiently mature, it will be possible to directly compare a MOBILE-based emissions inventory with an inventory produced using the newer generation models. This will help identify critical differences and possible deficiencies in the models.

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Appendix A: Literature Review Summary

1. E. Achleitner, et al., "Electronic Engine Control System for Gasoline Engines for LEV and ULEV Standards", SAE Technical Paper Number 950479, 1995.

   The primary component for Siemens LEV/ULEV technology is an electronic control unit with a high potential processor, which fulfills all requirements for high calculation accuracy and OBDII-diagnostics. Several new functions were designed on this platform to make sure that the vehicle emissions are low in every operating condition and over the vehicle lifetime. The paper describes the emission benefits of selected new functions and components.

2. F. An and M. Ross, "A Model of Fuel Economy and Driving Patterns", SAE Technical Paper number 930328, 1993.

   A simple analytic relationship between fuel economy, vehicle parameters and driving cycle characteristics is established. Using publicly available information on vehicle characteristics, the model can be used to predict fuel economy with an accuracy of about 5%. The model is based on two approximations: 1) and engine map approximation, and 2) an approximation for tractive energy.

3. F. An and M. Ross, "A Model of Fuel Economy with Applications to Driving Cycles and Traffic Management", Transportation Research Record 1416, 1993.

   Fuel consumption by a vehicle is expressed in terms of a few vehicle characteristics and summary characteristics of any trip. This simple physical model can readily be adapted to any vehicle or combination of vehicles. The model shows that instead of a second-by-second velocity pattern being needed, fuel consumption can be estimated from a small number of speed characteristics

that summarize a trip: average speed, an average peak speed, braking time, stop time, and number of stops per unit of distance.

4. F. An and M. Ross, "Automobile Energy Efficiency at Part-Load: The Opportunity for Improvement", in presentation to the American Council for an Energy Efficient Economy, Washington, DC, 1993.

   The presentation provides an introduction to fuel economy problem and economics. Research findings show that a key parameter relative to fuel economy is the ratio of max power to weight, this parameter is also highly correlated to acceleration capability. Another key parameter is engine efficiency. Also suggested numerous points for improved fuel economy.

5. F. An and M. Ross, "Carbon Monoxide Modeling for High Power Episodes", in Proceedings of the Fifth CRC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 2-27 - 2-44, 1995.

   Presentation described a model developed to predict carbon monoxide emissions from conventional automobiles in high-power commanded enrichment operation. A mathematical formula for the rate of CO emissions relative to fuel consumption was established as a function of air-fuel ratio. This relationship was used to develop a second by second simulation model capable of estimating CO emissions for vehicles in high-power episodes. The model required that the air-fuel ratio be known in terms of engine speed and power. Reasonably satisfactory descriptions of CO emissions from individual vehicles have been obtained with this model; however, relatively few vehicles have been examined.

6. F. An, M. Barth, and M. Ross, "Vehicle Total Life-Cycle Exhaust Emissions", SAE Technical Paper number 951856, 1995.

A methodology is established to assess total life-cycle exhaust emissions for light-duty motor vehicles. The focus is to model a vehicle's carbon monoxide (CO), hydrocarbon (HC), and oxides of nitrogen (NOx) exhaust emissions over its lifetime in the state of California. Preliminary analysis shows that for an average late MY 80's or early MY 90's light duty vehicle registered in California, tailpipe emissions over its lifetime roughly total 2100 kg for CO, 120 kg for HC, and 190 kg for NOx. These emission levels are equivalent to 16 g/mi for CO, 0.9 g/mi for HC, and 1.4 g/mi for NOx.

7. F. An, et al., "Catalyst Cold-Start Characterization and Modeling", In preparation, 1995.

In this paper, vehicle catalyst efficiency during cold-start is characterized and modeled. The catalyst cold-start efficiency is characterized based on two components: 1) catalyst efficiency-temperature characteristics; and 2) catalyst temperature-operation time characteristics.

8. F. An and F. Stodolsky, "Modeling the Effect of Engine Assembly Mass on Engine Friction and Vehicle Fuel Economy", SAE Technical Paper Number 950988, 1995.

In this paper, an analytical model is developed to estimate the impact of reducing engine assembly mass (the term engine assembly refers to the moving of components of the engine system, including crankshafts, valve train, pistons, and connecting rods) on engine friction and vehicle fuel economy.

9. F. An and M. Barth, "A Comparison Between Emission Speed Correction Factors and Vehicle Fuel Consumption", submitted to the Sixth CRC On-Road Vehicle Emissions Workshop, San Diego, California, 1996.

Speed Correction Factors (SCFs) are used by EMFAC and MOBILE to adjust hot-stabilized vehicle exhaust emissions based on average trip speed. This paper addresses the relationship between vehicle emissions that are characterized by these SCFs and vehicle fuel consumption. A

strong correlation has been found between fuel consumption and vehicle tailpipe emissions under engine hot-stabilized conditions for properly functioning vehicles.

10. F. An, A. Frank, and M. Ross, "Meeting Both ZEV and PNGV Goals with a Hybrid Electric Vehicle - An Exploration", in the Third Annual World Car Conference, Riverside, California, 1996.

This paper is written to provide information on the fuel efficiency, emissions, and energy cost of vehicles ranging from a pure electric (ZEV) to gasoline hybrid vehicles with electric range varying from 30 mi (50km) to 100 mi (160km). Since there are many possible configurations for hybrid electric vehicles, a technique of generalizing the vehicles for analysis is created. The analysis compares these vehicles by simulating them being driven on the Federal Urban Driving Cycle (FUDC) and the Highway Cycle (HWY). From the analysis, the sensitivity to weight and controls are explored. Energy from the power plant and "on-board" fuel will be analyzed for efficiency, emissions, cost and consumer acceptance. Control policy implications and some social implications will be presented. The SAE/CARB testing procedures for determining energy and emission performance for EV and HEV are also evaluated. The Federal Government's PNGV and CARB's ZEV have different goals, this paper also explores some possibilities for hybrid-electric vehicle designs to meet both goals. A summary of design parameters for a "PNGV-ZEV" vehicle will be provided as a guideline for vehicle design.

11. F. An and M. Ross, "A Simple Physical Model for High Power Enrichment Emissions", Journal of Air and Waste Management Association, Vol. 46,1996.

A model was developed to predict CO emissions from conventional automobiles during high-power operations. This effort is aimed at improving regulatory modeling through the use of parameterized physical modeling, with minimal parameterization. The emissions studied here are associated with command enrichment of the mixture at high power. An approximate mathematical

formula for the rates of CO emissions relative to fuel consumption is established as a function of air-fuel ratio. The CO emissions are modeled by combining a fuel consumption model with a description of a vehicle's enrichment behavior.

12. M. Andre, et al., "Driving Cycles for Emission Measurements Under European Conditions", SAE Technical Paper Number 950926, 1995.

For a particular type of vehicle, fuel consumption and pollutant emission rates are mainly a function of the vehicle's use and of the vehicle's operating conditions and depend on both the traffic conditions and the individual behavior of the driver. Thus, a realistic assessment of emissions, pollution reduction methods and the effectiveness of emission control technologies cannot be carried out without taking into account the actual operating conditions of the vehicles.

13. A. Atanasyan, et al., "Infrared Method to Visualize the Benefit of Improved Transient Control on Catalyst Temperature", SAE Technical Paper Number 950476, 1995.

Siemens has developed advanced software algorithms in order to better predict cylinder air intake efficiency and to better compensate for the fuel wall wetting evolution. This more precise air-fuel ratio control significantly improves engine emissions during transient mode. The improved software algorithms provide better control of the catalyst temperature fluctuations. The proposed temperature visualization method allows a complete system approach in terms of transient control optimization for better catalyst overheating protection.

14. T. Austin, et al., "An Analysis of Driving Patterns in Los Angeles During 1992", in Proceedings of the Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 6-145 - 6-189, 1992.

Results were presented for an on-road chase vehicle driving characterization study. The chase vehicle was equipped with a laser range finder system to record speed-time profiles of vehicles as

they were being driven in Los Angeles. The data collected during this study show that the speed-time profile of the FTP does not represent all of the vehicle operating conditions currently occurring in Los Angeles, mainly due to higher speeds and acceleration rates than in the FTP. Austin used a computer model to show that if these new data are correct, CO and oxides of nitrogen emissions may be 50-100% higher than on the LA-4 cycle, while HC emissions are nearly identical in both cases.

15. M. J. Barth and J. M. Norbeck, "A Power-Demand Approach to Estimating Vehicle Emissions", in Fourth CRC-APRAC On-Road Vehicle Emission Workshop, San Diego, California, pp. 5-51 - 5-72, 1994.

The presentation described a load based emission model that can be combined with microscopic transportation simulation models to estimate fleet average on-road emissions for different driving situations. The initial application was for the case of uninterrupted traffic flow on a freeway segment. As expected, it was found that emissions increase during heavy congestion due to unstable stop-and-go traffic flow. For example, the maximum CO generated at a congestion average speed of 11 mph was 152 times as much as that produced at 40 mph. The model was also used to predict freeway on-ramp emissions. The effect of on-ramp grade was dramatic. It was noted that a much larger data base of second-by-second emissions correlated to vehicle operation data is needed for further model development. Transportation simulation models for different roadway facility types must also be developed, and need to account for driver behavior.

16. M. Barth and J. Norbeck, "Transportation Modeling for the Environment", Final Report, University of California, Riverside, College of Engineering Center for Environmental Research and Technology, 1994.

In this research report, a description is given for preliminary research dealing with vehicle emissions associated directly with 1) Automated Highway Systems (AHS) and 2) ramp metering.

In performing this analysis, a power-demand modal emissions model has been integrated with several transportation simulation models in order to quantitatively determine the effects of ITS technology on vehicle emissions.

17. M. Barth and J. Norbeck, "Phase Two Development of an Integrated Transportation/Emission Model", Final Report #94:TS:024F, Center for Environmental Research and Technology, for the South Coast Air Quality Management District, 1994.

An Integrated Transportation / Emissions Model (ITEM) is currently under development. ITEM was designed to incorporate the most finely time-resolved modal emissions data, i.e., data that directly related to vehicle operating modes, such as acceleration, deceleration, idle, and cruise. In this phase two development of ITEM, the macroscale component has been extended from a freeway-only implementation to an arterial/freeway implementation. Also, microscale simulation modules were developed for signalized intersections and for rural highways.

18. M. J. Barth, R. R. Tadi, and J. M. Norbeck, "The Development of an Integrated Transportation/Emissions Model for Estimating Emission Inventories", in 1995 American Society of Civil Engineers Transportation Congress, San Diego, California, 1995.

An Integrated Transportation/Emission Model (ITEM) is currently being developed. The detail and structure of ITEM allow more reliable calculations of mobile source emissions based on appropriate time resolved consideration of vehicle activity within a traffic network.

19. M. Barth, et al., "Modal Emissions Modeling: A Physical Approach", in The 75th Annual Transportation Research Board Meeting, Washington, D.C., 1996.

This paper describes a new modal emissions modeling approach that is deterministic in nature and is based on analytical functions that describe the physical phenomena associated with vehicle operation and emissions production. This type of model relies on highly time-resolved emissions and vehicle operation data that must be collected from a wide range of vehicles of varying emission control technologies. This paper describes the modeling approach and implementation plan for a new, three year NCHRP Project 25-11 entitled "Development of a Modal Emissions Model".

20. G. Bishop and D. Stedman, “On-Road Carbon Monoxide Measurement Comparisons for the 1988-1989 Colorado Oxy-Fuels Program”, Environmental Science and Technology, Vol. 24, Issue 6, pp. 843 - 847, 1990.

The University of Denver's remote sensor for carbon monoxide has been used to perform a study of CO emissions from in-use vehicles during Colorado's 1988-1989 Oxygenated Fuels program. The results show a statistically significant decrease in average CO emissions of 16%.

21. G. A. Bishop, et al., “Remote Sensing of Real-World Automotive Emissions Evaluation of the Methodology in Highway Tunnels”, in Fourth CRC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 7-119 - 7-132, 1994.

Several analyses were presented based on the CO and HC remote sensing data collected in California in 1991. This three-month field study, which was conducted at sixteen sites, produced 91,679 CO and HC measurements with vehicle information for 66,053 unique vehicles. It was demonstrated that there are significant differences in the age adjusted average CO emissions for different areas within the Los Angeles basin. With databases of this size, it is possible to examine emissions performance and changes in vehicles as a function of make and model. For example, emission differences were seen between Hondas with and without automatic transmissions. Hyundai vehicle emissions were much worse than average for 1989 and earlier models, but were comparable for 1990 and 1991 vehicles. Vehicles of European manufacturer were found to be consistently lower emitting than the rest of the fleet. In addition, plotting the percentile distributions of emissions concentrations for the lowest emitting 85% of the remote sensing measurements by manufacturer and by model age showed that emissions increase with vehicle age, and that significant differences exist between the fleets produced by different manufacturers. It was not determined if some of the observed differences could be attributed to differences in the car vs. truck composition of the fleet for different manufacturers.

22. D. J. Boam, T. A. Clark, and K. E. Hobbs, "The Influence of Fuel Management on Unburnt Hydrocarbon Emissions During the ECE 15 and US FTP Drive Cycles", SAE Technical Paper Number 950930, 1995.

Unburnt hydrocarbon (uHC) emission levels, from three vehicles driving the ECE 15 and US FTP75 test cycles, have been measured on a crank angle timescale. High levels of uHC emissions have been linked to particular drive-cycle features and can be explained as features of the engine management strategy. The data highlights the need to pay close attention to the fueling of every cycle if large excursions in uHC levels are to be avoided.

23. D. J. Brzezinski, "MOBILE5 IM240 Based Basic Emission Rates", in Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 3-69 - 3-76, 1992.

David Brzezinski of EPA's Office of Mobile Sources discussed the use of the IM240 dynamometer test to obtain basic emission rates as input for MOBILE5. This is the first EPA mobile source emission factor model that will use data based on the IM240. FTP data were used in all earlier model versions. The data are being obtained from IM240 tests conducted at the Hammond, IN I/M inspection lanes. This approach will help eliminate problems with the recruitment of in-use vehicles for emission testing and will increase the amount of data available from older vehicles in the fleet. These new data may lead to higher vehicle emission estimates from the MOBILE models.

24. S. D. Burch, et al., "Reducing Cold-Start Emissions by Catalytic Converter Thermal Management", SAE Technical Paper Number 950409, 1995.

Vacuum insulation and phase-change thermal storage have been used to enhance the heat retention of a prototype catalytic converter. Storing heat in the converter between trips allows exhaust gases to be converted more quickly, significantly reducing cold-start emissions. Compared to the same converter at ambient conditions, overall emissions of CO and HC were reduced by 52% and 29%, to 0.27 and 0.037 g/mile respectively.

25. P. L. Burk, et al., "Cold Start Hydrocarbon Emissions Control", SAE Technical Paper Number 950410, 1995.

An effective, energy efficient strategy for dealing with cold start hydrocarbons using carbon-free hydrocarbon traps and heat exchange related TWC catalyst beds has been successfully tested on a wide variety of current model vehicles.

26. S. H. Cadle and R. D. Stephens, "Remote Sensing of Vehicle Exhaust Emissions", Environmental Science and Technology, Vol. 28, Issue 6, pp. 258 - 264, 1994.

Reviewed remote-sensing technology for exhaust emissions and remote-sensing applications that help characterize and minimize exhaust emissions in the real world. The method has a bright future as an aid in understanding in-use emissions, a monitor of progress in reducing fleet emission rates, and as an I/M and enforcement tool.

27. CARB, "Methodology for Estimating Emissions from On-Road Motor Vehicles, Volume II: Weight (E7FWT)", Report Technical Support Division, CARB, 1993.

The Air Resources Board (ARB) estimates on-road motor vehicle emission factors and motor vehicle emissions inventories using a series of computer models that approximate the emissions from California's motor vehicle fleet. This document describes one of the models that is part of that process, the Weight Program, also known in its current from as E7FWT. The other models that are part of the on-road motor vehicle emission inventory process are described in detail in other ARB documents. E7FWT is a Fortran computer model that provides estimates of average vehicle accumulated mileage, that is, the vehicle odometer reading, by model year for a specified calendar year.

28. CARB, "Derivation of the EMFAC7F Speed Correction Factors", Report, Mobile Source Division, Inventory Analysis Branch, Analysis Section, 1993.

This memorandum details the update to the speed corrections factors (SCF) for the latest version of the emission factor model EMFAC. A new methodology has been employed in modeling the SCFs of EMFAC7E. These SCFs will be incorporated into EMFAC7F, succeeding those of EMFAC7E as detailed in the July, 1990 EMFAC documentation.

29. CARB, "Test Report of the Light-Duty Vehicle Surveillance Program, Series 12 (LDVSP 12)", Final Report, California Air Resources Board, 1994.

The Air Resources Board (ARB) tested a total of 232 gasoline-powered passenger cars and light-duty trucks of model years 1983 through 1992 as part of its general in-use vehicle surveillance program for Budget Year 1992-93. The vehicles were randomly selected and procured from private owners in the Southern California Air Basin (SOCAB) consisting of Los Angeles, Orange, Riverside, and San Bernardino Counties. Upon receipt, each in-use surveillance vehicle was tested in the "as received" condition to establish compliance with its new vehicle certification standards. The fleet was also subjected to an I/M test ("Smog Check") similar to that conducted biennially on vehicles in non-attainment air basins such as the SOCAB or for change-of-ownership of a vehicle. Repairs were performed limiting the repair cost to $450, thus deviating from the previous LDVSP11 I/M repair limit of $175, and then the vehicles were retested.

30. W. Carter, et al., "Atmospheric Process Evaluation of Mobile Source Emissions", Technical Report #94:AP:043F, University of California, Riverside, College of Engineering Center for Environmental Research and Technology

This report identified the state-of-the-art technology and tools for modeling the impacts on ambient air quality of mobile source emissions from alternative and conventional transportation fuels.

31. K.-C. Chen, K. Dewitte, and W. K. Cheng, "Fuel Effects and Enrichment Effects on Engine Starting and Warm-Up Behavior", SAE Technical Paper Number 950065, 1995.

The effects of fuel volatility and degree of enrichment on the starting and warm-up behavior of a modern four-valve spark ignition engine with port-fuel-injection were studied and discussed.

32. P. Cicero-Fernandez and J. R. Long, "Modal Acceleration Testing on Current Technology Vehicles", in A&WMA The Emission Inventory: Perception and Reality, Pasadena, California, pp. 506 - 522, 1993.

Ten current technology vehicles were evaluated on a dynamometer under four testing cycles: a standard Federal Test Procedure (FTP), the third bag of the FTP (HOT-505), a modified hot New York City Cycle (NYCC), and a specially designed acceleration (ACCEL1) cycle. The cycles were inter-compared in terms of emission rates. Additionally the acceleration cycle was separated into ten modes. These modes represent FTP-like conditions, hard acceleration at low and high speeds, and other conditions likely to be encountered in current on-road driving such as ramps, merging and passing slower vehicles. Real-time, second-by-second emissions were also analyzed, providing a profile of the most severe emitting events. Preliminary findings show the high emitting potential of acceleration events greater than those encountered in the FTP.

33. P. Cicero-Fernandez and J. R. Long, "Instantaneous and Short Term Emission Rates Observed during Modal Acceleration Testing", in Proceedings of the Fourth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 3-1 - 3-25, 1994.

Pablo Cicero-Fernandez from CARB presented the emission results for 23 1983 and 1984 vehicles tested on the EPA-CDS driving cycle and 24 1988-1992 vehicles on the CARB ACCEL1 driving cycle. The 95th percentile emissions for high emissions events was 0.04 to 0.15 g/sec for HC, 1.1 to 6.1 g/sec for CO, and 0.01 to 0.16 g/sec for NOx. These can be compared to the FTP standards of 0.002, 0.019, and 0.005 g/sec HC, CO, and NOx, respectively. The HC results were slightly higher than had been observed in two on-road instrumented vehicle studies, while CO was in good agreement with these studies. Attention was brought to the impact of combined high-speed and medium to hard-acceleration events. It was concluded that such events have the potential to substantially impact emission inventories.

34. P. Cicero-Fernandez and J. R. Long, "Grades and Other Loads Effects on On-Road Emissions: An On-Board Analyzer Study", in Proceedings of the Fifth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 8 - 45, 1995.

The CARB is conducting an ongoing project to assess driving patterns likely to promote emission excursions greater than those encountered in current dynamometer driving cycles, using an instrumented vehicle equipped for on-road testing on hills. The authors found out that, when driving on grades above 3%, HC, CO were above the emission rates calculated using EMFAC's SCFs 86% and 100% of the time respectively. While driving on negative grades or flat terrain emission rates were closer to the SCF estimates. Effects on total engine load, such as passengers or AC, may also important. On average, the emission effects are exacerbated with a fully occupied vehicle (4 passenger) while driving on a hill (4.5%) both for HC and CO a factor of 2. For AC operation, tests were performed on two hills (4.5 and 6.7%). The HC emission rates showed an increase of 57% when AC was used at a maximum of setting. For CO the increase was 268% for AC operation.

35. J. P. Cohen, et al., "Overall Comparison of Driving Operation Patterns and Event Characteristics Between Three-Parameter and Six-Parameter Instrumented Vehicle Data", Technical

Memorandum, Systems Applications International. Department of Mechanical Engineering, University of California, Berkeley, 1992.

Systems Applications and subcontractor Sawyer Associates have been retained by the MVMA and AIAM to analyze instrumented vehicle data recently collected in Spokane, Washington and Baltimore, Maryland together with FTP driving cycle data that are currently being collected by some of the motor vehicle manufacturers. The instrumented vehicle data contain measurements collected every second for about a week on 224 vehicles. The three-parameter (3P) data contain measurements of vehicle speed, engine speed, and either manifold absolute pressure, manifold air flow, or LV8. The six-parameter (6P) data additionally include the throttle position, coolant temperature, and equivalence ratio.

36. M. J. S. Denis, P. Cicero-Fernandez, and A. M. Winer, "On-Road Analysis of Potential Open Loop Operation With Current On-Board Computer Technology", in Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 6-215 - 6-244, 1992.

Discussed the frequency of open-loop (enrichment) operation using a 1991 Ford Taurus in Los Angeles. The objectives of this study were: 1) to assess how real-world driving conditions vary from those present in the FTP; 2) to provide information on the frequency and contribution of off-cycle emissions to total mobile source emissions; 3) top investigate possible changes to the FTP and their influence on emission readings; and 4) to examine possible methods for modeling mobile source emissions. St. Denis reported that the FTP under represents the amount of time in medium and hard accelerations, and that the FTP contains no time coasting, compared with real-world vehicle operations. He also reported that open loop (enrichment) operation occurs during higher speeds, uphill driving, and acceleration conditions.

37. M. S. Denis and A. M. Winer, "Prediction of On-Road Emissions and Comparison of Modeled On-Road Emissions to Federal Test Procedure", in A&WMA The Emission Inventory: Perception and Reality, Pasadena, California, pp. 495 - 505, 1993.

An instrumented 1991 Ford Taurus was used to collect on-road driving pattern data from a matrix of freeway and urban routes in California's South Coast Air Basin (SOCAB) under varying driving conditions, and emissions tests were conducted with the test vehicle for the Federal Test Procedure (FTP), the Highway Fuel Economy Test (HFET) and three new dynamometer driving schedules. Two vehicle emissions models were developed to model on-road vehicle emissions as a function of acceleration and speed-based modes and as a function of load and speed-based modes. Validation of the two models found the load-based model more accurate than the acceleration-based model.

38. M. S. Denis, et al., "Effects of In-Use Driving Conditions and Vehicle/Engine Operating Parameters on "Off-Cycle" Events: Comparison with Federal Test Procedure Conditions", Journal of Air & Waste Management, Vol. 44,pp. 31 - 38, 1994.

Provides a direct evaluation of real-time, on-road vehicle and engine operating parameters, and investigated their relationship to rich open-loop (or "off-cycle") emissions for 1991 Ford Taurus driven in morning and evening commute hours over a matrix of eight freeway and eight urban routes in California's South Coast Air Basin.

39. K. D. Drachand, "Modal Acceleration Testing", Mailout Report #91-12, Mobile Source Division, California Air Resources Board, 1991.

Ten current technology vehicles were tested on a dynamometer under a specially designed acceleration (ACCEL1) cycle. Extremely high emission levels were observed during hard accelerations.

40. R. C. Effa and L. C. Larsen, "Development of Real-World Driving Cycles for Estimating Facility-Specific Emissions from Light-Duty Vehicles", in A&WMA The Emission Inventory: Perception and Reality, Pasadena, California, pp. 549 - 568, 1993.

To improve emission estimates, over 1100 miles of real-world driving data gathered in the greater Los Angeles area were used to develop ten cycles. Seven cycles representing average speeds from 9 to 60 mph on freeways, and three cycles representing average speeds from 14 to 34 mph on arterials. The new cycles differ from existing cycles in two important ways: 1) they are based on observed contemporary driving behavior; and 2) they recognize different driving characteristics between freeways and arterial facilities.

41. J. Ellis, "Development of Real-World Driving Cycles for Estimating Facility-Specific Emissions from Light-Duty Vehicles", in 5th CRC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 7-111 - 7-126, 1995.

John Ellis, California Air Resources Board, reported CARB's efforts to develop multiple cycles representing different levels of speed and congestion for both freeways and surface streets. These cycles are based on observed speed-time profiles, in one-second increments, of hundreds of vehicles in the Los Angeles area. Ultimately, a representative fleet of 250 light-duty vehicles will be tested on all cycles in order to develop new emission factors. To date, 86 vehicles have been tested on ten new cycles. Preliminary emission test results for these vehicles indicated that HC and CO emissions on the new facility cycles have similar shape to the speed correction factor cycles currently used for inventory purposes. Two noted and potentially important differences between the current speed correction factor cycles and the new facility cycles for HC and CO emissions for the limited number of vehicles tested are: 1) emissions are 15% higher on the arterial type cycles compared to the freeway type cycles and 2) the new freeway type cycles do not show increasing emissions as average cycle speed exceeds 50 mph. The highest mean speed freeway cycle tested was 60 mph. In order to determine where the 'tail' of the curve lies, CARB created two additional high speed cycles with mean speeds of 65 and 75. These cycles have not yet been tested for emissions. NOx emission on the facility cycles, however, do not resemble emissions on the current speed, while emissions on the freeway cycles generally increase with increasing speed.

42. P. Enns, J. German, and J. Markey, "EPA's Survey of In-Use Driving Patterns: Implications for Mobile Source Emission Inventories", Report Office of Mobile Sources, Certification Division, USEPA, 1993.

Preliminary data on in-use driving behavior and vehicle emissions are presented in this review of the Federal Test Procedure (FTP) Review Project. The driving surveys suggest that certain in-use driving modes, such as high speeds and high accelerations, are not represented by the FTP. Also, in-use start driving behavior, trip length, and the distribution of soak times all differ from their FTP representation. Through a limited vehicle emission test program, EPA evaluated the emission impact of the above factors, as well as the emission impact of road grade and air conditioning. In looking at the emission inventory implications of the test results, several pieces stand out. Emissions for HC, CO, and NOx were all higher for in-use driving relative to the FTP; the largest increase was in CO emissions. Start driving and soak effects impacted NOx and HC emissions. The use of air-conditioning had a large impact on NOx emissions, while road grade significantly elevated CO emissions.

43. EPA, "Highway Vehicle Emission Estimates -- II", White Paper Report EPA, 1995.

This second OMS "White Paper" on highway vehicle emission estimates provides the revisions that have been made to EPA's highway vehicle emission factor model and the effects of these changes on emission factor estimates are summarized in Section 1. A summary of various ambient studies is given in Section 2, and in Section 3 more recent tunnel studies are discussed. A comparison of emission factors estimated by MOBILE5 to those calculated by the 1987 Van Nuys

tunnel study, as well as the 1992 Fort McHenry and Tuscarora tunnel studies, is presented in Section 4. Section 5 provides a recap of many of the issues concerning the accuracy of highway vehicle emission factors and inventory estimates, with regards to the format used in the first July 1992 paper. Finally, Section 6 outlines some of EPA's plans for the next major revision to the model (which will be MOBILE6), and other ongoing research is briefly discussed.

44. R. T. Gammariello and J. R. Long, "An Emissions Comparison Between the Unified Cycle and the Federal Test Procedure", in A&WMA The Emission Inventory: Perception and Reality, Pasadena, California, pp. 535 - 548, 1993.

The Unified Cycle was developed to more accurately represent "real world" driving patterns and motor vehicle emissions, and is based on data gathered using an instrumented chase car in the greater metropolitan Los Angeles area. Compared to the FTP, the Unified Cycle contains driving events which have higher speeds and higher acceleration/deceleration rates. In an attempt to analyze the Unified Cycle, the ARB's Light-Duty Surveillance Program, Series 12, will be used to compare the Unified Cycle's emission rates with the FTP. Approximately 230 vehicles will eventually be tested using various cycles, including the FTP and the Unified Cycle. Preliminary testing has shown a significant increase in hydrocarbon (HC), carbon monoxide (CO) and oxides of nitrogen (NOx) emission inventory estimates.

45. F. D. Genova and T. Austin, "Development of an Onboard Data Acquisition System for Recording Vehicle Operating Characteristics and Emissions", in Fourth CRC-APRAC On-Road Vehicle Emission Workshop, San Diego, CA, pp. 3-59 - 3-82, 1994.

Frank Di Genova of Sierra Research, Inc. described an instrumented vehicle with the unique feature of direct lateral and longitudinal acceleration measurement. Grade is estimated from measure speed changes and the longitudinal acceleration. Demonstration drives were conducted with drivers who had been rated as aggressive and non aggressive based on their PKE (positive

kinetic energy of acceleration) values. Up to and order of magnitude difference was found for CO emissions during essentially identical trips mad by these drivers, due to the more aggressive driver having commanded enrichment events.

46. J. German, "Overview of FTP Study Driving Surveys", in Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 6-81 - 6-90, 1992.

John German from EPA's Office of Mobile Sources presented an overview of driving survey studies conducted by EPA, CARB, the Motor Vehicle Manufacturers Association [now the American Automobile Manufacturers Association (AAMA)], and the Association of International Automobile Manufacturers (AIAM). These studies, required by the 1990 Amendments to the Federal Clean Air Act, are designed to determine whether the Federal Test Procedure represents actual driving conditions of today's urban motor vehicle fleet and to assess the impact of non-FTP driving on overall motor vehicle emissions. Two separate types of in-use driving surveys have been conducted: instrumented vehicle studies and chase car studies. Analysis of results from these studies will focus on real world speed and acceleration data, engine and catalyst cool down, cold start driving behavior, and trip measures (i.e., trips/day, trip time and distance, amount of idling time, etc.).

47. A. W. Gertler and W. R. Pierson, "The Use of Tunnel Studies for Assessing the Performance of Emissions Factor Model", in Fifth CRC On-Road Vehicle Emissions Workshop, San Diego, CA, 1995.

The most recent tunnel studies were performed in the Ford McHenry Tunnel (Baltimore), Tuscarora Mountain Tunnel (Pennsylvania Turnpike), Cassiar Tunnel (Vancouver, BC), and Caldecott (San Francisco Bay Area) [ref]. Results of these experiments were compared with emissions predicted by MOBLE and EMFAC. Results for the Cassiar, Fort McHenry, and Tuscarora tunnels were reported generally within +/- 50% of the model prediction. These results contrast with 1987 Van Nuys experiment, wherein the CO and HC were under predicted by factors of two and more. The 1993 Caldecott results deviate significantly from model predictions and are similar to those seen in Van Nuys.

48. S. E. Golunski, et al., "Low Light-Off Catalyst Technology and Its Low Emission Vehicle Application", SAE Technical Paper Number 950408, 1995.

This paper describes the development of a low temperature Pt/Pd catalyst technology which offers light-off advantages over Pd-only catalysts. Mathematical modeling, combined with confirmation testing on an engine dynamometer and vehicles, demonstrate that further reductions in catalysts light-off and cold-start emissions can be achieved by combining this low temperature catalyst technology with low thermal mass substrates.

49. R. W. Goodwin and M. H. Ross, "Off-Cycle Exhaust Emissions from Modern Passenger Cars with Properly-Functioning Emissions Controls", SAE Technical Paper, 1996.

This paper reports on part of a University of Michigan study of real-world emissions by conventional gasoline-fueled cars: the part associated with vehicle operations at higher power than emphasized in the emissions certification tests.

50. P. J. Groblicki, "Characterization of Driver Behavior Affecting Enrichment", in Fourth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 3-25 - 3-40, 1994.

Peter Groblicki from GM also discussed the characterization of driver behavior as it affects the frequency of enrichment events. Thirty-seven drivers drove the same route in Atlanta, GA using and instrumented 3.1 L Corsica. A number of driving parameters were used to characterize the aggressiveness of the drivers. A factor analysis showed that two factors could be used to characterize the aggressiveness: 1) a roughness factor related to throttle position change; and 2) a high speed factor. Four drivers were selected for further studies. When the vehicle was driven over the same routes by these drivers, the seconds of enrichment ranged from zero for the two least aggressive drivers to 378 for the most aggressive driver.

51. R. Guensler, "Vehicle Emission Rates and Average Vehicle Operating Speeds", Ph.D. Thesis, UC Davis, 1993.

    This dissertation first describes the mobile source emission modeling regime and establishes the major sources of emission rate uncertainty. The research findings demonstrate that the date and analytical methods employed in regulatory agency analyses to derive speed correction factors result in estimates with high standard errors. The statistical shortcomings of the existing modeling approach include: data screening techniques, data aggregation techniques, and model functional form. A new weighted-disaggregate speed correction factor modeling approach is developed. The most important component of the research is the development of confidence and prediction intervals associated with using the speed-related outputs from emission models.

52. D. A. Hamrin and J. B. Heywood, "Modeling of Engine-Out Hydrocarbon Emissions for Prototype Production Engines", SAE Technical Paper Number 950984, 1995.

    A model has been developed which predicts engine-out hydrocarbon (HC) emissions for spark-ignition engines. The model consists of a set of scaling laws that describe the individual processes that contribute to HC emissions. The model inputs are the critical engine design and operating variables.

53. H. M. Haskew and J. J. Gumbleton, "GM's In-Use Emission Performance Past, Present, Future", SAE Technical Paper Number 88162, 1988.

    EPA and GM test programs have quantified the in-use emission performance of the GM close-loop emission control systems. The purpose of this paper is to summarize the results of these in-use programs, and show how this progress affects current and future air quality inventories. This paper is organized into four sections, as follows: 1) In-use Test Programs; 2) Exhaust Emission Performance; 3) Evaporative Emission Performance; and 4) Future Air Quality Inventories.

54. H. M. Haskew, et al., "The Execution of a Cooperative Industry/Government Exhaust Emission Test Program", Society of Automotive Engineers, Vol. 94C016,1994.

The EPA, the California Air Resources Board (CARB), and the Automotive Industry agreed to participate in the design and execution of a cooperative program to: 1) measure the driving characteristics of the in-use fleet in urban areas; and 2) determine the emissions contribution from driving modes not included in the current FTP. A comprehensive emissions testing program was developed at the Vehicle Emissions Laboratory at the GM Milford Proving Ground during late 1993 and early 1994. The testing included 27 vehicles provided by eight participating manufacturers representing a cross section of the current fleet of passenger cars and trucks up to 10,000 pounds GVW.

55. Y. Horie, "Critical Evaluation of On-Road Motor Vehicle Emission Estimation System", in Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 2-55 - 2-56, 1992.

Yuji Horie of Valley Research Corporation presented an evaluation of the on-road motor vehicle emission estimation system. Inasmuch as it has been shown from independent projects in the Southern California Air Quality Study that mobile source inventories are seriously underestimated for HC and CO relative to the oxides of nitrogen, he proposed a number of changes to the present inventory system: 1) make the vehicle procurement system more representative of the in-use fleet to better address the important contribution of high emission vehicles; 2) supplement the FTP with additional cycles that cover all engine operating conditions; 3) improve evaporative emission test procedures; 4) do more representative testing of the heavy duty fleet; and 5) obtain more vehicle activity data with electronic data acquisition systems.

56. L. Hrynchuk, “Preview of Future Changes Being Considered In the California Motor Vehicle Emission Inventory”, in Fourth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 5-119 - 5-128, 1994.

Lesha Hrynchuk from the California Air Resources Board (CARB) reported that major changes are being considered in the California motor vehicle emission inventory (MVEI). Preliminary estimates have been obtained for five areas. 1) Emission results from alternative driving cycles including the unified cycle will be incorporated. 2) New data from 550 vehicles indicates that high emitter frequency will be increased while keeping emission rates approximately unchanged. 3) Rather than considering only cold and hot starts, there will be a continuous start function based on soak time. 4) Increasing the number of starts to 6 to 8 per day. 5) It will be assumed that starts per vehicle is not a function of vehicle age, but that mile per vehicle per start is a function of age. This is the reverse of the current modeling approach. If all these changes are implemented, the inventory could increase 80-90% for ROG, 100-110% for CO and 35-45% for NOx. Other changes are under consideration. These include the addition of CO2, addition of an unregistered vehicle category, speed correction factors per particulate matter, and revised urban bus, evaporative, and heavy-duty emission rates.

57. L. Hrynchuk, “Changes in California's Inventory Models and the Effects on Motor Vehicle Emissions Estimates”, in 5th CRC On-Road Vehicle Emissions Workshop, San Diego California, pp. 1-1 - 1-14, 1995.

Lesha Hrynchuk, California Air Resources Board, discussed changes in the treatment of start emissions in California's inventory models and the effects on motor vehicle emissions estimates. Start emissions account for approximately 20% of the ROG, 25% of the NOx, and 50% of the CO in the current official inventory. Starts are not the same as trips since starts include non-destination trips. The old trip rate was 3.8 trips per vehicle per day, the proposed start rate is 6.3 starts per vehicle per day. Starts will no longer be classified either cold or hot. There will be multiple points over a continuum of soak times from 0 to 12 hours. The emissions impacts of the start changes have resulted in increased ROG, NOx, and CO emissions.

58. T. Inoue, et al., "Effect of Engine Design/Control Parameters and Emission Control Systems on Specific Reactivity of S.I. Engine Exhaust Gases", SAE Technical Paper Number 950807, 1995.

Since the reactivity of each chemical species in exhaust emissions differs, the effect on ozone formation varies depending on the composition of the exhaust gas components. This study examined the effect of different engine types, fuel atomization conditions, turbulence and emission control systems on emission species and specific reactivity.

59. G. Jession, et al., "Studies Relating On-Board Emissions Measurements with Engine Parameters and Driving Modes", in Fourth CRC-APRAC On-Road Vehicle Emission Workshop, San Diego, California, pp. 3-41 - 3-58, 1994.

Gerald Jession from Ford described their instrumented Aerostar. This vehicle acquires data directly from the EEC, uses other sensors for ambient temperature and pressure and catalyst temperature, includes an A/F sensor, an accelerometer, and an FTIR for exhaust composition. The FTIR is the unique feature of this vehicle. The vehicle has been driven on a chassis dynamometer to facilitate comparisons between the FTIR and traditional bench analyzers. Results of the comparison were excellent for CO, CO2, NOx, and NMHC. In addition to the regulated pollutants, the FTIR can measure a variety of other species. Results to date show very low emissions of NO2 and HONO on the road.

60. R. Joumard, P. Jost, and J. Hickman, "Influence of Instantaneous Speed and Acceleration on Hot Passenger Car Emissions and Fuel Consumption", SAE Technical Paper Number 950928, 1995.

Emission measurements have been conducted in three laboratories in France, Germany, and UK on the basis of 14 driving cycles specially designed to cover the whole range of vehicle speed and acceleration in urban traffic. 150 vehicles, representing the European 1995 fleet, were tested. Average unit emissions are presented as a function of average speed and vehicle type. Subsequently, a model was developed to calculate emissions during an urban trip as a function of the vehicle type and its instantaneous speed and acceleration.

61. E. W. Kaiser, et al., "Effect of Engine Operating Parameters on Hydrocarbon Oxidation in the Exhaust Port and Runner of a Spark-Ignited Engine", SAE Technical Paper Number 950159, 1995.

The effect of engine operating parameters (speed spark timing, and fuel-air equivalence ratio) on hydrocarbon (HC) oxidation within the cylinder and exhaust system is examined using propane or isooctane fuel. Quench gas (CO2) is introduced at two locations in the exhaust system (exhaust valve or port exit) to stop the oxidation process.

62. H. Katashiba, et al., "Development of an Effective Air-Injection System with Heated Air for LEV/ULEV", SAE Technical Paper Number 950411, 1995.

The paper describes the development of an effective secondary air-injection system that reduces harmful substances such as HC and CO. The secondary air in this system is heated to 300 C and injected into the exhaust pipe.

63. N. A. Kelly and P. J. Groblicki, "Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles", Journal of the Air & Waste Management Association, Vol. 43,pp. 1351 - 1357, 1993.

The emissions of hydrocarbons, nitric oxide, and carbon monoxide from a modern production vehicle were measured using on-board instrumentation during about 350 miles of driving in Los Angeles, CA. The driving routes, which were occasional heavily loaded conditions during the on-road testing led to the engine control computer calling for richer-than-stoichiometric operation.

During these brief enrichment events, which lasted for up to 29 seconds, CO emissions were increased by a factor of 2500 and HC by a factor of 40 over closed-loop stoichiometric operation. NO emissions were similar during low-load stoichiometric operation and high-load enriched operation.

64. T. Kirchstetter, et al., "Measurements Of California Light-Duty Vehicle Emissions in the Caldecott Tunnel", in Fourth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 6-49 - 6-60, 1994.

Thomas Kirchstetter from the University of California at Berkeley reported on a study on light-duty vehicle emissions in the Caldecott tunnel. The Caldecott tunnel has less than 1% HD vehicle traffic. The tunnel grade is 4.2%, with traffic flowing downhill in the morning and uphill in the afternoon. The average speed was approximately 45 mph with driving characterized as being within the FTP domain. The goals of the study were to compare fleet average LD vehicle emissions to predictions of EMFAC7F. NO2 was found to be 0.9 to 1.5% of the total NOx, in good agreement with Auto/Oil measurements. The effect of roadway grade was large, a factor of three for all pollutants. However, the grade effect was significantly diminished when emissions were expressed on a g/gal basis. The CO/NOx and HC/NOx ratios were not sensitive to roadway grade. However, it was found that the CO/NO ratio (14.7-16.7) was higher than predicted by EMFAC7F and the HC/NOx ratio (1.3-14) was 2.5 times higher than predicted by EMFAC7F. These ratios are similar to those observed in the Van Nuys tunnel in 1987 (13.3 for CO/NOx and 1/7 for HC/NOx).

65. J. Klimstra and J. E. Westing, "NO2 from Lean-Burn Engines - On its Lower Sensitivity to Leaning than NO", SAE Technical Paper Number 950158, 1995.

In this paper, Investigations on the NOx reduction for natural-gas-fueled spark-ignition engines with lean-burn techniques revealed that NO2 is less sensitive to reduction measures than NO.

66. J. Koupal and J. German, "Real-Time Simulation of Vehicle Emissions Using VEMISS", in Fifth CRC On-Road Vehicle Emissions Workshop, San Diego, CA, pp. 2-65 - 2-77, 1995.

An evaluation of real-time vehicle emission simulation using steady state emission map methodology was performed using EPA's computer model VEMISS. EPA developed this model from tests which generated steady state emission maps across a range of vehicles. A pilot evaluation was performed comparing model results against bag and real-time transient emission data with favorable results. However, several areas for improvement were identified. These include use of an electric dynamometer for data generation over the full range of vehicle operation and the development of methodologies to predict real-time catalyst conversion efficiency and deceleration emission events. John Koupal, U.S. EPA, noted that methodologies for incorporating a cold start component to the model based on cold start emissions testing performed by EPA were investigated under contract. The model prediction is more accurate for engine-out than for tail-pipe emissions.

67. J. Koupal, "In-Use Emissions Over Intermediate Vehicle Soak Periods and Start Driving", in 5th CRC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 7-53 - 7-66, 1995.

In order to evaluate the exhaust emission impact of in-use soak duration, EPA performed testing following a variety of soak periods. John Koupal, U.S. EPA, reported results which showed significant emission increases following soak periods of even relatively short duration, due to the rapid cooling of the catalyst after the vehicle was shut off. In order to assess strategies for reducing emissions following intermediate soaks, the relative merits of catalyst insulation and catalyst light-off technologies were evaluated. In addition, a comparison of in-use driving and emission behavior following vehicle startup to FTP start driving and emission levels was performed. Proof of concept testing with external insulation showed significant NMHC and NOx reduction on soaks less than 90 minutes. EPA is also investigating internal insulation systems.

Insulation, however, impacts catalyst durability. An important issue is whether the benefit of controlling soak emissions is cost effective.

68. M. Lapuerta, J. M. Salavert, and C. Domenech, "Modeling and Experimental Study About the Effect of Exhaust Gas Recirculation on Diesel Engine Combustion and Emissions", SAE Technical Paper Number 950216, 1995.

An experimental study has been made on a small size single cylinder supercharged DI Diesel engine, with adequate equipment for its measurement, control, and diagnostics. The primary purpose of the study was to analyze the effect of exhaust gas recirculation on engine emissions, at partial loads.

69. J. Laurikko and P. Aakko, "The Effect of Ambient Temperature on the Emissions of Some Nitrogen Compounds: A Comparative Study on Low-, Medium-and High-Mileage Three-Way Catalyst Vehicles", SAE Technical Paper Number 950933, 1995.

Using fast FTIR-technology to complement the normal regulated emission analysis, VTT Energy has performed exhaust emission measurements for several light-duty motor vehicles representing a variety of current level technologies, mostly employing a tree-way catalytic converter. Test results suggest that nitrous oxide output varies largely from vehicle to vehicle, and its is also dependent on the ambient temperature. Most significant factor, however, seems to be vehicle mileage, or rather catalyst activity, as already suggested in previous studies.

70. D. R. Lawson, "Los Angeles In-Use Vehicle Emissions Study: High Emitter Phase", in Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 5-15 - 5-44, 1992.

Doug Lawson of the Desert Research Institute reported results from the High Emitter Phase of the 1991 Los Angeles In-Use Vehicle Emissions Study. The objective of the study was to test the effectiveness of remote sensing devices to identify high emitters, with emphasis on 1980 model year and newer vehicles. The ten-day study obtained more than 60,000 valid remote sensing readings of passing vehicles. Three hundred thirty-four vehicles that were stopped based on the remote sensor reading received roadside inspections. Of these vehicles, 92% failed the California Smog Check test, 41% were found to be tampered with; and another 25% had defective emission control systems. The smog check records (from the scheduled inspection) for these vehicles showed no correlation with their in-use emissions levels. Eighty of the cars also received an IM240 test, using a transportable dynamometer provided by K. Knapp of EPA. Nearly all the cars that were given the IM240 failed. An unexpected finding was that three vehicles emitted > 100 gm/mi of NOx.

71. D. C. LeBlanc, et al., "Carbon Monoxide Emissions From Road Driving: Evidence of Emissions Due to Power Enrichment", in 73rd TRB Meeting, Washington, D.C., 1994.

This paper examines one aspect of vehicle emissions behavior, that is, emissions due to engine power enrichment, that is not well represented in existing models. A 46 instrumented vehicle database was used to analyze the importance of enrichment emissions to overall vehicle trip emissions records, while relating these emissions to velocity-acceleration characteristics. The authors conclude that enrichment emissions can be a significant contributor to overall vehicle emissions.

72. C. Little, "DOT Research Activities Related to Vehicle Emissions", in Fourth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 5-169 - 5-180, 1994.

Cheryl Little from the US DOT Volpe Center reviewed DOT's broad research interests in vehicle emissions. Overall goals are to provide DOT with information to make national policy decisions, provide technical guidance to State and local transportation/air quality professionals, and to examine common beliefs about mobile sources of emissions. Activities include policy analysis of

regulatory activities and control measures such as gasoline taxes and "Cash for Clunkers"; examination of emissions/air quality models such as MOBILE5 and California's TCM Tool model retrofit; and emissions/air quality measurement programs such as the California border crossing study of super-emitting vehicles. A major program area is the determination of intelligent vehicle highway systems (IVHS) impact on emissions. The goal is to be able to predict changes in emissions due to changes in driving patterns due to traffic management systems, traveler information systems and public transit systems.

73. T. Lusk, "Sensitivity of Motor Vehicle Inventory to Change In Vehicle Activity Data", in Fourth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 5-129 - 5-140, 1994.

Tom Lusk of CARB examined the sensitivity of the motor vehicle inventory to changes in vehicle activity data. Mileage accrual rates and vehicle age distributions have been assumed to be uniform throughout the State of California. This, however, is not actually the case. Accounting for actual county level differences can change ROG, CO and NOx emissions 20-25%. A number of sensitivity tests were also performed. It was found that changing the number of trips by 100% can change ROG 48%, CO 56% and NOx 33%. Other factors that made large changes in emissions were changing the ambient temperature profile, changing the cold start/hot start split, and skewing the speed profile to low speeds. Overall, the sensitivity tests demonstrated the need for further work on activity factors and the need for local data.

74. H. Maldonado, et al., "Air Resources Board's Research Projects to Improve the Mobile Source Emissions Inventory", in A&WMA The Emission Inventory: Perception and Reality, Pasadena, California, pp. 51 - 70, 1993.

EMFAC/BURDEN is now called MVEI (Motor Vehicle Emission Inventory) model. Future EMFAC version will have multiple emission factors for different applications (modal & aggregate). The study contains a detailed description of Sierra Research's SCAB chase car study

and the resulting UNIFIED cycle. Description of the work they did creating a model called VEHSIM and VEHSIME which calculates second-by-second emissions given a driving trace and using emission maps is also presented.

75. J. P. Markey, "Findings From EPA's Study of In-Use Driving Patterns", in Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 6-107 - 6-120, 1992.

James Markey from the EPA's Office of Mobile Sources presented findings from EPA's study of in-use driving patterns. The information obtained from this work will provide information on vehicle operating conditions of today's fleet and whether these conditions are adequately represented by the FTP. The main areas of emphasis include driving behavior (speed and acceleration); trip behavior (trip distance, duration, average speed, idle, stops, etc.); and cold start emissions (including soak time and driving behavior after starts). Analysis of the driving survey data base had just begun at the time of the workshop.

76. H. Nakamura, H. Motoyama, and Y. Kiyota, "Passenger Car Engines for the 21st Century", SAE Technical Paper Number 911908, 1991.

Reviewed various passenger car engine technologies and their impacts on the environment. Also discussed various alternative transportation energy sources such as alcoholic fuels, natural gas, hydrogen and electricity.

77. T. Noguchi, et al., "New Light Weight 3 Liter V6 Toyota Engine with High Output Torque, Good Fuel Economy and Low Exhaust Emission Levels", SAE Technical Paper Number 950805, 1995.

A new generation 3.0 Liter V6 engine, the 1MZ-FE, has been developed. Through improvement of the basic technical characteristics of each individual component, the 1MZ-FE has achieved compactness, weight reduction and good fuel economy without adding systems or components.

78. A. Ohata, et al., "Model Based Air Fuel Ratio Control for Reducing Exhaust Gas Emissions", SAE Technical Paper Number 950075, 1995.

In order to satisfy future demands of low exhaust emission vehicles (LEV), a new fuel injection control system has been developed for SI engines with three-way catalytic converters. An universal exhaust gas oxygen sensor (UEGO) is mounted on the exhaust manifold upstream of the catalytic converter to rapidly feedback the UEGO output signal and a heated exhaust gas oxygen sensor (HEGO) is mounted on the outlet of the converter to achieve an exact air fuel ratio control at stoichiometry. The control law is derived from mathematical models of dynamic air flow, fuel flow and exhaust oxygen sensors. Experimental results on FTP exhaust emissions show a dramatic reduction of HC, CO and NOx emissions and a possibility of practical low emission vehicles at low cost.

79. U.S. Office of Technology Assessment, Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles, Washington, DC: U.S. Government Printing Office, 1990.

In this report, OTA gives a broad overview of the qualities of the competing fuels and examines in depth some of the most contentious issues associated with the wisdom of active Federal support for introducing the fuels. Areas of uncertainty that affect the debate on Federal support include: fuel cost; the air quality effects of the new fuel; effects on energy security; other environmental impacts of the fuel; and consumer acceptance.

80. K. N. Pattas, et al., "Computer Aided Assessment of Catalyst Ageing Cycles", SAE Technical Paper Number 950934, 1995.

The purpose of this paper is to extend the author's approach for 3WCC modeling and evaluation in the direction of covering some aspects of ageing behavior. This methodology takes into account the effect of thermal loading, high-temperature oxidation, and poisoning of the catalyst.

81. W. R. Pierson, et al., "Summary of Recent Tunnel Studies in the Fort McHenry and Tuscarora Mountain Tunnels", in Fourth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 6-1 - 6-48, 1994.

A summary of the tunnel studies conducted in the Tuscarora and Fort McHenry tunnels, both of which are on interstate freeways with speeds averaging approximately 50 mph, were presented. Tuscarora has negligible grade while Ft. McHenry has maximum grades of 3.76%. It was noted that the vehicle fleets were dominated by relatively clean, late model vehicles and thus were not representative of a typical urban fleet. Light-duty (LD) vehicle emissions were separated from heavy-duty (HD) emission by regressing the total emission rate versus the relative fraction of LD and HD vehicles. The fractions vary significantly by time of day and day of the week. Results were compared to MOBILE5 and it was concluded that the model predictions were generally reasonable (within 50%). Road grade has a large effect on emissions on a grams-per-mile basis, but not on a grams-per-fuel consumed basis. Remote sensing was used to determine CO/CO2 and HC/CO2 ratios, but HC/CO2 remote sensing did not work well. NMHC emissions were speciated and separated by regression into LD and HD components. Chemical mass balance was used to separate running loss emissions from LD exhaust emissions. It was found that running loss emissions were less than 20% of the total NMHC, in reasonable agreement with MOBILE5. It was concluded that emissions models need to account for grade, that improvements are needed in HC remote sensing, that better real-world on-road exhaust NMHC speciation profiles are needed, and that further tunnel studies are needed to address vehicle fleets and driving conditions that are more representative of urban conditions.

82. Auto/Oil Program, "Emissions Results of Oxygenated Gasolines and Changes in RVP", Technical Bulletin No. 6 Report 1991.

The study evaluated the emissions impacts of oxygenated fuels for 20 1989 model year vehicles. Results for CO emissions showed reductions of less than 15% for oxygenated fuels relative to conventional fuels.

83. Radian Corporation, "Evaluation of the California Pilot Inspection/Maintenance (I/M) Program", Final report submitted to the California Bureau of Automotive Repair Report Radian Corporation, 1995.

Determined the emission reduction effectiveness of alternative loaded mode tests such as the acceleration simulation mode (ASM) tests compared to the IM240 test. Demonstrated how well high emitting vehicles within a designated geographical area can be identified using remote sensing equipment. Demonstrated the effectiveness of using a high-emitting vehicle profile (model year, engine family defect history, tampering, probability, number of times vehicle was sold, remote sensing data, etc.) to identify vehicles with the highest probability of failing an emission test.

84. M. Reineman and R. Nash, "EPA/Industry Dynamometer Comparison Study - Nine Vehicle Fleet", Report United States Environmental Protection Agency National Vehicle and Fuel Emissions Laboratory, 1995.

Between October 1993 and September 1994 a test program was conducted at the EPA National Vehicle and Fuel Emissions Laboratory (NVFEL) to evaluate emission and fuel economy differences between tests conducted on a large single roll electric and a twin small roll hydrokinetic chassis dynamometers. The principal objective of the program was to compare emissions and fuel economy results from a twin 8.65 in. roll chassis dynamometer, adjusted per current EPA practice, to results obtained with the 48 in. electric dynamometer, which was adjusted to more closely duplicate actual on-road forces over a wide speed range (70 to 10 mph/hr).

85. C. T. Ripberger, et al., "Feasibility of Using Bag II Average Emissions to Represent All Closed-Loop Emissions In A Modal Model", in Fourth CRC On-Road Vehicle Emission Workshop, San Diego, California, pp. 5-73 - 5-88, 1994.

Carl Ripberger from the US EPA discussed the feasibility of using FTP bag 2 average emissions to represent all closed-loop emissions in a modal vehicle emission model. When cumulative emissions during the bag 2 portion of the FTP were plotted as a function of time for 13 1986-1990 light-duty cars, it was found that the emissions rate was constant over time scales greater than a couple of minutes. On shorter time scales. vehicle emissions variability is quite evident. The results suggest that vehicle emissions could be modeled using four general categories, cold start, hot start, commanded enrichment, and closed-loop operation. All emissions would be based on vehicle operating time or, in the case of starting, on an event basis.

86. M. Rodgers, et al., "The Impact of Enrichment on Atlanta Vehicle Emissions", in Fourth CRC-APRAC On-Road Vehicle Emission Workshop, San Diego, California, pp. 5-3 - 5-10, 1994.

This work was extended by Richard Du Bose from the Georgia Institute of Technology. A 1993 Chevrolet Lumina, 3.1 L and a 1993 2.2 L Chevrolet Corsica were instrumented to record throttle position, RPM, an A/F commanded environment indicator, and other parameters. They were driven by four drivers representing the various behavior groups over five routes that were selected as representative of typical drives in a large metropolitan area. Determining the impact of grade, location, and congestion on enrichment frequency was a major goal of the study. Drivers were instructed to drive the prescribed routes in their usual manner of driving and were asked to maintain a log of the drives, including notation of congestion and other driving conditions. It was confirmed that drivers make an important difference in the enrichment frequency, and that the results matched the driver selection study. It was also concluded that transportation network features (i.e. grade, congestion) are good enrichment predictors. Mike Rodgers of the Georgia Technology discussed the overall impact of enrichment on the Atlanta Emissions Inventory. It was

noted that the 1990 inventory shows highway mobile sources to be the predominant contributor to CO and a major contributor to the HC. Studies have been conducted which allow estimation of emission factors for typical and enriched operational modes, as well as associated activity factors. There are 2.1 M vehicles in Atlanta averaging 16K miles per year. Activity data shows 2.7 cold starts (1 hour or more soak time) per day and 4.9 warm starts. Assuming enrichment emission rates of 5 g/sec and 50 mg/sec., respectively, for CO and HC car and truck emission lead to the conclusion that the 1.0% enrichment frequency rate in Atlanta driving would account for 66% of the CO and 4% of the HC emitted from well-maintained, current technology vehicles.

87. M. Ross and F. An, “The Use of Fuel by Spark Ignition Engines”, SAE Technical Paper 930329, 1993.

Fuel consumption per revolution is approximately a linear function of work output per revolution, for power levels less than about two-thirds of the power at wide open throttle. Thus Pf /N= a + bPb /N, where N is engine speed, Pf is fuel energy rate (kW), and Pb is power output (kW). The approximation is relatively good for engine speeds typical of regulatory driving cycles.

88. M. Ross, et al., "Real-World Emissions from Conventional Cars: 1993, 2000 & 2010", Report, Physics Department, the University of Michigan, 1995.

There are three major sources of exhaust emissions: test, off-cycle, and malfunction, i.e. emissions measured in the regulatory or certification tests, the excess caused by driving at higher power than in the tests, and the excess caused by malfunction of on-board emissions control systems (ECS), respectively. Fuel-related sources other than exhaust are evaporation and upstream fuel processing. These four sources are roughly comparable in importance. This report deals with all these, but focuses on the two loopholes in the exhaust emissions control program: off-cycle and malfunctioning emissions.

89. J. C. Sagabiel, et al., “Ozone Reactivities of Real-World Emissions of Organic Species From Motor Vehicles”, in Fourth CRC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 6-61 - 6-82, 1994.

As discussed in the summary section on diesel emissions, John Sagabiel of DRI presented reactivity factors for NMHC observed in the Tuscarora and Forth McHenry tunnels. Individual hydrocarbons were binned into three groups: parafins, olefins, and aromatics. On a mass basis at Tuscarora, these groups accounted for 35, 24, and 42% of the LD emissions, respectively. However, using Carter MIR factors, the parafins, olefins, and aromatics were found to constitute 11, 41, and 49% of the reactivity, respectively. LD reactivity-weighted emissions (mg ozone/mg NMHC) were 4.09 at Tuscarora and 4.03 at Fort McHenry. It must be kept in mind that these are for hot stabilized emissions with as much as a 20% running loss component. HD emissions had somewhat lower reactivity-weighted emissions of 3.63 mg ozone/mg NMHC. The HD reactivity is heavily influenced by the semi-volatile aromatics.

90. SAIC, "Assessment of Computer Models for Estimating Vehicle Emission Factors, Volumes 1-3", Technical Report Systems Application International Corporation, for CRC-APRAC, 1991.

Critically assessed MOBILE4 and EMFAC7E under the sponsorship of the Coordinating Research Council. First, a side-by-side structural comparison of the two models was conducted. Second, the sensitivity of MOBILE4 and EMFAC7E to numerical changes in model inputs and parameters was evaluated.

91. L. Schipper, et al., "Energy Use In Passenger Transport in OECD Countries: Changes Between 1970 and 1987", Report #LBL-29830, Lawrence Berkeley Laboratory, 1991.

Between 1970 and 1987, energy-use patterns in industrialized countries changed in significant ways. In this paper, changes were analyzed that took place in the structure and intensity of energy use for travel in industrialized countries.

92. S. Shepard, et al., "Results for Analysis and Development of Cold-Start Emission Model", Final Report #SYSAPP-93/177, Systems Applications International, 1993.

This report describes the analysis of EPA cold start data performed on a dyno for different engine speeds/loads. The testing is part of the FTP revision. Describes the development of a catalyst conversion model.

93. S. B. Shepard, et al., "Cold-Start Motor Vehicle Emissions Model", Report #A669, Systems Applications International, 1994.

In response to a mandate in the Clean Air Act Amendments (CAAA) of 1990 to review the federal test procedure (FTP), the EPA is conducting an intensive study of real-world driving behavior to determine the representativeness of the FTP. As part of the study, the EPA completed a test program where cold-start emissions data were collected from 29 model year 1990-1992 vehicles at five different targeted RPM and engine load points. We analyzed the data collected from a subset of five of the tested vehicles and developed a cold-start mobile emissions model that predicts grams per second of HC, CO, and NOx for these five vehicles. The model was designed to be compatible with the existing EPA computer simulation models VEMISS (which predicts vehicle emissions under warm and stabilized operating conditions) and VEHSIM (which predicts vehicle fuel economy).

94. B. C. Singer and R. A. Harley, "A Fuel-Based Motor Vehicle Emission Inventory for Los Angeles", in 5th CRC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 1-35 - 1-46, 1995.

Brett Singer, University of California-Berkeley, discussed a fuel-based motor vehicle emission inventory for Los Angeles. The UC-Berkeley approach advocated calculating vehicle emissions based on fuel specific emission factors (i.e. grams of pollutants emitted per unit of fuel burned combined with fuel sales data). This technique was demonstrated using a large data base of infrared remote sensing measurements collected in Los Angeles during the summer of 1991 (Stedman et al., 1994). CO emission factors were computed by model year, separately for cars and trucks, from remote sensing data. Fuel economy-weighted average emission factors were computed and combined with fuel sales data. Calculations indicate that BURDEN7F underestimates CO exhaust emissions from gasoline powered vehicles. This approach offers several advantages over traditional motor vehicle emission inventory methods: 1) fuel-specific emission factors fluctuate much less than gram-per-mile emission factors as driving conditions change; 2) emission factors are based on measurements from large, on-road samples, which include malfunctioning and tampered vehicles. Measurements can be from remote sensing and/or tunnel studies; 3) the distribution of total miles driven by vehicle type and age is measured directly; and 4) gasoline and diesel fuel sales are already tracked at a statewide level. Using this method, site to site average emissions looked very similar.

95. L. S. Socha, et al., "Emissions Performance of Extruded Electrically Heated Catalysts in Several Vehicle Applications", SAE Technical Paper Number 950405, 1995.

This paper discusses the impact of these design parameters on cold-start emissions reduction. Low mass, extruded electrically heated catalysts (EHC) followed directly by a light-off and air converter reduced cold start non-methane hydrocarbons (NMHC) by greater than 80 percent. To achieve this level of reduction, the design of the EHC cascade system, power level, and heating time must be appropriately established.

96. J. H. Southerland and R. Myers, "Developing Improved Emission Factors and Assessing Uncertainties", in A&WMA The Emission Inventory: Perception and Reality, Pasadena, California, pp. 339 - 350, 1993.

This paper discusses how to handle uncertainty in emission factors (doesn't deal much with mobile sources). Emission factors are often used under exacting circumstances which may affect their validity when precise control limits are developed.

97. J. Staab, et al., "Catalyst Efficiency Under Real Road Conditions", SAE Technical Report #890495, 1989.

The latest technical state of the on-board exhaust emissions measurement system is described. The capability of the system of measuring the low emissions down-stream a catalyst under real-time conditions is pointed out.

98. D. H. Stedman, “Automobile carbon monoxide emission”, Environmental Science and Technology, Vol. 23,□□2, pp. 147 - 149, 1989.

Looked in detail at all the programs currently in place in the state of Colorado that support to control mobile source CO emissions. These programs include Inspection and Maintenance (I/M), Oxygenated Fuels, and a Better Air Campaign featuring voluntary no-drive days.

99. D. Stedman, et al., “Results of CO, HC, and NOx Studies”, in Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 5-67 - 5-88, 1992.

Donald Stedman from the University of Denver presented a summary of his group's remote sensing studies from a number of locations around the world, including the United States, Canada, Australia, and Sweden. The remote sensing data from all these locations show a consistent pattern: the majority of the vehicles' emissions are extremely low, with just a few gross polluters. These few gross polluters have been shown to be responsible for most of the pollution coming from the measured fleet. Remote sensing data from Melbourne, Australia also demonstrated that the CO emissions from LPG-fueled vehicles were nearly twice those from gasoline-powered vehicles. The remote sensing data have raised serious questions about mobile source emission estimates based on models and the assumptions contained therein. Stedman also presented results from a Provo, Utah study where his group used remote sensing to find high emitters that were subsequently repaired. Their data showed that repairs of nearly 40 high-emitting vehicles resulted in a 35% reduction in CO emissions, (about 0.5 ton/vehicle). If repairs are effective for two years, that equates to $200 per ton of CO reduction.

100. D. Stedman, et al., "On-Road Remote Sensing of CO and HC Emissions in California", Report #A032-093. CARB Research Division, California Air Resources Board, 1994.

This report summarizes the results of a study to demonstrate the accuracy of remote sensors in measuring tailpipe emissions from in-use vehicles. The study included three phases: a comparison of remote sensor and instrumented vehicle readings; a comparison of remote sensor readings with roadside dynamometer tests; and a survey of emissions from over 90,000 vehicles at various locations in Northern and Southern California. The study found that emissions from most vehicles are almost negligible; a small fraction (3 percent) of cars account for a large portion of overall emissions (23 percent of CO and 27 percent of HC).

101. D. Stedman and D. Smith, “NOx Data by Remote Sensing”, in Fifth CRC On-Road Vehicle Emissions Workshop, San Diego, California, 1995.

Donald Stedman, reported on progress made using remote sensing for detecting NOx emissions. Data were presented showing the continuous improvement of the NOx channel. Most vehicles were low emitting for NOx, however, a few high NOx emitters were noted. High CO emissions corresponded to low NOx readings and vice-a-versa as would be expected based on combustion chemistry.

102. R. Stephens and S. Cadle, “Remote Sensing Measurements of Carbon Monoxide Emissions from On-Road Vehicles”, J. Air and Waste Management Association, Vol. 41, Issue 1, pp. 39 - 46, 1991.

Describes instrumentation that remotely measures the CO emissions from 4000 vehicles that were identified by make and model year from Colorado state vehicle registration records during January 1989.

103. R. Stephens, "FTP Emissions Variability and the Significance to Remote Sensing Measurements", in Proceedings of the Third Annual CRC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 5-87 - 5-111, 1992.

Robert Stephens from GM presented preliminary results of a study that examined the second-by-second exhaust emissions data from 21 FTP tests performed on the seven high emitters tested in the A/O AQIRP. The objectives of the study were: to investigate the representatives of one-second emissions measurements during the FTP to overall FTP mass emission rates for the same vehicles; to identify the engine operating conditions that would optimize remote sensing study results; to understand errors of omission (false passes, Eo); and to determine whether one-second emissions readings can be used to represent average emissions measurements. Preliminary analysis showed that randomly selected one-second emissions data points correlated well with overall FTP emissions for CO and HC. Differences between average emission rates for accelerations, cruise, and deceleration conditions were not large enough to recommend one mode over another for remote sensing identification of these high emitters. Errors of omission were presented for various definitions of what constitutes a high emitter. At reasonably high cut points, such as 4% CO, errors of omission were low. Overall, the data suggest that random one-second remote sensing measurements can be used to estimate average CO FTP emissions from high emitters, and hence are useful for inventory purposes. More information would be required before the same conclusion could be made for HC emissions.

104. R. D. Stephens, "Remote Sensing Data and A Potential Model of Vehicle Exhaust Emissions", in Third Annual CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, California, pp. 3-97 - 3-119, 1992.

Bob Stephens of General Motors presented remote sensing data acquired by GM during the Los Angeles In-Use Vehicle Emissions Study of 1991. The data he presented showed that the top 10% of CO emitters produced 56% of the total estimated CO and 34% of the estimated total exhaust HC. He reported that the top 10% of the HC emitters produced 66% of the HC and 28% of the CO. He also developed a model of vehicle emissions using remote sensing data, and showed that for each vehicle model year, a log-normal relationship exists between the fractions of vehicles and observed emission concentrations. This approach has the potential of improving models of vehicle exhaust emissions. However, it was stated that additional research is required to determine if these same relationships hold for vehicle fleets at different locations.

105. R. Stephens, “Remote Sensing Data and A Potential Model of Vehicle Exhaust Emissions”, Journal of Air Waste Management Association., Vol. 44,pp. 1284 - 1292, 1994.

The GM R&D remote sensing was used to measure the CO and HC emissions from approximately 15,000 vehicles. Analysis were performed separately for each vehicle type and for passenger cars by separate model years. The data indicate that the passenger cars with the highest 10% of CO emissions generate approximately 58% of the total CO from all cars. Similarly, the 10% highest HC-emitting cars generated 65% of the total HC from cars.

106. P. J. Sturm, K. Pucher, and R. A. Almbauer, “Determination of Motor Vehicle Emissions as a Function of the Driving Behavior”, in A&WMA The Emission Inventory: Perception and Reality, Pasadena, California, pp. 483 - 494, 1993.

This paper describes the use of emission maps and driving cycles to predict total trip emissions. Emission maps are determined from dynamometer tests. Paper addressed the importance of elevation changes. The study utilized speed/acceleration for emission map indexing. Specialized driving cycles were developed for constant accelerations and constant speeds. A complete estimate was determined combining vehicle activity and emission factors.

107. K. Takeda, et al., “Mixture Preparation and HC Emissions of a 4-Valve Engine with Port Fuel Injection During Cold Starting and Warm-up”, SAE Technical Paper Number 950074, 1995.

This paper quantitatively analyzed the fuel intake port and cylinder wall-wetting, burned fuel and engine-out hydrocarbon emissions, and cycle by cycle firing condition, utilizing a specially designed analytical engine. The effect of mixture preparation and fuel properties for engine-out hydrocarbon emissions, during the cold engine start and warm-up period, were quantitatively clarified.

108. M. Todd and M. Barth, “The Variation of Remote Sensing Emission Measurements with respect to Vehicle Speed and Acceleration”, in Coordinated Research Council, 5th Annual On-Road Vehicle Emissions Workshop, San Diego, California, 1995.

Examined the variation of vehicle emissions measured by a remote sensing device with respect to different speeds and accelerations. The parameters of speed and acceleration were carefully measured for a vehicle traveling by the remote sensor, and the development of a functional relationship between speed and acceleration with remotely sensed emission levels was explored.

109. US EPA, "Review of Federal Test Procedure Modifications Status Report", Technical Report, Office of Mobile Sources, Office of Air & Radiation, US Environmental Protection Agency, 1993.

This status report addressed the progress EPA has made to date in complying with the CAA provision and the status of future research efforts. The newly proposed modifications to the existing Federal Test Procedure - the Supplement Federal Test Procedure, is reviewed.

110. US EPA, "Support Document to the Proposed Regulations for Revisions to the Federal Test Procedure: Detailed Discussion and Analysis", Technical Report, US EPA, Office of Air and Radiation, 1995.

This technical report documents the need for certain proposed additions to the Federal Test Procedure (FTP) to ensure that it reflects current driving behavior. The first section provides background information on the current FTP driving cycle and discusses the need for the proposed modifications to the FTP. In section two, information is presented on the differences between in-use driving and the FTP. This is followed, in section three, by a summary of emission testing results, which quantify the emission impact of the non-FTP driving. Methods for controlling emissions from non-FTP driving are discussed in section four. This section also discusses the appropriate level of control, as well as adjustments for special cases. Section five review feasibility issues, followed by a cost and benefits discussion in section six. The final section presents a discussion of the required test procedures.

111. US EPA, "Regulatory Impact Analysis, Federal Test Procedure Revisions", Technical Report, Office of Mobile Sources, Office of Air and Radiation, US Environmental Protection Agency, 1995.

This RIA briefly addresses the air quality problems and needs within the United States. However, the primary purpose of this RIA is to present the Agency's cost, emission reduction, and cost effectiveness estimates associated with the proposed regulations. Various regulatory and control options were also considered.

112. S. Washington and T. Young, “"Modal" Activity Models for Predicting Carbon Monoxide Emissions from Motor Vehicles”, in Fifth CRC On-Road Vehicle Emissions Workshop, San Diego, CA, pp. 2-109 - 2-125, 1995.

Troy Young presented a summary of the Institute of Transportation Studies, University of California-Davis program to develop new activity based emission prediction model algorithms. The improved algorithms need to be sensitive enough to capture the effects of microscopic flow adjustments, or flow smoothing, that are now commonly considered among transportation and air quality planners. Specifically the models being developed are for predicting carbon monoxide emissions from motor vehicles. Two regression model algorithms were determined based on bag data from the speed correction factor data base and an elemental model algorithm developed from an Australian vehicle's second-by-second emissions data. Troy showed that a modal elemental model, based on second-by-second emissions data from one vehicle, shows how emissions for a given speed profile can be predicted with the use of simple variables such as: final speed of acceleration; initial speed of deceleration; acceleration/deceleration rate; and cruise speed. Further development is required to extend this work for application to a fleet, but the potential exists to use this for of emission model for detailed project level analyses, particularly where there is a desire to capture effects of small changes in speed profile.

113. H. C. Watson, “Effects of a Wide Range of Drive Cycles on the Emissions from Vehicles of Three Levels of Technology”, SAE Technical Paper Number 950221, 1995.

Exhaust emission tests were performed on a fleet of vehicles comprising a range of engine technology from leaded fuel control methods to closed loop three-way catalyst meeting 1992 U.S. standards but marketed in Australia. Each vehicle was tested to 5 different driving cycles including the FTP cycles and steady speed driving.

114. D. S. Weiss, et al., “Durability of Extruded Electrically Heated Catalysts”, SAE Technical Paper Number 950404, 1995.

Extruded metal honeycombs are used as electrically heated catalysts (EHCs). The durability requirements of this application make demands on high surface area, thin cross-section metal honeycombs. Significant durability improvements over previous extruded metal honeycomb EHCs have been achieved by material and package design changes.

115. T. Wenzel and M. Ross, “Emissions from Modern Passenger Cars with Malfunctioning Emission Controls”, SAE Technical Paper, 1996.

This paper reports on part of a University of Michigan study of real-world emissions by conventional gasoline-fueled cars. The paper focuses on vehicles whose emission control systems (ECS) are malfunctioning.

116. D. J. Williams, J. N. Carras, and D. A. Shenouda, "Traffic-Generated Pollution Near Arterial Roads Models and Measurements", in Fourth CRC-APRAC On-Road Vehicle Emission Workshop, San Diego, California, pp. 5-89 - 5-117, 1994.

This project outlines approach of using instantaneous emissions. Model does loose job of taking into account the emission control system function. Methods are suggested for appropriately evaluating the emission control systems. Catalyst is modeled with a warm up period, and relative efficiency. Dispersion models were applied for CO modeling.

117. J. Zamurs and R. Conway, "Comparison of Intersection Air Quality Models' Ability To Simulate Carbon Monoxide Concentrations in an Urban Area", Report, New York DOT, 1989.

Instruments were set up at six intersections to measure carbon monoxide concentrations and meteorological data. Traffic data were collected by videotaping. To date, results from two of the six intersections have been analyzed. Model performance was disappointing. The models, on average, under predicted observed concentrations, with only those models that separate composite emissions into their more discrete components indicating a potential for approaching or over predicting observed carbon monoxide levels.

118. Z. Zhang, et al., "Worldwide On-Road Vehicle Exhaust Emissions Study by Remote Sensing", Environmental Science & Technology, Vol. 29, Issue 9, pp. 2286 - 2294, 1995.

Presents an analysis and comparison of 22 fleet profiles collected by the remote sensor in different regions around the world. The absolute emissions differences between well and badly maintained

vehicles of any age are considerably larger than observable effects of emission control technology and vehicle age.

Appendix B: Vehicle Testing Summary Sheet

This vehicle testing summary sheet lists all of the vehicles that were tested in this NCHRP 25-11 project. The columns are as follows:

num is vehicle test number (note bad tests were deleted);

Veh. Name is the vehicle name;

MY is model year;

date is date tested;

testn1 is the first VERL test number;

testn2 is the second VERL test number;

Cat is the vehicle/technology category (based on recruitment bins);

Emitter is the emitter level classification;

FTP, US06, MEC: **E** engine-out data, **T** tailpipe data;

AC - air conditioning hill performed; **E** engine-out data, **T** tailpipe data;

RPT - repeat hill performed; **E** engine-out data, **T** tailpipe data;

veh par - detailed vehicle parameters measured;

Mass – weight of vehicle (lbs.);

Tier is the emission certification category;

Veh Type is the type of vehicle;

State is the origin state of the vehicle;

Odom – odometer reading on test date;

Z/weight is power to weight ratio;

THCgm is grams per mile total HC over the FTP;

TCOgm is grams per mile total CO over the FTP, and

TNOxgm is grams per mile total NO_x over the FTP.

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
9	**Ford_E_150_83**	83	6/3/96	h9606004	h9606005	13	high	ET	ET	ET	ET	ET	yes	4250	0	truck	CA	38812	0.041	2.21	79.57	0.39
13	**Toyota_Celica_8**	81	6/16/96	h9606028	h9606044		high	ET	ET	ET	ET	ET	yes	3000	0	car	CA	24601	0.035	4.41	21.13	2.08
14	**Ford_Bronco_82**	82	6/18/96	h9606038	h9606039	13	high	ET	ET	ET	ET	ET	yes	4500	0	truck	CA	61706	0.039	2.03	9.05	1.75
15	**Honda_Civic_76**	76	6/20/96	h9606042	h9606043	1	normal	ET	ET	ET	ET	ET	yes	2000	0	car	CA	88705	0.034	0.91	3.99	0.91
16	**Honda_Civic_91**	91	6/21/96	h9606047	h9606048	4	normal	ET	ET	ET	ET	ET	yes	2500	0	car	CA	73546	0.037	0.16	3.57	0.36
17	**Toyota_Tercel_9**	95	6/25/96	h9606054	h9606055	10	normal	ET	ET	ET	ET	ET	yes	2250	1	car	CA	23249	0.041	0.09	1.20	0.06
18	**Toyota_PU_90**	90	6/25/96	h9606056	h9605058	15	normal	ET	ET	ET	ET	ET	yes	2750	0	truck	CA	91080	0.042	0.24	2.64	0.17
19	**Honda_Prelude_8**	82	6/26/96	h9606059	none	2	high	ET	none	none	none	none	yes	2500	0	car	CA	191203	0.040	5.80	11.73	4.01
20	**Buick_Century_8**	86	6/27/96	h9606062	h9606063	4	normal	ET	ET	ET	ET	ET	yes	3500	0	car	CA	74009	0.032	0.48	4.90	0.49
21	**Datsun_240Z_73**	73	6/27/96	h9606064	none	1	high	E	none	none	none	none	yes	3000	0	car	CA	42843	0.039	7.87	43.50	3.36
22	**Chevy_Suburban_**	87	6/28/96	h9606066	h9606067	14	normal	ET	ET	ET	ET	ET	yes	6000	0	truck	CA	96394	0.041	0.65	5.89	0.59
23	**Cadillac_84**	84	7/2/96	h9607007	h9607008	20	high	ET	ET	ET	ET	ET	yes	3500	0	car	CA	14955	0.039	1.13	15.93	4.55
24	**Dodge_Spirit_91**	91	7/3/96	h9607010	h9607011	6	normal	ET	ET	ET	ET	ET	yes	2750	0	car	CA	13718	0.036	0.15	1.96	0.22
25	**Oldsmobile_98_7**	79	7/9/96	h9607018	h9607019	2	high	ET	ET	ET	ET	ET	yes	4000	0	car	CA	36425	0.041	3.68	72.08	1.82
26	**Oldsmobile_89**	89	6/13/96	h9606026	h9606027	5	normal	ET	ET	ET	ET	ET	yes	3250	0	car	CA	112614	0.049	0.43	4.19	1.55
27	**Honda_Accord_85**	85	7/10/96	h9607022	h9607023	3	normal	ET	ET	ET	ET	ET	yes	2500	0	car	CA	222517	0.039	0.35	5.69	0.76
28	**Plymouth_MV_88**	88	7/11/96	h9607025	h9607026	19	high	ET	ET	ET	ET	ET	yes	3500	0	truck	CA	169982	0.029	1.14	7.48	2.12
29	**Chevy_Suburban_**	94	7/11/96	h9607027	h9607028	16	normal	ET	ET	ET	ET	ET	yes	6000	0	truck	CA	38629	0.033	0.38	7.80	0.66
30	**GMC_Safari_96**	96	7/12/96	h9607029	h9607030	17	normal	ET	ET	ET	ET	ET	yes	5500	1	truck	CA	8125	0.035	0.15	1.28	0.23
31	**Ford_Aerostar_8**	86	7/12/96	h9607031	h9607032	14	normal	ET	ET	ET	ET	ET	yes	3500	0	truck	CA	14926	0.041	0.40	8.07	0.84
32	**Cadillac_NS_96**	96	7/16/96	h9607037	h9607038	11	normal	ET	ET	ET	ET	ET	yes	4000	1	car	CA	13287	0.069	0.05	0.54	0.15
33	**Buick_Lesabr_96**	96	7/23/96	h9607045	h9607046	11	normal	ET	ET	ET	ET	ET	yes	3500	1	car	CA	22607	0.059	0.07	0.55	0.10
34	**Buick_Lesabr_BO**	96	7/24/96	h9607049	h9607050		high	ET	ET	ET	ET	ET	no	3500	1	car	CA	22651	0.059	0.27	3.55	1.69
35	**Jeep_Cherokee_9**	95	7/26/96	h9607055	h9607056	9	normal	ET	ET	ET	ET	ET	yes	3750	1	car	CA	50541	0.051	0.16	1.43	0.45
36	**Dodge_MiniVan_9**	95	8/2/96	h9608005	h9608006	19	high	ET	ET	ET	ET	ET	yes	4125	1	truck	CA	23392	0.039	0.22	3.41	1.16
37	**Honda_Civic_95**	95	8/6/96	h9608008	h9608009	11	normal	ET	ET	ET	ET	ET	yes	2250	1	car	CA	49814	0.045	0.13	0.93	0.19
38	**Ford_Van_95**	95	8/7/96	h9608011	none	18	normal	ET	none	none	none	none	yes	8000	1	truck	CA	46266	0.026	0.15	3.59	0.30
39	**GMC_S15_Truck_8**	85	8/27/96	h9608057	h9608058	22	high	ET	ET	ET	ET	ET	no	3500	0	truck	CA	27754	0.039	2.66	49.70	5.89
40	**Nissan_Truck_84**	84	8/28/96	h9608061	h9608062	22	high	ET	ET	ET	ET	ET	no	3000	0	truck	49	131983	0.035	2.98	27.42	2.19
41	**Chevy_Cavalier_**	90	8/30/96	h9608069	h9608070		high	ET	ET	ET	ET	ET	no	3250	0	car	49	112434	0.029	0.38	8.74	0.36
42	**Pontiac_90**	90	9/4/96	h9609003	h9609004	22	high	ET	ET	ET	ET	ET	no	3125	0	car	CA	103649	0.051	2.53	13.24	4.73
43	**Dodge_Truck_91**	91	9/5/96	h9609007	h9609008	22	high	ET	ET	ET	ET	ET	yes	3500	0	truck	CA	140298	0.033	0.86	11.90	2.00
44	**Honda_Accord_90**	90	9/6/96	h9609009	h9609010	5	normal	ET	ET	ET	ET	ET	no	3000	0	car	CA	77229	0.042	0.15	2.41	0.78
45	**Honda_Civic_95**	95	9/10/96	h9609017	h9609018	10	normal	T	T	T	T	T	no	2250	1	car	CA	43708	0.031	0.12	0.80	0.23

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
47	**Honda_Civic_89**	89	9/12/96	h9609026	h9609027	19	high	ET	ET	ET	ET	ET	no	2250	0	car	CA	59360	0.041	0.23	6.16	1.81
48	**Infinity_G20_95**	95	9/13/96	h9609031	h9609032	11	normal	ET	ET	ET	ET	ET	no	3000	1	car	CA	21468	0.047	0.15	1.40	0.22
49	**Ford_Mini_93**	93	9/20/96	h9609055	h9609056	15	normal	ET	ET	ET	ET	ET	yes	3750	0	truck	49	76489	0.039	0.22	2.72	0.15
50	**Honda_Civic_96**	96	9/24/96	h9609061	h9609062	11	normal	T	T	T	T	T	no	2625	1	car	CA	20975	0.048	0.06	1.33	0.03
51	**Ford_F150_75**	75	9/25/96	h9609065	none	12	high	T	none	none	none	none	no	3500	0	truck	CA	16464	0.042	1.29	20.31	1.41
52	**Toyota_Camry_92**	92	10/3/96	h9610007	h9610008	5	normal	ET	ET	ET	ET	ET	yes	3250	0	car	49	77272	0.042	0.20	1.65	0.52
53	**Plymth_Breeze_9**	96	10/3/96	h9610009	h9610011	11	normal	ET	ET	ET	ET	ET	no	3000	1	car	CA	15096	0.044	0.12	1.58	0.20
54	**Chevy_Capri_94**	94	10/4/96	h9610012	h9610013	11	normal	ET	ET	ET	ET	ET	no	4250	1	car	CA	43625	0.047	0.24	3.57	0.35
55	**Chevy_Van_86**	86	10/8/96	h9610018	h9610019	21	high	ET		ET	ET	ET	no	4000	0	truck	CA	62890	0.041	3.02	17.85	0.86
56	**Mazda_Protege_9**	90	10/8/96	h9610020	h9610021	6	normal	ET	ET	ET	ET	ET	no	2750	0	car	CA	46261	0.035	0.28	3.59	0.46
57	**Cad_Eldorado_82**	82	10/9/96	h9610022	h9610023	22	high	ET	ET	ET	ET	ET	yes	4000	0	car	CA	51233	0.041	1.24	12.15	2.73
58	**Ford_Ranger**	92	10/9/96	h9610024	h9610025	0	normal	ET	ET	ET	ET	ET	no	3500	0	car	CA	52009	0.041	0.24	4.54	0.50
59	**GM_Reagal_86**	86	10/11/96	h9610030	h9610031	6	normal	ET	ET	ET	ET	ET	yes	3500	0	car	CA	26103	0.031	0.26	0.71	0.92
60	**Ford_Aerostar_9**	94	10/16/96	h9610042	h9610043	15	normal	ET	none	ET	ET	ET	yes	3750	0	truck	CA	51061	0.039	0.21	1.97	0.62
61	**Toyota_Corolla_**	94	10/1796	h9610045	h9610046		high	T	T	T	T	T	no	2750	1	car	CA	27339	0.042	0.47	4.34	0.20
62	**Honda_Accord_85**	85	10/18/96	h9610049	h9610050	23	high	ET	ET	ET	ET	ET	no	2625	0	car	49	189506	0.033	2.94	88.49	0.37
63	**Honda_Passport_**	94	10/29/96	h9610064	h9610061	17	normal	ET	ET	ET	ET	ET	no	5500	1	truck	CA	30475	0.032	0.26	2.22	0.34
64	**Ford_F150_86**	86	10/30/96	h9610062	h9610063	14	normal	ET	none	ET	none	ET	no	3500	0	truck	CA	20930	0.042	0.66	2.08	0.85
65	**Toyota_Tercel_9**	93	10/31/96	h9610066	h9610067	6	normal	ET	ET	ET	ET	ET	no	2250	0	car	CA	25384	0.036	0.32	2.69	0.15
66	**Chevy_PU_88**	88	11/1/96	h9611001	h9611002	16	normal	ET	ET	ET	ET	ET	no	4000	0	truck	CA	26201	0.041	0.65	3.96	0.43
67	**Ford_T-Bird_96**	96	11/1/96	h9611003	h9611004	11	normal	ET	ET	ET	ET	ET	no	4000	1	car	CA	16390	0.051	0.15	1.77	0.06
68	**Ford_F150_84**	84	11/6/96	h9611011	none		high	T	none	none	none	none	no	3500	0	truck	CA	62689	0.042	1.11	5.66	1.57
69	**Oldsmobile_71**	71	11/5/96	h9611017	h9611018	1	high	ET	none	ET	none	ET	no	3500	0	car	CA	95629	0.042	10.01	41.69	2.13
71	**Toyota_CLA_92**	92	11/12/96	h9611027	h9611028	22	high	ET	ET	ET	ET	ET	no	2500	0	car	CA	101019	0.041	1.89	10.83	1.83
72	**Ford_Festiva_88**	88	11/13/96	h9611030	h9611031	3	normal	ET	ET	ET	none	ET	no	2000	0	car	CA	155944	0.029	0.40	5.32	1.13
73	**Chevy_Camaro_88**	88	11/14/96	h9611034	h9611035	4	normal	ET	none	ET	none	ET	no	3500	0	car	CA	93424	0.039	0.57	6.36	0.47
74	**Dodge_Neon_96**	96	11/15/96	h9611038	h9611039	11	normal	ET	ET	ET	ET	ET	no	2500	1	car	CA	5312	0.053	0.08	0.94	0.13
75	**Ford_Mustange_9**	95	11/19/96	h9611044	h9611045	10	normal	ET	none	ET	ET	ET	yes	3500	1	car	CA	28905	0.041	0.11	1.51	0.12
76	**Mazda_626_93**	93	11/20/96	h9611048	h9611049	5	normal	ET	ET	ET	ET	ET	no	2750	0	car	CA	54244	0.043	0.21	2.97	0.30
77	**Toyota_Tercel_9**	92	11/21/96	h9611052	h9611053	20	high	ET	ET	ET	ET	ET	no	2250	0	car	49	64393	0.036	0.99	7.86	1.21
78	**Honda_Prelude_8**	85	11/22/96	h9611054	h9611055	19	high	ET	ET	ET	ET	ET	no	2750	0	car	49	204385	0.036	1.02	10.19	1.03
79	**Toyota_Celica_8**	83	11/22/96	h9611056	h9611057		high	ET	none	ET	ET	ET	no	2750	0	car	CA	158954	0.038	0.50	4.32	1.67
80	**Ford_Taurus_97**	97	11/26/96	h9611063	h9611064	10	normal	ET	ET	ET	ET	ET	no	3625	1	car	CA	3415	0.039	0.02	0.80	0.34
82	**Toyota_Camry_89**	89	11/25/96	h9611066	h9611067	4	normal	ET	ET	ET	ET	ET	no	3000	0	car	CA	117470	0.038	0.30	4.06	0.66

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
83	**Mazda_B300_94**	94	11/27/96	h9611068	h9611069	17	normal	ET	none	ET	ET	ET	yes	4000	1	truck	CA	44873	0.035	0.29	3.03	0.22
84	**Jeep_Wrangler_9**	95	12/2/96	h9612003	h9612004	17	normal	ET	none	ET	none	ET	no	4000	1	truck	CA	39029	0.045	0.27	2.95	0.12
85	**Ford_Taurus_85**	85	12/2/96	h9612005	h9612006	5	normal	ET	ET	ET	ET	ET	yes	3500	0	car	CA	56471	0.040	0.28	4.52	0.26
86	**Ford_Mustang_67**	67	12/13/96	h9612008	h9612009	1	high	ET	none	ET	none	ET	no	3000	0	car	CA	92374	0.039	3.48	83.86	0.95
87	**Toyota_Tercel_8**	81	12/13/96	h9612022	h9612023	21	high	ET	none	ET	ET	ET	no	2250	0	car	CA	105699	0.028	1.39	10.32	0.88
88	**Dodge_88**	88	12/5/96	h9612017	h9612018	15	normal	ET	ET	ET	none	ET	no	3625	0	truck	CA	85372	0.063	0.45	8.85	0.74
90	**Ford_Aerostar_9**	94	12/11/96	h9612024	h9612026	15	normal	ET	none	ET	ET	ET	yes	3750	0	truck	CA	71207	0.036	0.29	3.16	0.38
91	**Ford_Tempo_90**	90	12/11/96	h9612027	h9612028	4	normal	ET	none	none	none	none	no	3000	0	car	CA	71696	0.033	0.18	4.36	0.31
92	**Saturn_96**	96	12/12/96	h9612032	h9612033	10	normal	ET	ET	ET	ET	ET	no	2625	1	car	CA	18000	0.038	0.09	0.63	0.20
93	**Datsun_81**	81	12/16/96	h9612035	h9612036	2	high	ET	none	none	none	none	no	2375	0	car	49	118577	0.034	0.41	7.13	0.99
95	**Olds_Regency_90**	90	12/17/96	h9612040	h9612041	4	normal	ET	ET	ET	ET	ET	no	3625	0	car	CA	146761	0.039	0.17	1.70	0.21
96	**Cadillac_BHM_96**	96	12/18/96	h9612044	h9612045		high	ET	none	ET	ET	ET	no	4500	0	car	49	73865	0.039	0.30	1.10	0.95
97	**Oldsmobile_98_8**	83	12/19/96	h9612048	h9612049	23	high	ET	none	ET	none	ET	no	4250	0	car	49	16347	0.041	7.80	162.88	0.24
98	**Toyota_PU_85**	85	12/19/96	h9612050	h9612051	14	normal	ET	none	ET	none	ET	no	2750	0	truck	CA	126328	0.035	0.37	5.84	1.21
99	**Pont_Firebird_8**	89	12/20/96	h9612053	h9612054	5	normal	ET	none	ET	ET	ET	no	3375	0	car	CA	104631	0.064	0.78	4.95	0.98
100	**Ford_Thunbird_8**	80	12/20/96	h9612056	h9612057	2	high	ET	none	ET	none	ET	no	3500	0	car	CA	76087	0.040	3.14	30.31	1.28
101	**Chevy_K1500_95**	95	12/23/96	h9612057	h9612058	18	normal	ET	none	ET	none	ET	no	6500	1	truck	CA	20085	0.031	0.20	2.31	0.55
102	**Dodge_Spirit_94**	94	1/3/96	h9701003	h9701004	11	normal	ET	ET	ET	ET	ET	yes	3000	1	car	CA	49492	0.047	0.13	1.08	0.23
103	**Ply_Sundance_93**	93	1/4/97	h9701005	h9701006	4	normal	ET	ET	ET	ET	ET	yes	2875	0	car	CA	76590	0.032	0.21	3.56	0.92
104	**Nissan_Sentra_9**	95	1/6/97	h9701007	h9701008	11	normal	ET	ET	ET	ET	ET	no	2750	1	car	CA	35291	0.042	0.11	1.47	0.12
105	**Saturn_96**	96	1/7/97	h9701009	h9701010	10	normal	ET	ET	ET	ET	ET	no	2625	1	car	CA	7107	0.038	0.11	0.76	0.12
106	**Saturn_93**	93	1/7/97	h9701011	h9701012	6	normal	ET	ET	ET	ET	ET	no	2625	0	car	CA	30232	0.038	0.16	1.29	0.33
107	**Nissan_PU_92**	92	1/8/97	h9701013	h9701014	15	normal	ET	none	ET	ET	ET	no	3125	0	truck	CA	57196	0.043	0.27	6.86	0.19
108	**Toyota_Camry_94**	94	1/8/97	h9701015	h9701016	11	normal	ET	ET	ET	ET	ET	yes	3625	1	car	CA	22258	0.052	0.13	2.08	0.12
109	**Chevy_Chevel_72**	72	1/9/97	h9701017	h9701018	1	high	ET	none	ET	E	ET	no	3500	0	car	49	15639	0.042	21.79	302.77	0.66
110	**Cadillac_CDV_84**	84	1/9/97	h9701019	h9701020	22	high	ET	none	ET	ET	ET	yes	3625	0	car	CA	94221	0.037	1.19	15.07	3.89
111	**Ford_T_Bird_93**	93	1/10/97	h9701021	h9701022	6	normal	ET	none	ET	ET	ET	yes	4250	0	car	CA	26347	0.033	0.27	4.33	0.32
112	**Mazda_Protege_9**	92	1/10/97	h9701023	h9701024	5	normal	ET	ET	ET	ET	ET	no	2750	0	car	CA	75174	0.045	0.31	3.41	0.23
113	**Nissan_Sentra_9**	90	1/14/97	h970127	h970128	4	normal	ET	ET	ET	ET	ET	no	2625	0	car	CA	141134	0.034	0.43	10.69	0.22
114	**Dodge_Ram_MV_88**	88	1/14/97	h970129	h970130	15	normal	ET	ET	ET	ET	ET	yes	3500	0	truck	49	139526	0.039	0.80	4.03	0.81
115	**Ford_Aerostar_9**	92	1/15/97	h970131	h970132	15	normal	ET	none	ET	ET	ET	yes	3750	0	truck	CA	67620	0.039	0.19	2.68	0.45
116	**Chevy_Cavalr_96**	96	1/15/97	h970133	h970134	11	normal	ET	ET	ET	ET	ET	no	2875	1	car	CA	5690	0.042	0.06	1.04	0.47
117	**Honda_Accord_92**	92	1/16/97	h970135	h970136	4	normal	ET	ET	ET	ET	ET	no	3250	0	car	CA	80394	0.038	0.14	1.37	0.18
118	**Chevy_AstroV_88**	88	1/16/97	h970137	h970138	22	high	ET	none	ET	E	ET	no	3750	0	truck	CA	27257	0.036	1.46	8.85	2.01

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
119	**Toyota_Camry_95**	95	1/17/97	h970139	h970140	10	normal	ET	ET	ET	ET	ET	yes	3500	1	car	CA	29209	0.036	0.10	0.62	0.34
120	**Chevy_Camaro_96**	96	1/17/97	h970141	h970142	11	normal	ET	none	ET	E	ET	no	3625	1	car	CA	25877	0.055	0.10	1.39	0.17
121	**Toyota_4Runn_95**	95	1/21/97	h970143	h970144	17	normal	ET	none	ET	E	ET	yes	5400	1	truck	CA	40243	0.028	0.23	3.17	0.62
122	**Toyota_Tercel_9**	91	1/22/97	h9701047	h9701048	4	normal	ET	ET	ET	ET	ET	no	2250	0	car	CA	104710	0.036	0.51	3.44	0.35
123	**Chry_Lebaron_95**	95	1/22/97	h9701049	h9701050	11	normal	ET	ET	ET	ET	ET	yes	3375	1	car	CA	22197	0.042	0.16	1.19	0.28
125	**Dodge_Spirit_90**	90	1/24/97	h9701053	h9701054	20	normal	ET	ET	ET	ET	ET	yes	3125	0	car	CA	183392	0.048	0.51	13.14	0.51
126	**Suzuki_Swift_92**	92	1/24/97	h9710155	h9701056	7	normal	ET	ET	ET	ET	ET	no	2125	0	car	CA	48461	0.047	0.25	2.44	0.20
127	**GMC_Sonom_PU_92**	92	1/24/97	h9701057	h9701058	16	normal	ET	none	ET	E	ET	no	4250	0	truck	CA	63684	0.038	0.37	5.05	1.07
128	**Ford_T_Bird_78**	78	1/28/97	h9701063	h9701064	2	high	ET	none	ET	E	ET	no	4500	0	car	CA	1255	0.041	2.06	46.77	3.37
129	**Honda_Accord_95**	95	1/28/97	h9701065	h9701066	10	normal	ET	ET	ET	ET	ET	no	3250	1	car	CA	37194	0.040	0.07	0.94	0.19
130	**Subaru_Gl_86**	86	1/29/97	h9701067	h9701068	20	high	ET	ET	ET	ET	ET	no	2500	0	car	CA	96949	0.044	1.13	24.72	0.34
131	**Toyota_PU_85**	85	1/30/97	h9701070	h9701071	14	normal	ET	none	ET	E	ET	no	2750	0	truck	CA	162398	0.035	0.27	6.40	0.57
132	**Honda_Civic_79**	79	1/30/97	h9701072	h9701073	1	high	ET	ET	ET	none	E	no	2000	0	car	CA	48372	0.034	2.85	17.94	0.95
133	**Honda_Civic_95**	95	1/31/97	h9701074	h9701075	8	normal	ET	ET	ET	ET	ET	no	2375	1	car	CA	52111	0.029	0.13	1.72	0.16
134	**Saturn_SL_92**	92	1/31/97	h9701076	h9701077	4	normal	ET	ET	ET	ET	ET	no	2625	0	car	CA	94427	0.032	0.19	2.64	0.58
135	**Nissan_Sentra_9**	91	2/3/97	h9702004	h9702005	5	normal	ET	ET	ET	ET	ET	no	2625	0	car	CA	75800	0.042	0.31	4.60	0.28
136	**Nissan_240SX_93**	93	2/3/97	h9702006	h9702007	7	normal	ET	ET	ET	ET	ET	no	3125	0	car	CA	43009	0.050	0.26	6.58	0.32
137	**BMW_325i_89**	89	2/4/97	h9702008	h9702009	5	normal	ET	ET	ET	ET	ET	no	3750	0	car	CA	101470	0.045	0.56	5.67	0.28
138	**Pontiac_Bonn_88**	88	2/4/97	h9702010	h9702011	5	normal	ET	ET	ET	ET	ET	yes	3750	0	car	CA	79114	0.040	0.14	1.75	0.29
139	**Toyota_PU_95**	95	2/5/97	h9702012	h9702013	17	normal	ET	none	T	E	T	no	4400	1	truck	CA	52322	0.026	0.18	0.88	0.49
140	**Dodge_Dakota_96**	96	2/5/97	h9702014	h9702015	17	normal	ET	none	T	E	T	no	4390	1	truck	CA	3722	0.027	0.09	0.73	0.11
141	**Ford_Escort_96**	96	2/6/97	h9702016	h9702017	10	normal	ET	ET	ET	ET	ET	no	2875	1	car	CA	13719	0.031	0.06	0.74	0.07
142	**Honda_Accord_83**	83	2/6/97	h9702018	h9702019	2	normal	ET	ET	ET	E	ET	no	2500	0	car	CA	181208	0.030	0.55	7.58	0.45
143	**Chevy_C10_81**	81	2/26/97	h9702030	h9702024	13	high	ET	none	T	E	T	no	3875	0	truck	CA	41332	0.039	3.57	24.95	1.46
144	**Ford_Ranger_95**	95	2/26/97	h9702025	h9702026	17	normal	ET	none	ET	E	E	yes	4220	1	truck	CA	43551	0.027	0.12	1.27	0.33
145	**Toyota_PU_88**	88	2/27/97	h9702029	h9702028	20	high	ET	none	T	E	T	no	2750	0	truck	CA	194042	0.042	1.46	27.70	0.21
146	**Chevy_G10_81**	81	2/27/97	h9702031	h9702032	13	high	ET	none	ET	ET	ET	no	4250	0	truck	49	206341	0.041	3.45	61.37	0.62
147	**Mazda_Protege_9**	94	2/28/97	h9702034	h9702035	7	normal	ET	ET	ET	ET	ET	no	2875	0	car	CA	40201	0.042	0.25	3.02	0.42
148	**Jeep_CJ5_83**	83	2/28/97	h9702036	h9702037	13	high	ET	none	T	E	T	no	2875	0	truck	CA	51544	0.039	0.91	23.48	0.71
149	**Ford_Tbird_89**	89	3/3/97	h9703003	h9703004	6	normal	ET	ET	ET	ET	ET	no	3875	0	car	CA	30800	0.036	0.23	1.70	0.54
150	**Dodge_Dakota_92**	92	3/4/97	h9703005	h9703006	19	high	ET	none	ET	ET	ET	no	4000	0	truck	CA	76384	0.045	1.57	8.70	1.93
151	**Toyota_PU_91**	91	3/5/97	h9703007	h9703008	15	normal	ET	none	ET	ET	ET	no	3000	0	truck	CA	30440	0.039	0.13	0.99	0.30
152	**Dodge_Dakota_95**	95	3/5/97	h9703009	h9703010	17	normal	ET	none	ET	ET	ET	no	5630	1	truck	CA	44432	0.039	0.39	5.15	0.80
153	**Hyundai_Excel_8**	89	3/6/97	h9703011	h9703012	21	high	ET	ET	ET	E	ET	no	2500	0	car	CA	61058	0.027	1.03	6.33	0.87

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
154	**Ford_Mustang_65**	65	3/6/97	h9703013	h9703014	1	high	ET	none	ET	none	ET	no	3000	0	car	CA	25426	0.039	5.34	24.23	1.51
155	**GMC_1500_92**	92	3/7/97	h9703015	h9703016	16	normal	ET	none	ET	ET	ET	yes	4250	0	truck	CA	66270	0.049	0.73	8.72	1.15
156	**Nissan_Altima_9**	96	3/7/97	h9703017	h9703018	11	normal	T	T	T	T	T	no	3250	1	car	CA	14212	0.046	0.15	3.56	0.34
157	**BMW_735i_85**	85	3/11/97	h9703023	h9703024		high	ET	none	ET	none	ET	no	4000	0	car	49	141715	0.052	1.50	9.02	4.30
158	**Ford_F_150_86**	86	3/11/97	h9703025	h9703026	19	high	ET	none	ET	ET	ET	no	3750	0	truck	CA	22001	0.039	0.75	2.33	2.55
159	**Toyota_PU_88**	88	3/12/97	h9703028	h9703029	15	normal	ET	none	ET	ET	ET	no	2750	0	truck	49	162245	0.042	0.56	2.38	1.17
160	**Nissan_PU_90**	90	3/12/97	h9703030	h9703031	20	normal	ET	none	ET	ET	ET	no	3125	0	truck	CA	114720	0.043	0.48	13.90	0.84
161	**Buick_Regal_84**	84	3/13/97	h9703034	h9703035	20	high	ET	none	ET	ET	ET	no	3500	0	car	CA	46057	0.031	2.04	14.55	0.25
162	**Mazda_MX6_88**	88	3/13/97	h9730336	h9703037	4	normal	ET	ET	ET	ET	ET	no	3000	0	car	CA	151512	0.037	0.38	5.77	0.48
163	**Honda_Civic_94**	94	3/14/97	h9703038	h9703039	8	normal	ET	ET	ET	ET	ET	no	2625	1	car	CA	78056	0.039	0.10	0.99	0.22
164	**Nissan_280zx_79**	79	3/25/97	h9703053	h9703054	2	normal	T	none	T	T	T	no	3000	0	car	49	35355	0.048	1.00	11.61	2.69
165	**Acura_Integra_9**	96	3/25/97	h9703055	h9703056	11	normal	T	T	T	T	T	no	2875	1	car	CA	4280	0.049	0.12	0.50	0.25
166	**Dodge_Ram_1500_**	96	3/26/97	h9703057	h9703028	18	normal	ET	none	ET	none	ET	no	6400	1	truck	CA	24104	0.034	0.27	1.63	0.71
167	**Ford_Explorer_9**	92	3/27/97	h9703060	h9703061	16	normal	ET	none	ET	ET	ET	yes	4250	0	truck	CA	92324	0.036	0.23	4.19	0.71
168	**Toyota_Pickup_8**	84	3/28/97	h9703062	h9703063	19	normal	ET	none	ET	ET	ET	no	2750	0	truck	49	138310	0.035	0.80	4.24	1.49
169	**Mercury_Tracer_**	81	3/28/97	h9703064	h9703065	7	normal	ET	ET	ET	ET	ET	no	2500	0	car	49	6025	0.051	0.52	2.71	0.98
170	**Chevy_Corsica_8**	88	3/28/97	h9703066	h9703067	19	normal	ET	ET	ET	ET	ET	yes	3125	0	car	CA	124806	0.029	0.45	4.46	1.24
171	**Dodge_Ram_Picku**	85	3/31/97	h9703068	h9703069	22	high	ET	none	ET	ET	ET	no	2750	0	truck	CA	93385	0.035	1.04	23.68	1.82
172	**Toyota_Pickup_9**	91	4/2/97	h9704005	none	15	normal	ET	none	none	none	none	no	3000	0	truck	CA	93178	0.039	0.21	2.31	0.25
173	**Ford_Ranger_92**	92	4/2/97	h9704006	h9704007	15	normal	ET	none	ET	none	ET	yes	3375	0	truck	CA	61976	0.030	0.41	2.26	0.37
175	**Dodge_Caravan_8**	88	4/3/97	h9704010	h9704011	19	high	ET	ET	ET	ET	ET	yes	3625	0	truck	CA	101045	0.039	1.26	7.64	1.17
176	**GMC_Sierra_89**	89	4/4/97	h9704016	h9704015	16	normal	ET	none	ET	ET	ET	yes	3875	0	truck	CA	100890	0.054	0.87	6.67	1.04
177	**Dodge_250_Van_9**	90	4/4/97	h9704017	h9704018	16	normal	ET	none	ET	ET	ET	no	3875	0	truck	CA	60753	0.049	0.36	6.61	0.66
178	**Chevy_S_10_Pick**	92	4/7/97	h9704022	h9704023	21	high	ET	none	ET	ET	ET	no	2750	0	truck	CA	82519	0.038	1.20	5.25	0.69
179	**Chevy_Silverado**	84	4/8/97	h9704024	h9704025	14	normal	ET	none	ET	ET	ET	no	4000	0	truck	CA	39533	0.041	0.42	4.51	1.46
180	**Nissan_Pickup_9**	90	4/8/97	h9704026	h9704027	15	normal	ET	none	ET	none	ET	no	3125	0	truck	CA	130600	0.043	0.46	5.71	0.25
181	**Chevy_SUV_94**	94	4/9/97	h9704028	h9704029	16	normal	ET	none	ET	ET	ET	yes	4750	0	truck	CA	36449	0.044	0.41	4.63	0.49
182	**Dodge_Caravan_8**	89	4/9/97	h9704030	h9704031	19	normal	ET	ET	ET	ET	ET	yes	3750	0	truck	CA	83057	0.038	0.73	4.77	1.20
183	**Chevy_Spirit_85**	85	4/10/97	h9704032	h9704033	20	high	ET	T	ET	none	ET	no	1750	0	car	CA	55719	0.027	5.34	30.80	1.49
184	**Honda_Accord_Ex**	90	4/10/97	h9704034	h9704035	5	normal	ET	ET	ET	ET	ET	no	3125	0	car	49	109713	0.040	0.17	1.69	0.31
185	**Ford_Escort_94**	94	4/11/97	h9704036	h9704037	6	normal	T	T	T	T	T	yes	2625	0	car	CA	31924	0.034	0.12	0.48	0.23
186	**Pontiac_Transpo**	91	4/11/97	h9704038	h9704039	16	normal	ET	ET	ET	ET	ET	yes	4000	0	truck	CA	123618	0.030	0.28	4.11	0.83
187	**Toyota_Paseo_95**	95	4/15/97	h9704043	h9704044	9	normal	ET	ET	ET	ET	ET	yes	2375	1	car	CA	56213	0.042	0.19	1.62	0.13
188	**Toyota_Camry_94**	94	4/15/97	h9704045	h9704046	8	normal	T	T	T	T	T	no	3500	1	car	CA	56197	0.036	0.25	0.66	0.41

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
189	Alfa_Romeo_Spid	86	4/16/97	h9704047	h9704048	22	high	ET	ET	ET	ET	ET	no	2750	0	car	CA	46495	0.042	1.85	15.19	1.25
190	Toyota_X_cab_92	92	4/16/97	h9704049	h9704050	15	normal	ET	none	ET	ET	ET	no	2750	0	truck	CA	58773	0.042	0.18	1.39	0.24
191	Saturn_SL2_93	93	4/17/97	h9704051	h9704052	9	normal	ET	ET	ET	ET	ET	yes	2625	1	car	CA	63125	0.047	0.22	1.57	0.35
192	Honda_Civic_DX_	94	4/17/97	h9704053	h9704054	9	normal	ET	ET	ET	ET	ET	no	2375	1	car	CA	57742	0.043	0.16	2.22	0.31
193	Nissan_Pickup_8	86	4/18/97	h9704057	h9704058	14	normal	ET	none	ET	none	ET	no	2750	0	truck	CA	221760	0.035	0.32	5.52	0.49
194	Chrysler_5th_Av	86	4/18/97	h9704059	h9704060	4	normal	T	none	T	none	T	no	4000	0	car	CA	87798	0.035	0.60	11.17	1.19
195	Ford_Ranger_96	96	4/21/97	h9704064	h9704065	17	normal	ET	none	ET	ET	ET	no	4740	1	truck	CA	32612	0.024	0.13	0.90	0.46
196	Ford_Bronco_II_	86	4/22/97	h9704066	h9704067	22	high	ET	none	ET	ET	ET	no	3375	0	truck	49	45327	0.039	2.27	13.01	1.72
197	Dodge_Intrepid_	95	4/22/97	h9704068	h9704069	9	normal	T	T	T	T	T	no	3625	1	car	CA	62007	0.044	0.26	1.14	0.15
198	Chevy_C_20_78	78	4/23/97	h9704071	h9704072	12	high	ET	none	ET	none	ET	no	4250	0	truck	CA	974	0.041	1.83	7.25	2.44
199	Dodge_Spirit_94	94	4/24/97	h9704077	h9704078	9	normal	ET	ET	ET	ET	ET	yes	3000	1	car	CA	57407	0.047	0.16	1.03	0.25
200	Ford_Mustang_79	79	4/25/97	h9704085	h9704086	23	high	ET	none	ET	none	ET	no	3000	0	car	CA	18631	0.029	4.00	106.32	0.42
201	Dodge_Spirit_94	94	4/25/97	h9704091	h9704087	9	normal	ET	ET	ET	ET	ET	no	3000	1	car	CA	56338	0.047	0.14	0.83	0.28
202	Ford_Windstar_9	97	4/29/97	h9704094	h9704095	19	high	ET	ET	ET	ET	ET	no	4250	1	truck	CA	19743	0.036	0.06	5.70	4.62
203	Ford_Explorer_9	97	4/29/97	h9704096	h9704097	17	normal	ET	ET	ET	ET	ET	no	4700	1	truck	CA	15164	0.034	0.11	0.58	0.12
204	Ford_Ranger_73	73	4/30/97	h9704098	h9704099	12	normal	ET	none	ET	ET	ET	no	3750	0	truck	CA	18037	0.042	2.56	40.96	1.47
205	Dodge_Caravan_8	85	4/30/97	h9704100	h9704101	23	high	ET	T	ET	none	ET	no	2750	0	truck	49	55665	0.035	8.62	98.58	0.50
206	Datsun_200sx_77	77	4/30/97	h9705004	h9705005	3	normal	ET	none	ET	ET	ET	no	2750	0	car	49	30224	0.035	0.41	5.47	1.12
207	Toyota_Pickup_8	88	5/1/97	h9705006	h9705007	15	normal	ET	none	ET	none	ET	no	2875	0	truck	CA	86911	0.040	0.33	3.82	0.56
208	Jeep_Wrangler_8	89	5/6/97	h9705014	h9705015	22	high	ET	none	ET	none	ET	yes	3625	0	truck	49	111622	0.031	3.68	7.27	4.03
209	Dodge_Caravan_9	94	5/6/97	h9705016	h9705017	21	high	ET	E	ET	ET	ET	yes	3875	1	truck	CA	77603	0.037	3.19	13.17	0.09
210	Chevrolet_Custo	72	5/7/97	h9705018	h9705019	12	high	ET	none	ET	none	ET	no	4000	0	truck	49	51170	0.041	9.20	27.44	6.30
211	Ford_Festva_93	93	5/7/97	h9705020	h9705021	6	normal	ET	ET	ET	none	ET	no	2000	0	car	CA	16938	0.032	0.15	1.33	0.11
212	Mazda_B2000_SE_	86	5/8/97	h9705023	h9705024	14	normal	ET	none	ET	none	ET	no	3000	0	truck	CA	166511	0.035	0.61	8.52	0.77
213	Ford_TBird_94	94	5/8/97	h9705025	h9705026	8	normal	ET	ET	ET	ET	ET	yes	3875	1	car	CA	72691	0.036	0.12	0.72	0.34
214	Chevrolet_C1500	88	5/9/97	h9705027	h9705028	21	high	ET	none	ET	ET	ET	no	3625	0	truck	CA	208028	0.039	1.51	8.10	0.87
215	Ford_SuperWagon	80	5/9/97	h9705029	h9705030	13	high	ET	none	ET	none	ET	no	5250	0	truck	CA	75463	0.041	2.66	18.73	2.94
216	Toyota_Pickup_9	92	5/13/97	h9705036	h9705037	15	normal	ET	none	ET	none	ET	no	2875	0	truck	CA	58159	0.040	0.15	1.78	0.27
217	Chevrolet_Capri	85	5/13/97	h9705038	h9705039	2	normal	ET	none	ET	ET	ET	yes	4250	0	car	CA	93486	0.040	0.55	6.20	1.39
218	Ford_Mustang_LX	90	5/14/97	h9705041	h9705042	7	normal	T	none	T	T	T	no	3000	0	car	CA	11302	0.075	0.18	0.44	1.06
219	Hyundai_Elantra	92	5/14/97	h9705043	h9705044		high	ET	ET	ET	none	ET	yes	2875	0	car	CA	50107	0.035	1.21	7.96	0.69
220	Nissan_Sentra_G	96	5/15/97	h9705046	h9705047	10	normal	T	T	T	T	T	no	2750	1	car	CA	13845	0.035	0.09	0.60	0.19
221	Honda_Prelude_9	92	5/15/97	h9705048	h9705049	5	normal	ET	ET	ET	ET	ET	no	3250	0	car	CA	90621	0.049	0.19	1.24	0.36
222	Ford_F250_72	72	5/16/97	h9705051	h9705052	12	normal	ET	none	ET	none	ET	no	4000	0	truck	CA	15731	0.041	4.06	59.28	3.92

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
223	**Toyota_Tercel_9**	93	5/16/97	h9705053	h9705054	4	normal	ET	ET	ET	ET	ET	no	2250	0	car	CA	52789	0.036	0.38	2.39	0.33
224	**Jeep_Wrangler_9**	92	5/19/97	h9705059	h9705060	15	normal	ET	none	ET	none	ET	no	3375	0	truck	CA	71210	0.036	0.27	4.25	0.16
225	**Dodge_Ram_84**	84	5/20/97	h9705061	h9705062	22	high	ET	none	ET	ET	ET	no	4250	0	truck	CA	14672	0.041	3.43	65.65	2.35
226	**Honda_Accord_LX**	94	5/20/97	h9705063	h9705064	8	normal	ET	ET	ET	ET	ET	no	3250	1	car	CA	57192	0.040	0.12	1.81	0.17
228	**Chevrolet_Camin**	78	5/22/97	h9705068	h9705069	12	high	ET	none	ET	none	ET	no	4000	0	truck	49	67974	0.041	8.97	173.77	0.70
229	**Honda_Civic_LX_**	93	5/22/97	h9705070	h9705071	9	normal	ET	ET	ET	ET	ET	no	2625	1	car	CA	61032	0.048	0.11	1.01	0.31
230	**Toyota_Celica_G**	85	5/23/97	h9705073	h9705074	4	normal	ET	ET	ET	ET	ET	no	2750	0	car	CA	52520	0.038	0.36	2.79	0.82
231	**Jeep_Wrangler_9**	90	5/23/97	h9705075	h9705078	20	high	ET	none	ET	none	ET	yes	3375	0	truck	CA	73234	0.035	0.71	21.45	0.36
232	**Mitsubishi_Ecli**	93	5/27/97	h9705079	h9705080	6	normal	ET	ET	ET	ET	ET	yes	3000	0	car	CA	40526	0.031	0.20	0.87	0.57
233	**Isuzu_Rodeo_95**	95	5/28/97	h9705082	h9705083	17	normal	ET	none	ET	none	ET	no	4450	1	truck	CA	14067	0.027	0.20	3.02	0.24
234	**Ford_F150_97**	97	5/29/97	h9705087	h9705088	18	normal	T	none	T	T	T	no	6550	1	truck	CA	13599	0.025	0.16	1.36	0.13
235	**Ford_Ranger_93**	93	6/3/97	h9706009	h9706007	15	normal	ET	none	ET	none	ET	yes	3625	0	truck	CA	74660	0.044	0.13	0.78	0.23
236	**Dodge_Neon_97**	97	6/1/97	h9706012	h9706010	10	normal	ET	ET	ET	ET	ET	no	2750	1	car	CA	370	0.035	0.36	4.74	0.28
237	**Ford_F150_96**	96	6/4/97	h9706013	h9706014	18	normal	ET	none	ET	none	ET	yes	6250	1	truck	49	24595	0.028	0.11	0.97	0.16
238	**Chevy_Astrovan_**	95	6/10/97	h9706025	h9706026	17	normal	ET	none	ET	none	ET	yes	5950	1	truck	CA	18885	0.032	0.46	4.13	0.60
239	**Buick_Park_Ave_**	88	6/10/97	h9706027	h9706028	4	normal	ET	ET	ET	ET	ET	no	3500	0	car	49	116544	0.039	0.21	1.56	0.20
240	**Nissan_Sentra_8**	84	6/11/97	h9706037	h9706038	20	high	ET	none	ET	none	ET	no	2375	0	car	CA	163270	0.029	1.23	21.01	1.20
241	**Geo_Tracker_93**	93	6/11/97	h9706043	h9706044	15	normal	ET	none	ET	none	ET	yes	2750	0	truck	CA	69008	0.029	0.70	10.03	0.48
242	**Saturn_SL2_94**	94	6/12/97	h9706041	h9706042	9	normal	ET	ET	ET	ET	ET	yes	2625	1	car	CA	64967	0.047	0.16	1.34	0.23
243	**Mitsubishi_PU_8**	85	6/16/97	h9706050	h9706051	14	normal	ET	none	ET	none	ET	no	2750	0	truck	CA	52296	0.035	0.46	10.74	0.55
244	**Crown_Victoria_**	94	6/17/97	h9706054	h9706055		high	ET	ET	ET	ET	ET	yes	4000	1	car	CA	58923	0.041	0.36	6.06	0.43
245	**Chevy_1500_96**	96	6/19/97	h9706056	h9706057	18	normal	ET	ET	ET	ET	ET	yes	6200	1	truck	CA	29697	0.028	0.18	1.39	0.30
246	**Nissan_Sentra_8**	85	6/23/97	h9706079	h9706080	23	high	ET	ET	ET	ET	ET	no	2375	0	car	CA	99665	0.034	1.88	69.05	0.33
247	**Chevy_Tahoe_95**	95	6/23/97	h9706077	h9706078	18	normal	ET	ET	ET	ET	ET	yes	6800	1	truck	CA	31734	0.027	0.29	3.16	0.79
248	**Saturn_SL2_93**	93	6/11/97	h9706032	h9706033	7	normal	ET	ET	ET	ET	ET	yes	2500	0	car	49	42264	0.050	0.16	2.08	0.18
249	**Toyota_Camry_91**	91	6/19/97	h9706058	h9706059	6	normal	ET	ET	ET	ET	ET	no	3500	0	car	CA	30781	0.033	0.24	4.52	0.12
250	**Olds_98_94**	94	6/24/97	h9706081	h9706082	8	normal	ET	ET	ET	ET	ET	yes	3875	1	car	CA	54825	0.039	0.17	0.92	0.24
251	**Chevy_1500_94**	94	6/24/97	h9706083	h9706084	18	normal	ET	none	ET	none	ET	yes	6100	1	truck	CA	57840	0.027	0.34	5.37	0.52
252	**Ford_F_150_95**	95	6/25/97	h9706087	h9706088		high	ET	none	ET	none	ET	yes	4250	1	truck	CA	77505	0.039	0.59	2.68	0.88
253	**Toyota_Corolla_**	96	6/25/97	h9706089	h9706090	10	normal	ET	ET	ET	ET	ET	no	2875	1	car	CA	29480	0.035	0.17	1.80	0.25
254	**Hyundai_92**	92	6/26/97	h9706095	h9706096	22	high	ET	ET	ET	none	ET	no	2625	0	car	49	131834	0.034	1.40	5.29	2.96
256	**Toyota_Corolla_**	78	6/10/97	h9706030	h9706031	2	high	ET	none	ET	none	ET	no	2500	0	car	CA	14836	0.028	2.55	9.10	1.63
257	**Nissan_Altima_9**	93	6/12/97	h9706035	h9706036	7	normal	ET	ET	ET	ET	ET	no	3250	0	car	CA	32058	0.046	0.20	1.90	0.47
258	**Chevy_Beretta_9**	91	6/20/97	h9706065	h9706066	5	normal	ET	ET	ET	ET	ET	no	3000	0	car	49	82723	0.047	0.28	6.55	0.88

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
259	**Honda_Accord_LX**	95	6/20/97	h9706067	h9706068	7	normal	ET	ET	ET	ET	ET	no	3000	0	car	CA	49764	0.042	0.13	1.89	0.40
260	**Toyota_Camry_LE**	95	7/1/97	h9707002	h9707003	9	normal	ET	ET	ET	ET	ET	no	4000	1	car	CA	51286	0.047	0.18	1.63	0.18
261	**Pontiac_Lemans_**	78	7/1/97	h9707004	h9707005	2	high	ET	ET	ET	E	ET	no	4000	0	car	CA	50041	0.041	1.48	19.18	2.79
262	**Pontiac_Lemans_**	90	7/2/97	h9707007	h9707008	4	normal	ET	ET	ET	E	ET	no	2500	0	car	CA	85012	0.030	0.47	2.12	0.45
263	**Honda_Civic_EX_**	95	7/2/97	h9707009	h9707010	8	normal	ET	ET	ET	ET	ET	no	2750	1	car	CA	54843	0.037	0.16	1.69	0.15
264	**Geo_Storm_90**	90	7/3/97	h9707013	h9707014	5	normal	ET	ET	ET	ET	ET	no	2625	0	car	49	109951	0.050	0.47	6.44	0.67
265	**Toyota_Camry_DX**	91	7/8/97	h9707023	h9707024	6	normal	ET	ET	ET	ET	ET	no	3500	0	car	CA	36061	0.033	0.14	3.11	0.15
266	**Plymouth_Acclai**	94	7/8/97	h9707025	h9707026	8	normal	ET	ET	ET	ET	ET	no	3125	1	car	CA	56936	0.035	0.13	2.91	0.10
267	**Buick_Roadmaste**	91	7/9/97	h9707028	h9707029		high	ET	ET	ET	ET	ET	no	4250	0	car	CA	56407	0.041	0.23	1.27	1.72
268	**Ford_Escort_91**	91	7/8/97	h9707030	h9707031	6	normal	T	T	T	T	T	no	2625	0	car	49	48075	0.034	0.16	1.71	0.18
269	**Honda_Accord_LX**	93	7/10/97	h9707034	h9707035	4	normal	ET	ET	ET	ET	ET	no	3250	0	car	CA	52557	0.038	0.10	1.31	0.32
270	**Mercury_Tracer_**	91	7/10/97	h9707036	h9707037	6	normal	ET	ET	ET	ET	ET	no	2750	0	car	CA	41866	0.032	0.09	0.60	0.23
271	**Datsun_510_81**	81	7/11/97	h9707039	h9707040	2	high	ET	ET	ET	E	ET	no	2625	0	car	CA	124170	0.034	0.72	13.67	2.20
272	**Dodge_Ram_1500_**	96	7/10/97	h9707041	h9704042	18	normal	ET	ET	ET	ET	ET	no	6400	1	truck	CA	21501	0.027	0.17	2.48	0.17
273	**Chevy_Corsica_9**	92	7/14/97	h9707051	h9707052	21	high	ET	ET	ET	ET	ET	no	3000	0	car	CA	134585	0.037	1.26	9.00	0.85
274	**Nissan_Sentra_8**	86	7/14/97	h9707053	h9707054	3	normal	ET	ET	ET	ET	ET	no	2375	0	car	CA	228988	0.029	0.43	7.54	0.69
275	**Ford_F_150_Van_**	83	7/15/97	h9707056	h9707057	13	normal	ET	ET	ET	E	ET	no	4000	0	truck	49	8255	0.039	0.89	3.76	1.12
276	**Mazda_626_83**	83	7/15/97	h9707058	h9707059	23	high	ET	ET	ET	E	ET	no	2750	0	car	49	166743	0.030	2.45	78.33	0.15
277	**Volkswagen_Fox_**	92	7/16/97	h9707062	h9707063	22	high	ET	ET	ET	ET	ET	no	2500	0	car	49	78738	0.032	2.82	38.87	1.24
278	**Honda_Accord_LX**	84	7/16/97	h9707064	h9707065	3	normal	ET	ET	ET	ET	ET	no	2625	0	car	CA	122391	0.033	0.38	5.50	0.96
279	**Honda_Civic_LX_**	93	7/22/97	h9707072	h9707073	6	normal	ET	ET	ET	ET	ET	no	2375	0	car	CA	44972	0.029	0.11	0.77	0.34
280	**Saturn_SL2_93**	93	7/23/97	h9707076	h9707077		high	ET	ET	ET	ET	ET	no	2625	1	car	CA	150139	0.047	0.38	4.58	0.33
281	**Honda_Accord_EX**	93	7/24/97	h9707079	h970780	9	normal	ET	ET	ET	ET	ET	no	3250	1	car	CA	72804	0.043	0.20	1.27	0.34
282	**Geo_Metro_96**	96	7/28/97	h9707091	h9707092	10	normal	ET	ET	ET	ET	ET	no	2000	1	car	CA	32034	0.030	0.07	0.54	0.17
283	**Monte_Carlo_81**	81	7/29/97	h9707094	h9707095	23	high	ET	ET	ET	none	ET	no	3500	0	car	CA	43254	0.039	2.20	53.31	1.29
284	**Honda_Accord_LX**	93	7/31/97	h9707101	h9707102	8	normal	ET	ET	ET	ET	ET	no	3500	1	car	CA	97869	0.040	0.22	2.22	0.46
285	**Chevy_1500_Pick**	90	7/31/97	h9707104	h9707105		high	ET	ET	ET	ET	ET	no	3625	0	truck	CA	162673	0.042	0.83	7.05	1.10
286	**Honda_Accord_LX**	95	8/1/97	h9708001	h9708002	11	normal	ET	ET	ET	ET	ET	no	3000	1	car	CA	20606	0.043	0.10	0.92	0.15
287	**Acura_Vigor_94**	94	8/1/97	h9708003	h9708004	8	normal	ET	ET	ET	ET	ET	no	3500	1	car	CA	61040	0.037	0.23	2.17	0.30
288	**Plymouth_Duster**	94	8/4/97	h9708009	h9708010		high	ET	ET	ET	ET	ET	yes	2875	1	car	CA	72483	0.035	0.14	1.52	0.64
289	**Ford_F_150_92**	92	8/5/97	h9708012	h9708011	18	normal	ET	ET	ET	ET	ET	no	6100	1	truck	CA	54962	0.024	0.16	1.63	0.07
290	**Toyota_Tercel_9**	93	8/6/97	h9708014	h9708015	4	normal	ET	ET	ET	ET	ET	no	2250	0	car	CA	111977	0.036	0.47	5.40	0.58
291	**Dodge_Ram_97**	97	8/6/97	h9708016	h9708017	18	normal	ET	ET	ET	ET	ET	no	6727	1	truck	CA	96	0.024	0.37	1.78	0.26
292	**GMC_Jimmy_90**	90	8/7/97	h9708021	h9708022	20	normal	ET	ET	ET	ET	ET	no	3500	0	truck	CA	109657	0.039	0.71	11.88	0.78

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
293	**Plymouth_Voyage**	94	8/8/97	h9708023	h9708024	17	normal	ET	ET	ET	ET	ET	yes	5200	1	truck	CA	80722	0.030	0.25	2.05	0.71
294	**Nissan_PU_88**	88	8/11/97	h9708029	h9708030	22	high	ET	ET	ET	ET	ET	no	3125	0	truck	CA	102556	0.035	3.34	18.19	2.86
295	**Chevy_AstroVan_**	90	8/12/97	h9708032	h9708033	19	high	ET	ET	ET	ET	ET	no	3000	0	truck	CA	127580	0.058	1.21	6.64	1.42
296	**Toyota_PU_94**	94	8/14/97	h9708039	h9708040	15	normal	ET	ET	ET	ET	ET	yes	3500	0	truck	CA	45964	0.039	0.15	2.10	0.20
297	**Chevy_Caprice_9**	94	8/14/97	h9708041	h9708042	19	high	ET	ET	ET	ET	ET	no	4500	1	car	CA	78060	0.044	0.36	5.59	2.16
298	**Chevy_AstroVan_**	90	8/21/97	h9708062	h9708059	19	high	ET	ET	ET	ET	ET	yes	3000	0	truck	CA	145799	0.058	0.84	1.78	7.41
299	**Honda_Civic_84**	84	8/26/97	h9708071	h9708072	20	high	ET	ET	ET	none	ET	no	2250	0	car	CA	173388	0.034	0.86	16.84	1.96
300	**Chevy_Celebrity**	90	8/28/97	h9708079	h9708080	23	high	ET	ET	ET	ET	ET	yes	3000	0	car	CA	133333	0.035	8.46	115.46	0.60
301	**Chevy_Corsica_9**	91	8/29/97	h9708082	h9708083	20	high	ET	ET	ET	ET	ET	yes	3000	0	car	CA	136424	0.032	3.96	42.18	1.71
302	**Ford_Taurus_Wg_**	95	8/29/97	h9708084	h9708085	8	normal	ET	ET	ET	ET	ET	yes	3625	1	car	CA	63558	0.039	0.10	0.84	0.33
303	**Geo_Metro_91**	91	9/3/97	h9709008	h9709009	19	normal	ET	ET	ET	ET	ET	yes	1875	0	car	49	11317	0.029	0.66	6.23	2.71
304	**Oldsmobile_Cutl**	94	9/4/97	h9709013	h9709014	20	high	ET	ET	ET	ET	ET	yes	3250	1	car	CA	80877	0.049	0.91	7.84	2.92
305	**Toyota_Pickup_8**	84	9/5/97	h9709016	h9709017	22	high	ET	ET	ET	none	ET	no	2750	0	truck	CA	174279	0.035	34.92	163.79	1.25
306	**Geo_Metro_91**	91	9/9/97	h9709027	h9709028	19	high	ET	ET	ET	ET	ET	yes	1875	0	car	CA	11441	0.029	0.69	4.67	2.36
307	**Toyota_Corolla_**	93	9/10/97	h9709018	h9709019	9	normal	ET	ET	ET	ET	ET	no	2750	1	car	CA	102240	0.042	0.25	2.56	0.44
308	**GMC_1500_95**	95	9/10/97	h9709037	h9709038	18	normal	ET	ET	ET	ET	ET	no	6100	1	truck	CA	83911	0.030	0.38	4.39	0.92
309	**Toyota_Pickup_8**	81	9/11/97	h9709042	h9709043	13	high	ET	ET	ET	none	ET	no	2875	0	truck	CA	64403	0.035	3.07	50.46	3.67
310	**Dodge_Caravan_9**	89	9/12/97	h9709050	h9709051	15	normal	ET	ET	ET	ET	ET	yes	3750	0	truck	CA	129418	0.027	0.54	11.97	0.77
311	**Chevy_Astrovan_**	92	9/16/97	h9709057	h9709058	19	high	ET	ET	ET	ET	ET	yes	4500	0	truck	CA	113522	0.033	0.63	3.07	4.49
313	**Honda_Civic_94**	94	9/17/97	h9709061	h9709062	8	normal	ET	ET	ET	ET	ET	no	2625	1	car	CA	91045	0.039	0.11	0.69	0.34
314	**Ford_Mustang_65**	65	9/17/97	h9709063	h9709064	1	high	ET	ET	ET	none	ET	no	3000	0	car	CA	26735	0.042	11.07	10.47	2.47
315	**Dodge_Dakota_91**	91	9/18/97	h9709065	h9709066	22	high	ET	ET	ET	none	ET	yes	3500	0	truck	CA	159209	0.036	0.95	11.73	2.06
316	**GMC_Sonoma_97**	97	9/19/97	h9709070	h9709071	17	normal	ET	ET	ET	ET	ET	no	4200	1	truck	CA	1240	0.033	0.10	0.59	0.19
317	**Toyota_Corolla_**	94	9/19/97	h9709072	none	11	normal	ET	none	none	none	none	no	2750	1	car	CA	28630	0.042	0.25	2.25	0.39
318	**GMC_1500_PU_95**	95	9/23/97	h9709080	h9709081	18	normal	ET	ET	ET	ET	ET	no	6200	1	truck	CA	48686	0.028	0.28	2.88	0.45
319	**Honda_Civic_DX_**	97	9/23/97	h9709082	h9709083	10	normal	ET	ET	ET	ET	ET	no	2625	1	car	CA	6172	0.034	0.04	1.13	0.02
320	**GMC_Sonoma_91**	91	9/24/97	h9709084	h9709085	16	normal	ET	ET	ET	ET	ET	no	4000	0	truck	CA	74322	0.039	0.45	4.61	1.81
321	**Dodge_Dakota_91**	91	9/30/97	h9710006	h9709117		high	ET	ET	ET	none	ET	yes	3500	0	truck	CA	159482	0.036	1.16	11.49	1.85
322	**Chevy_Astrovan_**	94	9/30/97	h9790989	h9709090	16	normal	ET	ET	ET	ET	ET	no	4625	0	truck	CA	102737	0.039	0.17	2.33	0.73
324	**Chevy_Malibu_97**	97	10/14/97	h9710026	h9710027	10	normal	ET	ET	ET	ET	ET	no	3375	1	car	CA	3015	0.039	0.13	1.32	0.18
326	**Acura_Integra_R**	89	10/16/97	h9710036	h9710037	5	normal	ET	ET	ET	ET	ET	no	2750	0	car	CA	138747	0.043	0.41	5.06	0.27
327	**Ford_Windstar_9**	97	10/17/97	h9710040	h9710041	17	normal	ET	ET	ET	ET	ET	no	5120	1	truck	CA	19386	0.032	0.11	0.44	0.09
328	**Dodge_Shadow_94**	94	10/21/97	h9710054	h9710055	4	normal	ET	ET	ET	ET	ET	no	2875	0	car	CA	78611	0.035	0.33	5.25	1.17
329	**Plymouth_Breeze**	97	10/32/97	h9710062	h9710063	10	normal	ET	ET	ET	ET	ET	no	3250	1	car	CA	23099	0.035	0.11	0.70	0.25

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
330	**Chevy_Suburban_**	97	10/32/97	h9710069	h9710064	18	normal	ET	ET	ET	ET	ET	no	6800	1	truck	CA	3327	0.041	0.19	1.43	0.29
332	**Chrysler_Town_8**	89	10/28/97	h9710077	h9710078	6	normal	ET	ET	ET	ET	ET	no	3250	0	car	CA	34193	0.035	0.29	5.46	0.34
333	**Plymouth_Carave**	87	10/28/97	h9710079	h9710078	4	normal	ET	ET	ET	ET	ET	no	2875	0	car	CA	53938	0.034	0.56	12.00	0.66
334	**Mercury_Cougar_**	92	10/29/97	h9710082	h9710083	4	normal	ET	ET	ET	ET	ET	no	3875	0	car	CA	55397	0.036	0.17	1.72	0.11
335	**Plymouth_Voyage**	91	10/29/97	h9710084	h9710085	15	normal	ET	ET	ET	ET	ET	no	3750	0	truck	CA	107944	0.027	0.25	7.93	1.16
336	**Acura_Integra_8**	88	10/30/97	h9710087	h9710085	5	normal	ET	ET	ET	ET	ET	no	2750	0	car	CA	158879	0.043	0.74	7.00	0.80
337	**Pontiac_Grand_A**	86	10/31/97	h9710092	h9710093	6	normal	ET	ET	ET	ET	ET	no	2750	0	car	CA	29025	0.035	0.23	1.11	0.91
338	**Ford_Bronco_86**	86	10/31/97	h9710094	h9710095	14	normal	ET	ET	ET	ET	ET	no	3750	0	truck	CA	16489	0.039	0.29	3.15	0.73
339	**Oldsmobile_Cutl**	83	11/4/97	h9711009	h9711010	2	high	ET	ET	ET	none	ET	no	3000	0	car	CA	99899	0.037	0.85	4.83	2.49
340	**Ford_Festiva_88**	88	11/6/97	h9711016	h9711017	2	normal	ET	ET	ET	none	ET	no	2000	0	car	49	68287	0.029	0.46	4.19	0.74
400	**Ford_F_350_95**	95	12/18/98	h9812047	h9812048	40	normal	T	T*	T	no	T	no	7000	1	truck	CA	37503	0.030	0.9653	2.03	7.0451
401	**Ford_F_250_87**	87	12/22/98	h9812055	h9812056	40	normal	T	T*	T	no	T	no	6600	0	truck	CA	81909	0.027	0.523	1.37	6.5021
402	**Dodge_250_90**	90	12/22/98	h9812057	h9812058	40	normal	T	T*	T	no	T	no	6900	0	truck	CA	118568	0.023	1.1765	1.8	0.5315
403	**Dodge_250_92**	92	12/23/98	h9812059	h9812060	40	normal	T	T*	T	no	T	no	6100	0	truck	CA	55745	0.026	0.718	1.25	3.3425
404	**Dodge_250_95**	95	12/24/98	h9812061	h9812062	40	normal	T	T*	T	no	T	no	6100	0	truck	CA	36615	0.026	0.514	1.41	8.2507
405	**Ford_F_250_86**	86	1/5/99	h9901006	h9901007	40	normal	T	T*	T	no	T	no	6600	0	truck	CA	61294	0.027	0.6449	1.72	4.2106
406	**Dodge_250_97**	97	1/5/99	h9901008	h9901009	40	normal	T	T*	T	no	T	no	6100	1	truck	CA	29862	0.035	0.5286	1.38	6.4494
407	**Ford_F_350_96**	96	1/6/99	h9901010	h9901011	40	normal	T	T*	T	no	T	no	7600	1	truck	CA	39855	0.028	0.552	1.28	4.593
408	**Ford_F_350_86**	86	1/6/99	h9901012	h9901013	40	normal	T	T*	T	T	T	no	7500	0	truck	CA	72695	0.024	0.6595	1.07	7.2564
409	**Ford_F_350_83**	83	1/7/99	h9901014	h9901015	40	normal	T	T*	T	no	T	no	6600	0	truck	CA	72461	0.027	0.957	2.42	6.6522
410	**Ford_F_350_96**	96	1/8/99	h9901016	h9901017	25	normal	ET	ET*	ET	ET	ET	no	6300	1	truck	CA	31380	0.039	0.153	1.2	0.1876
411	**Dodge_Ram_97**	97	1/9/99	h9901018	h9901030	25	normal	ET	ET*	ET	ET	ET	yes	5800	1	truck	CA	20048	0.041	0.1525	2.13	0.9028
412	**GMC_Sierra_89**	89	1/12/99	h9901031	h9901032	25	normal	ET	ET*	ET	ET	ET	yes	6300	0	truck	CA	91351	0.037	0.667	9.53	2.923
413	**Ford_F_350_92**	92	1/13/99	h9901033	h9901034	25	normal	ET	ET*	ET	ET	ET	no	5800	0	truck	CA	58665	0.040	1.039	11.97	5.0786
414	**Ford_F_350_87**	87	1/14/99	h9901035	h9901036	25	high	ET	ET*	ET	ET	ET	no	5800	0	truck	CA	14866	0.040	3.6349	49.36	5.3546
415	**Ford_F_350_96**	96	1/14/99	h9901037	h9901038	25	normal	ET	ET*	ET	ET	ET	no	6300	1	truck	CA	20224	0.039	0.2049	1.52	0.1114
416	**GMC_3500_88**	88	1/15/99	h9901040	h9901041	25	normal	ET	ET*	ET	ET	ET	no	5200	0	truck	CA	14408	0.045	1.048	6.16	2.0504
417	**Chevy_95_C3500**	95	1/20/99	h9901046	h9901047	25	normal	ET	ET*	ET	ET	ET	no	5800	0	truck	CA	53535	0.050	0.6111	9.76	3.1674
418	**GMC_3500_88**	88	1/26/99	h9910169	h9910172	25	normal	ET	ET*	ET	ET	ET	no	5200	0	truck	CA	103022	0.045	0.7801	8.04	0.5392
419	**95_GMC Jimmy**	95	1/27/99	h9901073	h9901074	21	high	ET	ET*	ET	ET	ET	no	3625	1	truck	CA	97202	0.054	2.74	8.33	0.4058
420	**95_Ford_Escort**	95	1/26/99	h9901070	h9901071	24	normal	ET	ET*	ET	no	RPT	yes	2625	1	car	CA	104890	0.034	0.1166	2.15	0.265
421	**96_Ford_Escort**	96	1/29/99	h9901080	h9901081	24	normal	ET	ET*	ET	no	ET	no	2625	1	car	CA	111203	0.034	0.1556	3.37	0.1147
422	**95_Ford_Windstar**	95	2/24/99	h9903007	h9902054	20	high	ET	ET*	ET	ET	ET	yes	3875	0	car	CA	104760	0.040	0.6158	24.11	0.287

num	Veh. Name	MY	date	test n1	test n2	Cat	Emitter	FTP	US06	MEC	AC	RPT	veh par	Mass	Tier	Veh Type	State	Odom	Z/weight	THCgm	TCOgm	TNOxgm
423	**96_VW_GTI**	96	2/26/99	h9902058	H9902061	24	normal	ET	ET*	ET	ET	ET	no	3250	1	car	CA	105430	0.035	0.1687	3.27	0.1127
424	**99 Buick_Century**	99	6/16/99	h9906051	h9906052		high	ET	ET*	ET	ET	ET	no	3625	1	car	CA	14510	0.044	0.1594	0.42	0.1095
426	**98_Pontiac_Sunfire**	98	6/23/99	h9906074	h9906075		high	ET	ET*	ET	ET	ET	yes	3000	1	car	CA	28278	0.038	0.1226	3.47	0.0608
427	**95_Jeep_Cherokee**	95	6/29/99	h9906093	h9906094	24	normal	ET	ET*	ET	ET	ET	no	3750	1	truck	CA	151740	0.051	0.2258	1.23	0.3877
428	**94_Mercury_Villager**	94	7/8/99	h9907015	h9907016	24	normal	ET	ET*	ET	ET	ET	-	4000	1	car	CA	100160	0.038	0.2878	2.11	0.5266
429	**98_Toyota_Camry**	98	7/16/99	h9907031	h9907034	20	high	ET	ET*	ET	ET	ET	no	3375	1	car	CA	13247	0.037	1.0337	37.47	0.0584
430	**95_Chevy_S10**	95	9/10/99	h9909032	h9909033	24	normal	ET	ET*	ET	ET	ET	no	2875	1	car	CA	100250	0.037	0.4818	4.81	0.2713

Appendix C: Calculation of Exhaust Emissions

The emission measurements presented in this report were obtained from CE-CERT's Vehicle Emission Research Laboratory (VERL). What follows is a brief description of some of the details of the emissions measurements and calculations. Depending on whether the vehicle is equipped with a catalytic converter or not, emission tests are conducted either by measuring the pre- and post- catalyst raw exhaust with a diluted tracer gas (CO_2) or by measuring the diluted exhaust only. In either case, simultaneous integrated bag samples are collected from a dilution tunnel. The raw exhaust collected from pre-catalyst and post-catalyst taps are sampled through heated sampling lines to a heated chemiluminescence detector for NO_X, two heated flame ionization detectors (FID) for THC and CH_4, and a sample conditioner followed by non-dispersive infrared (NDIR) detectors for CO and CO_2 measurements. The tracer CO_2 is sampled through a dilution tunnel, sample conditioner, and to another NDIR detector. For diluted sample measurements, the exhaust is sampled through a dilution tunnel (CVS) and to heated chemiluminescence and FIDs analyzers, or to sample conditioner then to the NDIRs. Modal data are converted into ASCII format by the VERL host computer. A dry-to-wet correction is applied to CO and CO_2 raw concentrations to compensate the volume change by the moisture removal. A humidity correction factor is applied to NO_X on both raw and diluted samples for moisture interference. All analyzers are then time aligned to within 1 second by the first aligning CO_2 tracer to a CO_2 post channel using Matlab's auto correlation function, and then all other channels are aligned to the CO_2 post channel by injecting a mixed gas to both pre and post lines. The diluted sample alignment is done by the same manor; injecting a mixed gas to a diluted line and aligned all channels to the CO_2 channel. Standard operational procedures have been established for VERL based on the requirements contained in the Federal Register.

The following are some equations used in the calculation to obtain mass emission of each pollutant.

FTP weighted mass emission

The weighted mass emission is calculated by the following equation:

$$Y_{WM} = 0.43 \times \frac{Y_{ct} + Y_s}{D_{ct} + D_s} + 0.57 \times \frac{Y_{ht} + Y_s}{D_{ht} + D_s}$$

where:

Y_{WM} is the weighted mass emission in g/mile

Y_{ct} is the mass emission in g during the cold transient phase

Y_s is the mass emission in g during the stabilized phase

Y_{ht} is the mass emission in g during the hot transient phase

D_{ct} is the distance in miles actually driven during the cold transient phase

D_s is the distance in miles actually driven during the stabilized phase

D_{ht} is the distance in miles actually driven during the hot transient phase

Calculation for Pre-Post Tracer Sampling Configuration

The Pre-Post-Tracer Configuration is applied for vehicles with catalytic converters. Sample is taken from both before and after catalyst. A CO_2 tracer analyzer is also used to monitor the diluted CO_2 concentration. The following equations are used to calculate the mass emission for each pollutant.

Dilution Ratio

Modal Analysis

The dilution ratio for modal data is calculated by the ratio of corrected raw CO_2 concentration and diluted (Tracer) CO_2 concentration. The equation is expressed as following:

$$q_i = \frac{[CO_2+]_{i,raw,dry} - [CO_2]_{amb}}{[CO_2]_{i,Tracer,dry} - [CO_2]_{amb}} \dagger$$

where:

q_i is the dilution factor during bag sampling period

$[CO2]_{i,raw,dry}$ is the measured raw CO_2 concentration at dry condition (%)

$[CO_2]_{i,Tracer,dry}$ is the measured diluted CO_2 concentration at dry condition (%)

$[CO_2]_{amb}$ is the measured diluted CO_2 concentration from the ambient concentration (%)

†$[CO_2]_{amb}$ is not corrected to dry condition since the difference is very small

Bag Analysis

The dilution factor for the bag data is calculated by the fuel composition and carbon concentration:

$$q = \frac{\left[\dfrac{100}{1 + \dfrac{R_{H/C}}{2} + 3.76\left(1 + \dfrac{R_{H/C}}{4} - \dfrac{R_{O/C}}{2}\right)}\right]}{\left\{[CO_{2,\%}] + \dfrac{[THC_{ppm,C}] + [CO_{ppm}]}{10000}\right\}}$$

where:

q is the dilution factor during bag sampling period

$R_{H/C}$ is the hydrogen to carbon ratio from fuel analysis

$R_{O/C}$ is the oxygen to carbon ratio from fuel analysis

$[CO_{2,\%}]$ is the measured CO_2 concentration from the bag (%)

$[THC_{ppm,C}]$ is the measured THC concentration from the bag ($ppmC_1$)

$[CO_{ppm}]$ is the measured CO concentration from the bag (ppm)

For typical gasoline (C_1H_{18}) powered vehicles, the dilution factor can be simplified by the following equation:

$$q = \frac{13.4}{[CO_2]_{\%} + ([HC]_{ppmC_1} + [CO]_{ppm}) \times 10^{-4}}$$

where:

q is the dilution factor during bag sampling period

$[CO_2]_{\%}$, $[HC]_{ppmC_1}$, $[CO]_{ppm}$ are the corrected concentration measured in diluted sample

Exhaust Flow Rate

Instantaneous exhaust flow rate is calculated from the following equation:

$$V_{Exh_j} = \frac{V_{CVS}}{q_j} + V_{rM}$$

where:

Y_{Exh_j}, is the exhaust flow rate at time j (m^3/sec)

V_{CVS} is the CVS flow rate, or V_{mix}/T (m^3/sec)

q_j is the dilution factor at time j during bag sampling period

V_{rM} is the volume taken out by the analyzers bench (average of 0.001333m^3/sec)

Mass Emission Rate Calculation

The mass emission rate reported as grams per mile can be calculated by the following equation:

$$Y_1 = \frac{M_i}{d}$$

where:

Y_i is the mass emission rate (g/mile)

M_i is the emitted mass of pollutant i (g)

d is the actual distance of the driving cycle (mile)

Modal Mass Emission

Modal mass emission is measured by summing the mass of each pollutant on a second by second bases:

$$M_i = \sum_{j_{mc}=1}^{n} V_{Exh_j} \times p_i \times k_{r_H} \times k \times C_{r_V}$$

where:

M_i is the emitted mass of pollutant *i* (g)

V_{Exh}, is the exhaust volume at time *j* (m^3)

P_i is the density of pollutant *i* g/m^3 at 20 C (NO_x: 1910.1g/m^3, THC:1730.4 g/m^3; CO_2: 18300.0 g/m^3; CO:1164.7 G/M^3)

k_{r_H}†† is the humidity correction factor for NO_x at exhaust condition ($k_{r_H} = \dfrac{1}{1-0.047(H+39.62-75)}$ for NO_X and "1" for all the other pollutant, where *H* is absolute humidity in g/lb)

K††† is the dry-to-wet volume correction factor ($k = [1-(1.21\times F/A) + 0.0407] \approx 0.8758$ for CO and CO_2 w/ F:A=14.5: 1 and "1" for all the other pollutant)

C_{r_v} is the concentration of the raw exhaust pollutant i at time j

sec. (THC: $ppmC_3X10^{-6}$; NO_X: ppm X 10^6; $CO/C0_2/0_2$: % X 10^{-2})

†† The NO_X measurement in the VERL LAB is sampled through heated lines and measured inside an oven with 80 C without passing through the sample conditioner. Humidity correction for chemiluminescence is applied to both the exhaust condition and the ambient condition.

††† The raw CO and CO2 measurements in the VERKL LAB is sampled through heated lines and sample conditioners. Since the moisture has been removed from the sample, a dry-to-wet correction is applied to both measurements.

Bag Mass Emission

The mass emission from the bag sample is calculated from the following equation:

$$M_i = V_{mix} \times p_i \times k_H \times C_i \times V_{rM} \times p_i \times k_{r_H} \times k \times \sum_{j_{mc}=1}^{n} C_{r_v}$$

where:

M_i is the emitted mass of pollutant i (g)

M_{mix} is the total diluted exhaust volume (m^3/phase)

P_i is the density of pollutant i in g/m^3 at 20 C (NO_X: 1910.1 g/m^3; THC:1730.4 g/m^3; CO_2:1830.0 g/m^3; CO:1164.7 g/m^3)

$k_H^{\dagger\dagger}$ is the humidity correction factor for NOX at ambient condition ($k_{r_H} = \dfrac{1}{1-0.047(H-75)}$ for NO_X and "1" for all other pollutant, where H is absolute humidity in g/lb)

C_i is the concentration of the raw exhaust pollutant i at time j sec. (THC: ppmC^{3}X10^{-6}; NO_X: ppm X 10^{-6}; $CO/CO_2/O_2$: % x 10^{-2})

$V_{rM} \times p_i \times k_{r_H} \times k \times \sum_{j_{mc}=1}^{n} C_{r_v}$ is the modal correction for pollutant i during the same phase

V_{rM} is the volume being taken out by the analyzers bench (average of 0.001333m3/sec)

$k_{r_H}^{\dagger\dagger}$ is the humidity correction factor for NO_X at exhaust condition ($k_{r_H} = \dfrac{1}{1-0.047(H+39.62-75)}$ for NO_X and "1" for all other pollutant, where H is absolute humidity in g/lb)

$k^{\dagger\dagger\dagger}$ is the dry-to-wet volume correction factor ($k = [1-(1.21\times F/A) + 0.0407] \approx 0.8758$ for CO and CO_2 w/ F:A=14.5: 1 and "1" for all the other pollutant)

C_{r_v} is the concentration of the raw exhaust pollutant i at time j sec. (THC: $ppmC_3X10^{-6}$; NO_X: ppm X 10^6; $CO/C0_2/0_2$: % X 10^{-2})

†† The NO_X measurement in the VERL LAB is sampled through heated lines and measured inside an oven with 80 C without passing through the sample conditioner. Humidity correction for chemiluminescence is applied to both the exhaust condition and the ambient condition.

††† The raw CO and CO2 measurements in the VERL LAB is sampled through heated lines and sample conditioners. Since the moisture has been removed from the sample, a dry-to-wet correction is applied to both measurements.

Calculation for Diluted Sampling Configuration

The diluted configuration is applied for vehicles without catalytic converters. Sample is taken from the dilution tunnel. The following equations are used to calculate the mass emission for each pollutant.

Dilution Factor

The dilution factor for both the bag and modal data is calculated by the fuel composition and carbon concentration:

$$q = \frac{13.4}{[CO_2]_{\%} + ([HC]_{ppmC_1} + [CO]_{ppm}) \times 10^{-4}}$$

where:

q is the dilution factor during bag sampling period

$[CO_2]_{\%}$, $[HC]_{ppmC_1}$, $[CO]_{ppm}$ are the corrected concentration measured in the diluted sample

Mass Emission Rate Calculation

The mass emission rate reported as grams per mile can be calculated by the following equation:

$$Y_1 = \frac{M_i}{d}$$

where:

Y_i is the mass emission rate (g/mile)

M_i is the emitted mass of pollutant i (g)

d is the actual distance of the driving cycle (mile)

Mass Emission

The mass emission from modal sample is calculated from the following equation:

$$M_i = \frac{V_{mix}}{T} \times p_i \times k_H \times \sum_{j=1}^{n} C_{r_V}$$

The mass emission from bag sample is calculated from the following equation:

$$M_i = V_{mix} \times p_i \times k_H \times C_i$$

where:

M_i is the emitted mass of pollutant *i* (g)

M_{mix} is the total diluted exhaust volume (m^3/phase) ††††

T is the time of testing cycle/phase (sec)

P_i is the density of pollutant *i* in g/m^3 at 20 C (NO_X: 1910.1 g/m^3; THC:1730.4 g/m^3; CO_2:1830.0 g/m^3; CO:1164.7 g/m^3)

k_H†† is the humidity correction factor for NO_X at ambient condition ($k_{r_H} = \frac{1}{1-0.047(H-75)}$ for NO_X and "1" for all other pollutant, where H is absolute humidity in g/lb)

C_i is the concentration of the raw exhaust pollutant *i* at time *j* sec. (THC: $ppmC^3 X10^{-6}$; NO_X: ppm X 10^{-6}; $CO/CO_2/O_2$: % x 10^{-2})

†† The NO_X measurement in the VERL LAB is sampled through heated lines and measured inside an oven with 80 C without passing through the sample conditioner. Humidity correction for chemiluminescence is applied to both the exhaust condition and the ambient condition.

†††† The bag volume correction is ignored since it is relatively small compare to V_{mix}.

Appendix D: Velocity/Acceleration-Indexed Lookup Tables

As described in Chapter 6, velocity/acceleration-indexed lookup tables have been created for the 26 different vehicle/technology categories. The lookup tables for fuel, CO, HC, and NO_x are illustrated as surface meshes in this appendix.

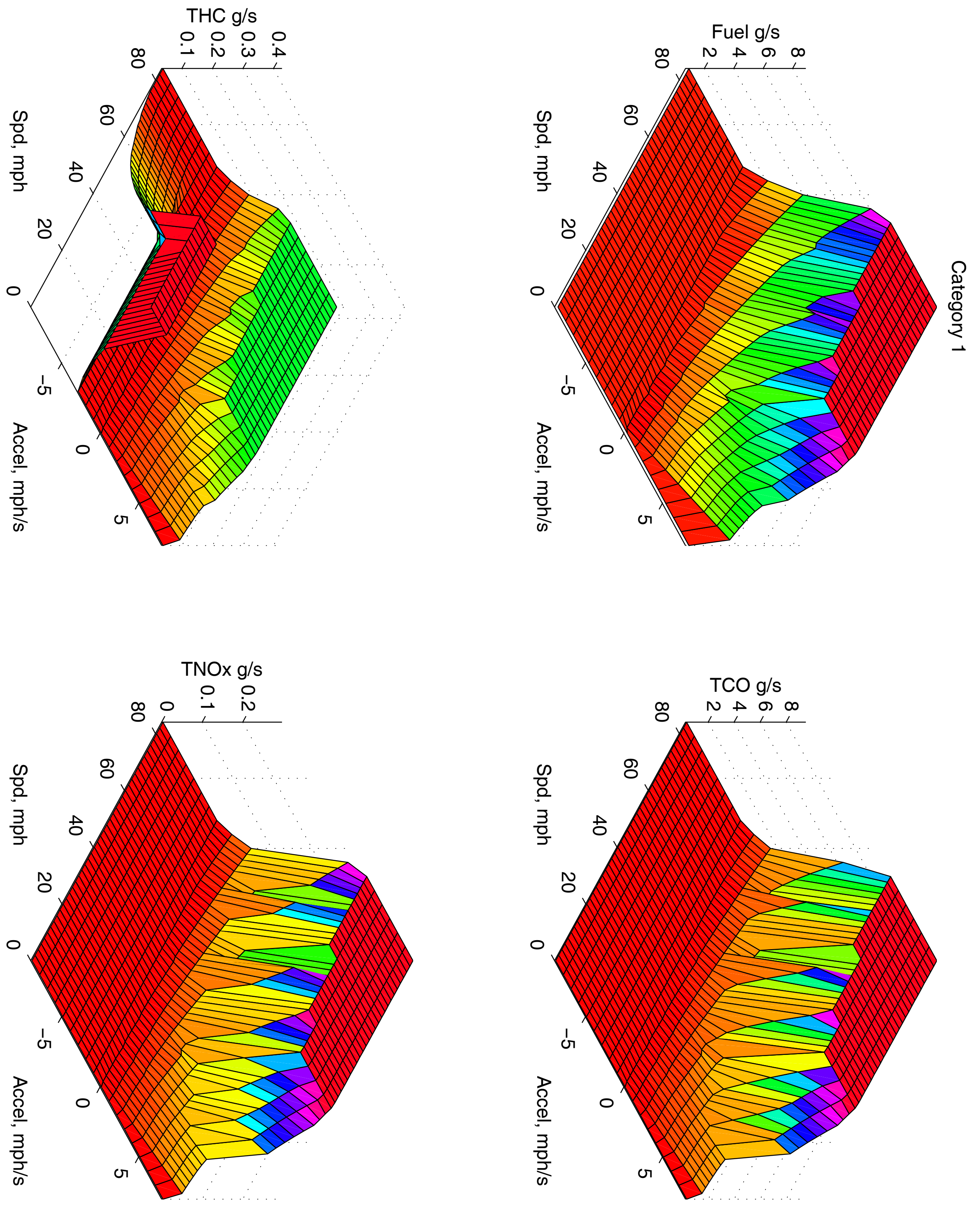

Figure D1. Category 1 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

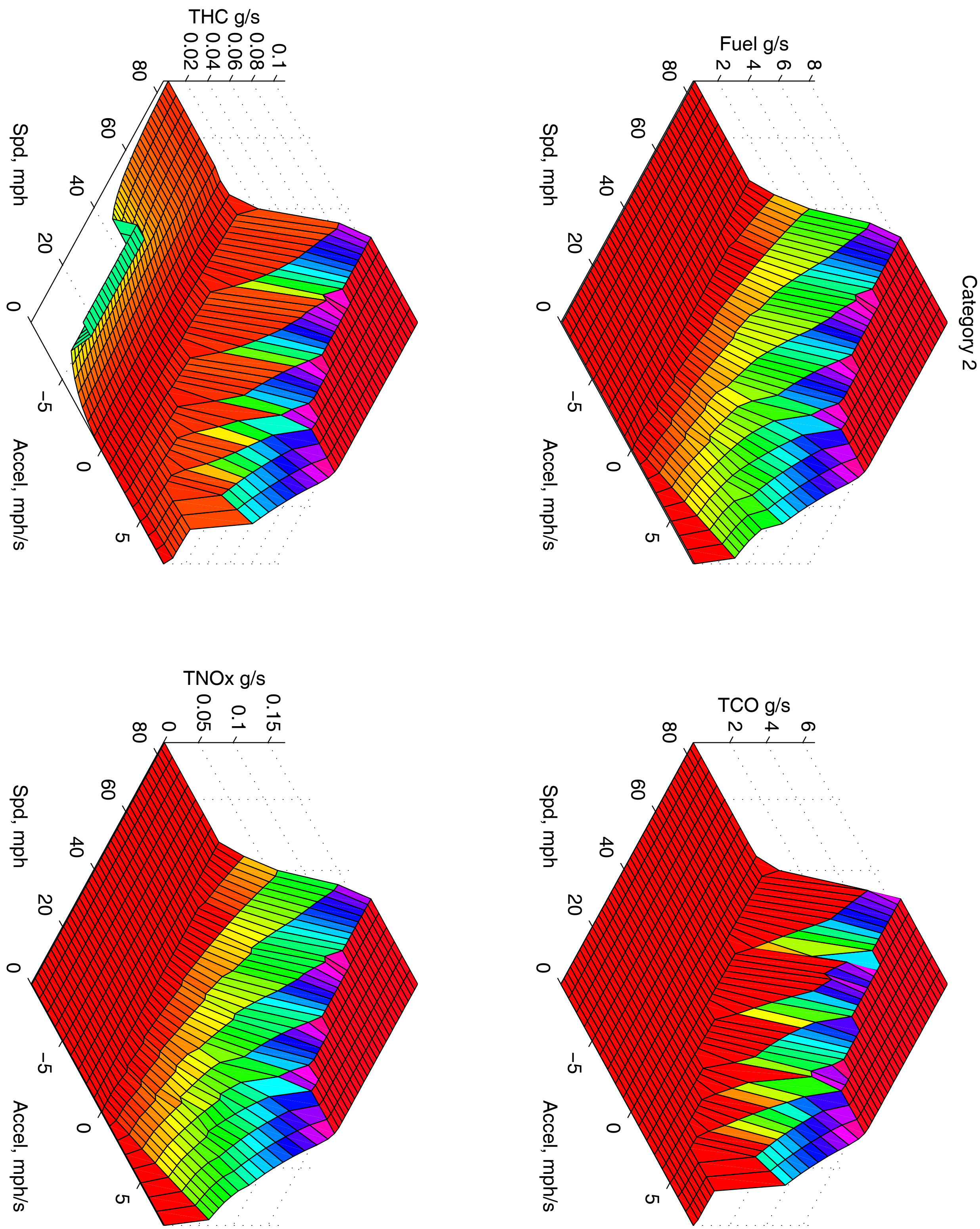

Figure D2. Category 2 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

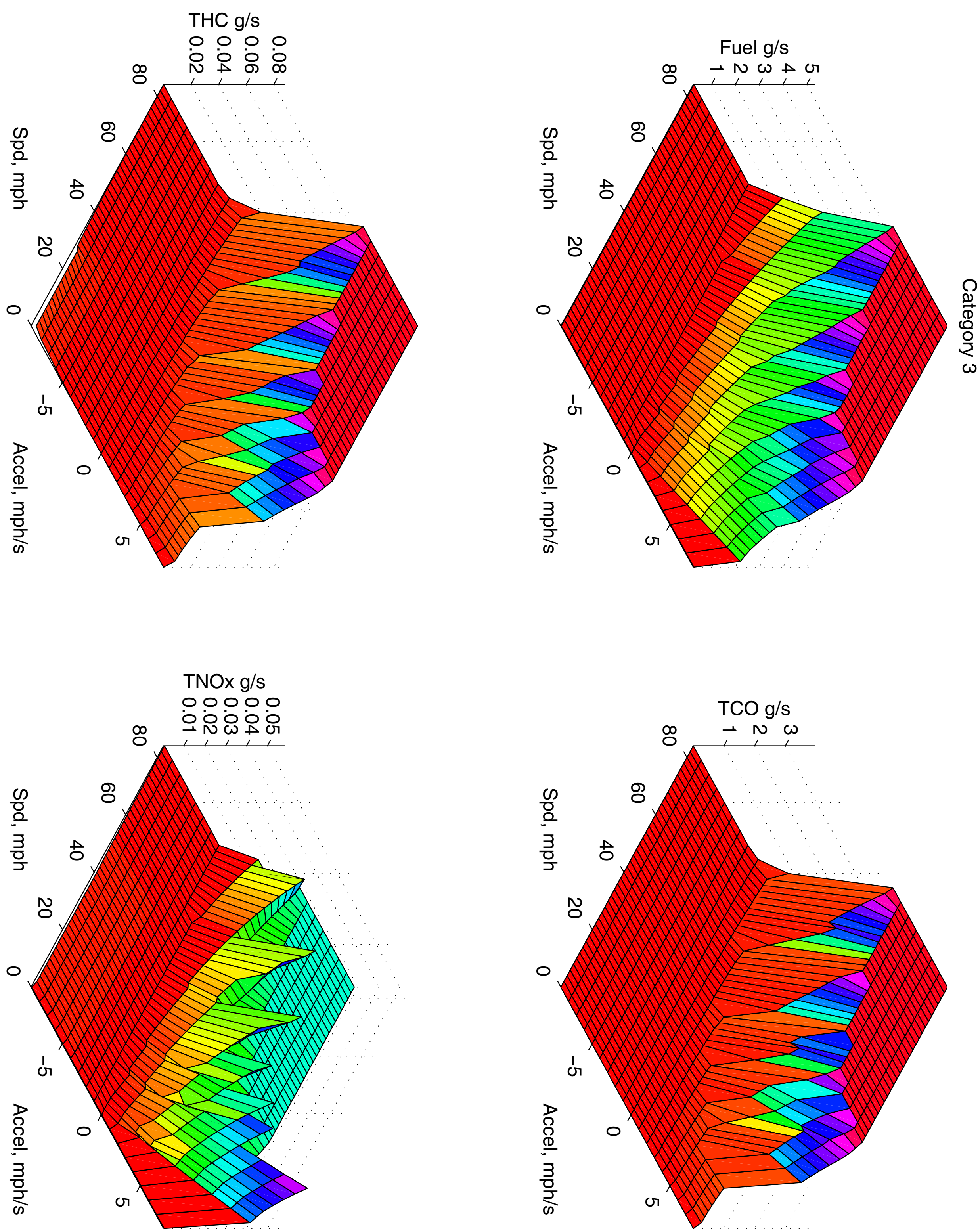

Figure D3. Category 3 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

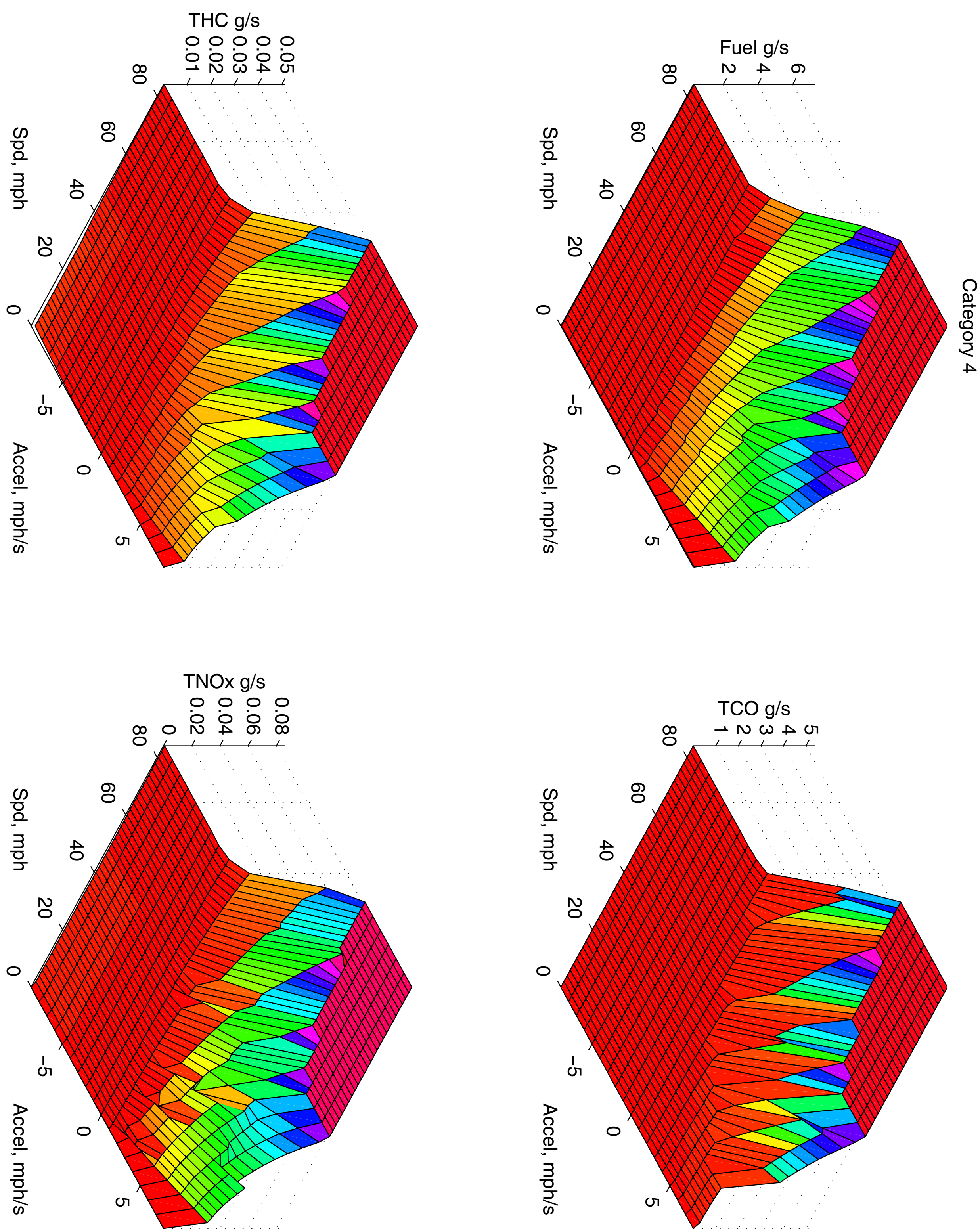

Figure D4. Category 4 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

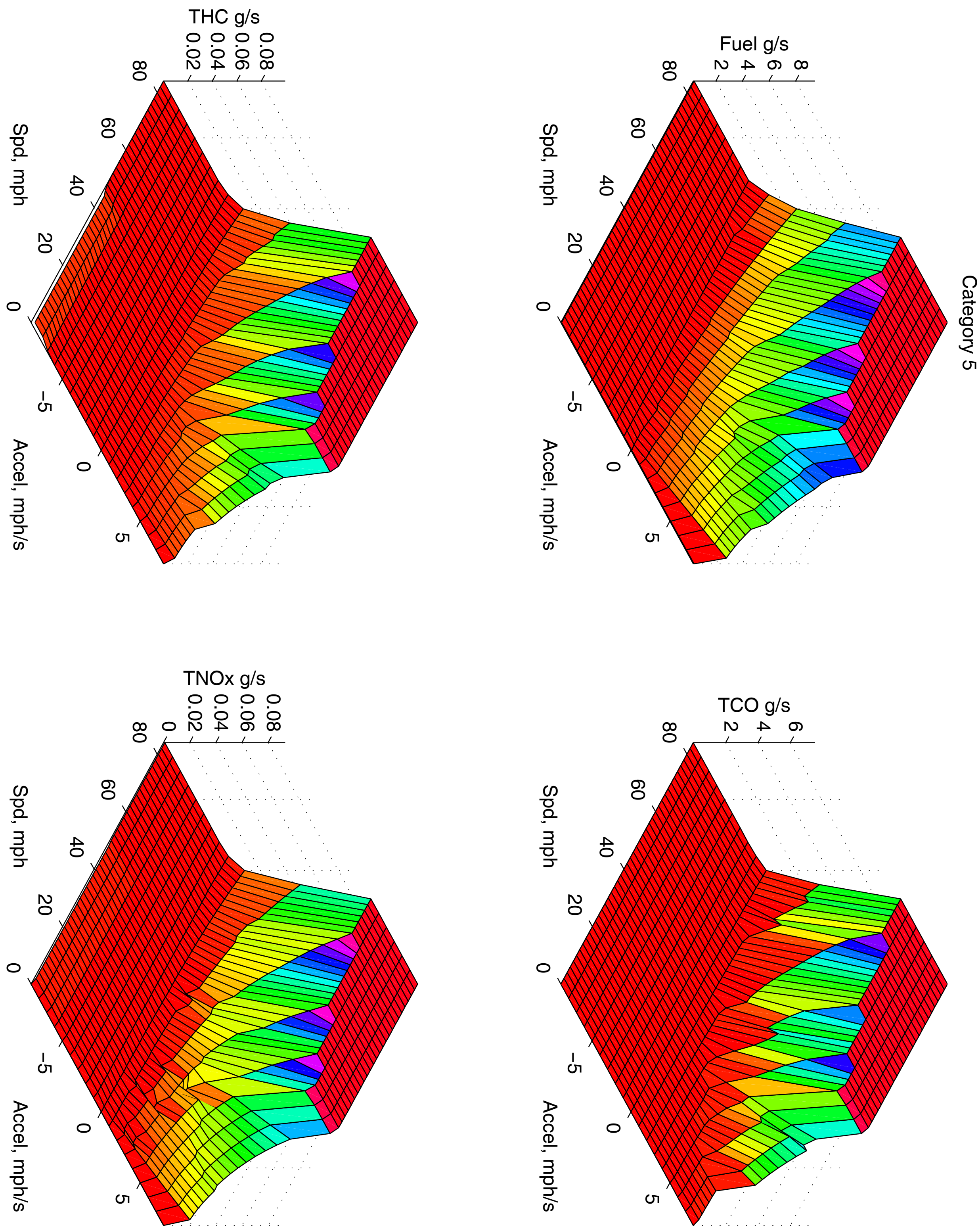

Figure D5. Category 5 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

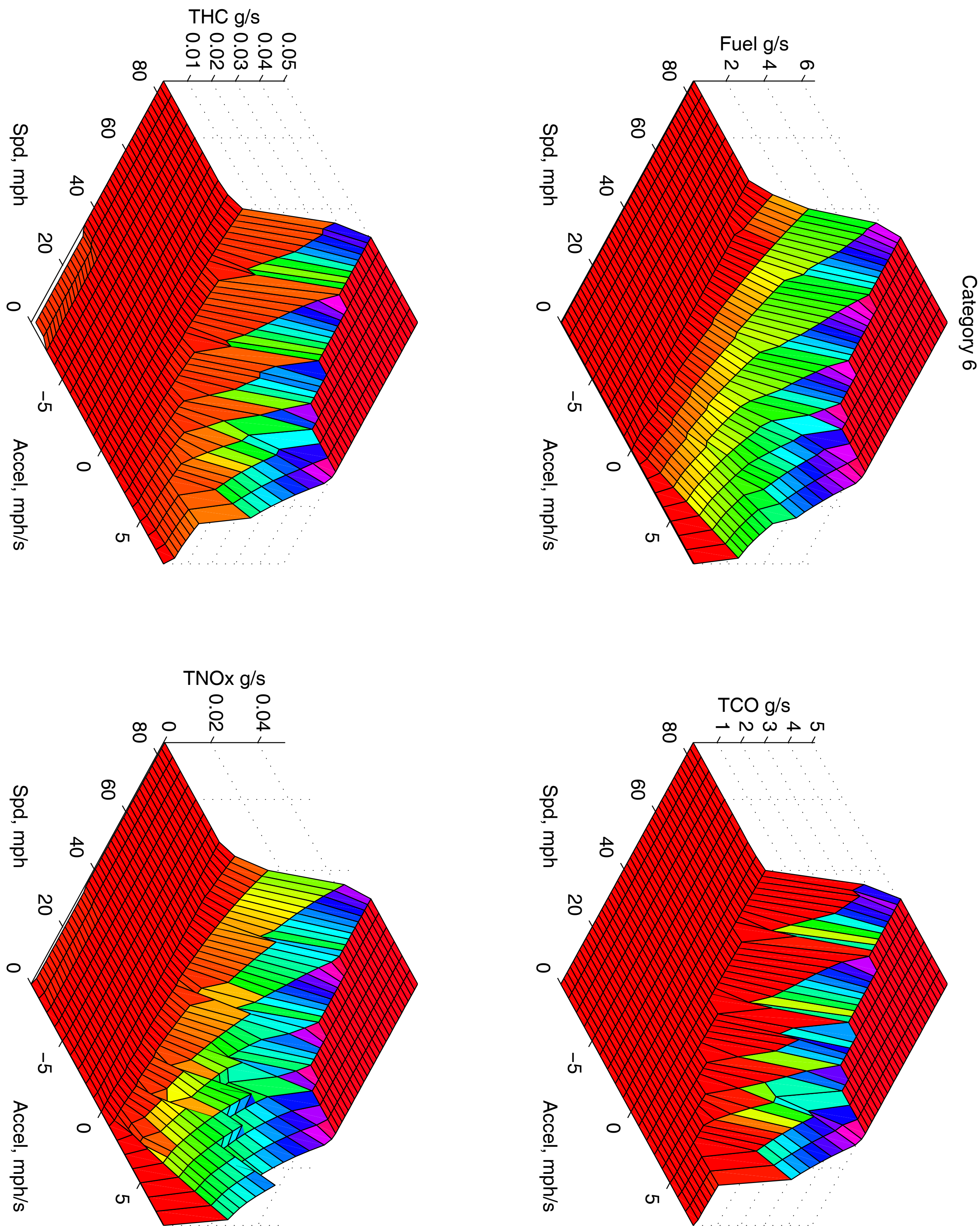

Figure D6. Category 6 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

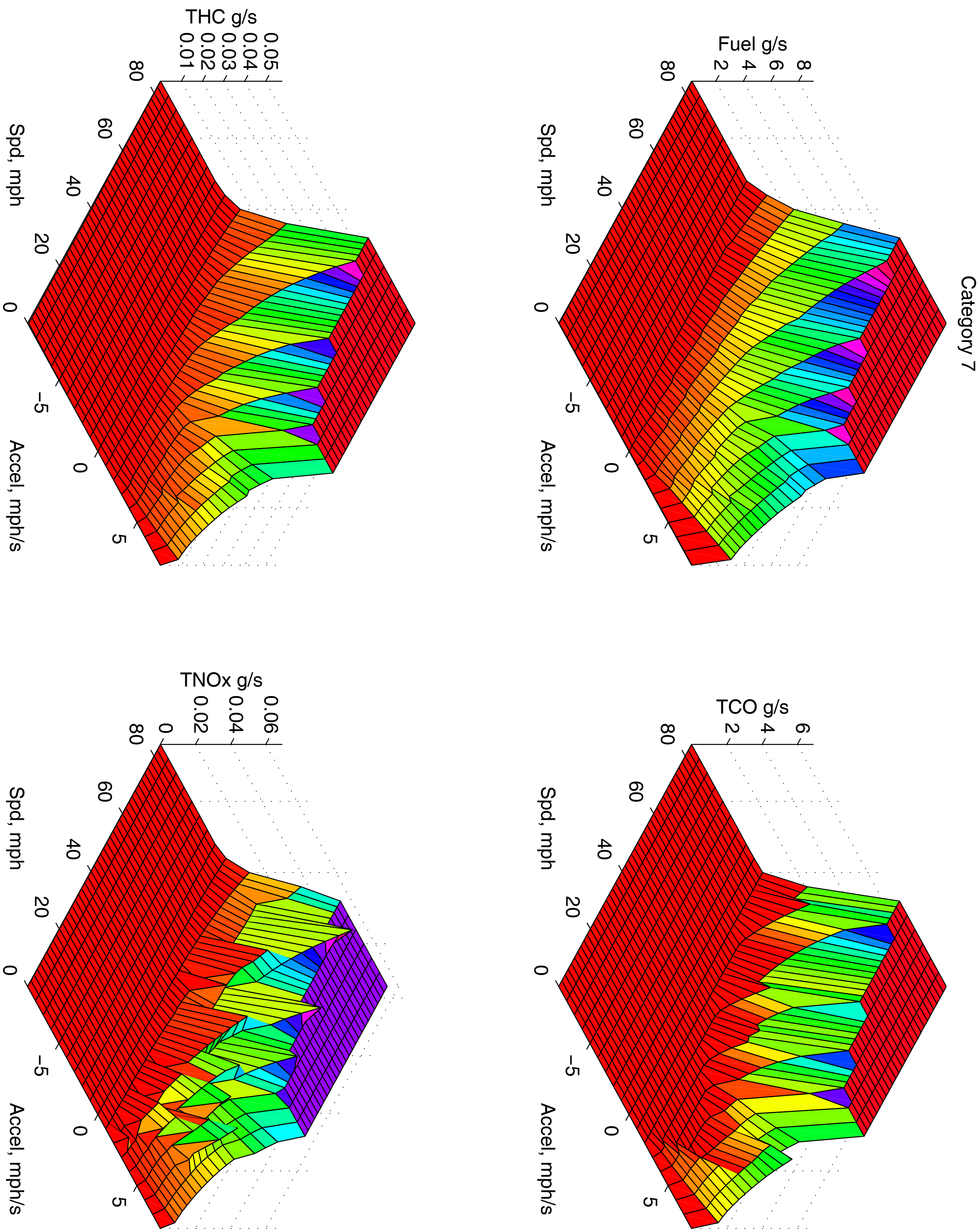

Figure D7. Category 7 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

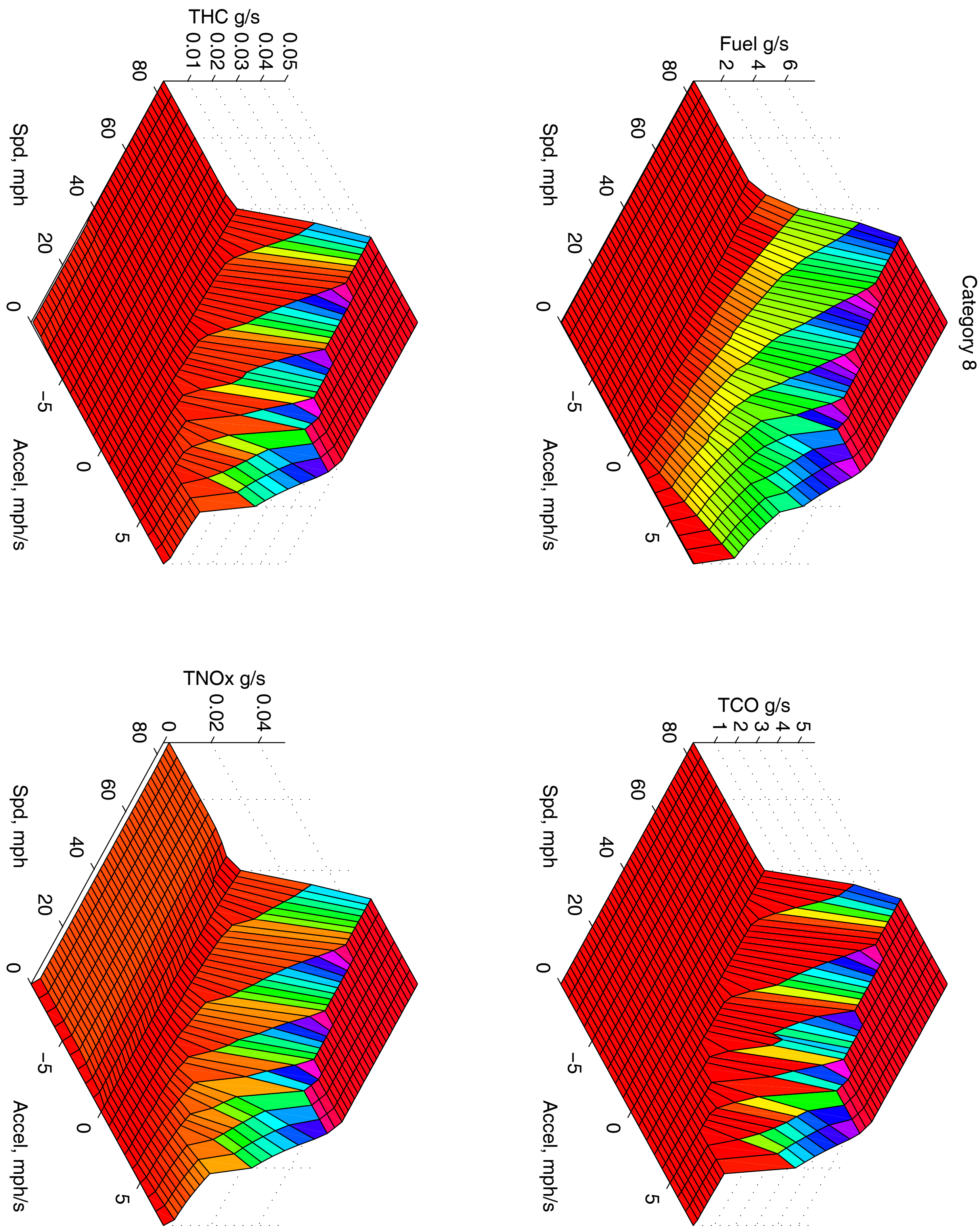

Figure D8. Category 8 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

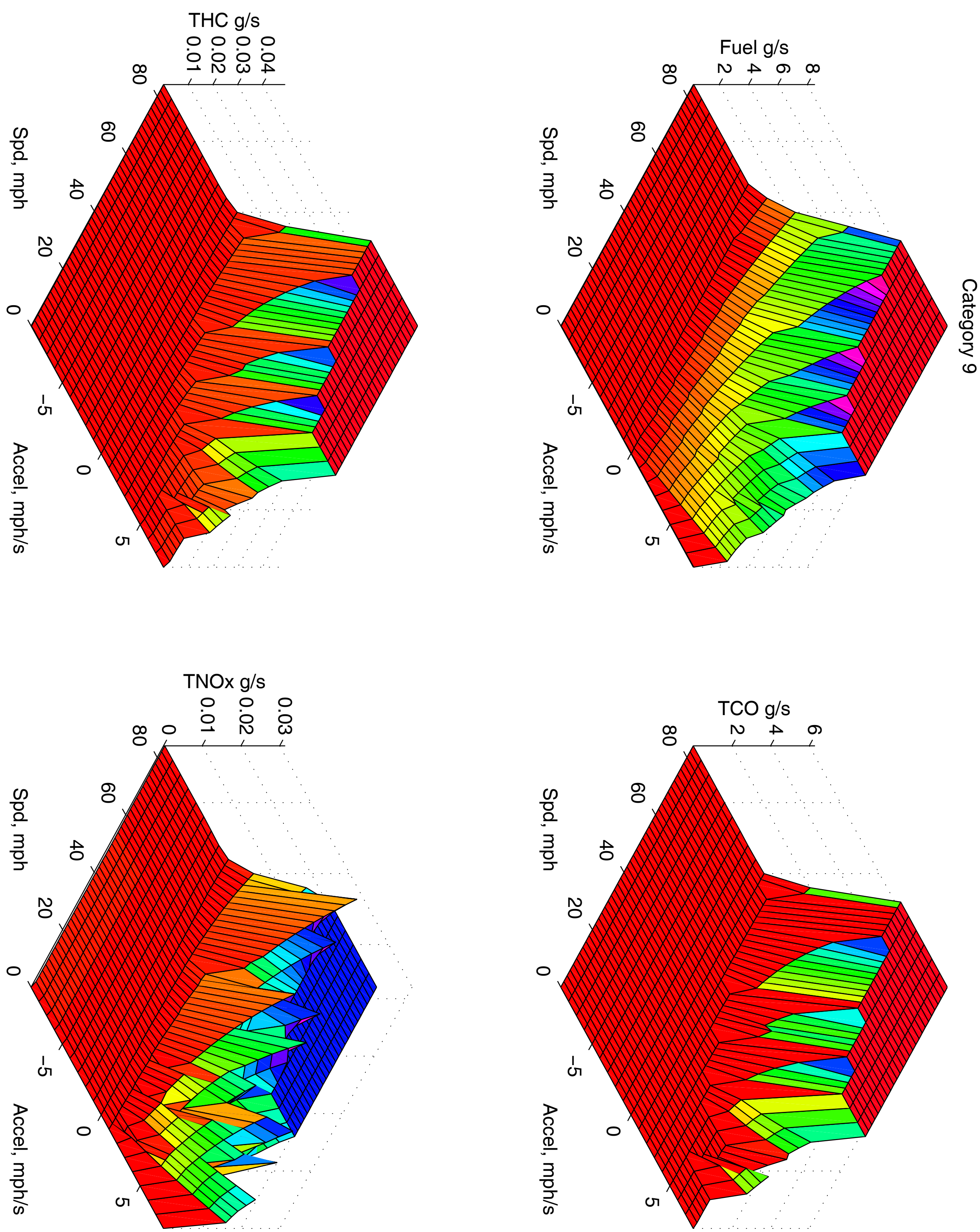

Figure D9. Category 9 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

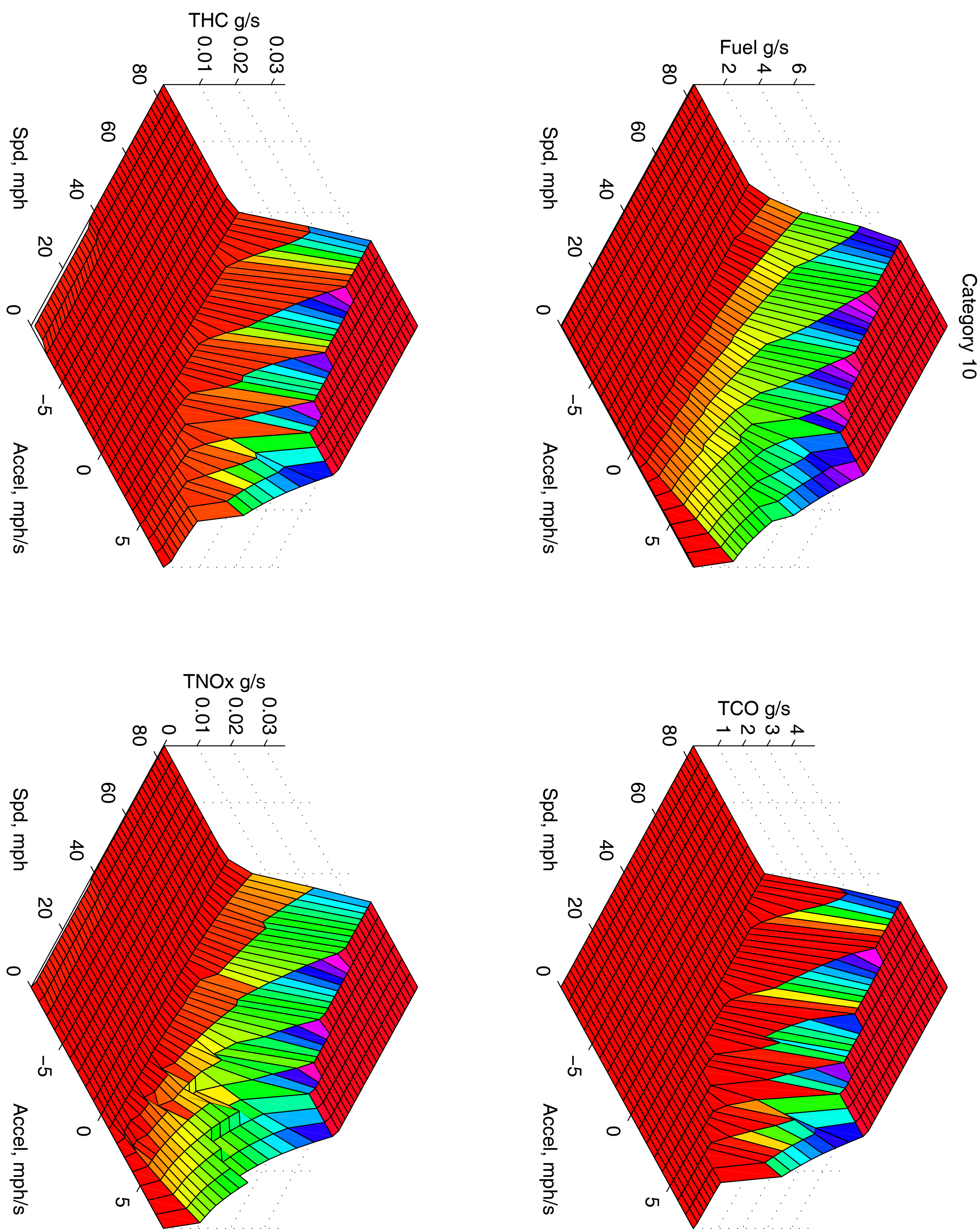

Figure D10. Category 10 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

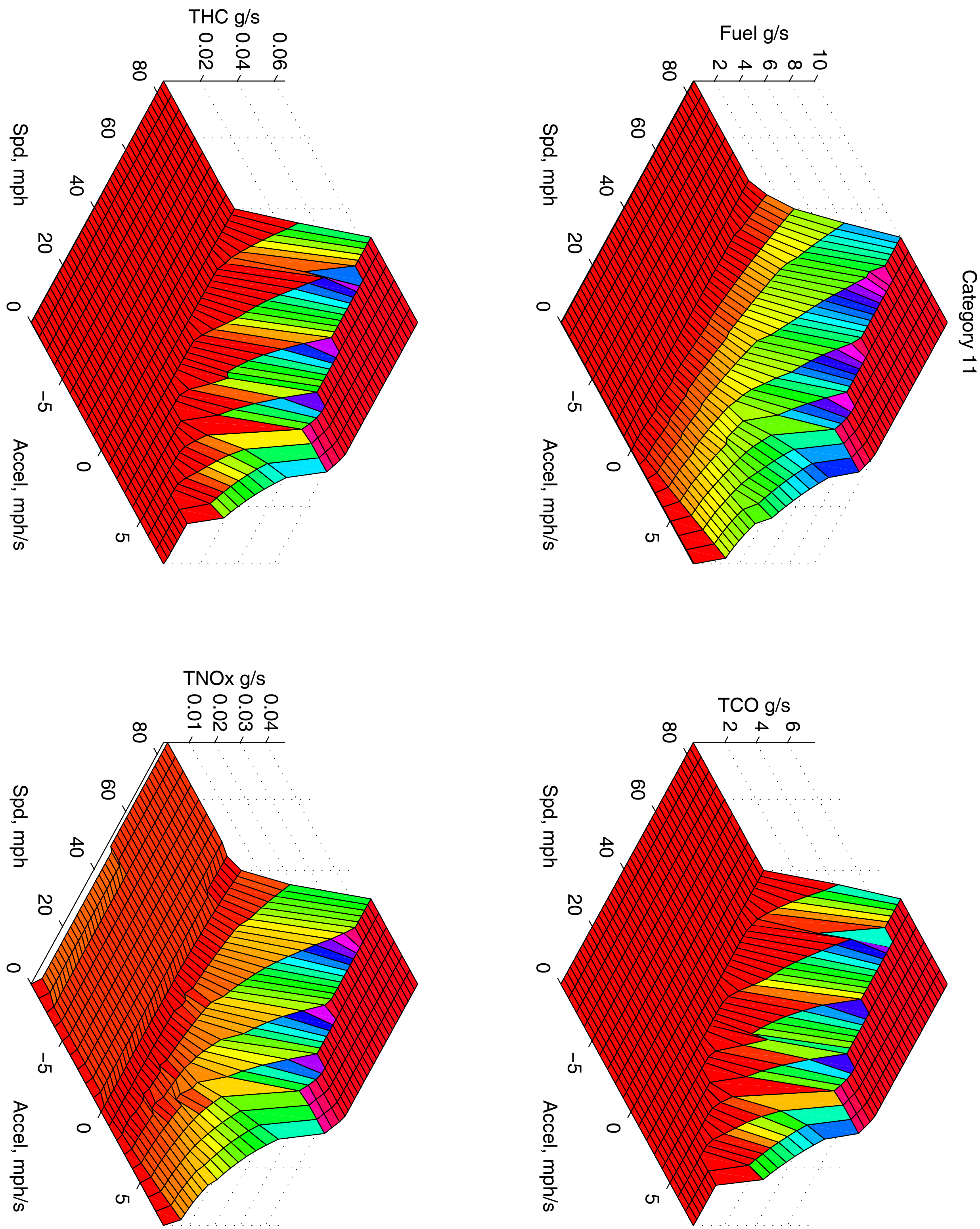

Figure D11. Category 11 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

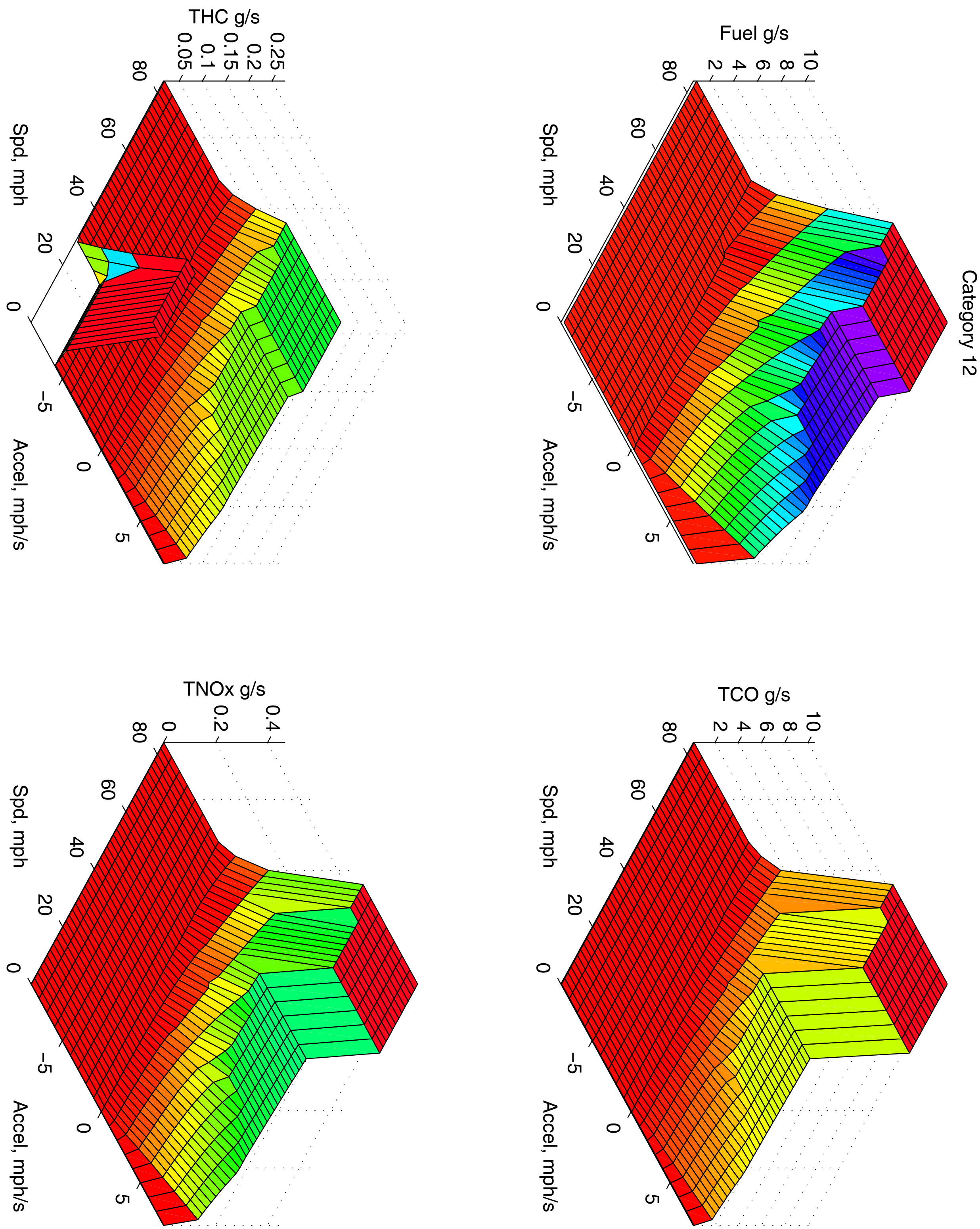

Figure D12. Category 12 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

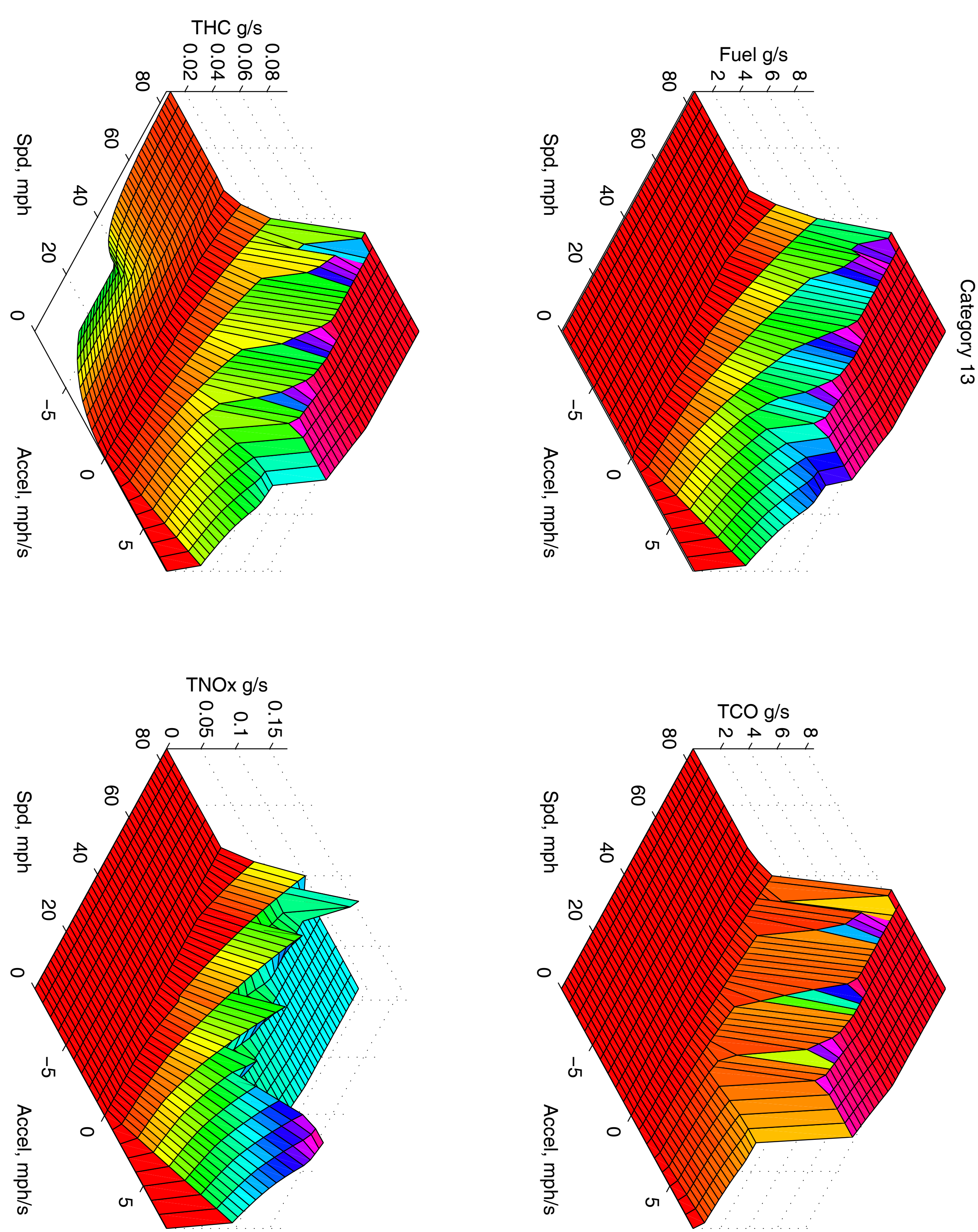

Figure D13. Category 13 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

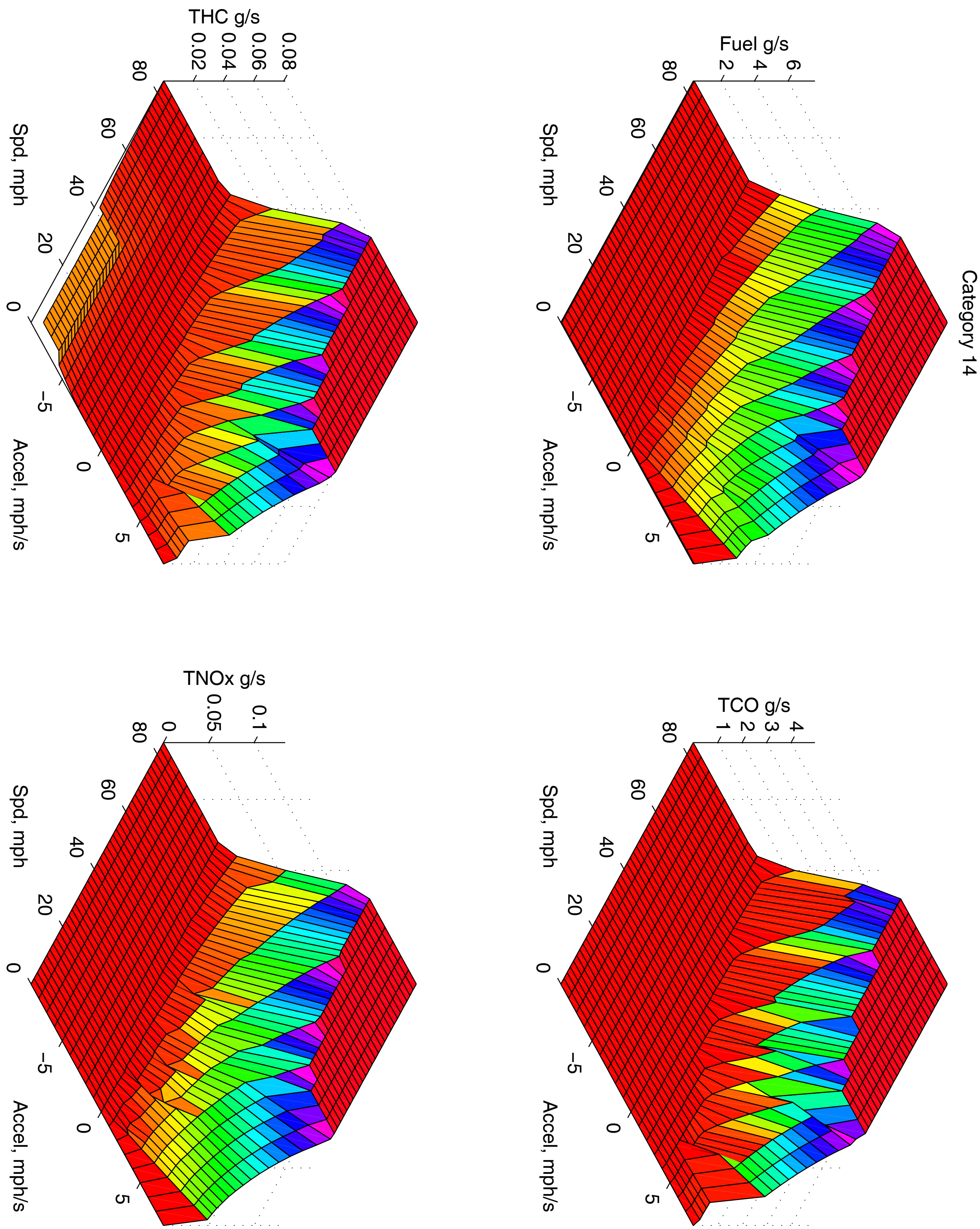

Figure D14. Category 14 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

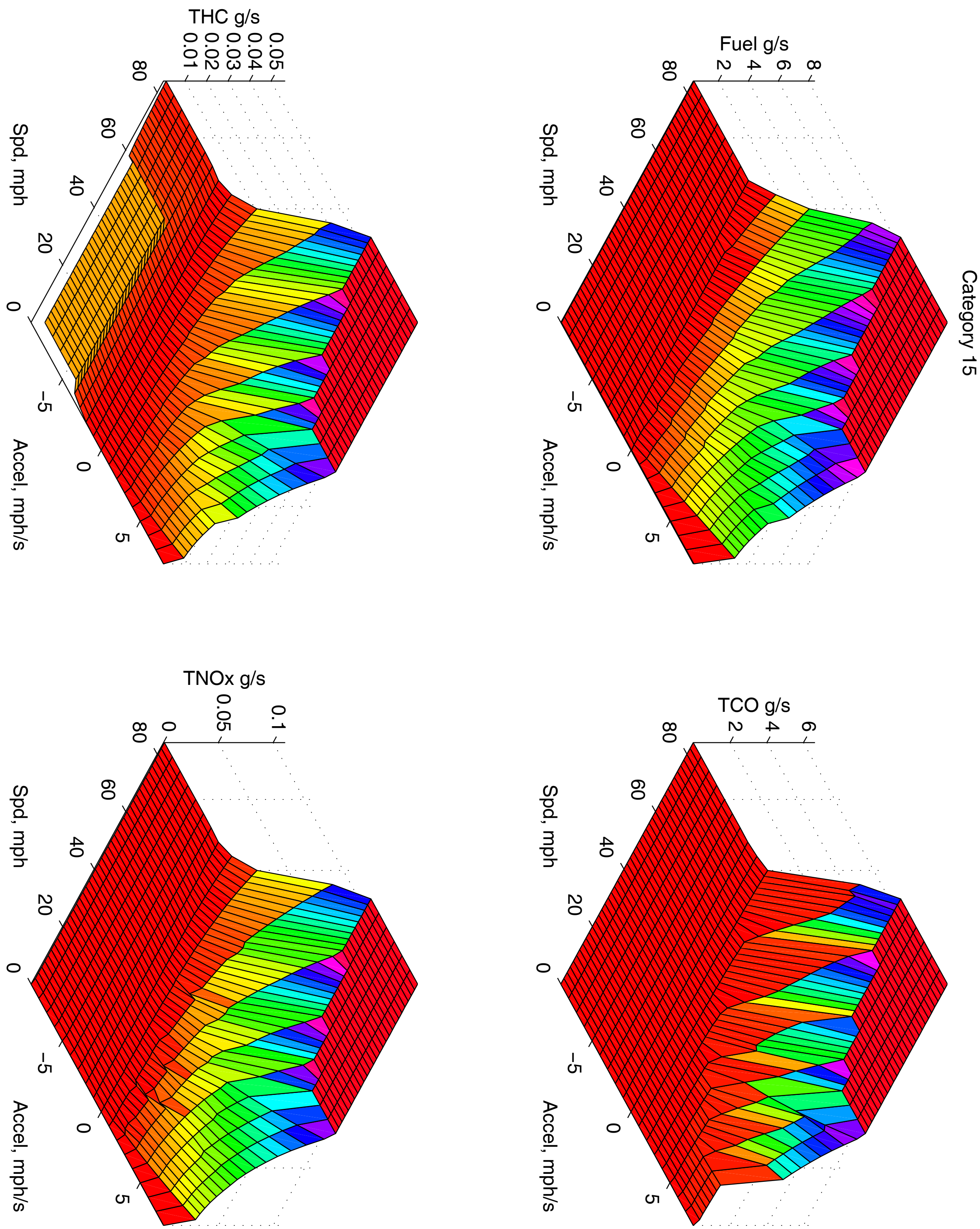

Figure D15. Category 15 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

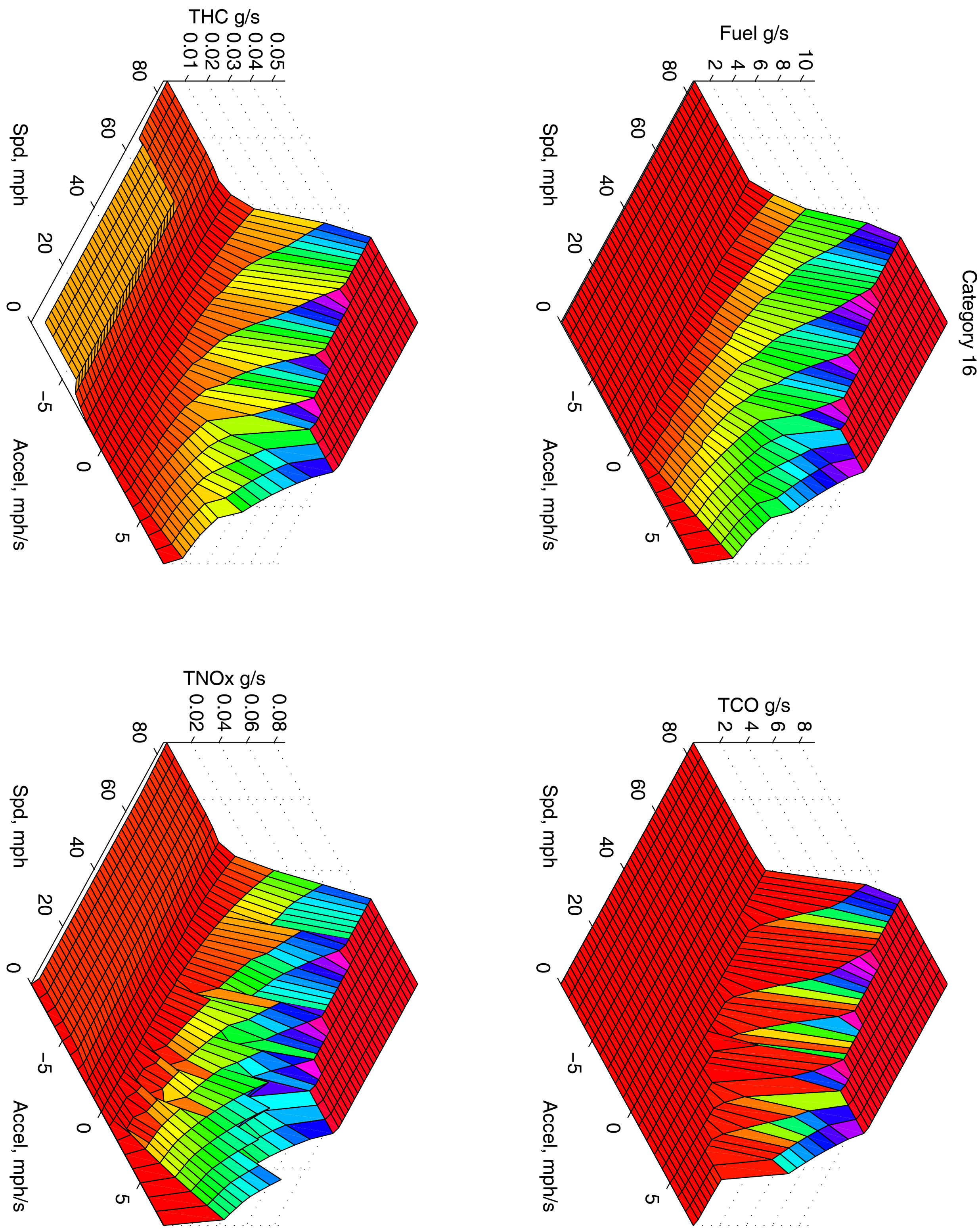

Figure D16. Category 16 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

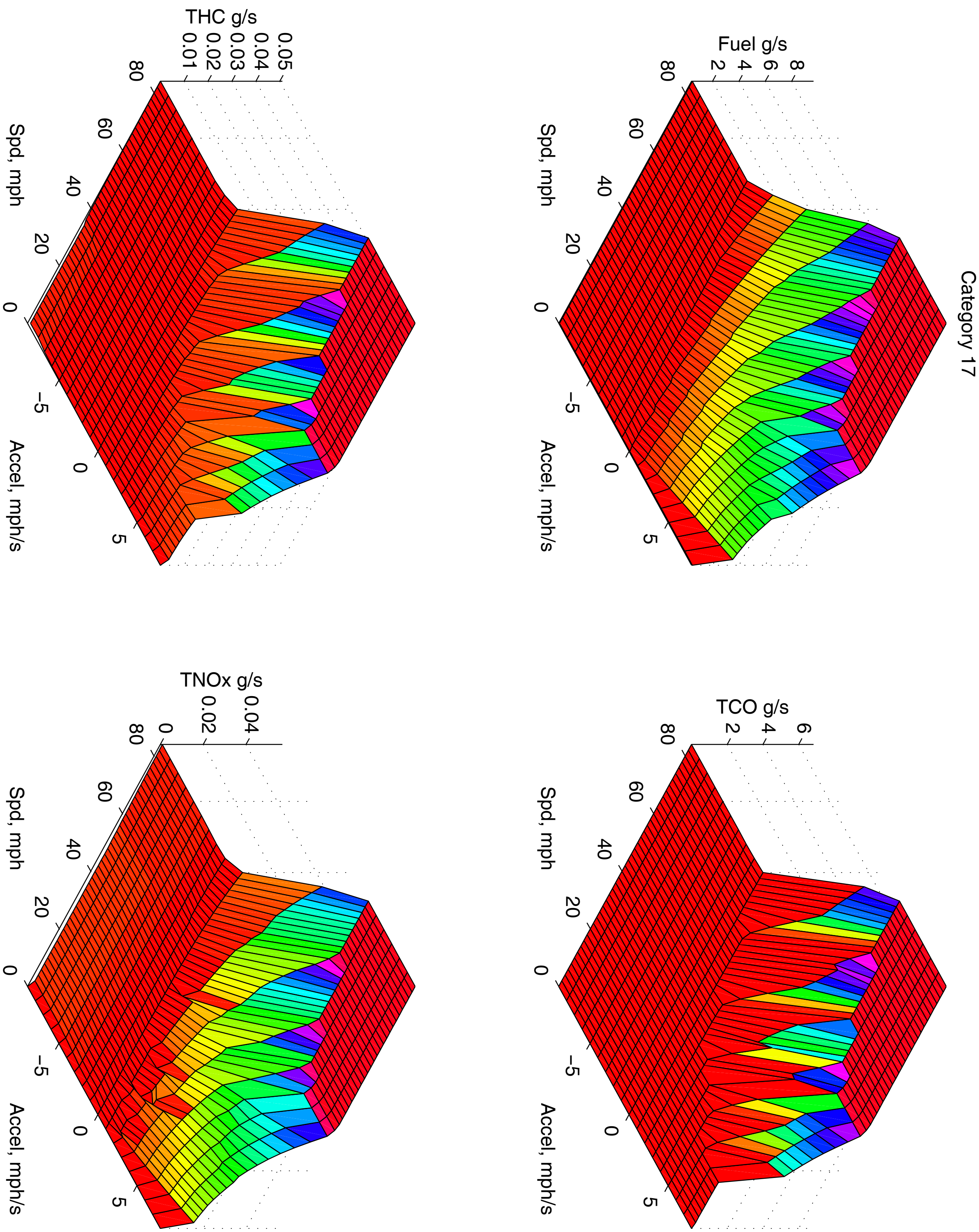

Figure D17. Category 17 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

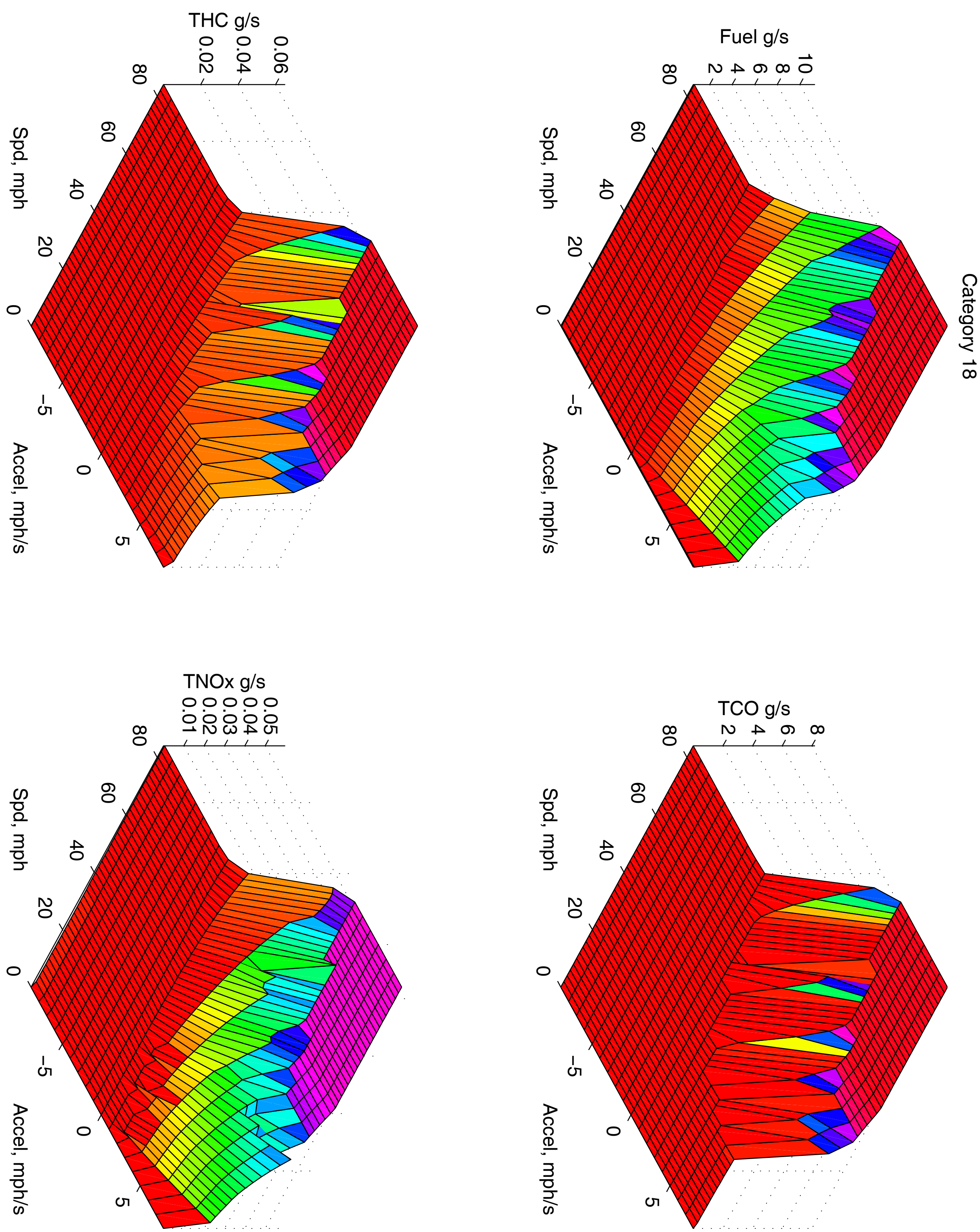

Figure D18. Category 18 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

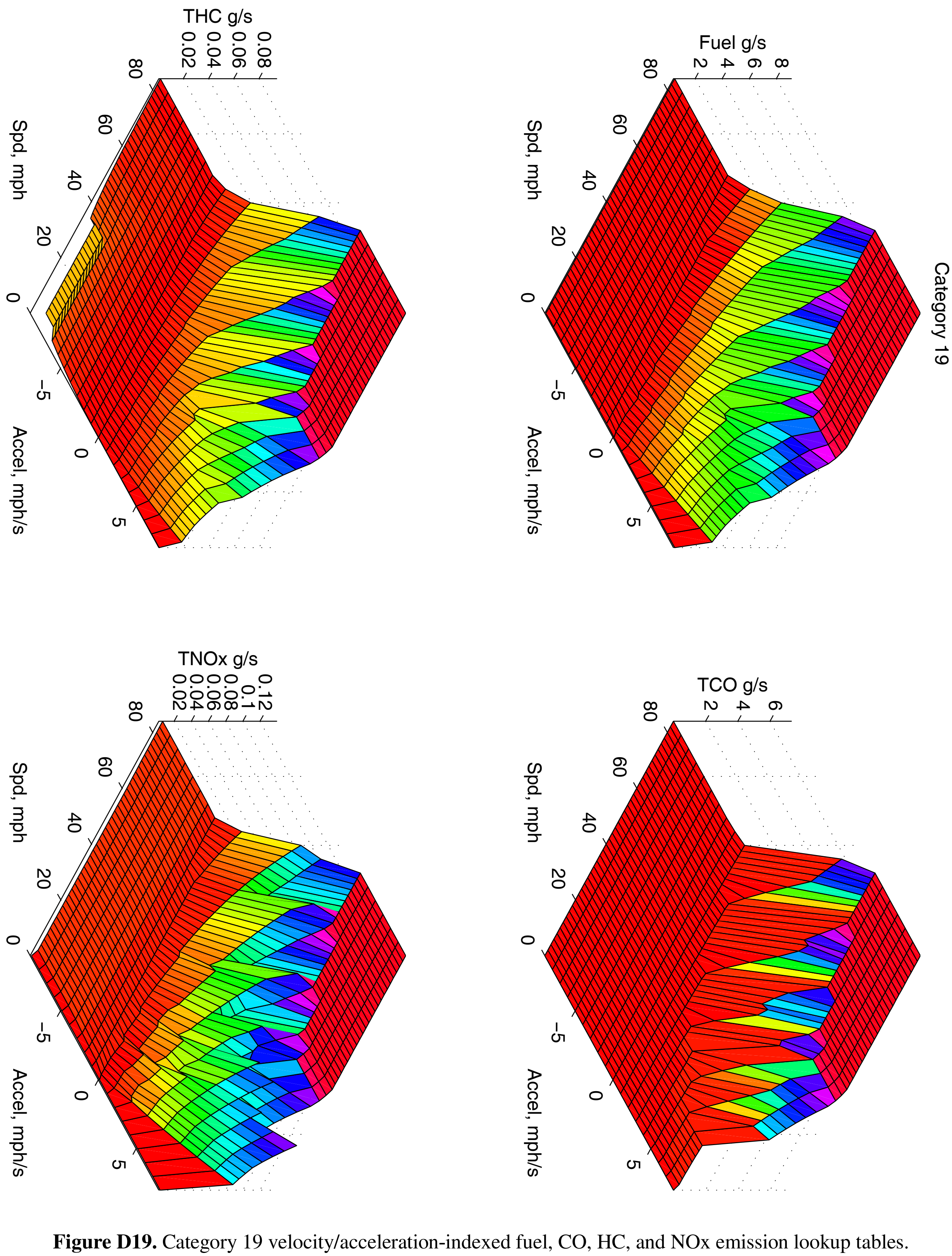

Figure D19. Category 19 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

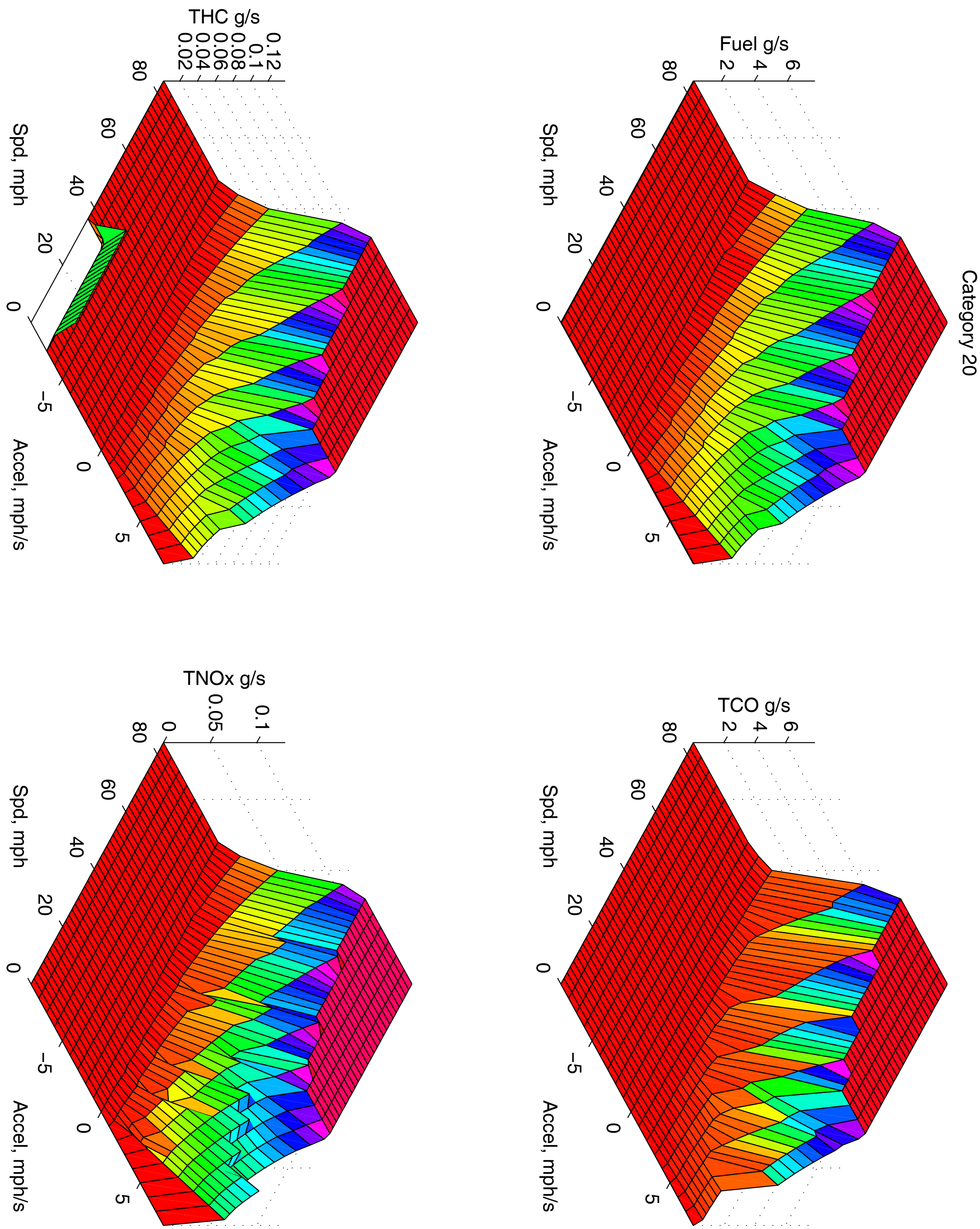

Figure D20. Category 20 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

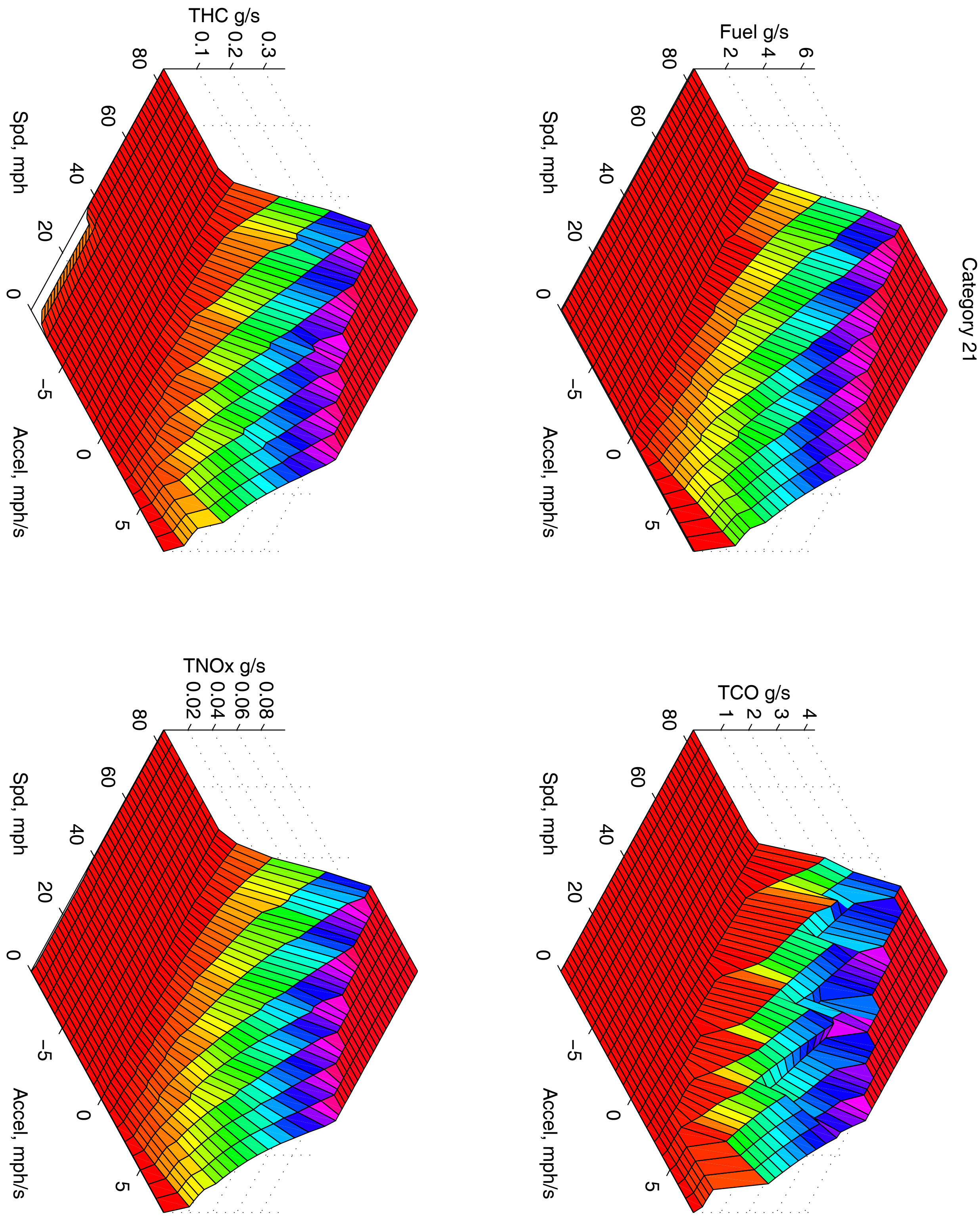

Figure D21. Category 21 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

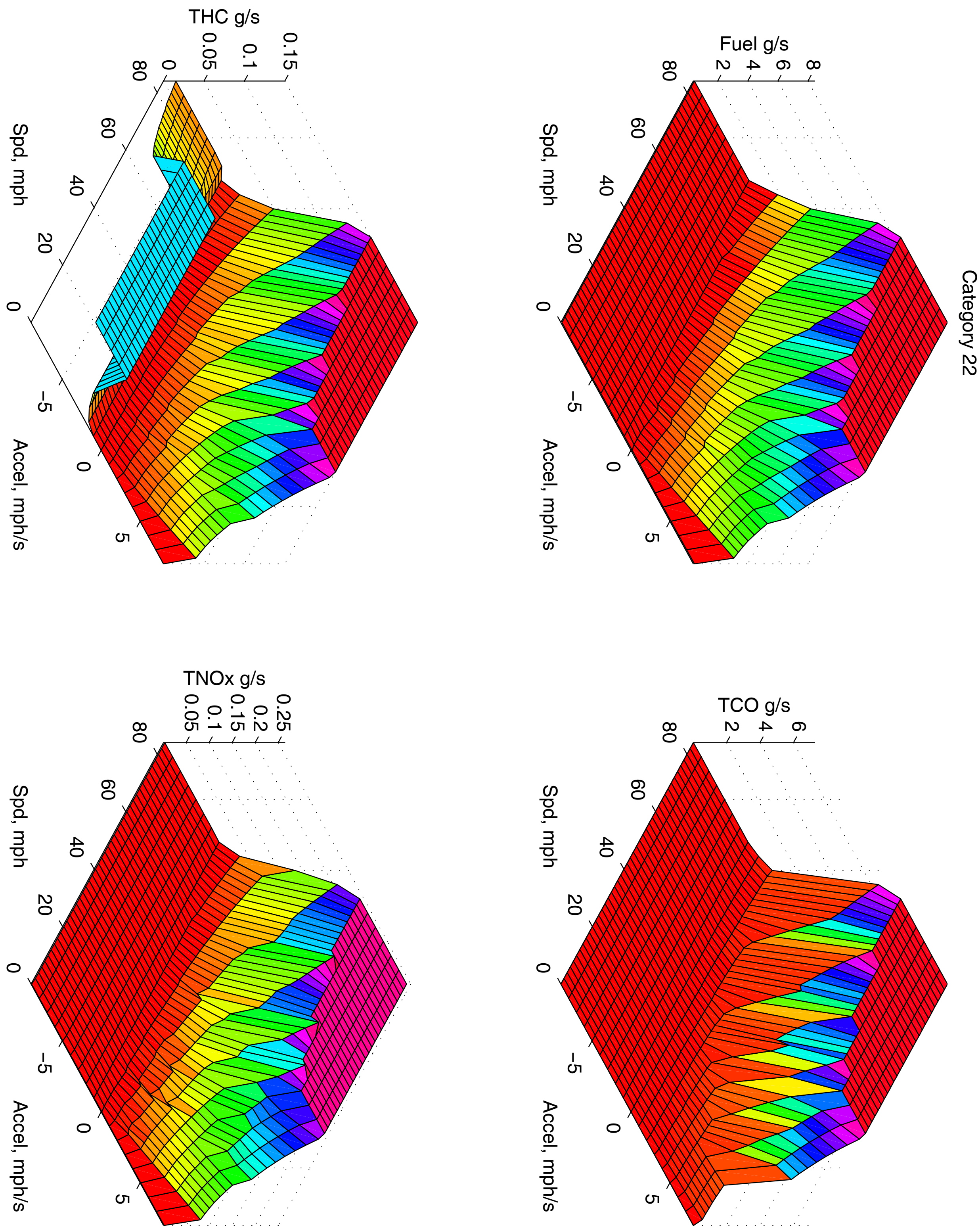

Figure D22. Category 22 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

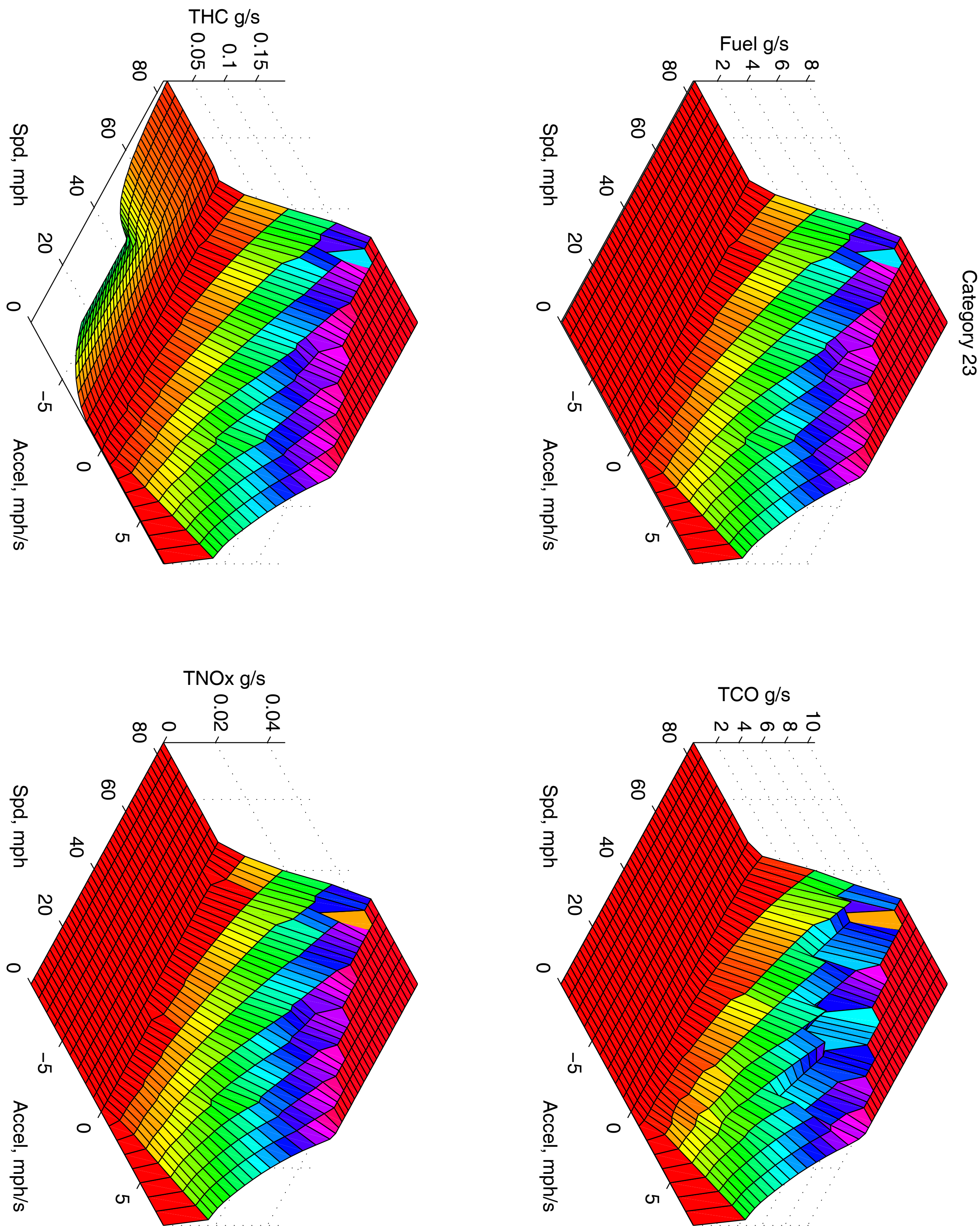

Figure D23. Category 23 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

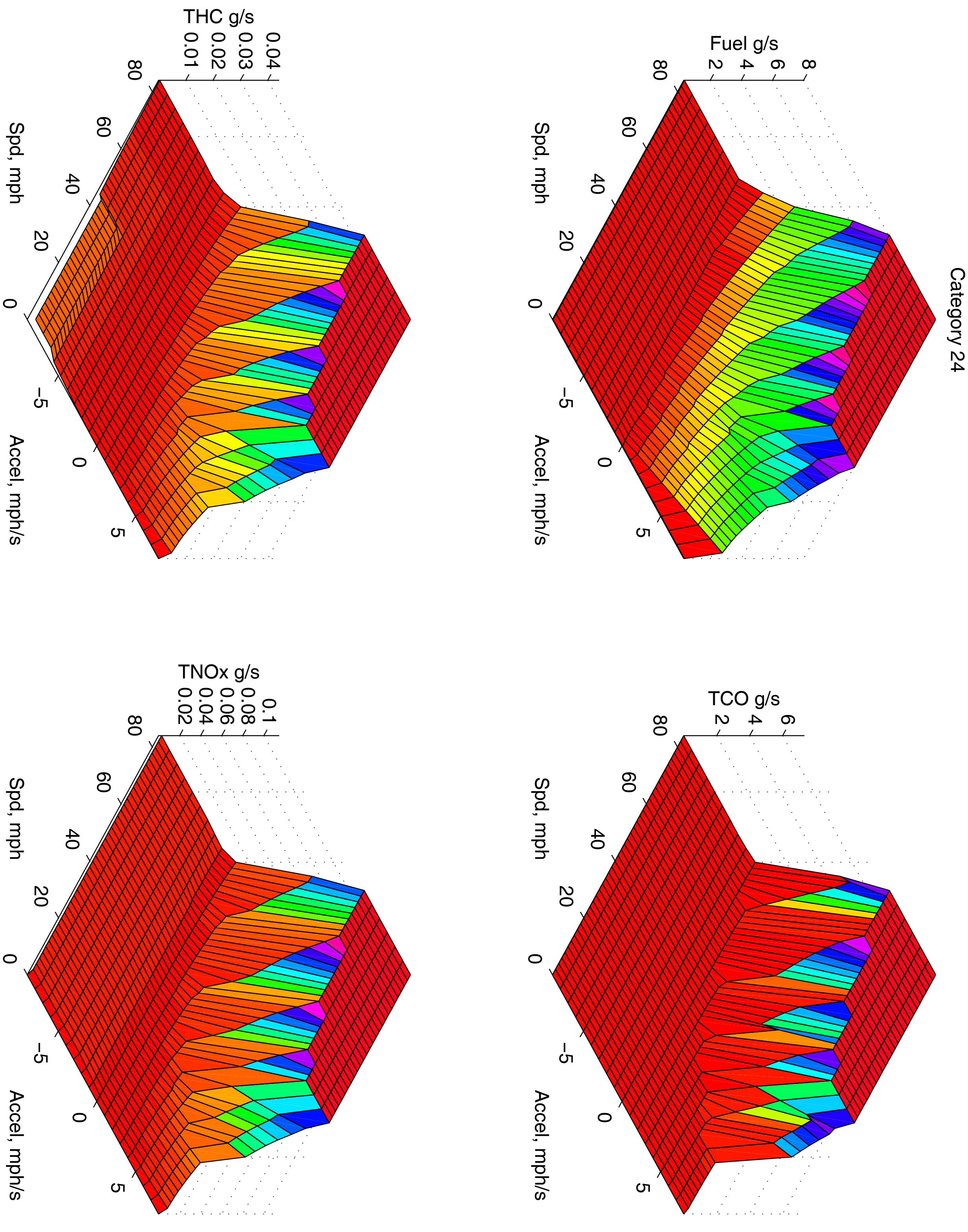

Figure D24. Category 24 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

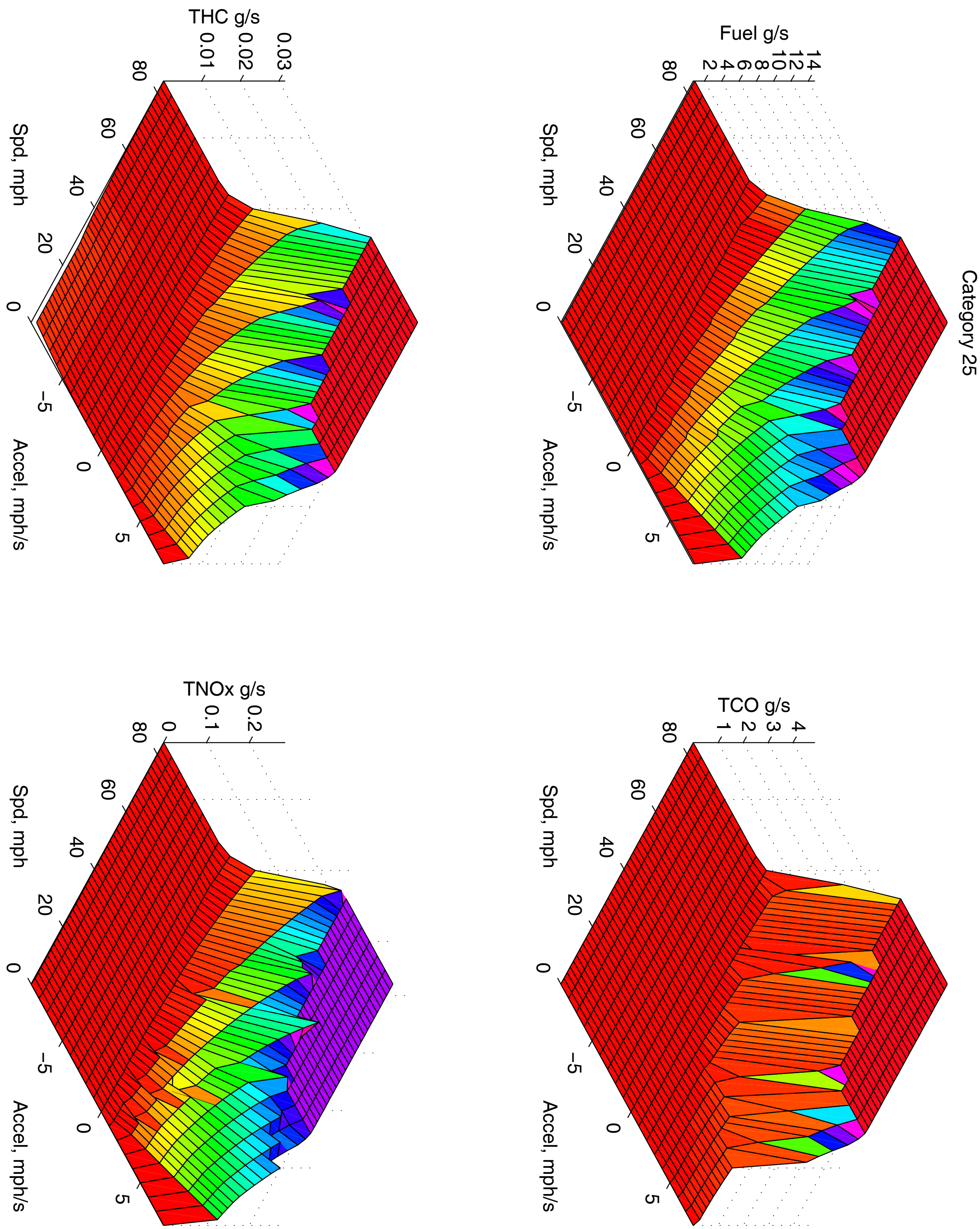

Figure D25. Category 25 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

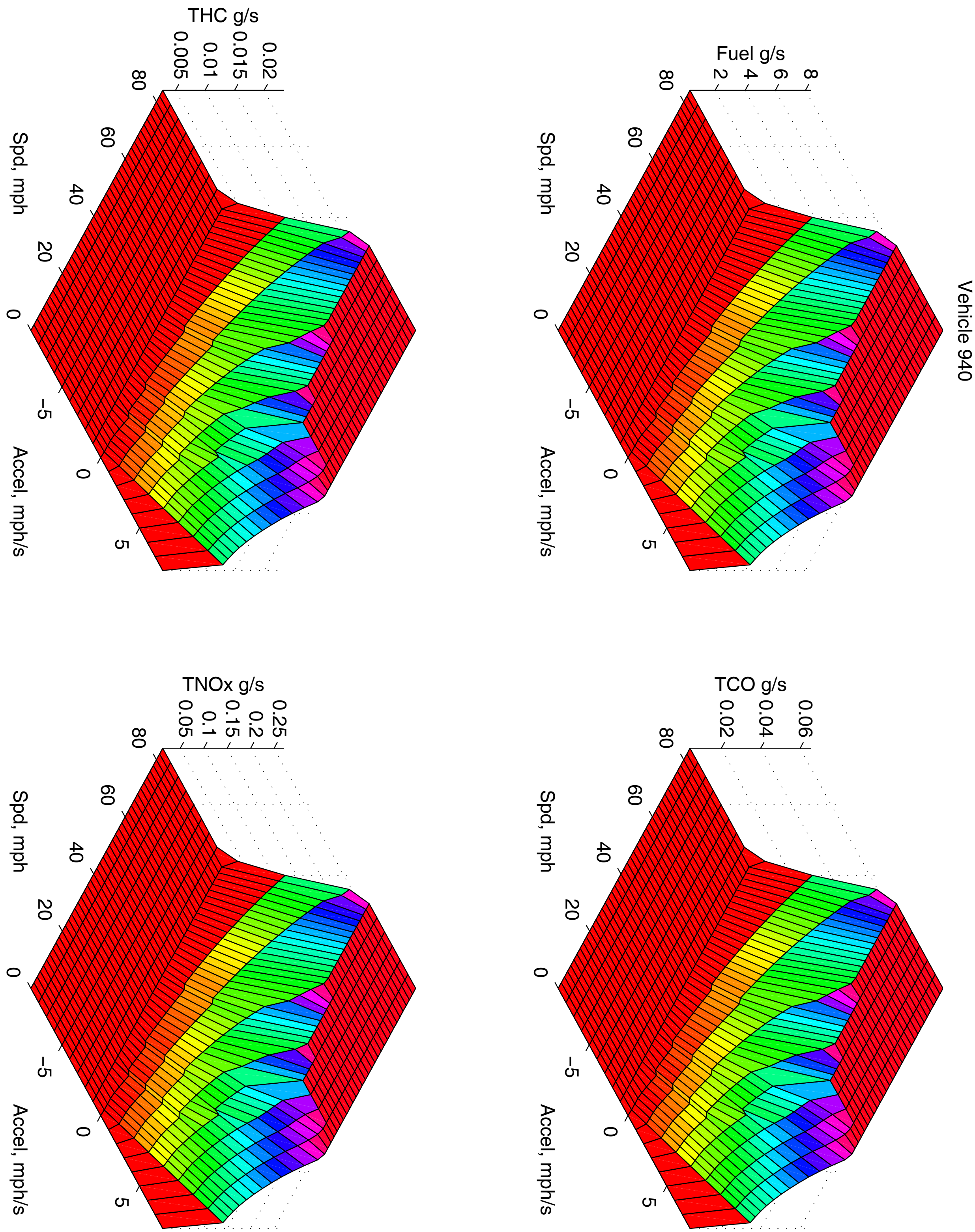

Figure D26. Category 40 velocity/acceleration-indexed fuel, CO, HC, and NOx emission lookup tables.

Appendix E: Roadway Facility Emission Factors

As described in Chapter 6, twelve driving cycles have been developed as part of EPA's proposed MOBILE 6 model. These cycles represent driving on both arterial and highways under different congestion levels. The names of the cycles are listed in Table E1 (see Chapter 6 for further details). These twelve cycles have been applied to the 26 different composite vehicles of CMEM. The resulting roadway facility/congestion emission factors are provided in Tables E2 – E13.

ART AB	Arterial driving at LOS A-B
ART CD	Arterial driving at LOS C-D
ART EF	Arterial driving at LOS E-F
LOCAL	Driving on local roads
NON FR	Non-freeway driving, includes arterials, collectors, local roadways
RAMP	Driving on ramps to highways
HWY LOS A+	Highway driving at LOS A+ (free flow)
HWY LOS A-C	Highway driving at LOS A-C
HWY LOS D	Highway driving at LOS D
HWY LOS E	Highway driving at LOS E
HWY LOS F	Highway driving at LOS F
HWY LOS F-	Highway driving at LOS F-

Table F1. Roadway facility/congestion cycles applied to CMEM composite vehicles.

#	Arterial LOS A-B cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	197.8	72.48	10.64	1.37
2	2-way Catalyst	140.9	5.58	0.68	1.75
3	3-way Catalyst, Carbureted	97.4	4.97	0.19	1.12
4	3-way Catalyst, FI, >50K miles, low power/weight	108.9	3.51	0.18	0.55
5	3-way Catalyst, FI, >50K miles, high power/weight	116.9	3.72	0.19	0.37
6	3-way Catalyst, FI, <50K miles, low power/weight	107.9	1.96	0.08	0.53
7	3-way Catalyst, FI, <50K miles, high power/weight	104.6	1.24	0.09	0.55
8	Tier 1, >50K miles, low power/weight	107.2	1.11	0.04	0.14
9	Tier 1, >50K miles, high power/weight	100.3	0.62	0.03	0.27
10	Tier 1, <50K miles, low power/weight	104.1	0.89	0.03	0.16
11	Tier 1, <50K miles, high power/weight	115.3	0.41	0.01	0.17
24	Tier 1, >100K miles	114.4	2.03	0.12	0.18
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	237.8	59.84	4.88	2.82
13	1979 to 1983 (<=8500 GVW)	187.6	24.87	1.92	2.34
14	1984 to 1987 (<=8500 GVW)	133.4	4.90	0.31	1.02
15	1988 to 1993, <=3750 LVW	129.7	4.53	0.33	0.54
16	1988 to 1993, >3750 LVW	176.8	2.99	0.32	0.84
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	147.3	0.98	0.06	0.28
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	182.7	1.46	0.08	0.36
25	Gasoline-powered, LDT (> 8500 GVW)	249.4	2.48	0.13	2.20
40	Diesel-powered, LDT (> 8500 GVW)	144.0	1.34	0.68	4.94
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	141.2	4.44	0.52	2.52
20	Runs rich	114.4	13.60	1.38	1.14
21	Misfire	124.8	11.59	1.85	0.46
22	Bad catalyst	139.9	12.04	2.90	2.31
23	Runs very rich	150.5	91.83	3.46	0.49

Table F2. Arterial, LOS A-B facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Arterial LOS C-D cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	240.2	88.54	13.26	1.58
2	2-way Catalyst	164.8	5.83	0.84	1.87
3	3-way Catalyst, Carbureted	110.5	5.58	0.22	1.19
4	3-way Catalyst, FI, >50K miles, low power/weight	126.5	3.91	0.20	0.61
5	3-way Catalyst, FI, >50K miles, high power/weight	135.9	4.32	0.21	0.42
6	3-way Catalyst, FI, <50K miles, low power/weight	125.0	2.48	0.10	0.58
7	3-way Catalyst, FI, <50K miles, high power/weight	120.6	2.30	0.11	0.57
8	Tier 1, >50K miles, low power/weight	125.1	1.28	0.04	0.19
9	Tier 1, >50K miles, high power/weight	115.5	0.69	0.04	0.29
10	Tier 1, <50K miles, low power/weight	121.2	1.00	0.04	0.18
11	Tier 1, <50K miles, high power/weight	134.5	0.48	0.02	0.20
24	Tier 1, >100K miles	131.7	2.23	0.13	0.22
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	281.9	70.53	6.93	3.07
13	1979 to 1983 (<=8500 GVW)	220.7	28.99	2.35	2.47
14	1984 to 1987 (<=8500 GVW)	153.1	5.30	0.35	1.06
15	1988 to 1993, <=3750 LVW	148.5	5.24	0.36	0.58
16	1988 to 1993, >3750 LVW	207.7	3.33	0.36	0.92
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	170.7	1.27	0.07	0.31
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	213.1	1.61	0.09	0.38
25	Gasoline-powered, LDT (> 8500 GVW)	296.1	2.84	0.16	2.43
40	Diesel-powered, LDT (> 8500 GVW)	164.3	1.57	0.82	5.69
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	165.3	5.20	0.61	2.81
20	Runs rich	131.6	14.92	1.55	1.21
21	Misfire	143.6	12.00	1.93	0.49
22	Bad catalyst	161.7	13.77	3.31	2.49
23	Runs very rich	175.2	104.56	4.03	0.51

Table F3. Arterial, LOS C-D facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Arterial LOS E-F cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	372.0	136.34	17.67	2.15
2	2-way Catalyst	245.1	9.51	0.92	2.45
3	3-way Catalyst, Carbureted	158.7	6.92	0.26	1.54
4	3-way Catalyst, FI, >50K miles, low power/weight	185.6	5.15	0.25	0.81
5	3-way Catalyst, FI, >50K miles, high power/weight	199.1	5.51	0.27	0.56
6	3-way Catalyst, FI, <50K miles, low power/weight	183.1	3.55	0.13	0.76
7	3-way Catalyst, FI, <50K miles, high power/weight	174.7	3.06	0.13	0.73
8	Tier 1, >50K miles, low power/weight	184.9	1.66	0.05	0.23
9	Tier 1, >50K miles, high power/weight	168.0	0.89	0.05	0.39
10	Tier 1, <50K miles, low power/weight	178.5	1.31	0.05	0.23
11	Tier 1, <50K miles, high power/weight	198.3	0.59	0.02	0.27
24	Tier 1, >100K miles	192.3	2.90	0.15	0.29
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	425.7	105.46	10.49	3.96
13	1979 to 1983 (<=8500 GVW)	332.0	42.83	3.37	3.20
14	1984 to 1987 (<=8500 GVW)	223.1	6.75	0.42	1.36
15	1988 to 1993, <=3750 LVW	215.8	6.31	0.36	0.73
16	1988 to 1993, >3750 LVW	311.6	4.49	0.38	1.18
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	251.4	1.40	0.09	0.40
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	319.2	2.14	0.12	0.52
25	Gasoline-powered, LDT (> 8500 GVW)	443.4	3.80	0.20	3.29
40	Diesel-powered, LDT (> 8500 GVW)	236.2	2.32	1.26	8.29
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	246.1	6.77	0.77	3.87
20	Runs rich	191.9	20.30	1.79	1.53
21	Misfire	209.1	15.41	2.48	0.63
22	Bad catalyst	237.2	18.25	3.18	3.36
23	Runs very rich	256.4	141.77	5.05	0.67

Table F4. Arterial, LOS E-F facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Local Road Cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	323.3	118.49	14.91	1.76
2	2-way Catalyst	215.1	5.54	0.75	2.07
3	3-way Catalyst, Carbureted	141.7	4.66	0.19	1.37
4	3-way Catalyst, FI, >50K miles, low power/weight	164.3	4.12	0.20	0.67
5	3-way Catalyst, FI, >50K miles, high power/weight	176.7	4.19	0.21	0.46
6	3-way Catalyst, FI, <50K miles, low power/weight	161.4	1.76	0.09	0.63
7	3-way Catalyst, FI, <50K miles, high power/weight	156.4	1.89	0.11	0.65
8	Tier 1, >50K miles, low power/weight	162.7	1.28	0.04	0.20
9	Tier 1, >50K miles, high power/weight	150.3	0.70	0.04	0.31
10	Tier 1, <50K miles, low power/weight	157.6	1.01	0.04	0.18
11	Tier 1, <50K miles, high power/weight	175.0	0.46	0.02	0.21
24	Tier 1, >100K miles	169.9	2.26	0.12	0.23
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	370.7	91.27	7.43	3.14
13	1979 to 1983 (<=8500 GVW)	288.8	36.66	2.97	2.63
14	1984 to 1987 (<=8500 GVW)	198.0	4.09	0.32	1.13
15	1988 to 1993, <=3750 LVW	191.4	4.89	0.31	0.60
16	1988 to 1993, >3750 LVW	273.0	3.57	0.33	0.96
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	221.5	1.09	0.07	0.33
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	278.5	1.65	0.10	0.40
25	Gasoline-powered, LDT (> 8500 GVW)	386.9	2.92	0.15	2.62
40	Diesel-powered, LDT (> 8500 GVW)	208.8	2.06	1.12	7.34
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	216.7	5.56	0.63	3.29
20	Runs rich	169.9	15.77	1.41	1.29
21	Misfire	185.5	9.16	1.84	0.51
22	Bad catalyst	210.3	15.00	2.94	2.89
23	Runs very rich	224.9	110.22	4.33	0.60

Table F5. Local roads facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Non-Freeway Cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	238.2	88.85	10.99	1.61
2	2-way Catalyst	164.9	6.46	0.63	1.88
3	3-way Catalyst, Carbureted	111.3	6.05	0.21	1.14
4	3-way Catalyst, FI, >50K miles, low power/weight	126.1	4.06	0.19	0.55
5	3-way Catalyst, FI, >50K miles, high power/weight	135.7	4.86	0.20	0.38
6	3-way Catalyst, FI, <50K miles, low power/weight	124.7	3.32	0.10	0.53
7	3-way Catalyst, FI, <50K miles, high power/weight	121.2	2.87	0.11	0.50
8	Tier 1, >50K miles, low power/weight	124.8	1.92	0.04	0.15
9	Tier 1, >50K miles, high power/weight	115.8	1.03	0.04	0.26
10	Tier 1, <50K miles, low power/weight	120.7	1.20	0.04	0.16
11	Tier 1, <50K miles, high power/weight	134.0	0.71	0.02	0.17
24	Tier 1, >100K miles	131.6	2.22	0.11	0.19
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	280.0	70.01	5.85	3.01
13	1979 to 1983 (<=8500 GVW)	220.1	30.16	2.20	2.45
14	1984 to 1987 (<=8500 GVW)	153.8	5.91	0.31	1.02
15	1988 to 1993, <=3750 LVW	149.2	6.05	0.30	0.54
16	1988 to 1993, >3750 LVW	207.6	3.59	0.30	0.83
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	171.0	1.91	0.07	0.27
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	212.5	1.60	0.09	0.35
25	Gasoline-powered, LDT (> 8500 GVW)	292.9	2.81	0.15	2.30
40	Diesel-powered, LDT (> 8500 GVW)	164.0	1.56	0.81	5.68
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	164.9	5.81	0.56	2.70
20	Runs rich	132.1	15.87	1.30	1.17
21	Misfire	144.2	13.09	1.90	0.50
22	Bad catalyst	162.5	14.81	2.53	2.45
23	Runs very rich	174.3	100.95	3.63	0.52

Table F6. Non-freeway facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Ramps cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	196.4	84.56	10.33	2.36
2	2-way Catalyst	149.2	25.12	1.16	2.32
3	3-way Catalyst, Carbureted	105.8	20.07	0.54	1.21
4	3-way Catalyst, FI, >50K miles, low power/weight	113.9	9.43	0.29	0.77
5	3-way Catalyst, FI, >50K miles, high power/weight	122.3	12.74	0.32	0.53
6	3-way Catalyst, FI, <50K miles, low power/weight	116.2	15.24	0.22	0.70
7	3-way Catalyst, FI, <50K miles, high power/weight	110.2	6.98	0.16	0.67
8	Tier 1, >50K miles, low power/weight	114.0	6.39	0.09	0.20
9	Tier 1, >50K miles, high power/weight	105.0	3.09	0.06	0.38
10	Tier 1, <50K miles, low power/weight	108.6	5.35	0.07	0.25
11	Tier 1, <50K miles, high power/weight	120.0	4.61	0.05	0.23
24	Tier 1, >100K miles	119.6	6.64	0.18	0.28
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	251.4	65.45	5.90	4.16
13	1979 to 1983 (<=8500 GVW)	198.2	40.35	2.04	2.95
14	1984 to 1987 (<=8500 GVW)	141.4	20.08	0.58	1.50
15	1988 to 1993, <=3750 LVW	139.3	18.36	0.47	0.83
16	1988 to 1993, >3750 LVW	180.7	10.25	0.41	1.12
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	155.1	9.37	0.14	0.41
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	190.4	2.38	0.13	0.55
25	Gasoline-powered, LDT (> 8500 GVW)	258.2	4.05	0.20	3.18
40	Diesel-powered, LDT (> 8500 GVW)	160.8	1.41	0.64	5.42
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	145.7	14.88	0.77	2.80
20	Runs rich	122.9	31.78	1.93	1.57
21	Misfire	129.1	33.27	2.86	0.67
22	Bad catalyst	147.6	31.06	3.26	3.12
23	Runs very rich	155.2	133.36	4.33	0.60

Table F7. Ramps facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Freeway, LOS A+ cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	139.7	57.23	7.27	1.78
2	2-way Catalyst	112.7	15.71	0.79	1.98
3	3-way Catalyst, Carbureted	85.1	13.12	0.41	1.09
4	3-way Catalyst, FI, >50K miles, low power/weight	86.8	7.24	0.25	0.61
5	3-way Catalyst, FI, >50K miles, high power/weight	93.4	8.58	0.26	0.42
6	3-way Catalyst, FI, <50K miles, low power/weight	87.9	7.65	0.15	0.57
7	3-way Catalyst, FI, <50K miles, high power/weight	84.7	4.52	0.14	0.58
8	Tier 1, >50K miles, low power/weight	84.0	4.88	0.07	0.11
9	Tier 1, >50K miles, high power/weight	79.5	3.40	0.06	0.28
10	Tier 1, <50K miles, low power/weight	82.4	4.08	0.06	0.21
11	Tier 1, <50K miles, high power/weight	91.7	3.95	0.05	0.15
24	Tier 1, >100K miles	95.9	6.84	0.19	0.21
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	191.2	56.27	3.35	3.83
13	1979 to 1983 (<=8500 GVW)	150.9	28.18	1.40	2.78
14	1984 to 1987 (<=8500 GVW)	113.3	15.04	0.52	1.31
15	1988 to 1993, <=3750 LVW	110.7	11.74	0.50	0.71
16	1988 to 1993, >3750 LVW	141.7	9.96	0.42	0.99
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	122.7	6.25	0.12	0.32
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	152.3	7.44	0.14	0.44
25	Gasoline-powered, LDT (> 8500 GVW)	186.2	4.92	0.16	2.38
40	Diesel-powered, LDT (> 8500 GVW)	114.2	0.97	0.42	3.79
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	111.1	9.83	0.64	2.45
20	Runs rich	97.2	24.39	1.73	1.38
21	Misfire	105.9	27.75	2.55	0.61
22	Bad catalyst	116.6	21.15	3.19	2.62
23	Runs very rich	123.0	106.60	3.48	0.53

Table F8. Freeway, LOS A+ facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Freeway, LOS A-C cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	137.2	54.87	7.35	1.60
2	2-way Catalyst	108.9	11.37	0.70	1.87
3	3-way Catalyst, Carbureted	82.0	10.13	0.34	1.12
4	3-way Catalyst, FI, >50K miles, low power/weight	84.7	6.92	0.23	0.57
5	3-way Catalyst, FI, >50K miles, high power/weight	91.0	7.74	0.24	0.39
6	3-way Catalyst, FI, <50K miles, low power/weight	85.3	6.38	0.13	0.55
7	3-way Catalyst, FI, <50K miles, high power/weight	82.2	3.77	0.13	0.57
8	Tier 1, >50K miles, low power/weight	81.9	4.58	0.07	0.10
9	Tier 1, >50K miles, high power/weight	77.4	2.94	0.05	0.27
10	Tier 1, <50K miles, low power/weight	80.5	3.93	0.06	0.19
11	Tier 1, <50K miles, high power/weight	89.5	3.83	0.04	0.14
24	Tier 1, >100K miles	93.1	6.40	0.18	0.19
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	184.6	50.33	3.29	3.45
13	1979 to 1983 (<=8500 GVW)	147.1	25.49	1.39	2.64
14	1984 to 1987 (<=8500 GVW)	109.1	11.12	0.45	1.22
15	1988 to 1993, <=3750 LVW	107.3	10.43	0.47	0.65
16	1988 to 1993, >3750 LVW	137.6	9.06	0.40	0.90
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	119.2	5.83	0.11	0.30
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	146.9	6.18	0.13	0.40
25	Gasoline-powered, LDT (> 8500 GVW)	181.4	4.30	0.14	2.23
40	Diesel-powered, LDT (> 8500 GVW)	112.0	0.95	0.42	3.72
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	108.3	9.41	0.60	2.32
20	Runs rich	93.7	20.67	1.69	1.33
21	Misfire	102.1	23.61	2.31	0.56
22	Bad catalyst	112.9	18.70	3.13	2.41
23	Runs very rich	119.6	101.1	3.34	0.51

Table F9. Freeway, LOS A-C facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Freeway, LOS D cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	136.4	53.19	7.75	1.46
2	2-way Catalyst	106.6	10.34	0.73	1.73
3	3-way Catalyst, Carbureted	79.3	8.77	0.29	1.03
4	3-way Catalyst, FI, >50K miles, low power/weight	82.4	4.83	0.20	0.52
5	3-way Catalyst, FI, >50K miles, high power/weight	88.4	5.73	0.21	0.35
6	3-way Catalyst, FI, <50K miles, low power/weight	83.2	5.36	0.12	0.50
7	3-way Catalyst, FI, <50K miles, high power/weight	79.8	2.42	0.11	0.50
8	Tier 1, >50K miles, low power/weight	80.3	2.74	0.05	0.10
9	Tier 1, >50K miles, high power/weight	75.4	1.13	0.04	0.25
10	Tier 1, <50K miles, low power/weight	78.3	2.24	0.04	0.17
11	Tier 1, <50K miles, high power/weight	86.7	1.92	0.03	0.13
24	Tier 1, >100K miles	89.7	4.11	0.15	0.17
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	181.6	48.71	3.94	3.18
13	1979 to 1983 (<=8500 GVW)	143.7	23.11	1.43	2.47
14	1984 to 1987 (<=8500 GVW)	105.7	9.42	0.40	1.11
15	1988 to 1993, <=3750 LVW	103.5	7.84	0.38	0.58
16	1988 to 1993, >3750 LVW	133.7	5.67	0.34	0.84
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	115.3	3.70	0.09	0.27
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	141.9	2.64	0.10	0.37
25	Gasoline-powered, LDT (> 8500 GVW)	180.0	2.57	0.13	2.12
40	Diesel-powered, LDT (> 8500 GVW)	111.2	0.96	0.44	3.72
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	105.4	7.15	0.54	2.18
20	Runs rich	90.5	17.87	1.57	1.18
21	Misfire	98.6	20.24	2.13	0.51
22	Bad catalyst	109.5	15.78	2.76	2.27
23	Runs very rich	116.4	94.90	3.29	0.48

Table F10. Freeway, LOS D facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Freeway, LOS E cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	166.5	62.95	11.00	1.29
2	2-way Catalyst	122.0	5.85	0.83	1.59
3	3-way Catalyst, Carbureted	86.5	5.40	0.22	1.04
4	3-way Catalyst, FI, >50K miles, low power/weight	95.6	4.76	0.18	0.53
5	3-way Catalyst, FI, >50K miles, high power/weight	102.7	4.76	0.19	0.36
6	3-way Catalyst, FI, <50K miles, low power/weight	94.6	3.24	0.10	0.49
7	3-way Catalyst, FI, <50K miles, high power/weight	92.4	1.76	0.09	0.53
8	Tier 1, >50K miles, low power/weight	93.3	2.65	0.05	0.14
9	Tier 1, >50K miles, high power/weight	88.5	1.40	0.04	0.25
10	Tier 1, <50K miles, low power/weight	91.0	2.19	0.04	0.15
11	Tier 1, <50K miles, high power/weight	100.7	1.71	0.02	0.16
24	Tier 1, >100K miles	100.7	3.84	0.13	0.19
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	205.2	53.93	5.31	2.67
13	1979 to 1983 (<=8500 GVW)	161.9	25.25	1.81	2.08
14	1984 to 1987 (<=8500 GVW)	117.1	4.98	0.34	0.97
15	1988 to 1993, <=3750 LVW	114.3	5.99	0.36	0.52
16	1988 to 1993, >3750 LVW	153.1	5.95	0.35	0.77
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	129.2	3.33	0.08	0.27
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	157.6	1.37	0.08	0.33
25	Gasoline-powered, LDT (> 8500 GVW)	213.1	2.66	0.13	1.99
40	Diesel-powered, LDT (> 8500 GVW)	126.3	1.16	0.59	4.31
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	122.9	6.63	0.54	2.24
20	Runs rich	101.1	14.05	1.62	1.09
21	Misfire	109.8	10.44	1.81	0.43
22	Bad catalyst	122.9	12.88	3.24	2.13
23	Runs very rich	131.3	81.76	3.56	0.44

Table F11. Freeway, LOS E facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Freeway, LOS F cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	242.1	89.46	12.14	1.56
2	2-way Catalyst	170.0	7.32	0.80	1.92
3	3-way Catalyst, Carbureted	115.6	5.68	0.21	1.26
4	3-way Catalyst, FI, >50K miles, low power/weight	131.9	4.81	0.20	0.65
5	3-way Catalyst, FI, >50K miles, high power/weight	141.7	4.96	0.20	0.45
6	3-way Catalyst, FI, <50K miles, low power/weight	130.1	3.46	0.10	0.60
7	3-way Catalyst, FI, <50K miles, high power/weight	127.3	2.06	0.11	0.63
8	Tier 1, >50K miles, low power/weight	130.5	2.51	0.05	0.20
9	Tier 1, >50K miles, high power/weight	122.6	1.25	0.04	0.30
10	Tier 1, <50K miles, low power/weight	125.9	1.96	0.04	0.18
11	Tier 1, <50K miles, high power/weight	139.7	1.29	0.02	0.21
24	Tier 1, >100K miles	136.7	2.91	0.12	0.25
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	287.7	71.77	6.06	2.98
13	1979 to 1983 (<=8500 GVW)	224.7	31.90	2.36	2.43
14	1984 to 1987 (<=8500 GVW)	159.1	6.73	0.34	1.11
15	1988 to 1993, <=3750 LVW	154.5	6.21	0.33	0.60
16	1988 to 1993, >3750 LVW	212.5	5.11	0.35	0.94
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	176.3	2.63	0.08	0.33
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	218.9	1.61	0.09	0.40
25	Gasoline-powered, LDT (> 8500 GVW)	303.7	2.81	0.14	2.52
40	Diesel-powered, LDT (> 8500 GVW)	175.5	1.66	0.86	6.07
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	170.3	6.71	0.60	2.88
20	Runs rich	137.4	16.59	1.36	1.26
21	Misfire	149.4	12.77	1.84	0.50
22	Bad catalyst	167.4	14.92	3.12	2.62
23	Runs very rich	179.7	100.65	3.91	0.55

Table F12. Freeway, LOS F facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.

#	Freeway, LOS F- cycle	Emissions/Fuel (grams/mile)			
	Normal Emitting Cars	Fuel	CO	HC	NOx
1	No Catalyst	297.2	108.91	14.47	1.43
2	2-way Catalyst	196.6	4.99	0.70	1.71
3	3-way Catalyst, Carbureted	129.7	3.82	0.16	1.20
4	3-way Catalyst, FI, >50K miles, low power/weight	150.4	3.40	0.17	0.60
5	3-way Catalyst, FI, >50K miles, high power/weight	162.3	3.49	0.18	0.44
6	3-way Catalyst, FI, <50K miles, low power/weight	147.3	1.43	0.08	0.56
7	3-way Catalyst, FI, <50K miles, high power/weight	143.2	1.23	0.09	0.59
8	Tier 1, >50K miles, low power/weight	147.4	1.01	0.04	0.24
9	Tier 1, >50K miles, high power/weight	137.7	0.57	0.03	0.28
10	Tier 1, <50K miles, low power/weight	143.9	0.82	0.03	0.16
11	Tier 1, <50K miles, high power/weight	160.2	0.37	0.01	0.25
24	Tier 1, >100K miles	155.2	1.85	0.10	0.27
	Normal Emitting Trucks	Fuel	CO	HC	NOx
12	Pre-1979 (<=8500 GVW)	339.1	82.84	6.47	2.42
13	1979 to 1983 (<=8500 GVW)	261.4	32.64	2.79	2.05
14	1984 to 1987 (<=8500 GVW)	181.3	3.38	0.27	0.94
15	1988 to 1993, <=3750 LVW	174.6	4.01	0.27	0.51
16	1988 to 1993, >3750 LVW	249.7	2.95	0.29	0.83
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	201.9	0.88	0.06	0.31
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	252.9	1.32	0.08	0.37
25	Gasoline-powered, LDT (> 8500 GVW)	351.4	2.32	0.12	2.21
40	Diesel-powered, LDT (> 8500 GVW)	190.7	1.91	1.06	6.74
	High Emitting Vehicles	Fuel	CO	HC	NOx
19	Runs lean	198.1	4.67	0.55	2.92
20	Runs rich	155.9	13.50	1.28	1.08
21	Misfire	170.9	7.78	1.54	0.45
22	Bad catalyst	192.7	12.97	2.62	2.55
23	Runs very rich	202.0	78.62	3.76	0.51

Table F13. Freeway, LOS F- facility/congestion-based emissions/fuel factors for the different vehicle/technology categories.