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Summary

There have been significant improvements in recent years in transportation and emissions modeling, in order to better evaluate transportation operational effects and associated vehicle emissions. In particular, instantaneous or modal emissions models have been developed for a variety of light-duty vehicles. To date, most effort has focused primarily on developing these models for light-duty vehicles with less effort devoted to Heavy-Duty Diesel (HDD) vehicles. Although HDD vehicles currently make up only a fraction of the total vehicle population, they are major contributors to the emissions inventory. Furthermore, it is generally believed that transit buses and heavy trucks will offer earlier opportunities for public implementation of automated operations compared to passenger cars. Thus, there is a critical need to have robust modal emissions and fuel consumption models for HDD vehicles.

This report describes a HDD truck model that is now part of a larger Comprehensive Modal Emissions Modeling (CMEM) program developed at the University of California, Riverside. Within the CMEM framework, several HDD truck fuel consumption and emission sub-models have been developed, each corresponding to a distinctive vehicle/technology category. The developed models use a parameterized physical approach where the entire emission process is broken down into different components that correspond to physical phenomena associated with vehicle operation and emission production.

As part of a parallel research program, UC Riverside has developed a Mobile Emissions Research Laboratory (MERL) that can be attached to a number of heavy duty rigs to measure instantaneous (i.e., modal) emissions and fuel consumption in-situ. Using MERL, a variety of trucks were extensively tested under a wide range of operating conditions. The collected data (along with other HDD truck data sources) were then used to calibrate the HDD models. Particular care was taken to investigate and implement the effects of varying grade and the effects of variable ignition timing.

In this report, background material is provide on HDD vehicle fuel consumption and emissions research, followed by a description of the vehicle testing program. The HDD vehicle model development process is then described, along with the model validation process. The model was subsequently integrated with a variety of transportation simulation modeling tools for the purposes of evaluating several automation scenarios. Particular emphasis has been placed on simulating the truck platoon scenario, where aerodynamic drafting effects can provide a significant benefit in terms of fuel and emissions savings. In addition to the modeling, experimentation has been carried out with MERL in real-world tests, examining trucks traveling in tandem with close inter-vehicle spacings. Results of these tests are also described herein.

Contents

SUMMARY

1. Introduction

In the past decade, Intelligent Transportation Systems (ITS) have generated considerable enthusiasm in the transportation community as a potential means to improve roadway safety, reduce congestion, enhance the mobility of people and goods, and reduce energy consumption and vehicle emissions. In order to estimate these potential benefits, new and improved analytical techniques and simulation models are being developed for ITS. In terms of environmental effects, the University of California, Riverside, College of Engineering-Center for Environmental Research and Technology (CE-CERT) has been very active in developing vehicle emissions and fuel consumption modeling tools. Much of this effort began in 1996 with a four-year National Cooperative Highway Research Program (NCHRP, Project 25-11) effort to develop a Comprehensive Modal Emission Model (CMEM) for light duty vehicles. This model (described in more detail in Chapter 2) predicts second-by-second emissions for virtually any type of light duty vehicle. Over the years, this model has been enhanced and maintained with support from the U.S. Environmental Protection Agency (EPA). In addition, this model has been integrated with a variety of ITS simulation models and analytical techniques to quantitatively estimate the environmental impact of ITS (see, [Barth et al., 2001]).

During the initial development, the emphasis of this modeling effort has been on *light-duty vehicles*. However, because it is generally believed that transit buses and heavy trucks will offer earlier opportunities for public implementation of automated operations than passenger cars, it was crucial that this modal emissions and energy consumption modeling framework be extended to *heavy-duty, diesel (HDD) vehicles*. By having a combined light-duty and heavy-duty vehicle emissions/energy model, it would be possible to estimate the total fuel consumption and emissions impact from use of automation on a systems-wide basis.

Although HDD vehicles currently make up only a fraction of the total vehicle population, they are major contributors to the emissions inventory, accounting for over 50% of the NOx and PM in many locations [Lloyd & Cackette, 2001; Yanowitz et al., 2000]. These vehicles will continue to play a major emissions inventory role with increases in goods movement along with their high durability and reliability. As of several years ago, heavy-duty vehicle modal emission models were not yet developed primarily due to the lack of appropriate second-by-second emissions data. In fact, prior to 1997, the regulatory emission models developed by the U.S. EPA and California Air Resources Board (CARB) relied primarily on 23 HDD vehicles [Yanowitz et al., 2000]. To be fair, there is a large amount of HDD engine certification data from laboratory test stands, however it is felt that these engine data do not properly represent real-world, on-road emissions when placed in a variety of vehicles. This dearth of information on real-world heavy-duty diesel emissions was recognized by the U.S. EPA, CARB, and other governmental agencies. In order to collect emissions data for a wide range of heavy-duty diesel vehicles, the U.S. EPA and heavy-duty engine manufacturers have funded CE-CERT to develop a state-of-the-art Mobile Emissions Research Laboratory (MERL) that can be attached to a number of heavy duty rigs to measure instantaneous (i.e., modal) emissions in-situ. MERL was constructed in 2000 and has since been used for a variety of projects, including serving as the basis of emissions data for this model development project (see Chapter 3 for a brief description of MERL).

Using data from MERL and supplementary HDD truck emissions data from CRC Project E-55 [CRC, 2004], we have developed a power-demand, physical instantaneous HDD fuel consumption and emissions model that is now part of CE-CERT comprehensive modal emissions modeling framework. In this report, the development of the HDD fuel consumption and emissions model is described in detail, with a specific focus on ITS evaluation. As part of this project, the HDD model has been integrated with several transportation modeling tools in order to estimate the impact of several automation scenarios. Also as part of this project, real-world HDD truck platooning experiments have been carried out to help calibrate the integrated transportation/emissions modeling tools.

In this report, Chapter 2 provides background on HDD vehicle fuel consumption and emissions research. A description of the mobile emissions research laboratory and vehicle testing that took place as part of this project is provided in Chapter 3. Chapter 4 then describes the HDD modal emissions model architecture and development procedure as part of CE-CERT's comprehensive modal emissions modeling framework. Model validation, uncertainty, and sensitivity issues are described in Chapter 5. Chapter 6 describes the integration of the model with transportation simulation modeling tools and the evaluation of several automation scenarios. Lastly, Chapter 7 briefly describes the HDD vehicle platoon tests and their fuel consumption and emissions results.

2. Background

2.1. Heavy-Duty Diesel Vehicle Emissions

It is estimated that HDD vehicles account for about 30% of the oxides of nitrogen (NOx) and 65% of the particulate matter (PM) emitted by mobile sources while comprising only 2% of the on-road vehicle fleet [CARB, 2002]. In addition, in many locations they are major contributors to the overall emissions inventory, accounting for over 50% of the NOx and PM [Lloyd & Cackette 2001; Yanowitz et al., 2000]. These vehicles will continue to play a major emissions inventory role with increases in goods movement along with their high durability and reliability. The California Air Resources Board has categorized a number of truck and bus sectors for California, including six HDD classes:

CARB HDD Class	Weight	Population (California)
Light heavy-duty trucks 1	8,501- 10,000 lbs.	272,000
Light heavy-duty trucks 2	10,001- 14,000 lbs.	84,000
Medium heavy-duty trucks	14,001- 33,000 lbs.	266,000
Heavy heavy-duty trucks	33,001+ lbs.	175,000
School buses	all	30,000
Urban buses	all	14,000

NO_x emissions from these categories, calculated with CARB's emission factor model EMFAC 2000, are shown in Figure 2.1. It can be seen that heavy-heavy-duty trucks dominate the emissions. VMT is a fairly good predictor of NO_x by category and vehicle population is not particularly useful because of the very different types of operational conditions between the vehicle classes. For example, although the population of medium-duty trucks equals that of the heavy-heavy-duty diesel (HHDD) trucks, their NO_x emissions are only 25% of those emitted by the HHDD by comparison.

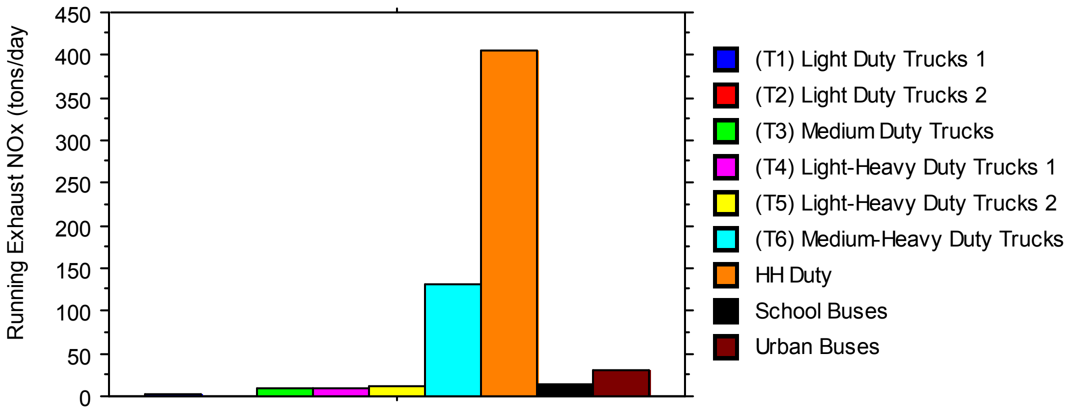

Figure 2.1. NOx emissions by class of truck, based on EMFAC. (Source: CE-CERT analysis using EMFAC 2000)

As part of this overall PATH project, we have carried out a literature review on HDD vehicles, spanning the past decade. The literature that was addressed covered several topics:

- policy and emission standards;
- heavy-duty truck physical attributes;
- driving activity;
- driving cycle development;
- emissions characterization;
- combustion modeling; and
- heavy-duty diesel emissions modeling.

These topic areas are briefly summarized below along with a listing of some key references.

Policy and Emissions Standards

The two primary emissions from diesel vehicles are NOx and particulate matter (PM). Emission controls in diesel vehicles frequently involve tradeoffs between NOx control and PM control. California state and federal standards for HDD truck NOx emissions have been revised downwards rapidly over the past two decades, from 10.7 g/bhp-hr[*] (Federal) and 7.5 g/bhp-hr (California) in the 1970's to 2.0 g/bhp-hr Federal and California currently. Emissions regulations are set to drop again in 2007. Since 1991, California and Federal standards have been identical, however some differences exist prior to 1991 with the California standards being lower. The manufacturers have primarily met these increasingly stringent standards through basic improvements to the combustion process rather than through the addition of exhaust after treatment or add-on controls [U.S. EPA, 1998] as was typically done with light duty vehicles.

In response to the potential health risks from diesel exhaust, regulators at both the state and national level have developed a series of regulations for diesel exhaust and diesel PM over the years. Initial regulations of diesel exhaust began with the regulation of diesel smoke in the early 1970's with regulations of gaseous diesel exhaust species added later that decade. Standards for PM emissions were first put in place for light-duty diesel cars and trucks in 1982. Standards for heavy-duty engines were implemented shortly thereafter in the mid-1980s and were harmonized between California and the US in 1988. Since 1988, the heavy-duty PM emission standard has been reduced from 0.60 g/bhp-hr to 0.10 g/bhp-hr today. With the introduction of the newest set of regulations, an additional reduction to levels of 0.01 g/bhp-hr will be required starting in 2007. The U.S., the European Union, and Japan all use different test procedures which makes exact comparison problematic, however on a grams per kilowatt-hour basis the US 2007 regulations for heavy-duty vehicles fall midway between Japan on the high end and the European Union on the most restrictive end [ECMT, 2000]. It is anticipated that achieving these

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[*] grams per brake horsepower-hour

low emission levels will require the use of diesel particle filters. Although reduction of PM mass has been the emphasis of regulatory efforts, there is an increasing body of evidence that PM size distributions may be as important if not more important in determining the potential health effects of PM. Some health studies indicated that the concentration of fine PM rather than the concentration PM_{10} may be more directly linked to health effects. Although PM size distributions have been studied since the late 1970s [Kittelson, 1998], the potential health effects have provided renewed interest in this area of study. There has also been considerable interest in ultrafine particles and nanoparticles due to increased health effects in this region [Kittelson, 1998].

In the 1990's it was found that seven of the largest heavy-duty diesel engine manufacturers violated certification requirements by turning off or defeating emissions control devices during highway operation. As a consequence, in the late 1990's the U.S. EPA and CARB signed consent decrees and settlement agreements with these engine companies that required, among other things, supplemental tests used for certification of heavy-duty diesel engines. The supplemental tests include the in-use Not-To-Exceed (NTE) test procedure, the EURO III European Stationary Cycle (ESC) test procedure, and measurement of smoke emissions within the NTE control area. The CARB is scheduled to begin implementation of the Not-To-Exceed (NTE) requirements for in-use heavy-duty diesel engines in the 2005-2006 time frame. These requirements require the collection and reporting of in-use pollutant emissions as a means of ensuring in-use compliance with applicable emissions standards[*].

Key references include:

1. Lloyd, A.C. and Cackette, T.A. (2001), "Diesel Engines: Environmental Impact and Control", *J. Air & Waste Manage Assoc.,* 51:809-847, June 2001;

2. California Air Resource Board (2000), "Supplemental Emission Test Procedures for 2005+ Model Year Heavy-Duty Diesel Engines", CARB Technical Report, December 8, 2000.

3. Kittelson, D. B. (1998), "Engines and Nanoparticles: A Review", *J. Aerosol Sci.* 29:575-588.

4. Mori, K., (1997), "Worldwide Trends in Heavy-Duty Diesel Engine Exhaust Emission Legislation and Compliance Technologies", SAE Technical Paper Series 970753.

5. Lueders, H., Stommel, P., and Geckler, S. (1999), "Diesel Exhaust Treatment-New Approaches to Ultra Low Emission Diesel Vehicles", SAE Technical Paper Series 99010108.

6. European Conference of Ministers of Transport, Council of Ministers (2000), "Vehicle Emission Trends: Conclusions", CEMT/CM(2000)6/Final.

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[*] For more general and detail information on the Consent Decree agreements see: http://www.epa.gov/Compliance/civil/programs/caa/diesel/index.html.

Heavy-Duty Truck Physical Attributes

HDD vehicles have a variety of important physical attributes that are critical to the physical modeling approach taken in this project. Compared to light-duty vehicles, HDD vehicles have much larger aerodynamic drag coefficients, as well as much lower and varied power-to-weight ratios. Many of the physical parameters necessary for our modeling approach are described in Chapter 4 and were obtained from the available literature. Several key sources include:

1. Society of Automotive Engineers, International (1996), "Commercial Truck and Bus SAE Recommended Procedure for Vehicle Performance Prediction and Charting", SAE J2188, issued March 1996.

2. U.S. Department of Energy (2000), "OHVT Technology Roadmap", U.S. Department of Energy, Office of Heavy Vehicle Technologies (OHVT), Office of Transportation Technologies. DOE/OSTI-11690/R1.

3. McCallen, R., R. Crouch, J. Hsu, F. Browand, M. Hammache, A. Leonard, M. Brady, K. Salari, W. Rutledge, J. Ross, B. Storms, J.T. Heineck, D. Driver, J. Bell, and G. Zilliac, (2000), "Progress in Reducing Aerodynamic Drag for Higher Efficiency of Heavy-Duty Trucks (Class 7-8)".

4. Roy, S., and P. Srinivasan (2000), "External Flow Analysis of a Truck for Drag Reduction", Society of Automotive Engineers, SAE Technical Paper 00C99R.

5. Westechperformance.com (2002), "Horsepower VS Torque: What's the difference, why it matters, and how to get it", http://www.westechperformance.com/pages/Tech_Library/Understanding/hpvstq.html

6. Michael L. Traver, (2002), "Emissions Formation in Compression Ignition Engines", http:/www2.cemr.wvu.edu/~englab/Tutorials/EmissTut/diesel.html.

Driving Activity and Driving Cycle Development

Just as important as correctly estimating emission factors, it is necessary to have a good understanding of HDD vehicle driving activity patterns. A variety of HDD vehicle driving activity pattern studies have taken place in recent years. These studies typically rely on GPS (Global Positioning System) dataloggers that collect position, speed, and vehicle operation information as the vehicles are driven. Example studies include a 140-vehicle study made in California from 1997-1999 [Battelle, 1999], and a 31 HDD vehicle study in California's South Coast Air Basin [JFA, 2000]. An important set of HDD driving cycles were developed by the CARB using 66 of the Battelle vehicles and 18 of the JFA vehicles that are described in [Maldonado, 2002]. Key references include:

1. Clark, N. N. and David L. Mckain (2001), "A Chassis Test Procedure to Mimic the Heavy-Duty Engine Transient Emission Certification Test", J. Air & Waste Manage Assoc. 51:432-442, March 2001.

2. Brown, S., Bryett, C., and Mowle, M., (1999), "Proposed Diesel Vehicle Emissions National Environment Protection Measure—Project 2, Phase 1, In-Service Emissions Performance - Drive Cycles", Technical Report Volume 1, March 1999. Can be accessed at http://www.nepc.gov.au/pdf/diesel_project2.1.pdf

3. Mckain, D. L., N. N. Clark, T. I. McDaniel, and J. A. Hopple, (1998), "Chassis Test Cycle Development for Heavy Duty Engine Emissions Test Compliance", SAE Technical Paper Series, 980407.

4. Clark, N. N., J. J. Daley, R. D. Nine, and C. M. Atkinson, (1999), "Application of the New City-Suburban Heavy Vehicle Route to Truck Emissions Characterization", SAE Technical Paper Series 1999-01-1467.

5. Hill, N., C. Levine, T. Younglove, J. Swineford and J. Lents, (1999) "Determination of Refuse Truck Activity And Modeling of Emissions", *Proceedings of the 9th CRC On-Road Vehicle Emission Workshop*, San Diego, CA.

6. Young, C., C. Levine, M. Smith, T. Younglove, and J. Norbeck, (1999), "Analysis of HDDT Activity, Cycle Development, and Emissions Comparison for Use in CE-CERT's Mobile Emissions Lab", *Proceedings of the 9th CRC On-Road Vehicle Emission Workshop*, San Diego, CA.

Emissions Characterization

Laboratory emissions testing data for HDD vehicles have been limited in the past, however several studies are adding to the available data. For example, an inter-laboratory comparison study has reported good repeatability between five heavy-duty chassis dynamometer laboratories [ATL, 2002]. West Virginia University has operated a transportable heavy-duty vehicle chassis dynamometer in collecting a substantial truck emissions data set [Clark et al., 1999]. More recently, a number of investigators have developed tools to measure emissions from engine/vehicle combinations driven over standard cycles on stationary or portable chassis dynamometers [Messer & Clark 1995; McKain et al, 1998; Yanowitz, et al., 1999]. The number of these facilities is quite limited due to their expense and using them still does not provide information on vehicles driven in the real world [McCormick et al., 1997; Brown et al., 2000]. Accordingly, some investigators are developing methods based on a mini-dilution tunnel with on-board instruments [Gautam et al., 2001; Weaver & Balam-Almanza, 2001; Reading et al., 2001; Spears, 2002]. Others trail a moving vehicle and sample the plume after dilution by ambient air [Brown et al., 2002]. Further, the U.S. EPA has carried out in 2001 an on-board emissions measurement data shootout, which included collecting emissions data from twelve diesel powered city buses using on-board analyzers [Ensfield et al., 2002]. It is important to point out that there also exists a large database of HDD engine dynamometer emissions data that has been collected for certification purposes, however it is felt that these engine data do not properly represent real-world, on-road emissions when placed in a variety of vehicles. Some example references for emissions characterization include:

1. Yanowitz, J., R. L. McCormick, and M. S. Graboski (1999), "Emissions from On-Road Heavy-Duty Diesel Vehicles: A Review of Data from Dynamometer, Tunnel, Remote

Sensing, and Idling Studies", *Proceedings of the 9th CRC On-Road Vehicle Emissions Workshop*, San Diego California, April 19-21,1999.

2. Welch, B., Smith, M, Pankratz, D., Park, C. S., Johnson K. and Norbeck, J.M., (2001), "Development of a Mobile On-road Heavy Duty Diesel Emission Laboratory", *Proceedings of the 11th CRC on-road Vehicle Emissions Workshop*, San Diego, California, March 26-28, 2001.

3. Clark, N. N., R. D. Nine, M. Gautam, C. M. Atkinson, J. M. Kern, and R. Ramamurthy (1999), "Effect of Test Cycles on Measured Emissions of Diesel Vehicles", *Proceedings of the 9th CRC On-Road Vehicle Emissions Workshop*, San Diego California, April 19-21, 1999.

4. Graboski, M., J. Yanowitz, and R. L. McCormick (1998), "In-Use Emissions from Heavy-Duty Vehicles Operating in The Colorado Northern Front Range Area", *Proceedings of the 8th CRC On-Road Vehicle Emissions Workshop*, San Diego, California, April 20-22, 1998.

5. Whitfield, J. K., and D. B. Harris (1998), "Comparison of Heavy-Duty Diesel Emissions from Engine and Chassis Dynamometers and On-Road Testing", *Proceedings of the 8th CRC On-Road Vehicle Emissions Workshop*, San Diego, California, April 20-22, 1998.

6. Gautam, M., D Gupa, S. Popuri, and D. W. Lyons, (1997), "Speciation and Reactivity of Diesel Exhaust Emissions", *Proceedings of the 7th CRC On-Road Vehicle Emissions Workshop*, San Diego California, April 9-11, 1997.

7. Clark, N. N. and D. W. Lyons (1997), "Emission from CNG and diesel Refuse Haulers Using Six Engine Types in New York City", *Proceedings of the 7th CRC On-Road Vehicle Emissions Workshop*, San Diego, California, April 9-11, 1997.

8. Moosmueller, H., W. P. Arnott, C.F. Rogers, J.L. Bowen, J. F. Collins, T. D. Durbin, and J. M. Norbeck (2001), "Time Resolved Characterization of Diesel Particulate Emissions: Instruments for Particle Mass Measurements", *Environ. Sci. Technol.* 2001, 35,781-787.

9. Ahlivik, P., L. Ntziachristos, J. Keskinen, and A. Virtanen, (1998), "Real Time Measurement of Diesel Particle Size Distribution with an Electrical Low Pressure Impactor", SAE Technical Paper Series 980410.

10. Maricq, M. M., D. Podsiadlik, D. Brehob and M Haghgooie (1999), "Particulate Emissions from a Direct-Injection Spark-Ignition (DISI) Engine", SAE Technical Paper Series 1999-01-1530.

11. McCormick, R. L., M. S. Graboski, T. L. Alleman, J. R. Alvarez, and K.G. Duleep (2003), "Quantifying the Emissions Benefits of Opacity Testing and Repair of Heavy-Duty Diesel Vehicles", *Environmental Science and Technology*, Vol. 37, No. 3, pgs 630-637.

12. Clark, N. N., J. M. Kern, C. M. Atkinson, and R. D. Nine (2002), "Factors Affecting Heavy-Duty Diesel Vehicle Emissions", *Journal of the Air and Waste Management Association*, Volume 52, pages 84-94.

Combustion Modeling

While our HDD vehicle fuel consumption and emissions modeling approach (see Chapter 4) does not specifically model combustion processes in detail, a review of available literature was conducted in order to obtain a working knowledge of the diesel combustion processes. Our modeling methodology estimates emissions as a function of fuel usage which is dependent upon combustion efficiency. There are many good references on diesel engine combustion, a few are listed here:

1. SAE International, (1999), *Diesel Engine Modeling*, SAE SP-1450, 1999.

2. Egnell, R. (1999), "A Simple Approach to Studying the Relation between Fuel Rate Heat Release Rate and NO Formation in Diesel Engines", SAE Technical Paper Series, 1999-01-3548.

3. Egnell, R. (1998), "Combustion Diagnostics by Means of Multizone Heat Release Analysis and NO Calculation", SAE Technical Paper Series 981424.

4. Zhang, Y., and G. T. Reader (1999), "Simulation and Experimental Studies on Closed-Cycle Diesel Engines", SAE Technical Paper Series, 1999-01-1536.

5. Kazakov, A., and D. E. Foster, (1998), "Modeling of Soot Formation During DI Diesel Combustion Using a Multi-Step Phenomenological Model", SAE Technical Paper Series 982463.

6. E. Mueller and M. Zillmer, (1998), "Modeling of Nitric Oxide and Soot Formation in Diesel Engine Combustion", SAE Technical Paper Series 982457.

7. Taskinen, P., P. v. Hollen, and R. Karvinen, G. Liljenfeldt, and H. J. Salminen (1998), "Simulation of Combustion, Soot and NOx-Emissons in a Large Medium Speed Diesel Engine", SAE Technical Paper Series 981449.

Heavy-Duty Diesel Emissions Modeling

Modeling of HDD emissions for inventory purposes has been generally restricted to the California Air Resources Board's EMFAC model and the U.S. EPA's MOBILE models. Recent efforts have begun to focus on modeling of HDD vehicles at greater levels of time resolution. In addition to the research described in this report, other instantaneous HDD emission models have been developed in recent years, most notably the work being carried out at West Virginia University [Clark et al., 2003]. Using data from their transportable heavy-duty chassis dynamometer systems, they have created an instantaneous emissions model using a speed-acceleration binning technique [Clark et al., 2003]. As discussed in [NRC, 2000], the speed-acceleration binning technique is very convenient for interfacing with activity data or traffic simulation models, however it does have some downfalls. For example, a wide range of vehicle-operating conditions are necessary when filling bins in the lookup tables, which usually requires a good deal of testing time. Also, using instantaneous lookup tables assumes that there is no time dependence in the emissions response to the vehicle operation. For many vehicle types, operating history (i.e., the last several seconds of vehicle operation) can play a significant role in an instantaneous emission value. For example, this assumption would not hold true for vehicle types incorporating variable fuel injection timing strategies (such as many of the vehicles tested in this study) or for vehicle types incorporating after-treatment devices involving oxygen storage or timers which are likely to become prevalent in the future. Lastly, there is no convenient method 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 applying a set of corrections. In addition, HDD trucks also have a wide range of weights (depending on the cargo that they are carrying) that will have a significant effect on emissions that is not easily modeled using a lookup table method.

In 2001 the U.S. EPA conducted a data analysis and modeling shootout as part of the development of their new MOVES modeling scheme [Koupal et al., 2002]. From this study, four different methods were developed to predict HDD (bus) emissions at the micro-, meso-, and macro-scales. UC Riverside employed a GIS database model [Barth et al, 2002]; Environ Corporation employed a micro-trip based model [Lindhjem et al, 2002]; North Carolina State University employed a Vehicle Specific Power bin model [Frey, 2002]; and the U.S. EPA internal model employed a second VSP bin methodology [Hart et al., 2002]. Yanowitz et al developed a load-based model for estimating HDD emissions from engine testing results [Yanowitz et al, 2002]. All of these models had various strengths and weaknesses [Hart et al., 2002]. Several key references include:

1. Clark, N., P. Gajendran, and J. M. Kern (2003), "A Predictive Tool for Emissions from Heavy-Duty Diesel Vehicles", *Environmental Science and Technology*, Vol. 37, No. 1, pgs 7-15.

2. Barth, M., G. Scora, and T. Younglove (2004) "A Modal Emissions Model for Heavy Duty Diesel Vehicles", to appear, *Transportation Research Record, Journal of the Transportation Research Board*, December 2004.

3. United States Environmental Protection Agency, (1998) Motor Vehicle Emissions Laboratory, Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6, Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission. May 1998.

4. Yanowitz, J., M. S. Graboski, and R. L. McCormick (2001), "On the Prediction of In-Use Emissions from Heavy-Duty Diesel Vehicles", *Proceedings of 11th CRC On-road Vehicle Emission Workshop*, San Diego, California, March 26—28, 2001.

5. Yanowitz, J., M. S. Graboski, and R.L. McCormick (2002), "Prediction of In-Use Emissions of Diesel Vehicles from Engine Testing", *Environmental Science and Technology*, Vol. 36, Number 2, pages 270-275.

6. Dreher, D. B. and Harley, R. A. (1998), "A Fuel-Based Inventory for Heavy-Duty Diesel Truck Emissions," *Journal of the Air & Waste Management Association*, Vol 48, 352-358, April 1998.

7. California Air Resource Board, (2000), "EMFAC: an Emissions Factor Model", http://www.arb.ca.gov/msei/msei.html.

8. Koupal, J., (2001), "Beyond MOBILE6: EPA's Plan for Developing a New Generation Mobile Source Emissions Model", *Proceedings of the CRC 11th On-Road Vehicle Emission Workshop*, San Diego, California, March 26,2001.

9. Ramamurthy, R., N. N. Clark, C. M. Atkinson, and D. W. Lyons, (1998), "Models for Predicting Transient Heavy Duty Vehicle Emissions", SAE Technical Paper Series, 982652.

10. Zhou, H., H. Moosmueller, and J. Norbeck, (2001), "Preliminary Modal PM Emission Model for Light-Heavy Duty Diesel Trucks", *Proceedings of 11th CRC On-Road Vehicle Emission Workshop*, San Diego, California, March 26-28, 2001.

11. Glover, E. L., (2002), "Development of Heavy-Duty NOx Off-Cycle Emissions Effects for MOBILE6", United Stated Environmental Protection Agency Technical Report, Assessment and Modeling Division, Office of Transportation and Air Quality. EPA420-R-02-004.

12. Traver, M. L., R. J. Atkinson, and C. M. Atkinson, (1999), "Neural Network-Based Diesel Engine Emissions Prediction using In-Cylinder Combustion Pressure", SAE Technical Paper Series, SAE 1999-01-1532.

13. Barth, M., Younglove, T., Malcolm, C., Scora, G., (2002), "Mobile Source Emissions New Generation Model: Using A Hybrid Database Prediction Technique" Final Report to U.S. Environmental Protection Agency ASD, 2000 Traverwood Drive, Ann Arbor, MI 48105.

14. M. Frey et al, (2002), "Methodology For Developing Modal Emission Rates For EPA's MOVES", EPA420-R-02-027, October 2002.

2.2. Heavy-Duty Engine Technology

Identification of the various engine technologies in use in the heavy-duty vehicle fleet is an essential part of determining how to make the vehicle/technology groups for development of the model categories. For light-duty vehicles, some of the most important technologies that influence emissions are after-treatment factors such as catalyst type and location. Engine technology factors that influence modal behavior of emissions are taken into account through the creation of vehicle/technology groups for the model. In the case of diesel vehicles, at the present time the technologies that influence emissions are primarily engine specific and do not include after-treatment technology. Simultaneous reduction of both NO_x and PM (and fuel consumption) is complex because a number of studies have shown that as NO_x is reduced, the PM will increase, and vice-versa. For example, retarding the injection of diesel fuel into a cylinder will reduce NO_x emissions but increase PM emissions, as well as increase fuel consumption.

2.2.1. Emissions-Related Engine Technology

Compression ignition engines in use in heavy-duty vehicles are primarily four-stroke engines, however some two-stroke engines continue in use today. The introduction of electronically controlled fuel injection in the early 1990's also had a significant effect on the modal behavior of heavy-duty vehicles. In the mid 1990's it was found that seven of the largest heavy-duty diesel engine manufacturers violated certification requirements by turning off or defeating emissions control devices during highway operation. Sophisticated engine operational strategies that allowed for changes in fuel economy and emissions based upon driving history play an important role in NO_x emissions, and a lesser role in CO_2, CO, and HC emissions. NO_x emissions can increase 400% or more under the alternative fuel control strategy. For example, in a steady-state dynamometer test (Figure 2.2), the engine switched control strategy after roughly 60 seconds of steady-state operation. The point at which a particular engine shifts modes is related to power, RPM, and time and through an unknown function and can vary in complexity. Each engine manufacturer designs their own engine control strategy so the potential exists for manufacturer specific modal behavior differences.

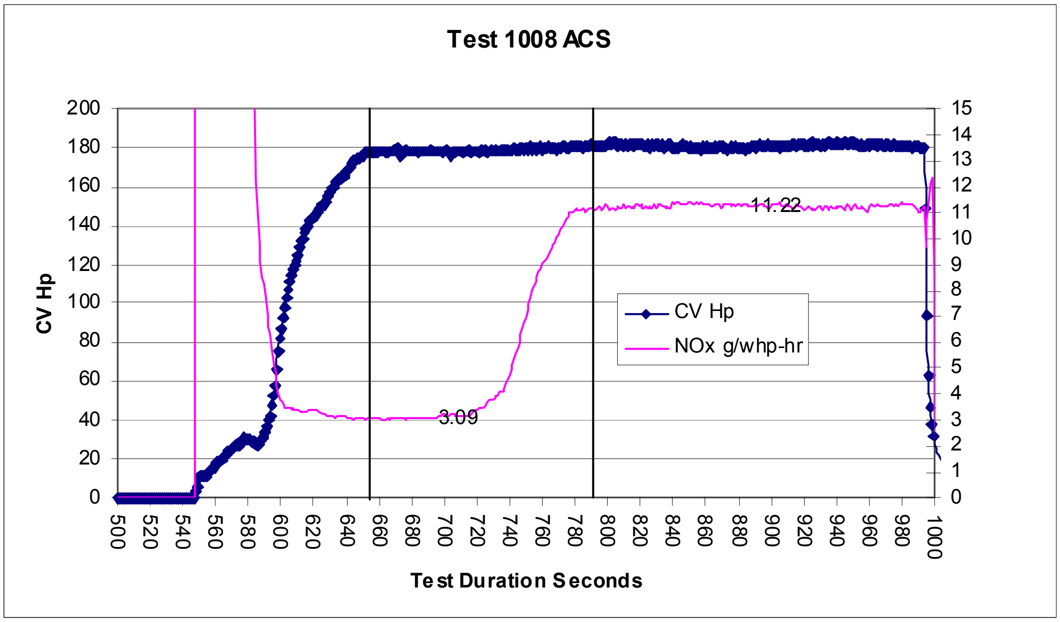

Figure 2.2. Steady-state dynamometer test results for Power (blue) and NO_x (magenta) showing alternative fuel control strategy.

The discovery of the operating feature on the engine control module that enabled NO_x emissions to triple was a very contentious issue that resulted in a number of consent decrees between the EPA and some engine manufacturers. In the agreements, the excess NO_x emissions were identified as the off-FTP cycle emissions or simply, off-cycle emissions, a term both parties agreed to describe the effect without the presumption of a “defeat device.” The Department of Justice and the Environmental Protection Agency [U.S. EPA, 2003] reported that vehicles producing off-cycle NO_x emissions were being phased into the heavy, heavy-duty diesel fleet in the late 1980’s and early 1990’s. On October 22, 1998 the seven major manufacturers of diesel engines agreed to spend more than one billion dollars to resolve claims that they installed computer devices in heavy-duty diesel engines that resulted in illegal amounts of air pollution emissions. In addition, they agreed to reduce the total NO_x emissions from diesel engines by one-third as of the year 2003. The involved companies comprised 95 percent of the U.S. heavy-duty diesel engine market: Caterpillar, Inc., Cummins Engine Company, Detroit Diesel Corporation, Mack Trucks, Inc., Navistar International Transportation Corporation, Renault Vehicules Industriels, s.a., and Volvo Truck Corporation. The agreements included the incorporation of more stringent HDDV standards earlier than originally required (pull ahead), and accelerated engine rebuild programs (rebuild) to get in-use engines into better compliance

2.2.2. Engine Technology Population Weights

Identification of the population percentages of the heavy-duty vehicle technology groups is important for determining the relative importance of the groups as well as for model implementation. Because of the limited number of vehicles that can be tested in any emissions testing project, sample size was not based on population percentage. Estimates of the fleet representation of the different vehicle/technology groups are necessary for estimation of fleet emissions when applying the resulting emissions model. Fleet population estimates developed in this report are based on California heavy-duty registration data. Thus the default values for this HDD modeling project are representative of California HDD fleet populations.

2.2.3. Malfunctioning and Tampered Vehicles

For light-duty vehicles, high emitting vehicles contribute a disproportionate percentage of total fleet emissions. Considerable effort in the development of the comprehensive modal emissions model went into the identification, testing, and modeling of high emitting vehicles. A portion of the emissions of the heavy duty vehicle fleet results from high emitting vehicles due to malfunctions and tampering; however, estimating these rates have proven difficult for a number of reasons, one being the lack of data from a program for HDD vehicles like “Smog Check.” Current EMFAC estimates of the incidences of HDD vehicle malfunctions and tampering were based on roadside programs for excessive smoke and considerable information is found in the regulatory development process [CARB, 1990; CARB, 1997; CARB, 1998]. In one CARB (1990) study, 912 HDD trucks were tested and 69 trucks were repaired. A study has recently been completed examining the incidence of malfunctioning and tampering in the on-road HDD vehicle fleet in California [CARB, 2003]. This study found general agreement between the current EMFAC estimates and the in-use methods in terms of number of malfunctioning and tampered vehicles (see Table 2.1). It was concluded that the incidence of most types of HDD vehicle tampering and malfunction are low, generally less than 5%.

Incidence of malfunctions and tampering likely to cause significant increases in CO, HC, and NO_x such as worn turbos and severe fuel injector problems were low. In general the overall lack of major emissions control equipment makes for a different distribution of fleet emissions from the light-duty vehicle fleet in which high-emitting vehicles play a very significant role in total fleet emissions. Recent analysis of testing results from CARB’s on-going M17 in-use HDD test program show a distribution of NO_x emissions that is not skewed towards high-emitting vehicles (Figure 2.3). These results, showing a lack of large numbers of high emitting vehicles in the on road HDD fleet, are in line with the low incidence of malfunctions and tampering found.

Table 2.1: Comparison of EMFAC HDD malfunction and tampering rates with on-road results.

Malfunction/Tampering Group	**EMFAC HHDT 94-97 Population%**	**EMFAC HHDT 98-02 Population%**	Warranty Repair Database	Roadside Inspection Database	Repair Shop Survey	Roadside Driver Survey
Injection Timing Advanced	**5%**	**2%**	<1%	NA	6%	NA
Injection Timing Retarded	**3%**	**2%**	<1%	NA	4%	NA
Minor Injector Problem	**15%**	**15%**	2%	<1%	16%	8%%
Moderate Injector Problem	**10%**	**10%**	23%	<1%	8%	4%
Severe Injector Problem	**3%**	**3%**	<1%	<1%	4%	4%
Puff Limiter Mis-Set	**4%**	**0%**	NA	NA	0%	NA
Puff Limiter Disabled	**4%**	**0%**	NA	NA	0%	NA
Max Fuel High	**3%**	**0%**	<1%	NA	2%	8%
Clogged Air Filter	**15%**	**15%**	NA	NA	4%	8%
Wrong/Worn Turbo	**5%**	**5%**	8%	NA	2%	4%
Intercooler Clogged	**5%**	**5%**	<1%	NA	3%	4%
Other Air Problems	**8%**	**8%**	<1%	14%	2%	NA
Mech. Failure	**2%**	**2%**	2%	NA	12%	2%
Excess Oil Consumption	**5%**	**3%**	<1%	NA	14%	NA
Electronics Failed	**3%**	**3%**	65%	<1%	11%	NA
Electronics Tampered	**5%**	**5%**	<1%	<1%	2%	NA
Catalytic Converter Removed	**0%**	**0%**	NA	NA	1%	NA
EGR Stuck Open	**0%**	**0%**	<1%	NA	0%	NA
EGR Disabled	**0%**	**0%**	NA	3%	0%	NA

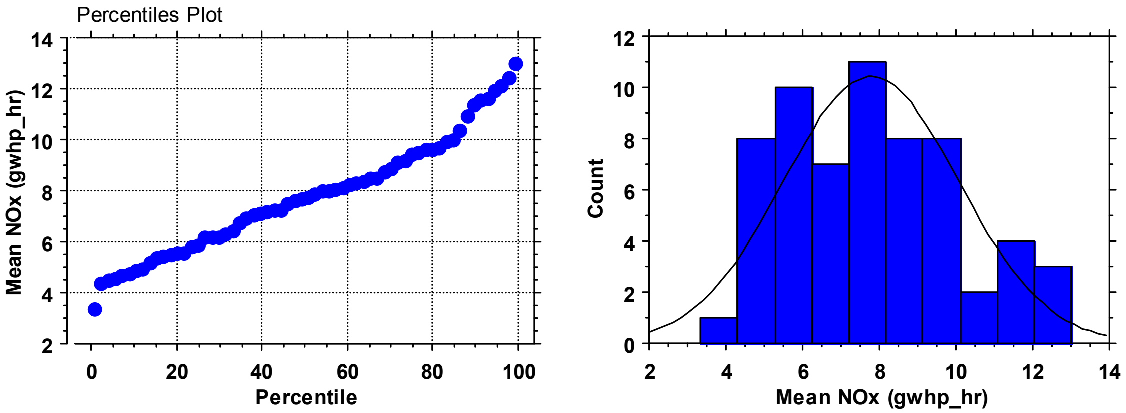

Figure 2.3: a) Percentile plot of in-use HDD NOx emissions and b) histogram of in-use HDD NOx emissions.

2.3. Heavy-Duty Vehicle Driving Cycles

In the original development of CE-CERT's comprehensive modal emissions model (CMEM) for light-duty vehicles, the vehicles were tested on a chassis dynamometer using the FTP test cycle, the US06, and a CE-CERT developed modal cycle, the Modal Emissions Cycle (MEC) [Barth et al., 1999]. The FTP and the US06 were designed to mimic the range of in-use driving typical for light-duty vehicles, while the MEC was designed to operate the vehicles over the full range of operational characteristics. In the current heavy-duty vehicle research, greater reliance has been placed on unspecified on-road driving data collection. In addition to the unspecified driving, the vehicles were tested on specified driving cycles. Further details are provided in Chapter 3, but the testing included:

- A certification test cycle to provide a reference point to previous dynamometer testing;
- A specified set of in-use driving cycles that were conducted on the highway to provide a set of relatively consistent testing data between trucks;
- A set of modal driving cycles to test the vehicles under a consistent set of specific accelerations, cruises, and decelerations; and
- Unspecified on-road driving to be conducted with the flow of traffic.

2.3.1. HDD Driving Cycles

In the last decade, 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 [FTP, 1989]. 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] and [Haskew et al., 1994]).

For HDD vehicles, the standard dynamometer test cycles consist of operation at pre-specified power and RPM levels over the range of operation of the engine. These cycles are ill suited to on-road testing and the primary cycle selected for on-road testing was the UDDS driving cycle. As a result, a new Heavy-Duty Diesel Test Cycle (HDDTC) has been developed by the California Air Resources Board [Maldonado, 2002]. The cycle contains four components: Idle, Creep, Transient, and Freeway types of driving. This cycle development was based on CARB's heavy-duty truck activity study [Battelle, 1999] which sampled heavy-duty truck activity in California using GPS dataloggers. The data were collected for use by CARB in forecasting emissions of heavy-duty vehicles. The project database contains data on nearly 87,000 miles of driving by 140 trucks. All California air basins except Lake County are represented in the database. Participation in the study was voluntary and the included vehicle fleet should not be construed as a statistical representation of the California HDD vehicle fleet.

2.3.2. Modal Driving Cycles

As part of the light-duty CMEM development process, CE-CERT developed the modal emissions cycle (MEC). This cycle and its development are described elsewhere [Barth et al., 1999]. A similar set of modal events were developed for HDD vehicles. However, the modal events had to be broken into smaller cycles due to the limited length of roads available in the test area. Many of the same modal events were included in the HDD truck testing which included various accelerations, steady-state cruises at pre-specified speeds, decelerations, and transitions. Further details on the vehicle testing is provided in Chapter 4.

2.4. Evaluation of Current Models and Recent Revisions

In this section, we briefly review the HDD vehicle emissions modeling methodology of both EMFAC (CARB) and MOBILE (U.S. EPA), and then focus the analysis on the limitations of these models, with respect to this project's modal emission model development.

2.4.1. Inventory Model Summary

Estimates of HDD truck emissions are currently available in both of the conventional on-road vehicle emissions models. CARB's EMFAC and US EPA's MOBILE emission models use very similar methodologies to estimate emission inventories. Emissions of heavy-duty trucks are broken down into classes, similarly to automobiles. Within the different vehicle classes, there are base emission rates for the different model years with the current versions of the models having 45 model years represented within the fleet. Emissions estimates are then calculated using the estimated fleet proportions and VMT in combination with the base emission rates.

Overall, the EMFAC model 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 2.2.

Table 2.2. Vehicle Classes in EMFAC.

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

2.4.2. Multi-Scale Modeling

The U.S. EPA is currently in the process of developing a new set of modeling tools for estimating mobile-source emission inventories. This new set of mobile-source modeling tools is known as the Multi-Scale Motor Vehicle & Equipment Emission System, or MOVES [Koupal et al., 2002]. MOVES is expected to address both on-road and off-road vehicles. The EPA has identified four broad objectives that the MOVES model must include:

1. The model should encompass all pollutants including CO_2, CO, HC, NOx, PM, air toxics, and greenhouse gases;
2. The model should be developed according to principles of sound science;
3. The software design should be efficient and flexible; and
4. The model should be implemented in a coordinated, clear, and consistent manner.

Once complete, MOVES in its final form will likely include everything necessary for the modeling of mobile sources, including modeling guidance, tools, algorithms, and supporting data. This modeling system is intended by the EPA for use in all official analyses associated with regulatory development, compliance with statutory requirements, and national/regional inventory projections.

A key difference with past mobile source emissions models is the reliance on on-board data collection rather than on laboratory dynamometer data. Emissions data gathered using on-board “portable” emissions measurement systems (PEMS) is to be an important part of the MOVES effort. EPA currently has a major effort in developing this on-board technology both in-house and through external contracts. “Real-world” emissions measurements in combination with the improved modeling methodology to be included in MOVES provide synergistic benefits for accurate emissions estimation. The technical challenges of collecting and modeling motor vehicle emissions using on-road data from actual driving instead of artificial laboratory driving cycles require careful consideration, but will significantly improve the accuracy of estimates of the emissions inventory in the United States.

In terms of HDD vehicle emissions estimation, MOVES will also rely on a large set of on-board emission measurements. The same type of PEMS equipment will be used to collect such data. Further, a vehicle specific power (VSP) – bin modeling methodology will be used, essentially the same technique that is being applied to light-duty vehicles. For further details on MOVES, please refer to http://www.epa.gov/otaq/ngm.htm.

2.5. COMPREHENSIVE MODAL EMISSIONS MODELING FRAMEWORK

For many years, agencies at the local, state, and federal levels have always relied on the mobile source emission-factor models MOBILE (U.S. EPA) or EMFAC (CARB) to develop and evaluate transportation policy. In recent years however, it was determined that these models are good for predicting emission inventories for large regional areas, but they are not well suited for evaluating operational improvements that are more “microscopic” in nature, such as ramp metering, signal coordination, and many ITS strategies. A need has developed for vehicle emission models that consider 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 1996, CE-CERT began a four-year research project to develop a comprehensive modal emissions and energy consumption model, 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 and fuel consumption 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). Further background on modal emission modeling and this NCHRP project is given in [Barth et al., 1996, 1997, 1999].

During the initial model development, 26 different vehicle/technology categories (see Table 2.1) were defined to serve as the basis for the model, as well as to guide the vehicle recruitment and testing performed. Because the eventual output of the model is emissions, the vehicle/technology categories and the sampling proportions of each were chosen based on a group's *emissions contribution*, as opposed to a group's actual population in the national fleet. Because of this, five distinct high-emitting vehicle/technology groups were included. The other vehicle/technology categories have been chosen based on vehicle class (e.g., car or truck), emission control technology (e.g., no catalyst, 3-way catalyst, etc.), emission certification standard (e.g., Tier 0, Tier 1), power-to-weight ratio, and mileage.

Table 2.3. Vehicle/Technology modeled categories in CMEM. Note diesel vehicles start at category 40; "blank" categories are user programmable from category #60.

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

For testing, vehicles were recruited randomly within each vehicle/technology bin in this matrix. Each vehicle was tested using a comprehensive dynamometer testing procedure that consists of a standard FTP test, the high-speed US06 cycle (used in Supplemental FTP testing procedure), and an in-house developed modal emission cycle. This modal emission cycle (MEC01) has been designed to include various levels of acceleration and deceleration, a set of constant speed cruises, speed-fluctuation driving, and constant power driving. Details of this dynamometer testing procedure are given in [Barth et al., 1997].

For each vehicle/technology category shown in Table 2.3, a different model "instance" or sub-model has been created using a parameterized physical approach (see [Barth et al., 1996]). For each sub-model, there are a number of vehicle parameters and operating variables that are considered. As shown in Figure 2.4, the generalized model for each category consists of six distinct modules that individually predict: 1) engine power; 2) engine speed; 3) air/fuel ratio; 4) fuel-use; 5) engine-out emissions; and 6) catalyst pass fraction. The vehicle parameters used in the model are divided into two groups: 1) parameters that are obtained from the public domain (or determined generically), and 2) parameters that need to be calibrated based on the second-by-second dynamometer emission measurements. Examples of the first group include vehicle mass, engine displacement, rated engine power and torque, etc. Examples of the second group include engine friction factor, enrichment threshold and strength, catalyst pass fraction, etc. This second group of parameters are determined based on an extensive calibration process, where a series of optimization procedures are applied to minimize the differences between the measured and modeled emissions over the test cycles. Details of the model structure are given in [An et al., 1997].

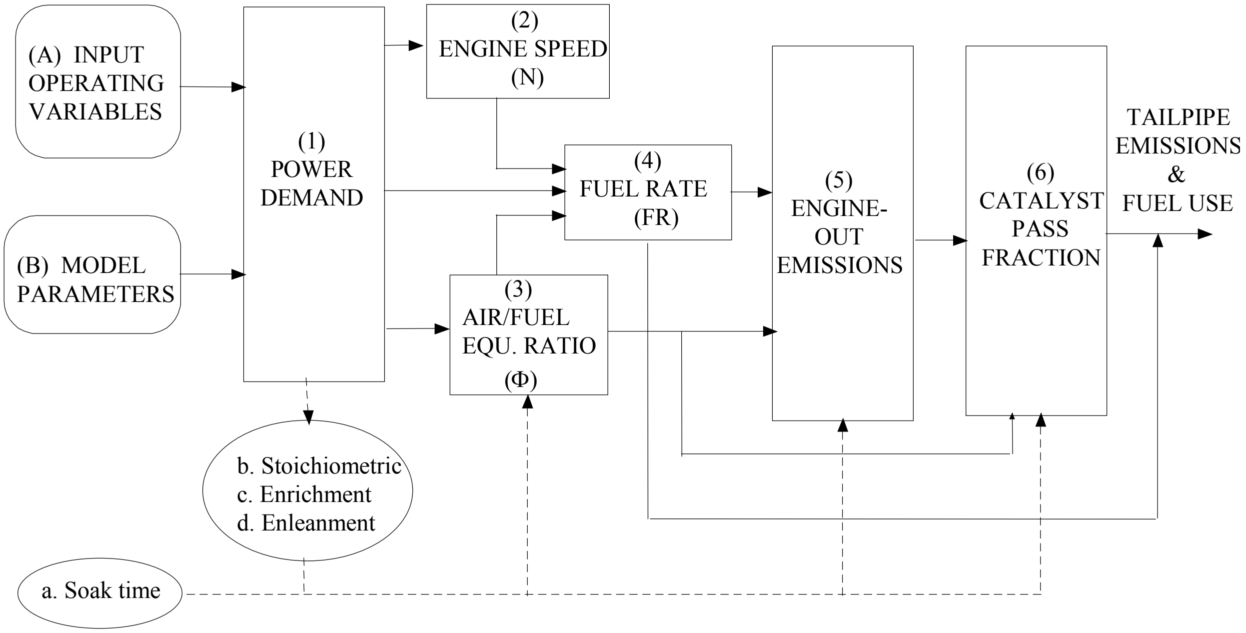

Figure 2.4. Generic Modal Emissions Model structure.

The comprehensive modal emissions model has been 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 2.5, 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.

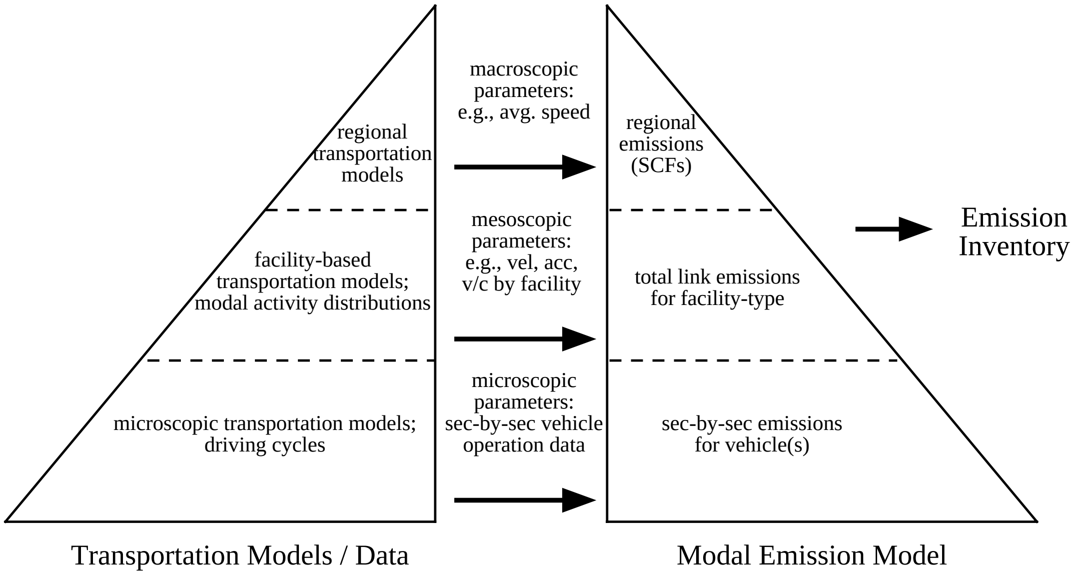

Figure 2.5. Transportation/Emission Model interface.

In order for the emission model to be closely integrated with 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 was 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. 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*

In addition to temporal aggregation, vehicle aggregation must also be considered. Given an appropriate parameter set, the model is capable of predicting emissions and fuel consumption 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. The compositing techniques used are based on developed stochastic distributions of the various model parameters. At the highest level of vehicle aggregation, the model outputs from each vehicle/technology category can be combined appropriately to represent emissions from the general vehicle population.

The CMEM model currently exists in several different forms. During development, the model was carried out in a research environment, using MATLAB modeling/analysis tools [Mathworks, 2000]. 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 initially developed. The command-line code was 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. In addition to the command line version of the code, a friendlier graphical user interface for the CMEM model has been implemented.

Since its initial development, CMEM has been incrementally improved and enhanced. There have been several version updates. It was the task of this project to add the ability to model heavy-duty diesel vehicles to the model. The details of this addition are given in Chapter 4.

3. Vehicle Testing and Data Collection

Prior to developing a modal HDD vehicle emissions and fuel consumption model, it was necessary to collect appropriate data through a vehicle testing program. The design of the heavy-duty diesel testing procedure follows the same basic outline as that used on the light-duty vehicles [Barth et al., 1997]. Based on the background information described in the previous chapter, we have designed a vehicle testing methodology that has provided data for developing the heavy-duty modules for the comprehensive modal emissions model. This vehicle testing methodology consists of several key components:

1) Defining the *vehicle/technology categories* for the heavy-duty modules;

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

3) Developing an on-road test procedure for the measurement of heavy-duty modal emissions.

The majority of the data collection was performed using CE-CERT Mobile Emissions Research Laboratory (MERL), described first in Section 3.1. Next, the three components outlined above are described in detail. The fifth section describes the emission testing that has been performed. The last section of this chapter describes the data post-processing that took place.

3.1. UC Riverside's Mobile Emissions Research Laboratory (MERL)

As described in Chapter 2, emissions from heavy-duty engines are currently certified on engine dynamometers, separately from the truck chassis and body in which they operate. This is because most engines are designed to work in multiple vehicle types — and, often, as stationary power generators. As a result, the actual emissions that an engine will produce under "real world" operating conditions can vary significantly, and measuring them is difficult. This is a particularly important area of emissions research because diesels emit more particulate matter than spark-ignition engines, and these particles are suspected of causing serious health effects.

Heavy-duty *chassis* dynamometers, which can test a truck-engine combination, solve part of this problem. Only a few such heavy-duty laboratories are in operation, however, and even the dynamometers cannot simulate many of the loads typical of truck operation. Other technologies to estimate truck emissions include portable units that measure smoke opacity or give approximate measures of the gases found in an exhaust stream. These systems generally are inadequate for regulatory and technical purposes.

In order to more realistically measure on-road, real-world emissions, UC Riverside has developed a unique Mobile Emissions Research Laboratory (MERL), shown in Figure 3.1. This unique laboratory contains all of the instrumentation normally found in a conventional vehicle emissions laboratory, but the equipment is mounted inside a 53-foot over-the-road truck trailer. As shown in Figure 3.2 and 3.3, the laboratory contains a dilution tunnel, analyzers for gaseous emissions, and instrumentation for particulate measurements. The system is reconfigurable, and an objective is to demonstrate real-time particulate measurement capability. Although much of the system is custom-designed, the laboratory was designed to conform as closely as possible to Code of Federal Regulations requirements for gaseous and particulate emissions measurements (Code of Federal Regulations (CFR) Parts 86 and 89 [CFR, 1986]). The laboratory is designed to operate as a class 8 tractor is pulling it over the road (or on a closed track over a repeatable cycle); it is not a roadside testing laboratory.

Figure 3.1. UCR's Mobile Emissions Research Laboratory (MERL).

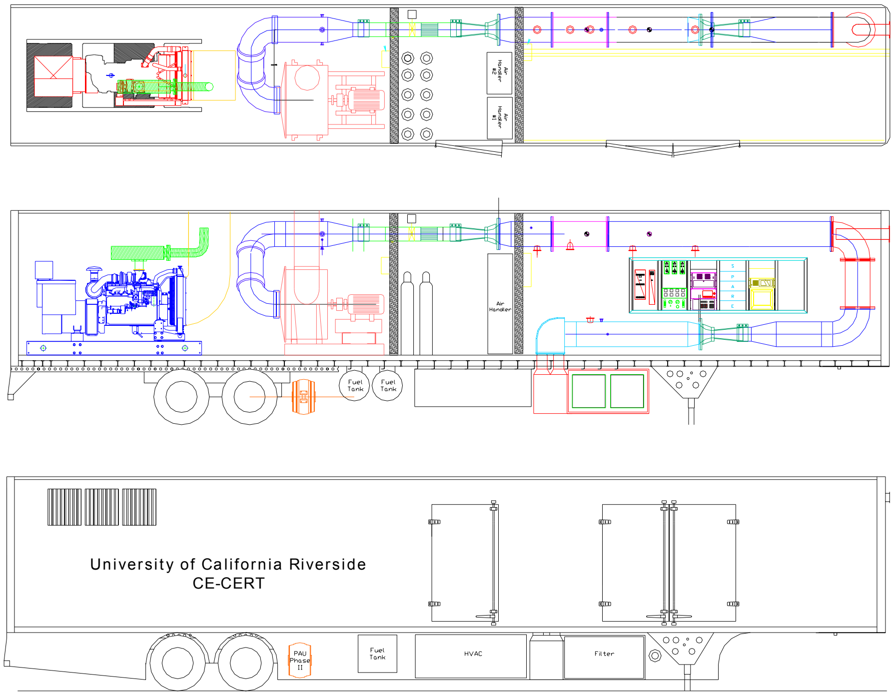

Figure 3.2. UCR's Mobile Emissions Research Laboratory (MERL).

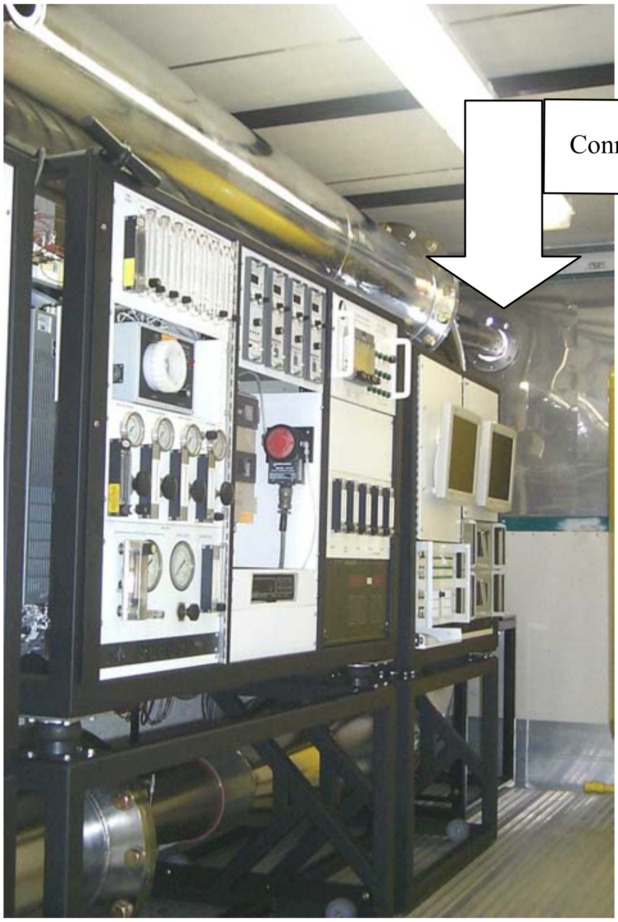

Figure 3.3. Left: Trailer laboratory interior, looking forward. Dilution tunnel travels beneath, forward of, and above analytical instruments. Connector at the front captures emissions as the truck pulls the trailer. Above: Trailer laboratory in operation at the California Speedway.

The dilution tunnel inside the trailer mixes the truck's exhaust (sampled directly from the exhaust pipe) with dilution air, and the samples are measured just as they would be in a stationary laboratory. Both gaseous and particulate matter (PM) emissions are measured with the same levels of accuracy as measurements made in a stationary facility. The laboratory weights approximately 45,000 pounds and serves as the truck's load. Thus, we are able to sample a truck's emissions under real-world operating conditions with the accuracy and precision normally restricted to a stationary laboratory. Any class-8 tractor can pull this trailer, and the lab has gone through extensive calibration and testing to ensure accuracy and repeatability [Cocker et al., 2004]. MERL serves as an important tool for understanding how trucks pollute and for quantifying the effects of different fuels (reformulated diesel, etc.), alternative powertrains, different control strategies, and a variety of emission control equipment. Further details on MERL can be found elsewhere [Cocker et al., 2004].

3.2. Heavy-Duty Vehicle/Technology Categorization

Prior to developing a modal emissions model for HDD vehicles, it was first necessary to determine appropriate vehicle/technology categories within the HDD vehicle class. The development of these categories not only determine the eventual “modules” that make up part of the CMEM framework, but they also drive which vehicles are recruited and tested.

Different types and characteristics of heavy-duty diesel vehicles were examined in detail and broken down by technology type. Due to budgetary constraints, the overall test program had a limited number of tests available, with the initial goal of testing approximately 25 different trucks. Because of the small sample size, the total number of cells in the test matrix was limited. Thus, the choice of vehicles for this sample is crucial, with minimum within-category variability in modal behavior important for the success of the model.

A number of factors influence the emissions behavior of heavy-duty diesel trucks. Some factors may result in differences in emission levels, while others may lead to differences in modal behavior. For model building, it is important that vehicles within the vehicle/technology groups behave in a similar fashion across operation modes as well as have similar emissions levels. The desire to split the HDD vehicle fleet into a greater number of vehicle/technology categories must be balanced against the limits of the total sample size and the within group sample size. A minimum within group sample size of four was chosen to allow for estimation of sample variance, even if one vehicle is tested and found to be an outlier requiring removal from the group.

Because the eventual output of the model is emissions, the vehicle/technology categories have been chosen based on a vehicle’s *emissions behavior*. Like automobiles, the trucks were grouped by technology factors that were expected to affect *modal behavior*. Technology factors such as fuel injection type (mechanical or electronic) that could result in emissions differences that were not consistent by operating mode were given priority over factors that were more likely to affect emissions level, but not modal behavior. Engine size and horsepower are two examples of factors more likely to affect level than modal behavior. The reason for this is that a composite vehicle that averages the different levels of vehicles having the same modal behavior will have lower vehicle-to-vehicle error rates across driving modes than a composite vehicle that averages trucks having different modal behaviors.

There are several key attributes that affect a truck’s emissions characteristics. These attributes are described below.

Influence of Emissions Standards

California state and federal standards for HDD truck emissions have been revised downwards rapidly over the past two decades, as shown in Table 3.1. From 1991 onward, California and Federal standards have been identical, however some differences existed prior to 1991 with the California standards being lower. The manufacturers have primarily met these increasingly stringent standards through basic improvements to the combustion process rather than through addition of exhaust after treatment or add-on controls [EPA, 1998] as was done with light duty vehicles.

Table 3.1. HDDT Emissions Standards (Source: [CARB, 2000]).

FEDERAL HEAVY-DUTY TRUCK STANDARDS						**CALIFORNIA HEAVY-DUTY TRUCK STANDARDS**					
MODEL YEAR	HC[1]	CO	NOX	PM	HC+NOX	MODEL YEAR	HC[1]	CO	NOX	PM	HC+NOX
	g/bhp-hr						g/bhp-hr				
						1975-76	---	30.0	---	---	10.0
1974-78	---	40.0	---	---	16.0	1977-79	1.0	25.0	7.5	---	---
1979-83	1.5	25.0	---	---	10.0	1980-83	1.0	25.0	---	---	6.0
1984-87	1.3	15.5	10.7	---	---	1984-86	1.3	15.5	5.1	---	---
1988-90	1.3	15.5	10.7	0.60	---	1987-90	1.3	15.5	6.0	0.60	---
1991-93	1.3	15.5	5.0	0.25	---	1991-93	1.3	15.5	5.0	0.25	---
1994-97	1.3	15.5	5.0	0.10	---	1994-97	1.3	15.5	5.0	0.10	---
1998-02	1.3	15.5	4.0	0.10	---	1998-02	1.3	15.5	4.0	0.10	---
2003+	0.5[2]	15.5	2.0	0.10	---	2003+	0.5[2]	15.5	2.0	0.10	---

[1] **Note:** the HC standards shown are total hydrocarbons except for model year 2003+ which is NMHC.

[2] Assumes 2.5 g/bhp-hr (NOx+NMHC) with a 0.5 g/bhp-hr NMHC cap effective October 2002.

Emission Control Technology

Several general HDD truck technology trends were taken into account when developing the vehicle/technology categories. The gradual nature of the changes to combustion processes have led to differences in operational behavior within the vehicle technology groups as fuel control and combustion chamber changes gradually change the emissions level to meet the decreasing standards. The major emission control technology changes are listed in Table 3.2.

Table 3.2. Major HDDT Emission Control Technology Changes.

Technology	**Model Years**
Naturally Aspirated	< 1989
Turbo Intercooling	1990 - present
Conversion of water jacket intercoolers to air-to-air type	In most models by 1996
Improved design of valve seals and piston rings	In most models by 1996
Increased injection pressure	In most models by 1996
Electronic fuel injection	In most models by 1996
Quiescent combustion chambers	In most models by 1996
Phase out of two-stroke engines	By 1998

It should be noted that a few models with non-electronic fuel injection continue to be sold under the averaging, banking, and trading provisions but should be phased out by 2000 (EPA, 1998).

Engine Power

The major manufacturers produce engines for the HDD truck class of vehicles in two basic power ranges, 250-320 HP and 320+ HP [EPA, 1998]. The dominant engine manufacturers are Cummins, Caterpillar, and Detroit Diesel with the L10/N14, 3306/3406, and 6-71/6-92 engine families respectively. The higher horsepower motors have the same emissions control technology and standards as the lower horsepower motors [EPA, 1998]. Many engine models come in a variety of horsepower levels. For example, the CAT C-10 motor comes in variants producing 305, 335, 350, and 370 horsepower. Because of the identical model name, determination of the fleet proportions of the different horsepower levels is difficult. In addition, vehicles with electronic engine controls can be re-programmed for higher horsepower levels after they leave the factory, making determination of the on-road horsepower distribution difficult.

Engine Cycle

Heavy Duty Diesel engines have been produced in both two-cycle and four-cycle models. The primary manufacturer of two-stroke engines has been Detroit Diesel, with smaller numbers produced by Mack. The Detroit Diesel 6-71 and 6-92 engines are two-stroke diesel while the others are four-stroke. As of 1998, the 6-71 and 6-92 engines have essentially been phased out and replaced with the Series 50 and Series 60 four-stroke models. In order to better understand the distribution of HDD vehicles in California, we queried the California vehicle registration database. In addition, we developed a VIN decoder for heavy-duty vehicles. This was used to identify vehicle/technology proportions within the California registered on-road vehicle fleet. Data fields include VIN, make, model, model year, and engine displacement. Evaluation of the DMV data provides fleet proportions for vehicle/technology types through VIN as well as basic fleet information such as engine displacement (Figure 3.4) and manufacturer (Figure 3.5).

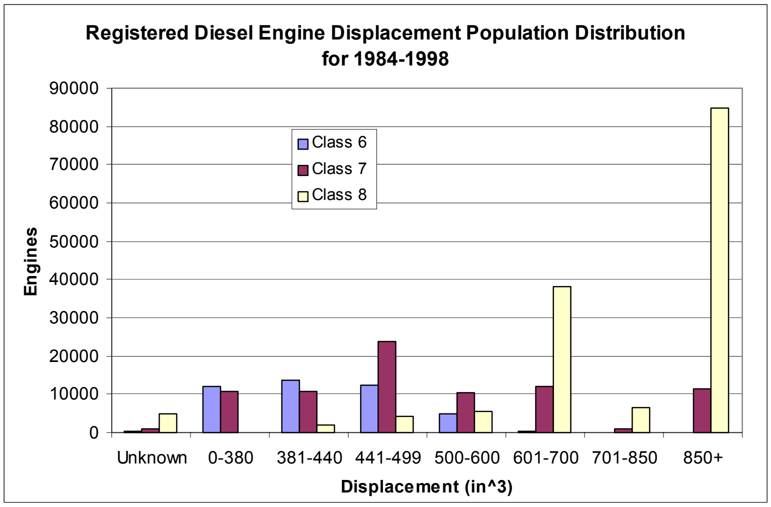

Figure 3.4. Registered diesel engine displacement population distribution, 1984-98 (from Department of Motor Vehicles database).

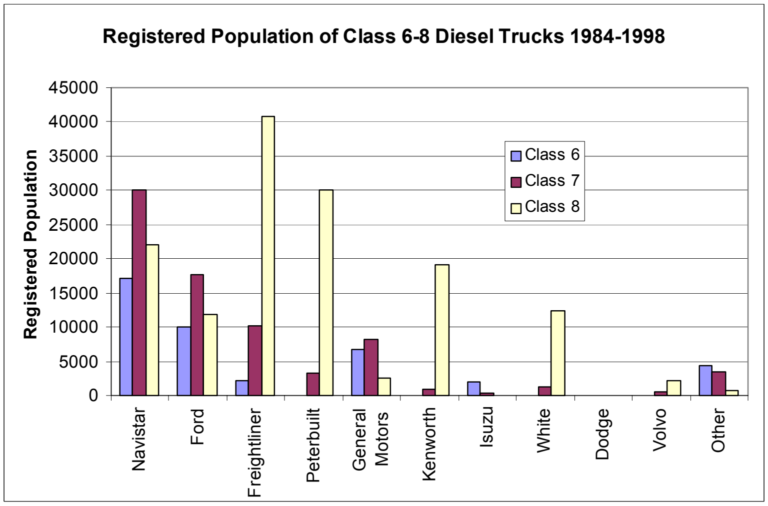

Figure 3.5. Registered population of class 6-8 diesel trucks, 1984-1998 (from Department of Motor Vehicles database).

Also using the California vehicle registration database, we estimated the proportion of two-stroke engines by model year. The VIN decoder was used to identify common character strings within VIN codes for known HDD vehicles. These character strings were then identified within the statewide vehicle registration database and used to estimate population size for two and four-stroke engines. The estimated percentage of on-road two-stroke HDD engines ranged up to about 12% (Figure 3.6).

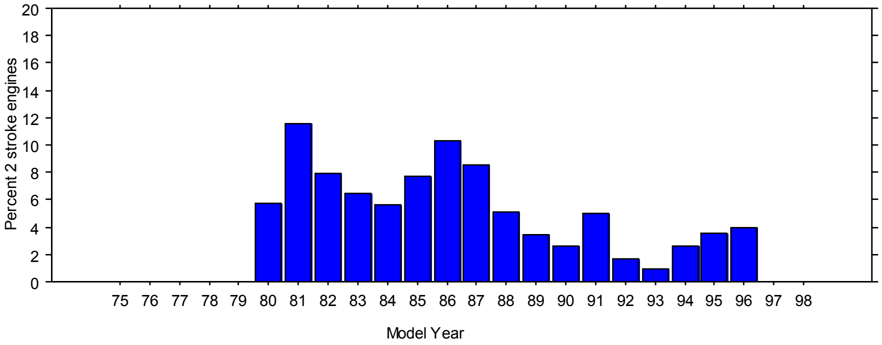

Figure 3.6. Percentage of two-stroke engines in the DMV registered HDD fleet.

The percentage of two-stroke engines identified prior to 1980 was less than 0.1%. The percentage of two-stroke engines during the early and mid 1980's model year ranges from about 6% to about 12% of the California HDD registered fleet. Starting in 1987 the percentage of two-stroke engines fell to a low of about 1% in 1993. The percentage began to rise again in the later model years, but may be an artifact of manufacturers recycling engine codes. Specific vehicles were subsequently identified and examined for engine type to resolve this anomaly. A secondary analysis compared the two-stroke percentages of HDD vehicles first registered in California against those brought into California for registration. The percentage of two-stroke engines was consistently higher on the CA registered fleet in comparison with the 49-state California registered fleet, as shown in Figure 3.7.

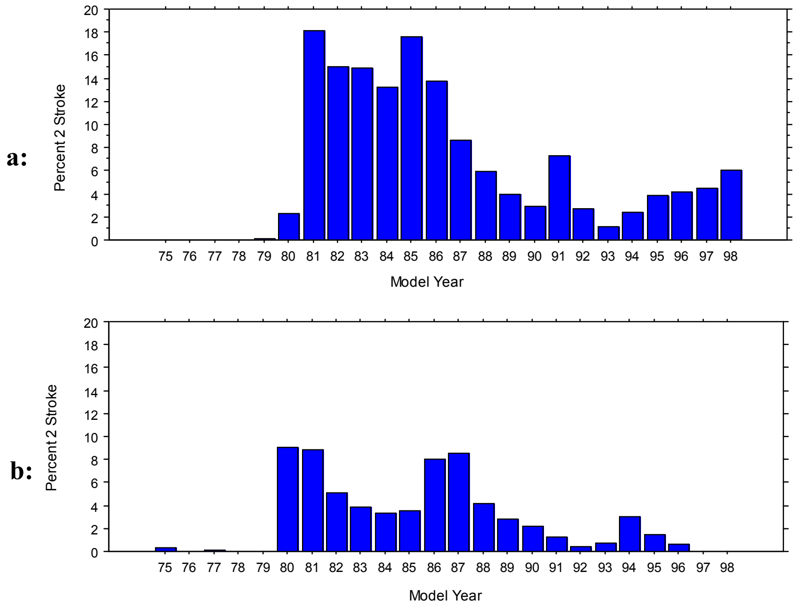

Figure 3.7. Percentage of two-stroke engines in the a) CA registered HDD fleet and b) 49-state registered HDD fleet.

Regulatory Exemptions

Manufacturers have been allowed to sell some low sales volume engine lines that do not meet the 1994+ emissions standards [EPA, 2000]. These sales were allowed under regulations for averaging, banking, and trading (ABT) and are a small percentage of the HDD truck fleet. The ABT sales were incorporated into the rules in order to provide flexibility to the engine manufacturers to make it easier to meet the new standards. ABT rules apply to NO_x emissions standards from 1991-2003, and from 1991-2004+ for PM emissions [EPA, 1997]. Because of their small sales numbers, these vehicles were ignored during this study and were excluded from testing in the unlikely event of their selection during recruitment.

Estimated HDD Population Technology Distribution

An important part of application of any emissions inventory model will be the identification of the population weights of the various vehicle/technology groups. However, for model building where the number of samples is limited (as is the case here), identification of vehicle/technology population weights is useful for selection of the categories, but is not used for allocation of the samples. This is because of the necessity of having a sufficient number of vehicles represented within each group for the construction of the composite vehicles that represent the vehicle/technology groups.

The development of the HDD engine family decoder program required a multi level approach. Three data sources were combined to fulfill the program objective of maximizing the total number of engines identified. The first source was compiled from a series of manufacturer reference manuals used to identify vehicle characteristics, weight, wheelbase, brake type and engine manufacturer and family. This reference provided the essential information regarding the VIN character placement and engine designation. The various manufacturers utilize a distinct position within the VIN character string to identify engine make and model. The resulting table is comprised of 427 manufacturer/engine permutations for less than 12 discrete engine families which constitute the bulk of the class 8 engine manufacturers.

The second data set was obtained from the CARB In-Use HDD Periodic Smoke Inspection Program. This data set contained in excess of 1000 trucks, which have been comprehensively inspected and systematically documented for inventory and enforcement purposes. In this CARB program, HDD vehicles are pulled over at various locations and times for safety and emissions inspection. The collected data includes VIN, make, model, engine, and model year information. The advantage of the data is that they are collected on-road and throughout the state. This CARB database was obtained and utilized for analysis. The database contains vehicle and site identification information as well as Snap and Idle test results and visual inspection results. The visual inspections were labeled: **P** = Pass; **N** = Not Applicable to vehicle; **S** = Missing; **D** = Disconnected; and **M** = Modified. As an initial step, the data were separated into individual years based on inspection date. Within each year of the database, the data were sorted by model year of the vehicles and tabulated. We used this database to develop a HDD VIN decoder for vehicle/technology characteristics such as combustion cycle and type of fuel injection. The engine VIN information obtained from the manufacturer reference manuals was used to further expand the number of manufacturer / engine families identified. The resulting data set identified an additional 150 manufacturer /engine family permutations.

The final reference source involved the use of the California registered vehicle database in two different approaches. Using the decoder developed from the earlier efforts, the VIN for every class 8 vehicle registered within the state was decoded. Engine families were grouped according to manufacturer and displacement. The remaining unidentified vehicles were subsequently queried based on engine displacement identified in the earlier searches. Each engine family has a specific displacement, which accurately identifies the manufacturer and family. The DMV requires this information for registration purposes and therefore is an effective method for identifying specific engines within each vehicle. The engine family displacement information is provided in Table 3.3 below and the California registered fleet proportions are presented in Table 3.4.

Table 3.3. Engine Displacement Identifier.

Make	Model	Displacement
Caterpillar	3406	893
Caterpillar	3306	640
Caterpillar	3208	636
Caterpillar	3176	629
Cummins	N14/NTC	855
Cummins	L10/M11	611
DDEC	S60 12.7	752 or 758
DDEC	S60 11.5	672 or 677
DDEC	8V92	736
DDEC	6V92	552
DDEC	6L71	426
Navistar		446

Table 3.4. Emissions grouping and engine cycle population estimates from 1998 DMV database.

Sample Categories	2-Stroke Estimated Number of Vehicles (Percent of Fleet)	4-Stroke Estimated Number of Vehicles (Percent of Fleet)
Pre-1991	4294	81729
	(2.72%)	(51.71%)
1991-1993	589	20950
	(0.37%)	(13.26%)
1994-1997	845	26172
	(0.53%)	(16.56%)
1999-2001	716	22756
	(0.45%)	(14.40%)
	Total	158051

Final Vehicle/Technology Categorization

In order to guide the vehicle recruitment and testing process, we have determined a vehicle/technology category set primarily driven by emissions certification level. The driving force behind many of the vehicle technology changes over time has been the change in emissions certification levels. The second factor chosen was the fuel injection type (mechanical, electronic) because of the potential for large differences in modal behavior for the two types of injection.

The vehicle/technology candidate categories underwent several iterations initially, with an initial emphasis on emissions standards. Increased importance was placed on a vehicle's certification standard over model year and other factors because of the relatively short time period in which standards were changed. Longer time periods with standards unchanged would allow for potential evolution in vehicle technology, resulting in differences in modal behavior between initial model years and model years later in the certification level. Unlike emissions standards for cars, the federal truck emissions standards have changed many times over the past 20 years (Table 3.1). These changes were substantial for all three pollutants, reducing the allowable emissions of each by almost one-half.

For the heavy-duty vehicle testing, there are expected to be 25 total vehicle tests to cover all heavy-duty vehicle/technology groups. A minimum of four vehicles was recommended for model fitting for any given category, based upon vehicle-to-vehicle variability in modal behavior observed within light-duty diesel vehicles. In order to guide the vehicle recruitment and testing process, we determined a vehicle/technology category set primarily driven by expected modal behavior. Differences in emission rates within groups average to produce a composite vehicle that represents the overall group. However, if there are differences in modal behavior within groups, the composite vehicle may not accurately model the behavior of the group across driving cycles. The vehicle/technology factors that may affect HDD truck emissions behavior are presented in Table 3.5.

The model year groupings combine several technological changes, such as improved combustion chamber design, increases in fuel injection pressure, intercooler type, and injector rate shaping.

These modifications are adopted over time at different rates by the various manufacturers and were not included as separate technology categories.

Table 3.5. HDD Truck Vehicle/Technology Factors

Model Year	Two-Stroke Low HP	Two-Stroke High HP	Four-Stroke Low HP	Four-Stroke High HP	California Variant
Pre 1987	MechFI	MechFI	MechFI	MechFI	Pre-1987
1987 – 1990	MechFI	MechFI	MechFI	MechFI	1987-1990
1991 – 1993	MechFI /ElecFI	MechFI /ElecFI	MechFI /ElecFI	MechFI /ElecFI	NA
1994 – 1997	MechFI /ElecFI	MechFI /ElecFI	MechFI /ElecFI	MechFI /ElecFI	NA
1998 - 2002	NA	NA	ElecFI	ElecFI	NA

While small numbers of two-stroke diesel engines are sold in the late 1990's, they do not comprise a large portion of the vehicle fleet. The late model two-stroke engines were deleted from the modeling sample matrix because they are primarily found in the bus fleet that can't be tested using CE-CERT's mobile emissions research laboratory. The emissions control technology for the high and low power engines is generally the same so the samples will be balanced between the two power ranges but will not be sampled as separate technology/model groups. While there are some Federal and California differences in emissions standards prior to 1991 and some emissions standards differences between 1988-1990 and pre 1988 (1987 in CA), it was not practical with the current sample size to incorporate additional vehicle/technology groups. However, the primary factor that may cause differences in modal emissions behavior in the Pre-1991 group is the two-stroke, four-stroke technology difference that is included in the sample matrix given in Table 3.6.

Table 3.6. Initial Sample Recruiting Matrix.

Model Year	Motor	Injection	Sample Size*
Pre 1991	2-stroke	Mechanical FI	4
Pre 1991	4-stroke	Mechanical FI	4
1991-1993	4-stroke	Mechanical FI	4
1991-1993	4-stroke	Electronic FI	4
1994-1997	4-stroke	Electronic FI	4
1998	4-stroke	Electronic FI	4
1999-2002	4-stroke	Electronic FI	4

* The initial total sample size of 28 vehicles was larger than the expected number of tests (25) because it was hoped that additional tests could be obtained.

The seven recruiting categories were set as:

Pre 1991 2-stroke Mechanical Fuel Injection—These vehicles make up less than 3% of the California vehicle fleet, however they are likely to have very different modal emissions behavior than the 4-stroke motors. Because the model is intended for use on a national level and the percentage of 2-stroke vehicles in other states was unknown, the category was included in the recruitment and testing. Recruitment of these vehicles may be difficult because of their low population numbers.

Pre 1991 4-stroke Mechanical Fuel Injection—Based on our VIN decoding of the California DMV database, these vehicles make up roughly 50% of the HDD on-road fleet. Because of their age, many of these vehicles may have newer motors replacing their original motors. Vehicles having new motors will be counted as new vehicles for modeling purposes so the actual model proportion of these vehicles is likely to be smaller than the registration percentage. Because of their age, these vehicles are less likely to be used in long-haul applications.

1991-1993 4-stroke Mechanical Fuel Injection—The 1991-1993 4-stroke mechanical and electronic fuel injected vehicles combined make up about 13% of the vehicle fleet, however the determination of the population percentages of each type was not possible with any confidence using the VIN decoding data. The manufacturers phased in electronic fuel injection at different times, with Caterpillar being the last to adopt widespread use of electronic fuel injection during this time period. It is likely that the mechanical fuel injected motors are a smaller part of the vehicle fleet, however determination of the actual percentages will have to be made from other sources such as roadside pullover data.

1991-1993 4-stroke Electronic Fuel Injection—The electronic fuel injected 1991-1993 vehicles are expected to be a larger part of the on-road fleet as noted above. These vehicles may have new motors in them also, and are less likely to be used in long haul applications now because of their age and mileage.

1994-1997 4-stroke Electronic Fuel Injection—The 1994-1997 4-stroke electronic fuel injection vehicles represent about 16% of the on-road fleet. With standard mileage accrual rates, many of these vehicles will likely have gotten a major re-build. This is the point at which the consent decree calls for installation of the low-NO_x kit by the manufacturers and may lead to two different sub-populations within this age group. This difference is not important if the low- NO_x kits only change the level of emissions without major differences in the modal behavior.

1998 4-stroke Electronic Fuel Injection—Based on emissions standards, the 1998 vehicles are the same as the 1999-2002 vehicles. However, these vehicles are the last of the vehicles manufactured prior to the consent decree and initially are given their own category to account for possible differences in modal behavior.

1999-2002 4-stroke Electronic Fuel Injection—The 1999-2002 4-stroke electronic fuel injection vehicles, combined with the 1998 vehicles, account for about 14% of the on-road fleet. These vehicles are expected to make up the majority of the long-haul vehicles and are not likely to have had a rebuild or installation of the low- NO_x kit.

3.3. Test Vehicle Recruitment Procedure and Results

3.3.1. Vehicle Recruitment Procedure

Given the recruitment targets set forth in Table 3.6, vehicles were recruited from a variety of sources within Southern California. The majority of the vehicles came from used vehicle dealerships that had a variety of trucks, in terms of manufacturers and age. Further, the vehicles had a wide variety of cab designs, sleeper configurations, and engine and transmission combinations. Other sources such as city, county, and school district vehicle fleets were also solicited for older vehicles, the pre-1991 in particular. Recruitment funds were limited, however a good sample of in-use vehicles was available from these sources.

After a variety of vehicles were identified, vehicles were recruited randomly within test categories by engine model year. Horsepower and manufacturer balance was set as a goal within each category. The selected vehicles underwent an inspection to determine if they were safe to test. Because of the necessity of testing on a variety of roadways, all trucks tested had to pass the CHP safety inspection at roadway weigh stations.

3.3.2. Final Category Numbers

After a particular vehicle was tested, it was placed in the appropriate category in the vehicle/technology matrix. Because of delays in the testing program, a total of eleven vehicles were initially tested. All vehicles exhibited more than one mode of operation, with the alternative control strategy (ACS) showing higher NO_x emissions relative to fuel. Because of the vehicle-to-vehicle variation in timing of when the ACS was utilized, the initial sample size was increased to five vehicles for electronic controlled vehicle groups. Considerable variation, even within individual vehicles, was observed in the timing of ACS events so the larger category sizes allow for more averaging within the composite groups. To keep the total sample size down, the sample size for the mechanical injection vehicle groups was reduced to three. The revised vehicle technology recruiting groups and the target number of vehicles tested are presented in Table 3.7.

Later in the project, additional modal emissions data became available from a parallel HDD truck dynamometer test program described in [CRC, 2004]. These supplemental data consisted of extensive testing of 25 addition HDD vehicles and allowed us to cover most of programmed vehicle/technology categories. The actual final sample sizes are given in Table 3.8, including the dynamometer test data used to augment the CE-CERT vehicles.

Table 3.7. Revised Test Matrix and Completed Tests (including dynamometer test vehicles).

Model Year (Group)	Engine	Injection	Target Vehicle Count
Pre 1991 (1)	2-stroke	Mechanical FI	3
Pre 1991 (2)	4-stroke	Mechanical FI	3
1991-1993 (3)	4-stroke	Mechanical FI	3
1991-1993 (4)	4-stroke	Electronic FI	5
1994-1997 (5)	4-stroke	Electronic FI	5
1998 (6)	4-stroke	Electronic FI	5
1999-2002 (7)	4-stroke	Electronic FI	5

Table 3.8. Completed Tests (HDD dynamometer test vehicles/on-road test vehicles).

Model Year (Group)	Engine	Injection	Target Vehicle Count
Pre 1991 (1)	2-stroke	Mechanical FI	0/0
Pre 1991 (2)	4-stroke	Mechanical FI	11/0
1991-1993 (3)	4-stroke	Mechanical FI	1/0
1991-1993 (4)	4-stroke	Electronic FI	4/0
1994-1997 (5)	4-stroke	Electronic FI	4/5
1998 (6)	4-stroke	Electronic FI	2/2
1999-2002 (7)	4-stroke	Electronic FI	3/4

3.3.3. Repeat Vehicle

Of the eleven vehicles tested on-road, one of the vehicles had extensive repeat tests performed. The rest of the vehicles were tested only for a two-day period. The individual driving events were repeated, except for the unspecified freeway driving events that cannot be replicated exactly due to traffic constraints. Each of the vehicles was tested over two consecutive days. The repeat testing for these vehicles was primarily focused on the cold start portion of the test on the second day, because of the extensive data collected on the vehicles under various operating conditions under both controlled and uncontrolled driving cycles.

3.4. Vehicle Testing Procedure

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

1) A complete CARB HDD test, including creep mode, transient mode, and freeway mode (see [Maldonado, 2002]);

2) A UDDS test cycle adapted for on-road use;

2) Real-world driving with the flow of traffic to and from the test area; and

3) A set of modal emission cycles developed by the research team. A complete CARB HDD test is necessary for two reasons. First, it is the standard testing procedure used by CARB in testing of HDD vehicles, and provides baseline information about a vehicle's emissions that can be used as a reference to compare with existing tests of other vehicles. Second, the cycle provides a structured set of driving to be compared with the unstructured "real-world" driving. The primary reason for including the freeway driving without a test cycle in our test protocol is that the emissions under this driving are directly representative of in-use emissions. The CARB HDD velocity traces are shown in Figure 3.8.

The UDDS cycle was included to provide a common baseline driving cycle that has been commonly used in emissions testing in the lab. For the on-road testing, the UDDS cycle was broken into two parts, with the split between the first two driving events. This was necessary because of the length of roadway sections available for testing. The UDDS cycle is illustrated in Figure 3.9.

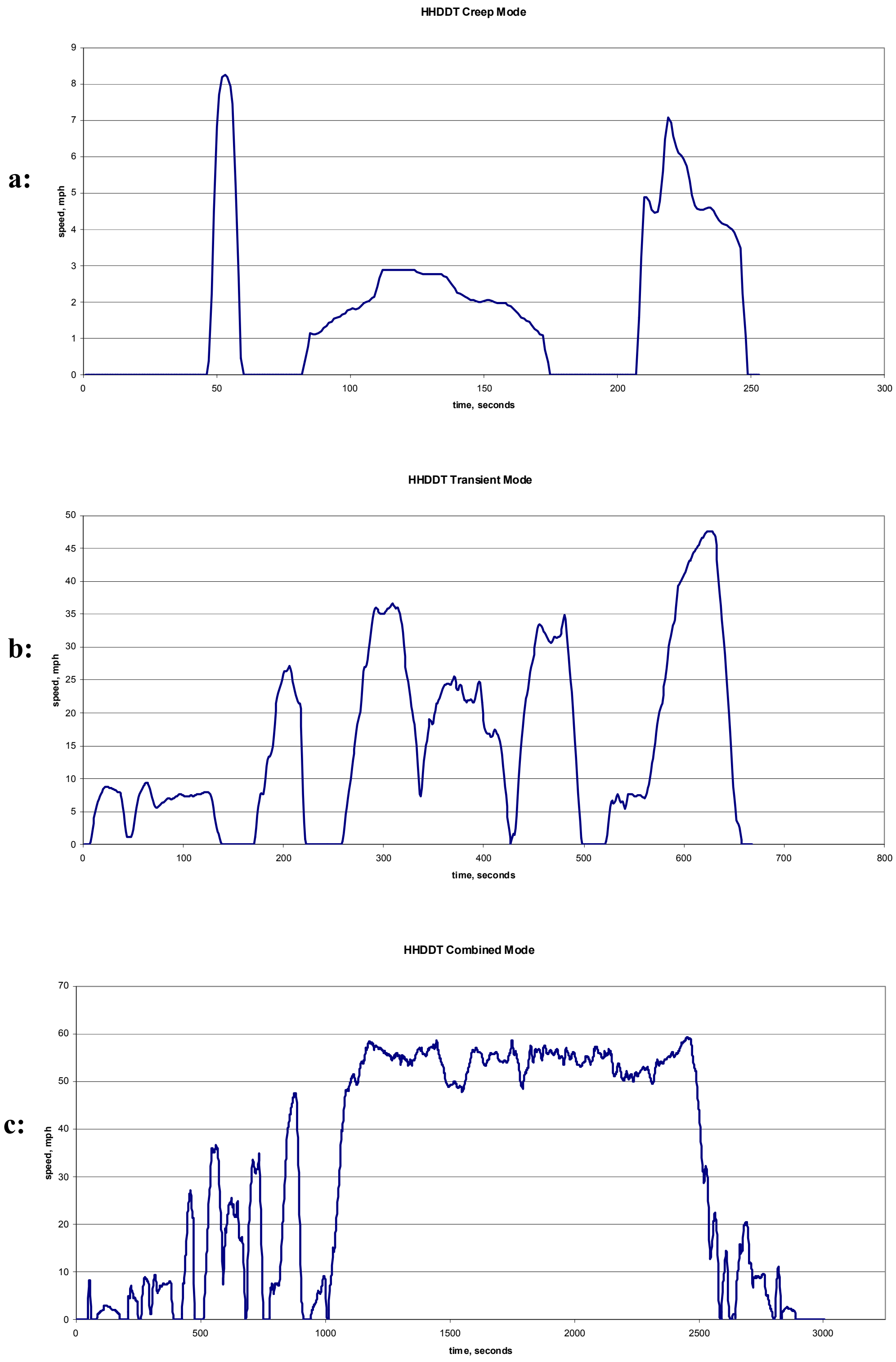

Figure 3.8. CARB HDD driving cycle speed traces for a) "Creep", b) "Transient", and c) "Freeway" segments.

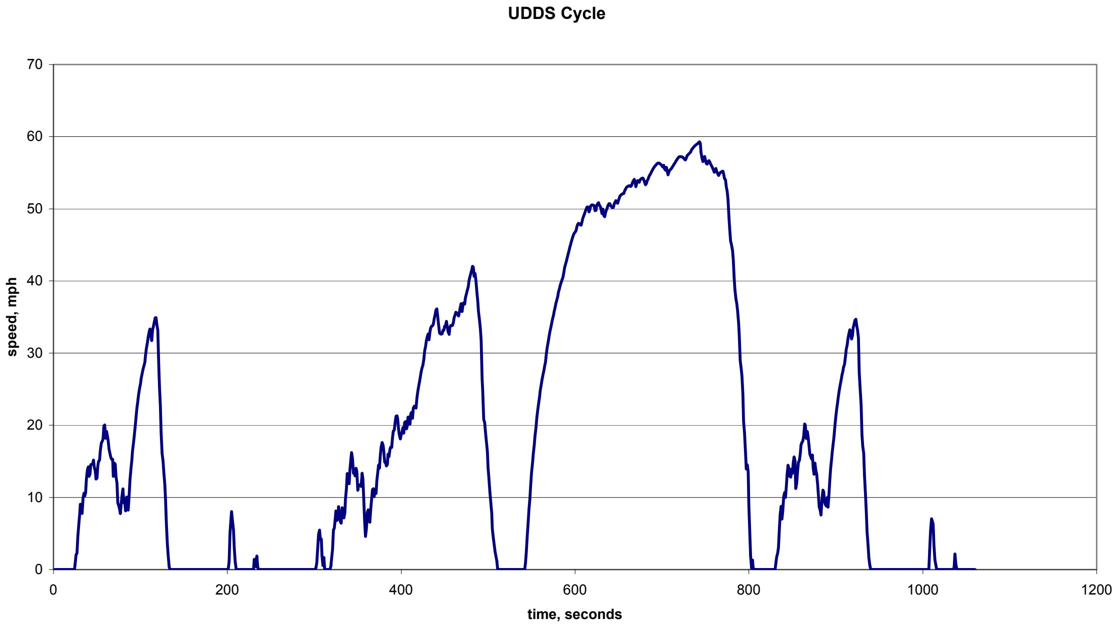

Figure 3.9. UDDS driving cycle.

3.4.1. Development of HDD Vehicle Modal Cycles

In order to capture specific modal emission events, a specific set of modal emissions cycles were designed and applied. These cycles were developed and iteratively refined during the early stages of the testing phase. The two general objectives of constructing these cycles were to: 1) cover the majority of speed, acceleration, and specific power ranges that span the performance envelope of most heavy duty vehicles; and 2) cover a series of modal events such as various levels of accelerations and decelerations, a set of constant cruise speeds, speed-fluctuation driving, and constant power driving. In addition to these criteria, the cycles had to conform to the lengths of the road segments, speed limits and otherwise safe driving practices of the testing area. Based on feedback from the initial tests and simulation runs, the modal cycles were iteratively refined prior to any substantial vehicle testing. The resulting three modal cycles are illustrated in Figures 3.10, 3.11, and 3.12. The “three hills” modal cycle examined hard accelerations, followed by steady-state cruise events at different speeds. The “single hill” cycle was simply a hard acceleration followed by steady-state cruising at 50 mph. Lastly, the “power modes” cycle was designed to contain different levels of acceleration, each holding power requirements constant. The cycle starts with the most aggressive accelerations, followed by decreasing power accelerations.

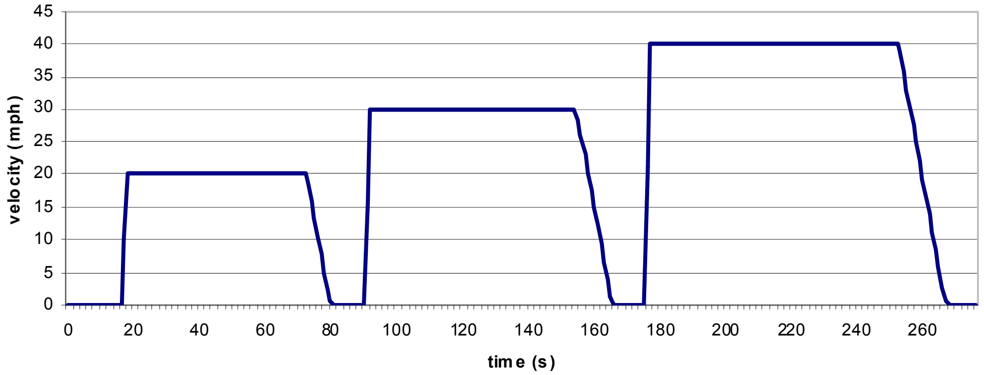

Figure 3.10. "Three hills" modal cycle.

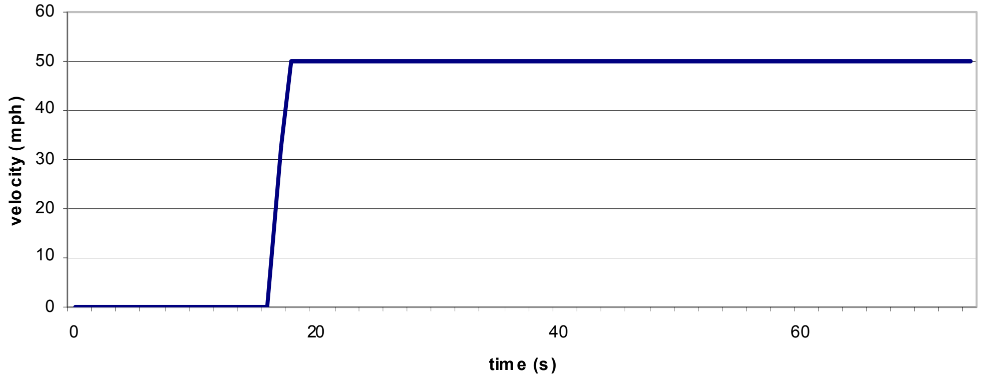

Figure 3.11. "One hill" modal cycle.

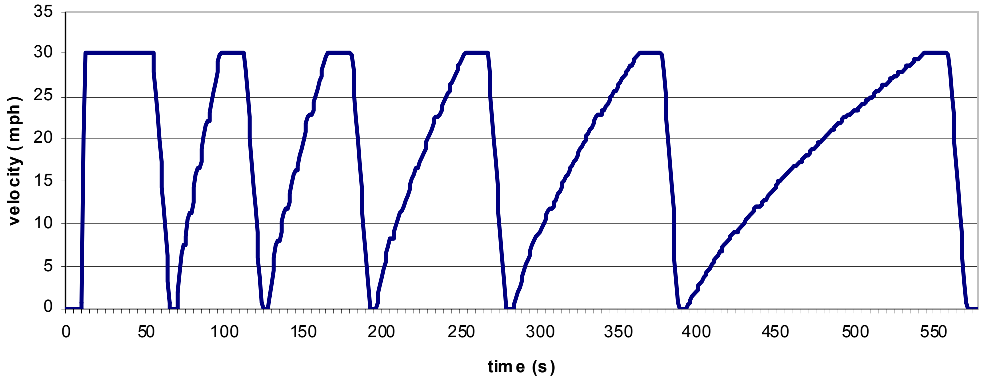

Figure 3.12. "Power modes" modal cycle.

3.4.2. Testing Sequence

Several protocols were evaluated during the initial emission testing conducted in the testing phase. Because of the on-road nature of the testing and the interaction of the test vehicles with other vehicles, careful planning and selection of the test sites was required.

During the initial vehicle testing, we had an 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. Since the testing was conducted on-road, our test driver was subject to California Highway Patrol regulations restricting total work hours in a day to twelve. This required careful selection of the tests to be run so that there was some extra time for traffic delays and other problems during the testing.

3.5. Emissions Testing Performed

A final test schedule was devised, containing all components described in the previous section. The test schedule begins with trailer hookup and pre-calibration at 6:00AM and ends back at the starting location at approximately 7:00PM. The entire test schedule is given in Table 3.9.

A total of eleven HDD vehicles were tested in the first phase using this test schedule. A total of 442 individual cycles were collected on the vehicles with a total of 376,371 seconds of data. Ambient temperature and humidity were measured continuously during testing and local hourly wind measurements were obtained when available. All vehicles were tested using standard fuel obtained from the same source with spot testing to ensure consistency.

The HDD vehicle testing with MERL was carried out on seldom-used roadways in California's Coachella Valley, approximately two hours from UC Riverside. This area was chosen for its relative proximity to UC Riverside and it's long, uninterrupted stretches of road at zero grade, approximately at sea level. This general area is shown in Figure 3.13.

Recruiting of older vehicles proved to be more difficult than anticipated so the test data were augmented with additional second-by-second data collected on 25 additional HDD vehicles in the CRC E-55 dynamometer study (CRC E-55) [CRC, 2004]. For our model building, two test cycles from the dynamometer data were used, the CARB Transient cycle and the CARB Freeway cycle.

Table 3.9. On-road HDD Testing Schedule.

Testing Day											
Time Begin	Time End	Duration	Location	Activity	Road Length	Cycle Length		Modal	Bag	Cycle Config	Comments
hr : min	hr : min	hr : min			miles	miles	sec				
6:00	6:21	0:21	CERT	Hookup, Pre-Calibration						1	
6:21	6:36	0:15	CERT	ARB Idle				X	X	2	
6:36	6:44	0:08	CERT	Analyze Bag						2	
6:44	7:05	0:21	CERT	Calibration						2	
7:05	8:21	1:16	CERT to G	Driving On Road data	51.00			X		3	
8:21	8:43	0:22	G to G_	freeway_cruise	23.00	8.39	523	X		3	AC Off, CC Off
8:43	9:05	0:22	G_ to H	freeway_cruise		8.39	523	X		3	AC On, CC On
9:05	9:27	0:22	H to Thermal	Driving On Road data	15.00			X		3	
9:27	9:57	0:30	Thermal	Calibration and Filter Set Up						3	
9:57	10:13	0:16	A to A_	ARB Creep; 1 bag	3.40	0.124	253	X	X	4	
10:13	10:29	0:16	A_ to B	ARB Trans; 1 bag	1.00	2.75	651				
10:29	10:45	0:16	B to C	Analyze 2 Bags	1.00					4	
10:45	10:50	0:05		Evacuate 2 Bags						4	
10:50	10:54	0:04	C to D	three_hills_1	1.90	1.83	277	X		4	
10:54	10:59	0:05	D to E	one_hill	0.95	0.82	75	X		4	
10:59	11:04	0:05	E to F	none	0.60						
11:04	11:07	0:03	F to A	one_hill	1.04	0.82	75	X		4	
11:07	11:23	0:16	A to A_	ARB Creep; 1 bag	3.40	0.124	253	X	X	4	
11:23	11:39	0:16	A_ to B	ARB Trans; 1 bag		2.75	651	X	X		
11:39	11:55	0:16	B to C	Analyze 2 Bags	1.00					4	
11:55	12:00	0:05		Evacuate 2 Bags						4	
12:00	12:04	0:04	C to D	three_hills_2	1.90	1.8	276	X		4	
12:04	12:09	0:05	D to E	one_hill	0.95	0.82	75	X		4	
12:09	12:14	0:05	E to F	none	0.60						
12:14	12:17	0:03	F to A	one_hill	1.04	0.82	75	X		4	
12:17	12:29	0:12	A to B	power_modes	3.40	2.92	581	X		4	
12:29	13:19	0:50	B to C ... to A	Calibration + Filter Change	5.50					4	
13:19	13:21	0:02	A to B	power_modes	3.40	2.92	581	X		5	
13:21	13:23	0:02	B to C	none	1.00					5	
13:23	13:25	0:02	C to D	UDDS Mode 1 w/bag	1.90	1.68	530	X	X	5	
13:25	13:34	0:09	D to E	UDDS Mode 3 w/bag	0.95	0.52	240	X	X	5	
13:34	13:43	0:09	E to F to A1	none							
13:43	13:50	0:07	A1 to B	UDDS Mode 2 w/bag	3.40	3.33	290	X	X	5	
13:50	14:14	0:24	B to C … to A	Analyze 3 Bags	2.00					5	
14:14	14:22	0:08		Evacuate 3 Bags						5	
14:22	14:34	0:12	A to B	power_modes	3.40	2.92	581	X		5	
14:34	14:36	0:02	B to C	none	1.00					5	
14:36	14:45	0:09	C to D	three_hills_3	1.90	1.83	277	X		5	
14:45	14:52	0:07	D to E	one_hill	1.00	0.82	75	X		5	
14:52	15:22	0:30	E to H	Drive to Freeway H; Calibration + Filer Change	15.00					5	
15:22	15:57	0:35	H to G	ARB Cruise w/bag	23.00	23.07	2083	X	X	6	
15:57	16:19	0:22	G to G_	freeway_cruise	23.00	8.39	523	X		6	AC On, CC Off
16:19	16:41	0:22	G_ to H	freeway_cruise		8.39	523	X		6	AC On, CC Off
16:41	17:16	0:35	H to G	ARB Cruise w/bag	23.00	23.07	2083	X	X	6	
17:16	17:32	0:16		Analyze 2 Bags + Collect Filters						6	
17:32	17:37	0:05		Evacuate 2 Bags						6	
17:37	17:58	0:21		Calibration						6	
17:58	18:08	0:10		Shutdown Trailer							
17:37	18:53	1:16	G to CERT	Return to CE-CERT	51.00						

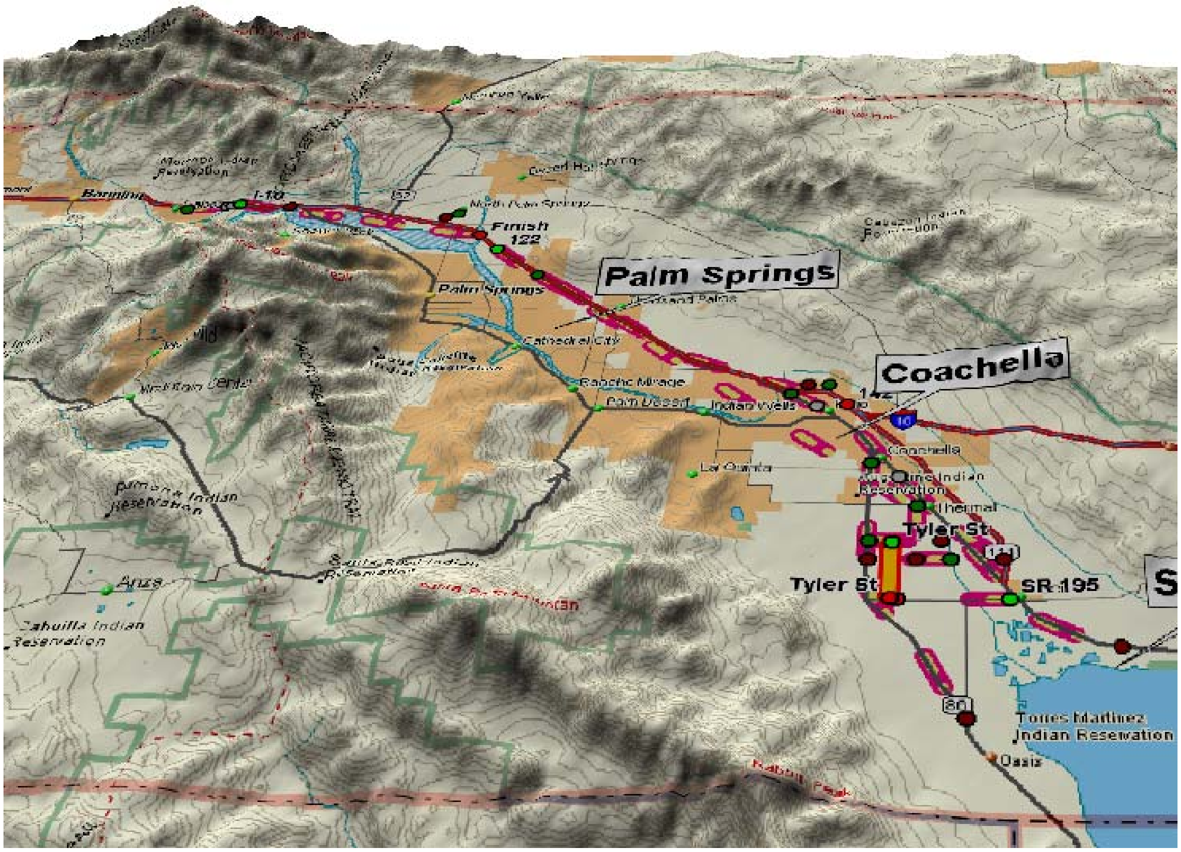

Figure 3.13. California's Coachella Valley, where much of the on-road testing took place.

3.6. Data Post-Processing

Data generated from the vehicle emission tests are stored on magnetic/optical drives in two separate databases. The raw emission data are stored on MERL's 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. Data Conversion

Mass emission data are transferred from MERL'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 and MERL's test name. Conversion of concentration data is more involved and is conducted as follows. First, the raw emission data are transferred from MERL 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 acting on vehicle parameters and gas analyzer information, accounting for parameters such as emission densities, exhaust flow rates, and differences in dry and wet gas measurements. 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's response times. The proper time shift is determined through several steps. An initial time shift for each pollutant is provided by MERL 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. 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 MERL. These are copied and stored on the UNIX platform in a raw-data directory. The first file includes second-by-second data for 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 project name in another data directory. This procedure automatically generates a log file which matches the test original name with the 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 standard conversion procedure, or simply properly formatted if they already contain mass emission rate data. In addition, the emission data are time aligned as described in the previous section. After post-processing of the file is complete, a refined version of the second-by-second data file is stored.

The supplemental dynamometer data were received already post-processed. Time alignment was checked and calculated fuel use was determined based on a carbon balance equations.

3.7. Data Quality Assurance and Control (QA/QC)

Because the CE-CERT laboratory represents a novel application of emissions measurement technology, we invested a significant amount of effort into assuring the accuracy, precision, and repeatability of its performance. In late 2001 and the first half of 2002, CE-CERT conducted a few tests of the trailer laboratory at the California Air Resources Board's heavy-duty emissions laboratory in Los Angeles. Tests were conducted on CE-CERT's 2000 Freightliner class 8 tractor with Caterpillar C-15 engine on the Hot UDDS driving cycle. Tests were conducted in series – first using one lab's measurement instrumentation, then the others.

Analysis of results indicated that the two labs had good agreement on gaseous emissions measurements. Particulate measurements through the secondary dilution system, however, initially did not agree. CE-CERT investigated the problem and made modifications to the secondary dilution system, and then returned to the ARB facility for further testing. In this second test, we found good agreement on the gaseous measurements and very good agreement on the PM measurements. Table 3.10 shows the differences in results from the last round of testing. These differences are within the test-to-test and lab-to-lab variability observed in other correlation exercises that have not involved the trailer laboratory. Therefore, we conclude that the trailer laboratory's precision and accuracy are comparable to those of other laboratories.

Table 3.10. Differences in MERL vs. CARB lab emissions measurements.

	NOx	CO_2	CO	Total hydrocarbon (THC)	Particulate matter (PM)
UCR vs. CARB	8%	2.7%	18%	12%	0.1%

Our experience has been that the laboratory's repeatability always has been good, despite the impacts that wind, temperature, humidity, and traffic can have on driving cycle, vehicle load, and instrument performance. Earlier reports have described a modified West Virginia University cycle that CE-CERT has used to test the laboratory in an area east of Riverside. The laboratory now has conducted a large number of these tests using two tractors, in summer and winter, with the wind and into the wind. Table 3.11 demonstrates that test-to-test repeatability of the trailer laboratory is very good.

Table 3.11. On-road repeatability of WVU 5-mode cycle.

Characteristic	Variability among tests
Fuel used	1.0%
Engine power	1.2%
Traction work	1.2%
Driver deviation	5.9%
PM mass emissions	8%

The U.S. Environmental Protection Agency has been a sponsor of the heavy-duty emissions research program as well as other programs at CE-CERT. In October 2002, EPA's project officer and Quality Control Manager for the National Vehicle and Fuel Emissions Laboratory visited CE-CERT to review the projects and, in particular, examine Quality Assurance/Quality Control practices. Overall, they concluded that the heavy-duty laboratory's Quality Control procedures are very strong; most aspects of the program were rated "excellent" or "very good."

3.8. Measured Vehicle Parameter Data

During testing, we were able to directly connect a datalogging tool to retrieve some second-by-second engine system data for all vehicles supported by the datalogger. With this datalogging tool, we obtained direct measurements of parameters such as engine speed, throttle position, fuel use 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 fairly consistent set of parameters that are reported to the datalogging tool.

4. HDD Modal Emission Model Development

This chapter provides a general description of the developed HDD truck emissions model, and how it was integrated within the CMEM framework. As described in Section 2.5, CMEM has a variety of vehicle/technology categories, each having different emissions and fuel consumption characteristics representative of the vehicle/technology sub-model. With this in mind, we have added several new vehicle/technology categories corresponding to the HDD vehicles outlined in Table 3.8.

The general functionality of the HDD truck sub-models in CMEM is the same as that of the light duty gasoline-fueled sub-models. 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 the vehicle/technology class they are representing. 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 the test data, derived as part of the model calibration procedure.

It is important to remember that the main purpose of the HDD emission sub-models 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 "off-cycle" events such as alternative fuel injection timing strategies. As discussed previously, we are concerned with a variety of in-use vehicles that vary by engine manufacturer, transmission manufacturer, age, and condition. 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 → truck/technology category → general vehicle mix (fleet)*

Using a bottom-up approach, the basic building block of our physical-based emissions model is the individual truck operating on a fine time scale (i.e., second-by-second). However, the HDD sub-models, like the light-duty sub-models, do not focus on modeling specific makes and models of trucks. Our primary goal is the prediction of emissions in several-second modes for average, *composite trucks* for each of the truck categories specified in Chapter 3 (Table 3.8). 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. Major fluctuations in throttle position are common in on-road driving, as the driver corrects for overshooting or undershooting the target speed trace as well as for moving with the flow of traffic during in-use driving. 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. On-road testing, much of it without a set driving cycle, was used in the development of the HDD model, so it is expected to be representative of throttle fluctuations found in typical in-use driving. 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 truck models based on measured parameters describing engine, transmission, and ECU behavior. Instead, we are developing the generic characterization of a composite truck within each truck category specified in Chapter 3 (Table 3.8). Using this generic approach, one obtains good modal-emissions predictions for composite trucks. Model accuracy also improves considerably with temporal aggregation.

Separate sub-models for each truck tested 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 truck representing the characteristics of a particular truck sampled randomly from that 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 trucks vary, there is always the temptation to add more input parameters for special situations of different trucks 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.

4.1. General Structure of the Model

In the developed HDD emissions model, second-by-second tailpipe emissions are modeled as the product of three components: fuel rate (FR), engine-out emission indices ($g_{emission}/g_{fuel}$), and any emission after-treatment pass fraction:

$$tailpipe\,emissions = FR \bullet \left(\frac{g_{emissions}}{g_{fuel}}\right) \bullet after - treatment\ pass\ fraction \tag{1}$$

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 the after-treatment pass fraction is defined as the ratio of tailpipe to engine-out emissions. To date, no HDD vehicles with after-treatment devices have been tested or are commonly available, so the after-treatment pass fraction for all of the current truck categories are being modeled as 100%[*].

The complete HDD 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-rate; 4) engine control

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[*] It is important to note that a variety of after-treatment devices can be modeled separately and integrated into this model structure without extensive retesting.

unit; 5) engine-out emissions; and 6) after-treatment 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.

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 on-road measurements, as well as the engine power demand calculated by the model.

The core of the model is the fuel rate calculation (3). It is a function of power demand (1) and engine speed (2). Engine speed is determined based on vehicle velocity, gear shift schedule and power demand.

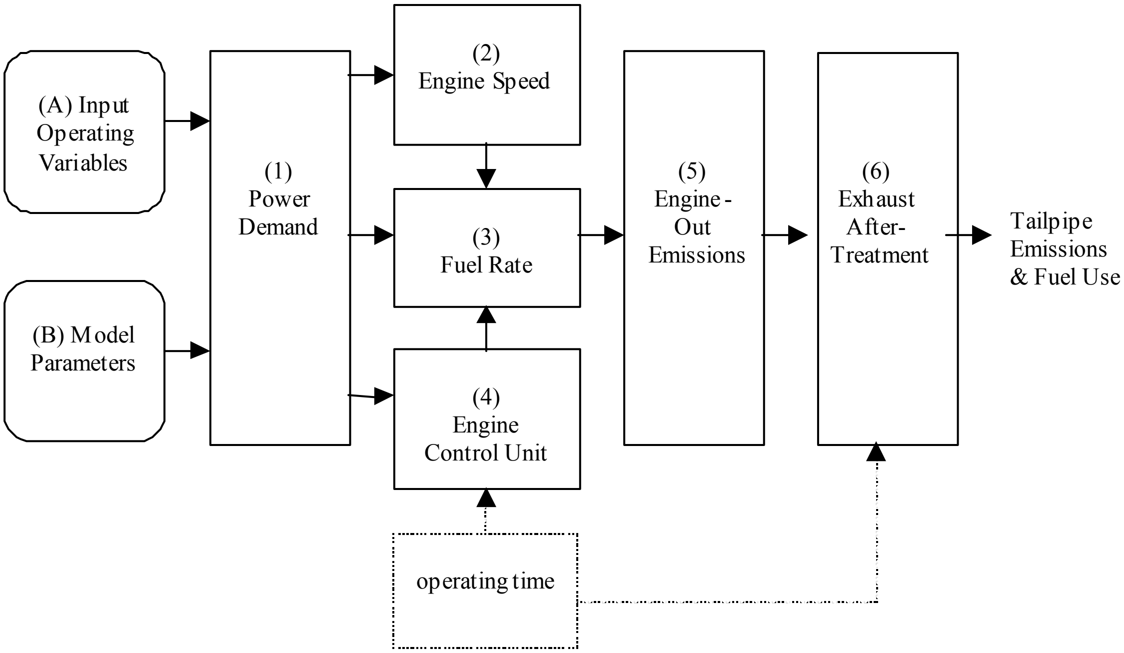

Figure 4.1. HDD Emissions Model Structure.

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 each of the truck categories and 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 truck (or each truck category) is straightforward. The total tractive power requirements (in kW) placed on the truck (at the wheels) is given as:

$$P_{tract.} = (M \cdot a + M \cdot g \cdot sin\theta + \tfrac{1}{2} Cd \cdot A \cdot \rho \cdot v + M \cdot g \cdot Cr \cdot \cos\theta) \cdot v / 1000 \qquad (2)$$

where M is the truck mass with appropriate inertial correction for rotating and reciprocating parts (kg), v is speed (meters/second), a is acceleration (meters/second^2), g is the gravitational constant (9.81 meters/s^2), and θ is the road grade angle in degrees, Cd is the coefficient of drag, A is the frontal surface area (meters^2), ρ is the air density (kg/m^3) and Cr is the coefficient of rolling resistance. The terms in parentheses represent resistance due to acceleration, grade, wind, and rolling friction.

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

$$P = \frac{P_{tract.}}{\varepsilon} + P_{acc} \tag{3}$$

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 running losses of the engine and the operation of vehicle accessories such as air conditioning usage.

Engine Power Validation

As the model was developed, we performed intermediate variable validation with actual measurements. As was discussed in the previous section, certain parameters were obtained from the vehicle's ECU on a second-by-second basis, percent engine load being one of them. Percent load is not based on measured power, but on a fuel based estimation performed by the ECU. Percent engine load can be converted to an estimation of actual power based on the performance map of the engine and knowledge of the running load of the engine. However, the performance map of the engine is not always clearly known and unless measured, the running load is only an estimation. The power and torque curves available from the manufacturer give a rough idea of what a vehicle's engine map may look like, but may differ greatly from actual performance characteristics depending on the application the ECU was programmed for. To some extent, there are also differences between engines from different production batches and differences between actual and reported performance numbers. Comparing modeled engine power with estimated actual load based on reported percent load generally gives good results. Factors leading to errors in modeled load are approximations for inertial and rotating forces of the engine, inaccuracies in engine speed modeling which influence inertial and rotating forces, approximations for drivetrain efficiencies at each second (see following section), approximations for second-by-second wind speed and direction, and resolution of the second-by-second road grade among others.

There is little information publicly available on HDD drivetrain losses and their relationship with torque, engine speed and vehicle speed. HDD drivetrain losses are commonly thought to be around 15% to 20% and vary with torque, engine speed and vehicle speed. As an approximation, the HDD model estimates drivetrain losses between 15% and 20%, increasing with increasing vehicle speed.

4.3. Engine Speed Module

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

$$N(t) = S \cdot \frac{R(L)}{R(L_g)} \cdot v(t) \tag{4}$$

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:

$$Q(t) = \frac{P(t) \cdot 5252}{N(t)} \tag{5}$$

where *Q(t)* = engine torque in ft.lb at time t and *P(t)* is engine power in horsepower. The engine torque at any engine speed must not exceed the WOT torque, $Q_{WOT}(t)$. The latter is based on an approximation of the manufacturer's supplied torque curve.

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 based on the equations above and a representation of the vehicle's torque curve. If necessary, this process is repeated (i.e., a second downshift is considered) to satisfy the operating conditions.

Engine Speed Validation

As the model was developed, we again performed intermediate variable validation with actual engine speed measurements, using engine speed obtained from the vehicle's ECU on a second-by-second basis. This facilitated the development of the engine speed model. Unambiguous prediction of engine speed is practically impossible because it depends in part on the behavior of the driver. However, modeling results for engine speed have shown satisfactory agreement on a second-by-second basis.

4.4. 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].

The basic diesel fuel consumption module is as follows:

$$FR \approx (k \cdot N \cdot V + \frac{P}{\eta})\frac{1}{43.2} \cdot (1 + b_1 \cdot (N - N_0)^2) \tag{6}$$

$$K = K_0 \cdot (1 + C \cdot (N - N_0)) \tag{7}$$

$$N_0 \approx 30 \cdot \sqrt{\frac{3.0}{V}} \tag{8}$$

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 engines. $b_1 \approx 10^{-4}$ and $C \approx 0.00125$ are coefficients； 43.2 kJ/g is the lower heating value of a typical diesel fuel.

It has been noted that alternate fuel injection timing strategies have been used to improve fuel economy at the expense of NOx emissions (discussed further in Section 4.5.3). For modeling purposes, we have introduced a fuel use reduction factor to account for alternative fuel injection timing strategies. Fuel use is modified in the following manner:

$$FR_{off} = FR \cdot (1 - \mathrm{f}_{\mathrm{Red}}) \tag{9}$$

where FR is the off-cycle fuel rate in grams/second and $\mathrm{f}_{\mathrm{Red}}$ is the fuel use reduction factor associated with off cycle fuel injection timing strategies.

Engine Fuel Rate Validation

Intermediate variable validation was again performed with engine fuel rate measurements from the vehicle's ECU on a second-by-second basis. This facilitated the development of the engine fuel rate model. Modeling results for engine fuel rate have shown satisfactory agreement on a second-by-second basis.

4.5. Engine-Out Emissions Module

In this section, we describe the modeling of engine-out CO, HC, and NO_x emissions.

4.5.1. Engine-out CO Emissions

CO emissions are a product of incomplete combustion and are greatly dependent on the air-fuel ratios occurring during combustion. Since fuel rich combustion leads to increased CO, diesel engines, which run lean, typically have extremely low CO emissions unlike spark ignition engines. Our analysis shows that there is a correlation between fuel use and engine-out CO, however, it is not a particularly strong one. The following equation is used for modeling CO:

$$ECO = a_{CO} \cdot FR + r_{CO} \tag{10}$$

where ECO is the engine-out emission rate in g/s and a_{CO} and r_{CO} are the CO emission index coefficients.

4.5.2. Engine-out HC Emissions

HC emissions from diesel engines are unburned hydrocarbons resulting primarily from combustion inefficiencies. Incomplete fuel-air mixing in the combustion chamber results in portions of the combustion mixture not supporting combustion. Our analysis shows that there is a correlation between fuel use and engine-out HC, however, it is not a particularly strong one. The following equation is used for modeling HC:

$$EHC = a_{HC} \cdot FR + r_{HC} \tag{11}$$

where EHC is in g/s and a_{HC} and r_{HC} are the HC emission index coefficients.

4.5.3. Engine-out NO_x Emissions

NO_x emissions along with particulate matter are the key diesel pollutants of primary concern. The formation of NO_x emissions in diesel engines is well understood and is dependent mainly on the presence of sufficient oxygen and high temperatures. NO_x emissions exhibit a strong linear relationship with load or fuel use. The following equation is used for basic NO_x emission modeling:

$$NO_x = a_{NO} \cdot FR + r_{NO} \tag{12}$$

where *FR* is fuel rate, a_{NO} is the NO_x emission index coefficient in grams emission/ grams fuel, and r_{NO} is a small residual value.

NO_x emissions may be controlled by reducing in-cylinder temperatures which can be accomplished with retarded fuel injection timing at the expense of increased particulate emissions and reduced fuel economy. This is commonly referred to as the NO_x, PM, fuel “trade-off”. For this reason fuel injection timing strategies are critical to the formation of NO_x emissions.

It has also been noted that the fuel injection timing strategies of many HDD vehicles do not always remain consistent with those used during engine certification testing. It has been determined that under certain modes of operation, many of the HDD vehicles found in today’s vehicle fleet utilize off cycle fuel injection timing strategies which results in higher NO_x emission rates in favor of increased fuel economy. Figure 4.2 illustrates dual NO_x /fuel emission rates as a result of off cycle fuel injection timing strategies.

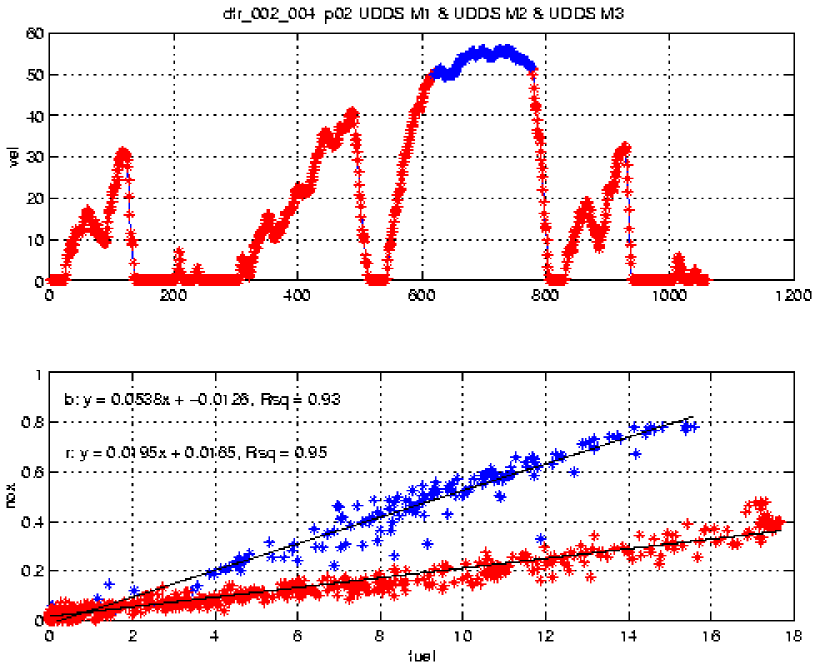

Figure 4.2. a) Velocity (mph) vs. Time (seconds) and b) NOx (grams) vs. fuel use rate (grams) with corresponding colors and associated regression lines. The high-speed cruise, off-cycle blue activity has higher NOx/lower fuel compared to the on-cycle red activity.

These off cycle strategies are not publicly documented or commonly well understood and seem to differ between manufacturers. For this reason it is very difficult to determine concretely the NOx emission rate at any given fuel rate.

Although the practice of off-cycle fuel injection timing strategies has been addressed and are to be eliminated in the future, many of these vehicles still exist and continue to pollute. In an effort to model off cycle fuel injection strategies, an off-cycle NO_x –fuel relationship is used:

$$NO_x = a_{NOh} \cdot FR + r_{NOh} \tag{13}$$

where a_{NOh} is the off cycle NO_x emission index coefficient in grams emission/grams fuel, and r_{NOh} is a small residual value associated with off cycle NO_x emissions.

The determination of NO_x emission factors for use with normal injection timing strategies and off-cycle fuel injection strategies is relatively straightforward and usually result in strong least squares fits, as illustrated in Figure 4.2. The difficulty lies in determining when, in a given cycle, each strategy is used. It was observed that the off-cycle timing strategies appear to have a history effect and in some cases show a somewhat predictable pattern across similar cycles. For our modeling purposes, off-cycle fuel injection strategies are being characterized as a function of time and velocity in which these strategies occur after a given amount of time (e.g., 80 seconds) above a certain vehicle speed (e.g., 30 mph) and then normal operation resumes once the vehicle speed drops below a certain point (e.g., 30 mph).

The off-cycle timing strategies appear to vary by manufacturer, model year, and sometimes from test cycle-to-test cycle during a single day of testing. Determining the best overall model formulation of the off-cycle strategy is therefore highly dependent upon the vehicle test fleet. Because of the difficulty in determining the best overall strategy with the current data set, a generic speed and time method was used for this version of the model, pending collection of more data*.

4.6. Exhaust Aftertreatment Modeling

Exhaust after-treatment is not yet commonly available for HDD vehicles, but will likely be standard in commercial HDD vehicles at some point. The major technologies available for diesel engines at this time are particulate traps, continuously regenerating traps, oxidation catalysts, and selective catalyst reduction systems. The emission reductions from these technologies can potentially be great, but to date they may not be practical, requiring special fuels or additives, functioning only during a limited range of operation, not addressing key pollutants such as NO_x or being cost prohibitive. Future HDD modules that represent HDD vehicles having exhaust after-treatment will require a model architecture like that developed for light-duty vehicles with catalysts. Testing of these vehicles for model building will require pre and post after-treatment emissions measurement capabilities.

4.7. Summary of Model Parameters and Variables

As discussed previously, separate sub-models for each HDD 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.

In addition to these operating variables, each sub-model uses a total of 31 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 4.1.

In Table 4.1, the model input parameters are first divided into two large categories: 15 *Readily Available Parameters* and 16 *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.

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* The model strategy is not intended to represent a particular manufacturer's truck but rather give a good approximation of the fleet behavior.

Table 4.1. HDD Emissions Model Input Parameters.

HDD EMISSIONS MODEL PARAMETERS AND VARIABLES	
Readily-Available Parameters	**Calibrated Parameters**
Specific Vehicle Parameters	***Fuel Parameters***
M - vehicle mass in lb. ( )	k_0 - eng. fri. factor in kJ/(lit.rev) ( )
V - engine displacement in liter ( )	F_{idle} – fuel at idle in grams ( )
N_{idle} – idle speed of engine ( )	f_A – fuel strategy parameter ( )
S - eng spd./veh spd. in rpm/mph ( )	f_B – fuel strategy parameter ( )
Q_m - max torque in ft.lb ( )	
N_m - eng spd. in rpm @ Q_m ( )	
P_{max} - max power in hp ( )	***Engine-out Emission Parameters***
N_p - eng spd. in rpm @ P_{max} ( )	a_{CO} - CO coefficient ( )
N_g - number of gears ( )	r_{CO} - CO coeffiecient ( )
GR- transmission gear ratios ( )	a_{HC} - HC coefficient ( )
G_f- final drive ratio ( )	r_{HC} - HC coefficient ( )
A_f- frontal area of vehicle in m^2 ( )	a_{NOx} - NO_x coefficient ( )
C_{drag} - drag coefficient ( )	r_{NOx} - NOx coefficient ( )
	a_{NOxh} - NO_x off cycle coefficient ( )
	r_{NOxh} - NOx off cycle coefficient ( )
Generic Parameters	NOmaxh - maximum off cycle NOx in grams ( )
η - indicated efficiency ( )	minCO – minimum CO value in grams ( )
Hg - heavy diesel lower heating vaue in Mj/kg ( )	minHC – minimum HC value in grams ( )
	minNOx-minimum NOx value in grams ( )
Operating Variables	
θ - road grade ( )	
P_{acc} - accessory power in hp ( )	
v - speed trace in mph ( )	
v_w- wind velocity in m/s ( )	
θ_w – wind direction relative to vehicle ( )	
Ch - coefficient for road surface ( )	
T_c - ambient temperature in degrees Celsius ( )	
ρ - density of air in kg/m^3 ( )	
Pr- atmospheric pressure in kiloPascals ( )	

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: a *Fuel Parameters Set* (4 parameters) and an *Engine-out Emission Parameter Set* (12). In the *Fuel Parameter Set*, the model parameters are approximately known in advance. The parameters in the *Engine-out Emission parameter Set* need to be carefully determined from the testing data. Given all of these parameters, Figure 4.1 presents the detailed flow chart of the model and where the parameters are used.

4.8. 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 estimation procedures, using the measured emissions results for each test vehicle. Depending on the specific parameter, the values are determined either: 1) directly from measurements; or 2) based on several regression equations.

4.8.1. Measurement Process

Sixteen parameters are determined directly from the on-road emission measurements. The parameters are derived directly from the emissions traces for the driving-cycle specific and the on-road non-specific portions of the testing.

4.8.2. Regression Process

All seven parameters used to model engine-out emissions (a_{CO}, a_{NOx}, a_{HC}, a_{NOxh}, r_{CO}, r_{NOx}, r_{HC}, *and* r_{NOxh}) are determined through a regression process performed on the second-by-second data. Emission measurements from on-road driving are used to determine these parameters. These parameters are determined by regressing engine-out emissions against rate of fuel use. 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.

4.8.3. Aerodynamic Drag

Estimation of the aerodynamic drag for each truck is important because of the large frontal area and the resulting large influence in drag on power demand, fuel economy, and emissions. For heavy-duty vehicles, the frontal area is generally the frontal area of the trailer. The aerodynamic drag is affected by the shape of the truck, the degree of streamlining, and the spacing between the truck and the trailer. For this model building effort, the different trucks used in the test program were assigned to one of three groups. The aerodynamic drag for each of the example vehicles was estimated from existing data and engineering principals.

The generic truck shapes used in the model are illustrated in Figure 4.4. The estimated coefficient of drag for these generic truck shapes are given in Table 4.2.

Figure 4.3. Example HDD truck shapes: a) Conventional Non-Sleeper Cab, b) Conventional Raised Roof Sleeper Cab, and c) Cab Over Engine Raised Roof Sleeper Cab.

Table 4.2. Generic Truck Style Summary Table.

Type	Estimated Coefficient of Drag	Example
Style 1: Conventional Non-Sleeper Cab	Cd = 0.8	Truck #1
Style 2: Conventional Raised Roof Sleeper Cab	Cd = 0.6	Truck # 6
Style 3: Cab Over Engine Raised Roof Sleeper Cab	Cd = 0.65	Truck # 2

Differences in cab spacing and shape were found between some individual vehicles within generic truck types, however no specific method of determining the precise effect of the different interacting factors was available at the time of this report.

4.9. Vehicle Compositing

The eleven vehicles tested during the on-road testing phase had sufficient and acceptable data and have been modeled, using the process described above. In addition, the dynamometer-tested HDD vehicles were processed in a similar fashion. The primary modeling goal is to predict detailed emissions for each average, *composite* vehicle that represents the vehicle/technology categories listed in Table 3.8. Thus, a *compositing procedure* has been developed to construct a composite vehicle to represent each of the 7 different vehicle/technology modeled categories.

For the light duty version of CMEM, the individual vehicles within each category were blended into a composite vehicle with a composited emissions trace developed from the combined emissions traces of the individual vehicles. This methodology was made possible by the testing program based on uniform driving cycles for all vehicles. The advantage of this methodology was that it averaged out vehicle-to-vehicle differences in power enrichment and allowed for a vehicle fleet representation that was modeled as a smooth increase. The averaging of groups of vehicles prior to fitting the composite vehicle made the modeling of a non-linear process much more accurate and allowed good representation of the behavior of the fleet of vehicles represented within each vehicle/technology category.

For the heavy-duty modules of CMEM, there are two problems with this approach. The first is that the testing is on-road and compositing of vehicle traces is difficult or impossible for most of the driving. For example, two vehicles having the same exact speed trace could have considerably different engine power requirements because of the influence of wind and road grade. The second problem is the small number of vehicles available at present within the vehicle/technology categories. While the HDD trucks do not have power enrichment, they do exhibit non-linear behavior of the alternative fuel control strategy for the electronic fuel injected vehicles. At present it does not appear that the alternative control strategy could be fit by a smooth equation on a fleet basis. The reason for this is the very different timing of the switching between manufacturers which do not lead to monotonic increases in the number of vehicles in the fleet shifting to the high NO_x strategy.

A different approach was followed for the HDD vehicle sub-models because of the difficulty in implementing the light-duty compositing approach. For the heavy-duty sub-models, the following procedure was followed:

1. Individual vehicles were modeled using the on-road data, including both unspecified driving and specific driving cycles;

2. Estimates of the emissions of each vehicle/technology group for a modeled driving trace was obtained by modeling each individual on the trace;

3. The model output for the category was then the second-by-second average of the modeled emission traces for the vehicles within the group.

For the CMEM user, the output from light-duty and heavy-duty modules are the same, but the light-duty estimated emissions are produced from a single composite vehicle created from averaged test data in the model development process. The heavy-duty emissions will be the average of the individual estimated emissions from the modeled vehicles within the group.

4.10. Incorporation of Truck Automation Effects

Since this modal emissions and fuel consumption model is to be used for evaluating a variety of truck automation scenarios, it was necessary to model additional effects in the physical layer of the model. The key element here was modeling the aerodynamic drafting effect when vehicles travel at very close spacings. There has been a good deal of interest in having large class-8 trucks platoon together at close spacings to gain an advantage of fuel savings and emission savings ([Michaelian & Browand, 2001; Bonnet & Fritz, 2000; Browand et al., 2004; Browand & Hammache, 2004; Hammache et al., 2002]).

Researchers at the University of Southern California (USC) have extensively studied the load reductions due to vehicle following each other at close spacings ([Michaelian & Browand, 2001; Bonnet & Fritz, 2000; Browand et al., 2004; Browand & Hammache, 2004; Hammache et al., 2002]). They have recently conducted a number of experiments both in wind tunnels as well as real-world experiments. In order to capture the load reductions due to the drafting effect, we have used some of their recent data on how the aerodynamic drag coefficients change with respect to inter-vehicle spacings. The USC results are expressed as a ratio between coefficients of aerodynamic drag (C_D): C_D when vehicles are "platooning", over C_D when a truck is moving in isolation. It is expected that the C_D when moving in isolation would be larger than when platooning, therefore the resulting ratio is always less than one. Typical results from the USC tests are shown in Figure 4.4.

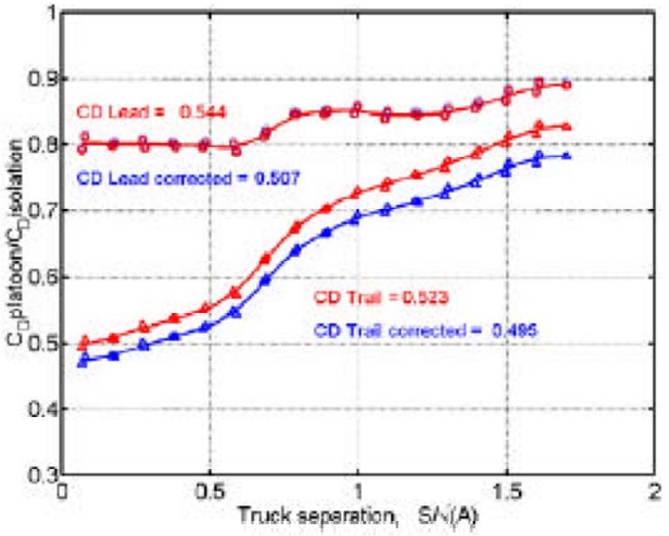

Figure 4.4. Aerodynamic drag ratio change as a function of truck separation. From [Hammache et al., 2002].

It can be seen in this diagram that the trailing vehicle in this case gets the greatest aerodynamic benefit, where the reduction in drag is between 30% and 50% depending on the following distance. It is important to note that the lead vehicle also gets a benefit from platooning, albeit not as great: in the range of 10% - 20%.

We have taken these data and applied it directly to the physical C_D parameters of our HDD vehicle. For example, if a HDD vehicle category has an average C_D of 0.8, then we were able to determine the new C_D value given a known vehicle spacing. This is illustrated in Figure 4.5. In this figure, we plot the adjusted C_D for both the lead vehicle and following vehicle. When the vehicle is in isolation, then the HDD vehicle model takes on its normal C_D value. However, when spacings are less than 10 meters, a lookup table function is used based on the USC data, reducing the C_D value accordingly, as shown in Figure 4.5.

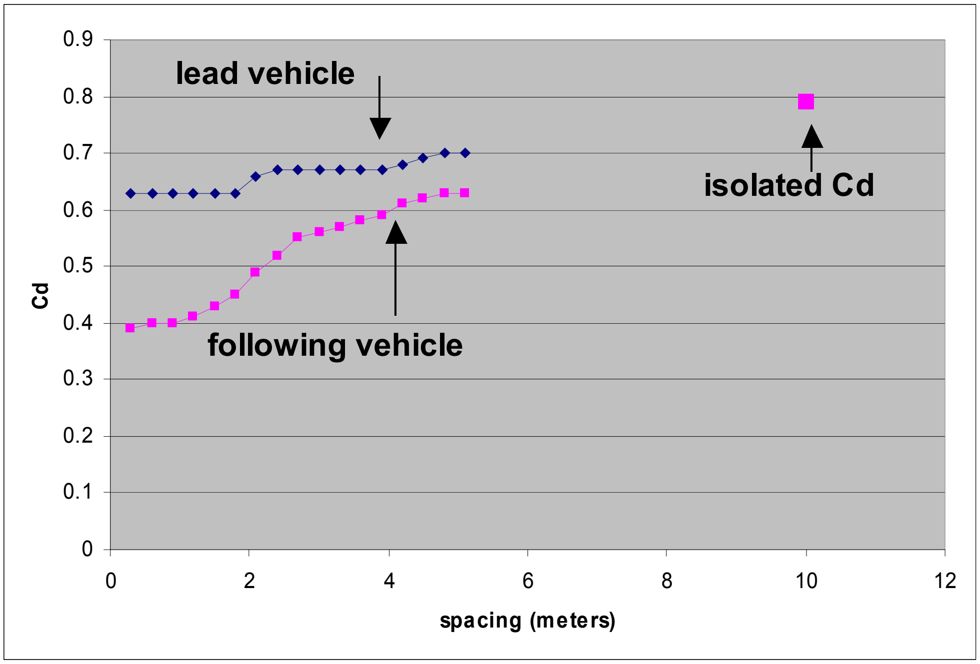

Figure 4.5. C_D adjustment factors embedded in the HDD vehicle sub-models; these were derived from the USC data [Hammache et al., 2002].

Thus when two or more trucks are platooning and the spacings are known, then the model can adjust the physical parameter C_D; as a result, the load, fuel consumption, and emissions for each vehicles are adjusted accordingly. Several example applications of this are described in more detail in Chapter 6.

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. With the HDD vehicle sub-models, the validation is complicated by the on-road nature of the data collected for modeling. Uncontrollable external factors such as wind, grade, humidity, and air temperature all complicate the modeling as well as the validation. Basing the model on in-use emissions measurements does however provide a better reflection of in-use emissions and emissions variability.

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. The validation of the HDD vehicle sub-models is similar to the validation efforts for the light-duty modules in the initial CMEM work. During model development, validation was conducted on the intermediate variables RPM and Power. This model validation is addressed in Section 5.1.

The larger-scale validation has been conducted by comparing composite vehicle integrated emissions values against model predictions, using linear regression. This was performed for CO_2, CO, HC, and NO_x for the following drive cycles: the UDDS, the CARB Idle, CARB Creep, CARB Transient, CARB Freeway, and the in-use driving on the freeway (e.g., driving to and from the test site). 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 exercise is addressed in Section 5.2.

A third validation exercise 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. This model validation is addressed in Section 5.3.

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 5.4.

Model Sensitivity

Parameter sensitivity of the HDD vehicle sub-models was not addressed during the scope of this project.

Data Analysis

In order to support the HDD vehicle model development, a good deal of data analysis has taken place. This analysis focused primarily on identification of the slopes relating fuel use to emissions under normal operation and alternative control strategies. A second critical analysis was focused on the identification of the criteria each motor used in deciding when to switch to the ACS. This analysis work has been included in Section 5.5.

5.1. Intermediate Variable Validation

During model development, a variety of intermediate variables were modeled and validated. The variables selected for this validation were fuel, RPM, and power. The strategy for the timing switch from the low NOx mode to the high NOx mode was also modeled and compared with the actual mode switching. Timing strategies were not specifically validated however, because the specific strategy varied considerably from one manufacturer to another while the modeled strategy was generic.

5.1.1. Fuel Validation

CMEM at its core is a fuel use model based on estimated power demand. Fuel is one of the variables available from the Engine Control Unit (ECU) and was used for comparison with modeled fuel as an intermediate variable validation. In addition, the model was tested using actual fuel in place of modeled fuel to test the accuracy of the model excluding variation due to fuel-use estimation. An example of the fuel validation is shown in Figure 5.1, where the measured and modeled fuel use are compared for the CARB transient cycle. It can be seen that in this example, the model slightly under predicts the measured values, by approximately 5%.

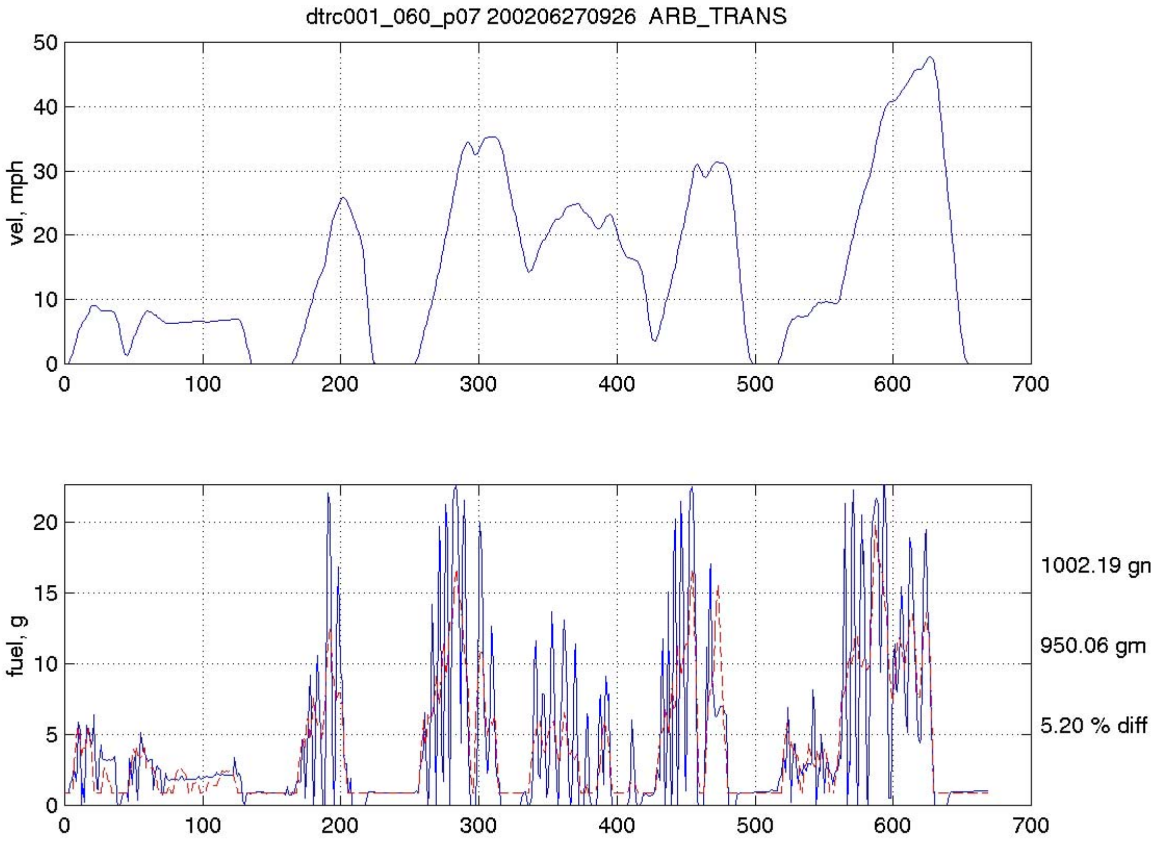

Figure 5.1. Modeled (red) vs. Observed (blue) fuel use for the CARB transient cycle.

Variability and bias varied from vehicle-to-vehicle with some vehicles showing a consistent positive bias (over-prediction of fuel use). Differences in average fuel predicted and observed varied from one cycle to another across vehicles is shown in Figure 5.2.

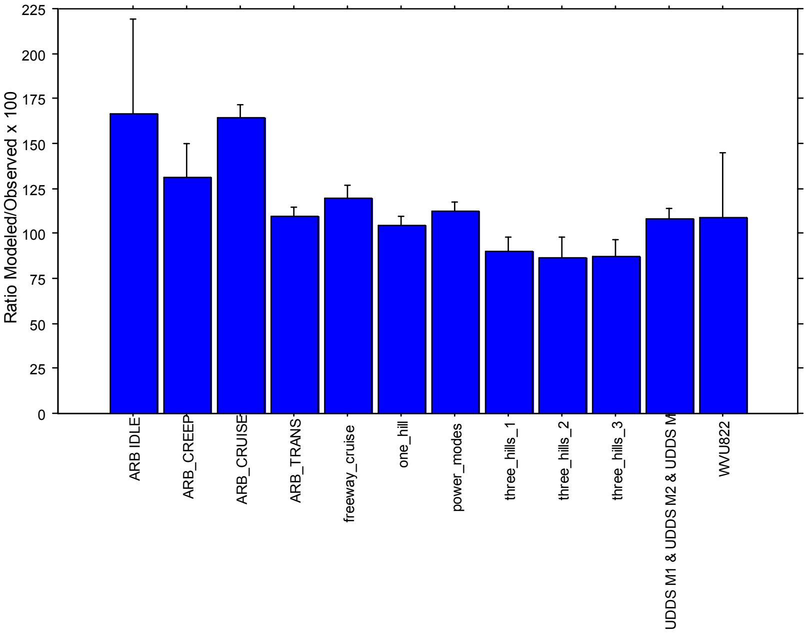

Figure 5.2. Average ratio of fuel modeled/fuel observed by cycle.

In general, the slower driving cycles show less average bias in fuel with the exception of the CARB Idle and CARB Creep cycles. It should be noted that the creep cycle has very low speeds and the idle cycle has no movement at all so they are operating at the very bottom end of the data collection and modeling range.

5.1.2. RPM and Power Validation

Analysis of RPM and power produced similar results to the fuel use results. In general, errors in power and fuel were correlated as would be expected. RPM and fuel, and RPM and power were inversely correlated, because the model shifts the vehicle to a lower gear to maintain speed under reduced power. Thus, overestimation of the power leads to an underestimation of the RPM. RPM validation was conducted at the second-by-second level because the cycle average was found to be a poor measure of the accuracy of the RPM modeling. Second-by-second plots of RPM and modeled RPM were examined visually to assess the overall effectiveness of the model in predicting gear selection. The plots are not presented here.

The power comparison across vehicles for all cycles is presented in Figure 5.3. From the plot it is apparent that there were problems in overestimating power for the creep and idle modes for this vehicle sub-model. It can also be concluded that while the average power estimated by the model is about right, considerable variation in the results within each vehicle exist across cycles. Some of this variation may be due to the inexact measurement of wind speed and direction as well as the roughness of grade measurements.

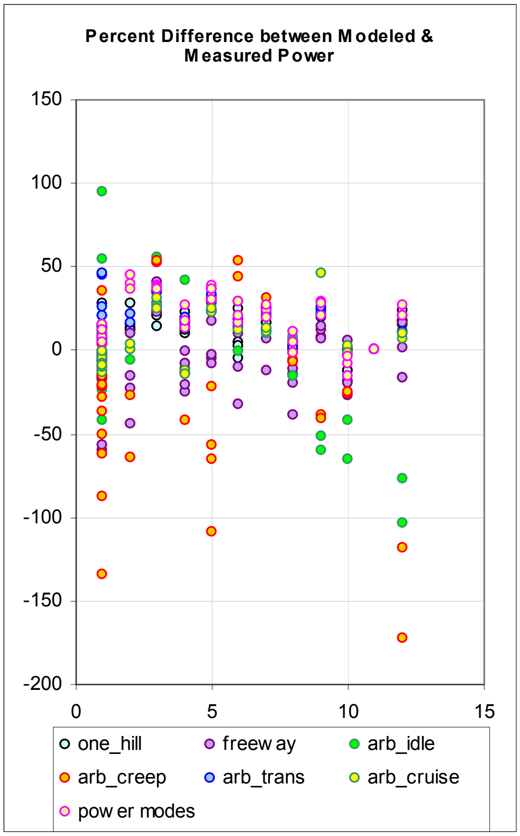

Figure 5.3. Modeled/Observed vehicle power.

5.1.3. Engine Control Strategy Shift Evaluation

The large differences in NO_x emissions when the trucks are operating in the alternative mode make prediction of the switching time critical. Unfortunately, the strategy varies from vehicle-to-vehicle and varies considerably by manufacturer, making a single strategy that fits all vehicles virtually impossible. At the present time, the strategy is determined based on time and speed and a single strategy is used for all vehicles. Because of the application of a single strategy to vehicles known to have multiple strategies, this validation was carried out on a general basis. It should be noted that no strategy worked all of the time, even on individual vehicles. This indicates that the actual variables being used to determine mode shifting likely include more variables than we are using in the modeling of the mode shift. Further research on this important topic is currently underway.

In order to show the value of modeling the fuel injection timing strategies, a comparison was made between the model with the timing strategy software module turned on, and the model with the timing strategy module turned off. The results are shown in Figure 5.4. Given the UDDS cycle (Fig 5.4a), second-by-second predicted NOx emissions are shown for both a measured truck and its modeled category with the timing strategy software module turned on (Fig 5.4b). For this cycle, the model predicted 23.57 grams compared to a measured 27.75 grams, a 15% difference. If the timing strategy module was removed all together, it can be seen in Figure 5.4c that the model grossly under predicts NOx when traveling a high-speed extended cruises. In this case, the model predicted 19.18 total grams, a difference of 31%.

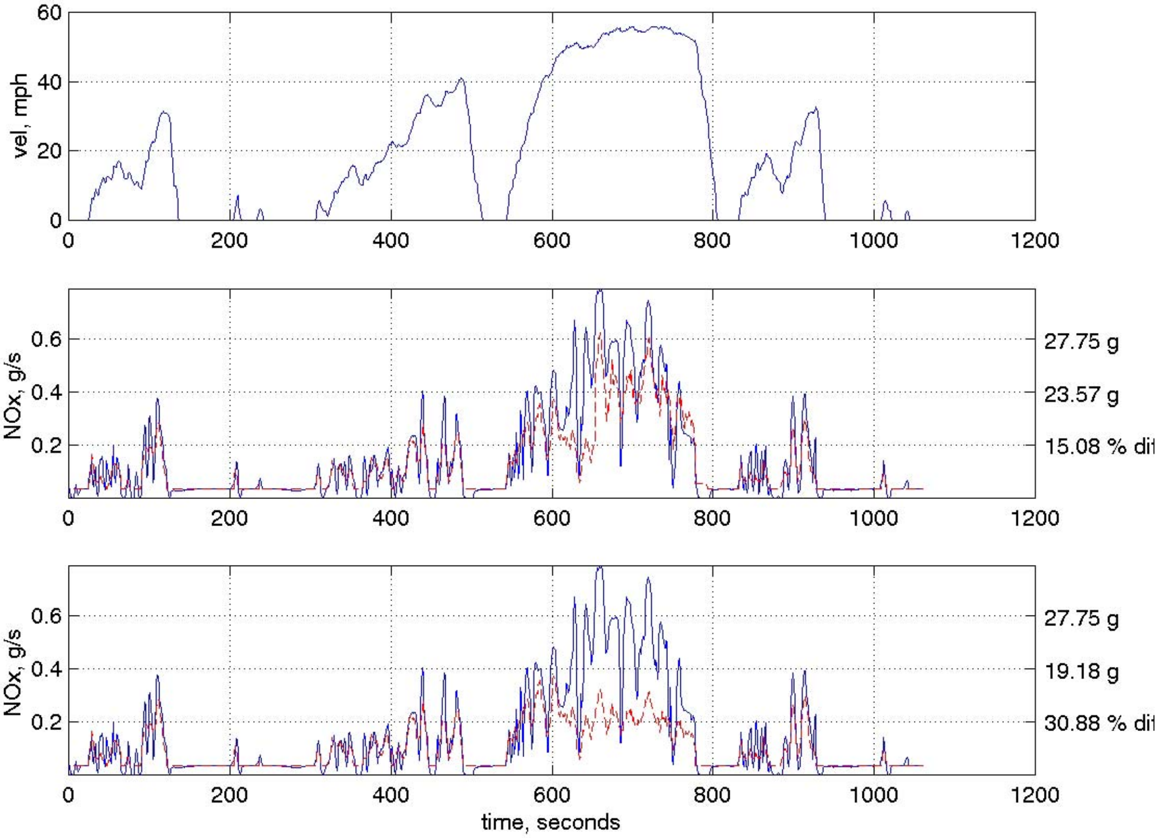

Figure 5.4. Comparison of second-by-second NOx emissions for the UDDS cycle. **a:** UDDS velocity profile; **b:** modeled (red-dash) vs. measured (blue-solid) with the timing strategy implemented; **c:** modeled (red-dash) vs. measured (blue-solid) with the timing strategy removed.

5.1.4. Road Grade Evaluation

Lastly, to show the advantage of a physical-based modal emissions model in how it inherently handles grade, another comparison was conducted for a driving pattern that traveled up and over a mountain pass. In this example, the elevation of the roadway is shown in Figure 5.5a (measured by differential GPS). The second-by-second measured and modeled NOx emissions are compared for the case when grade is used as input (Figure 5.5b) and in the case when the grade is set to 0 for the entire run (Figure 5.5c). It can be seen that the modeled emissions track pretty well with the measured emissions in Figure 5.5b for going both up and downhill. However, in Figure 5.5c, NOx emissions are grossly underestimated when going uphill and grossly overestimated when the truck is heading downhill (Figure 5.5c). Again grade is an important parameter to consider when dealing with HDD trucks since the power/weight ratios can vary widely. A physical modeling approach inherently handles grade better than methods that rely on speed and acceleration only.

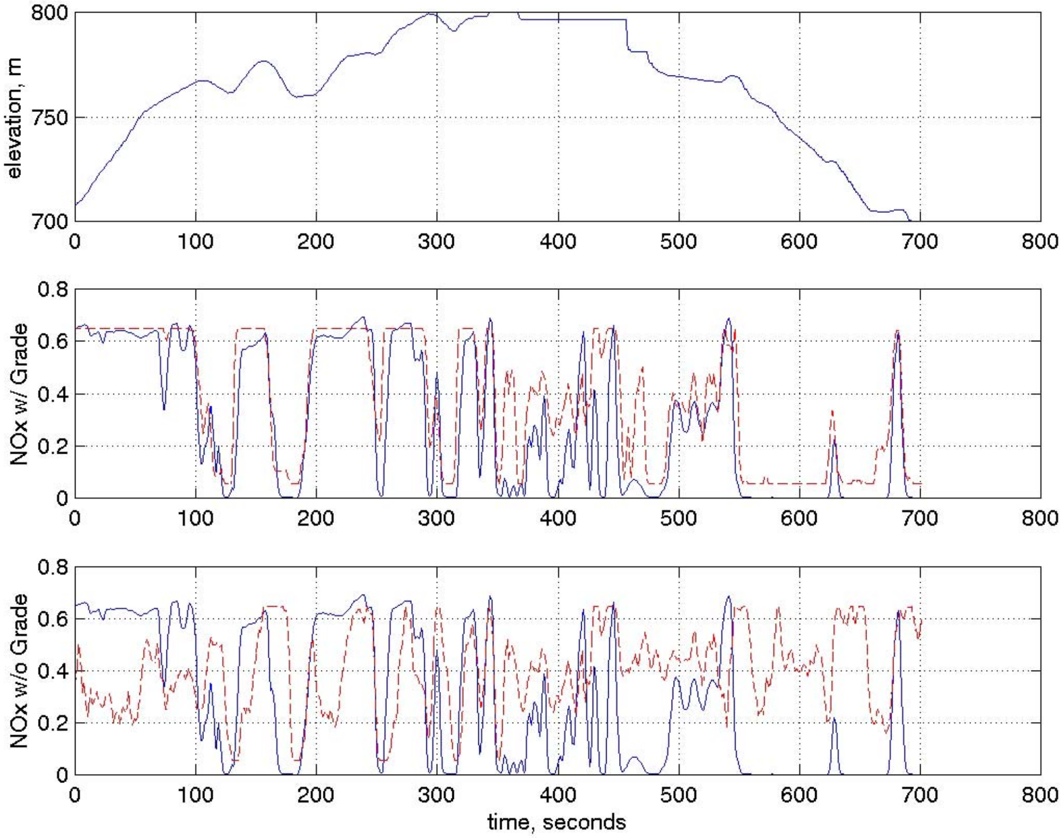

Figure 5.5. Comparison of second-by-second NOx emissions for varying grade. **a:** elevation profile for a specific driving pattern; **b:** modeled (red-dash) vs. measured (blue-solid) emissions using grade as input; **c:** modeled (red-dash) vs. measured (blue-solid) emissions with grade set equal to zero.

5.2. Overall Validation

The emissions of tailpipe CO_2, CO, HC, and NO_x for the vehicles were calculated for all of the test cycles. For this validation the total emissions for the driving cycles are compared across all vehicles and all cycles. 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 line with slope 1 is plotted for visual comparison. 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 5.6-5.9. 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.

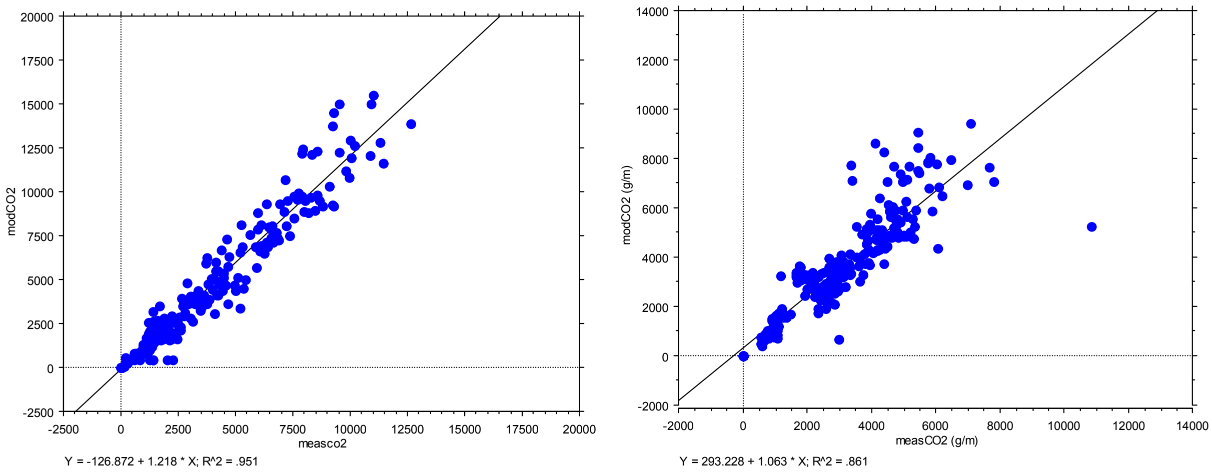

Figure 5.6. Validation plots for all vehicles and cycles for a) Total grams CO_2 and b) g/mi CO_2.

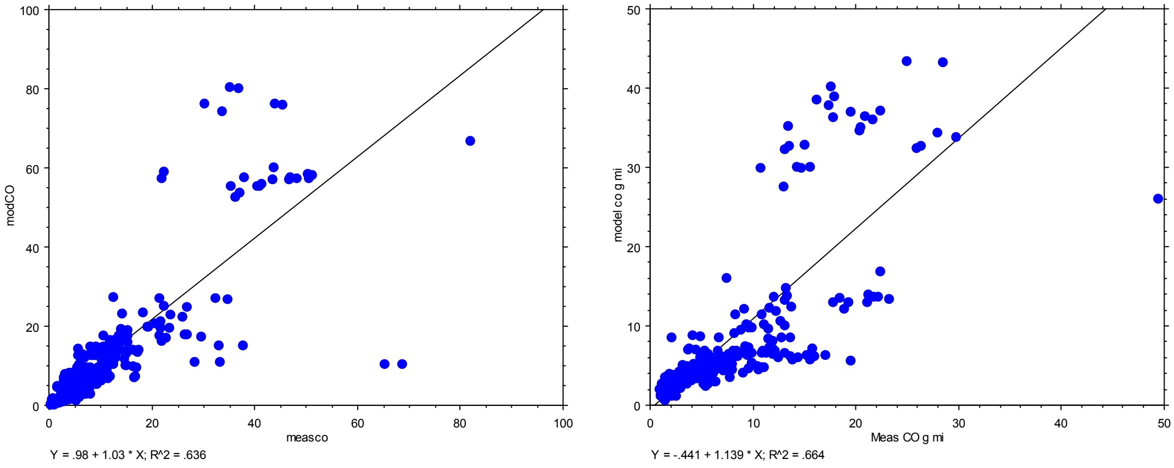

Figure 5.7. Validation plots for all vehicles and cycles for a) Total grams CO and b) g/mi CO.

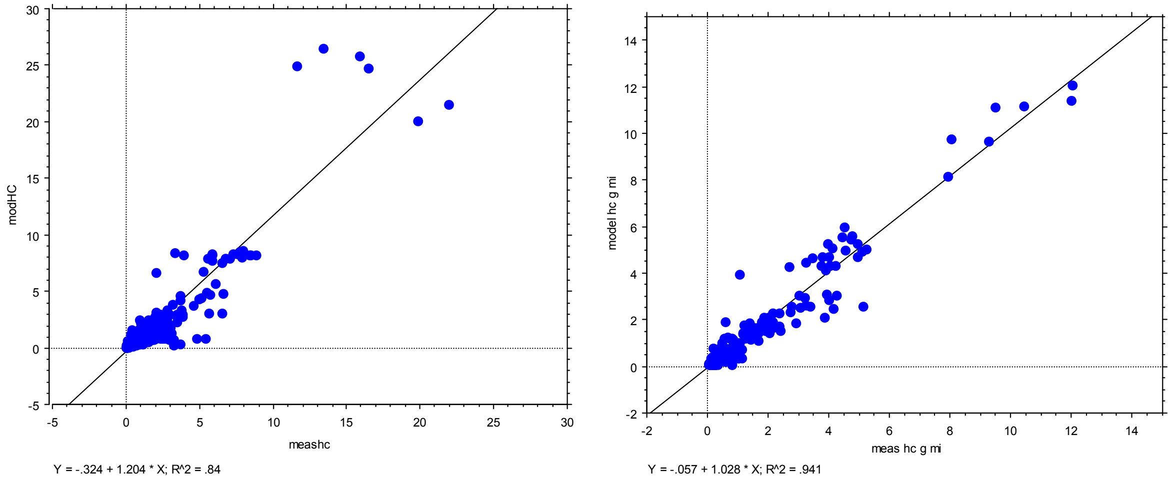

Figure 5.8. Validation plots for all vehicles and cycles for a) Total grams HC and b) g/mi HC.

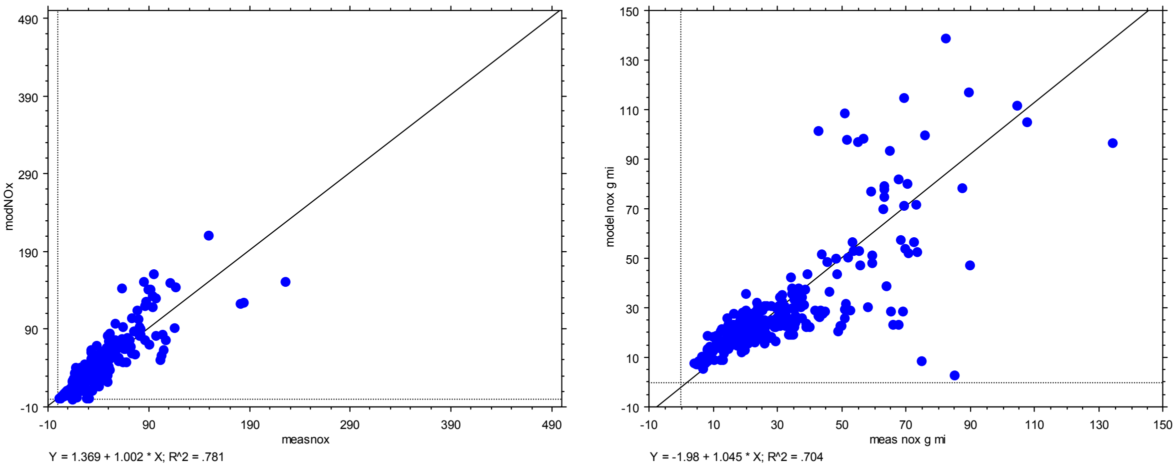

Figure 5.9. Validation plots for all vehicles and cycles for a) Total grams NO_x and b) g/mi NO_x.

Table 5.1. Summary of validation regression slope, Y-intercept, and R-Squared values.

Emission	Slope	Y-Intercept	R-Squared
CO2 (g)	1.218	-128.9	0.951
CO (g)	1.030	0.98	0.636
HC (g)	1.204	-0.324	0.840
NOx (g)	1.002	1.369	0781
CO2 (g/mi)	1.063	293.3	0.861
CO (g/mi)	1.139	-0.441	0.664
HC (g/mi)	1.028	-0.057	0.941
NOx (g/mi)	1.045	-1.98	0.704

5.3. Individual Vehicle Validation

Validation of test cycles was also broken down by individual vehicles and driving cycles within vehicles. These results are of greater importance for model diagnostics than for overall model evaluation, however they do provide some insight into the ability of the model to represent individual vehicles. The results are summarized graphically in Figures 5.10-5.11.

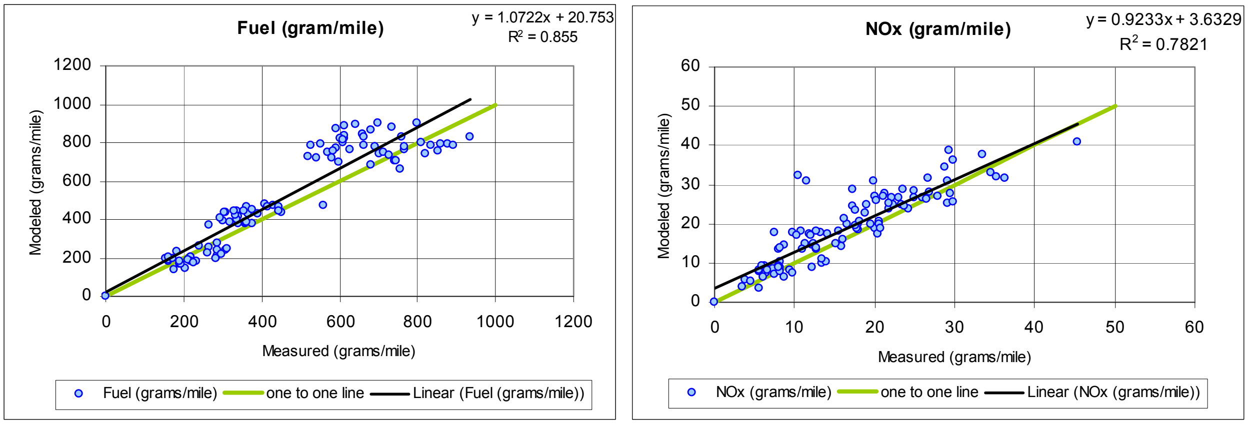

Figure 5.10. Example validation results for the 94-97 HDD category using independent cycles Modeled/Measured emissions for individual vehicles a) Fuel, b) NOx.

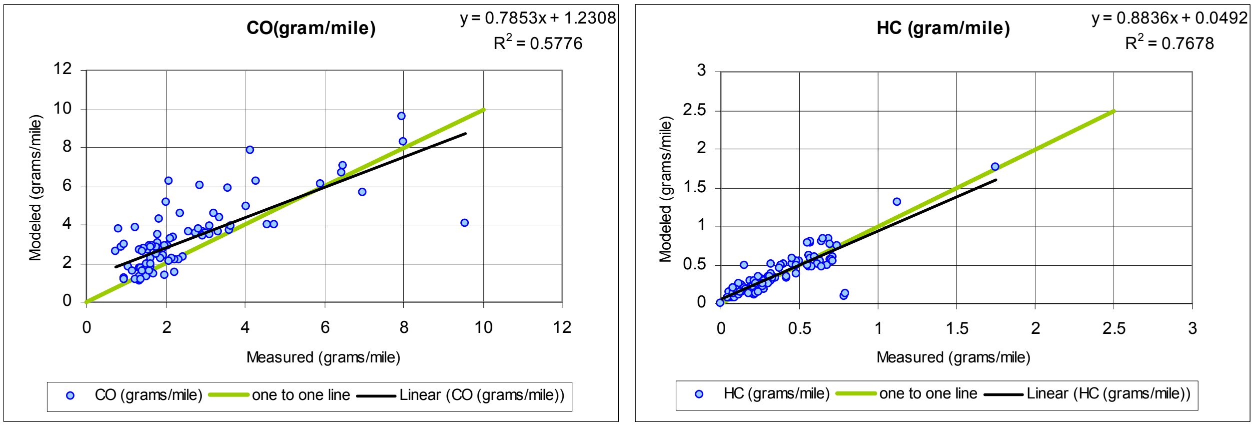

Figure 5.11. Modeled/Measured emissions for individual vehicles 94-97 HDD category a)CO, and b) HC.

The large scatter on individual driving cycles is not unexpected due to the real-world data collection and the influence of road grade and wind effects. The coarse nature of the wind and road grade measurements likely contribute significantly to the overall scatter in the data. Some trends in individual vehicles and specific driving cycles are being investigated further.

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. Unlike the light-duty CMEM analysis, bootstrap re-sampling was not used (see [Schulz et al, 1999]). Individual vehicles are used for bootstrap analysis to ensure that the population used for bootstrapping is sufficiently large. Bootstrapping on a small population can cause problems in the results. For this reason, bias was analyzed using standard parametric statistics with the sample based on the pooled results from all tests for each vehicle.

Bias in this case is defined as:

$$Bias(i) = Observed\ Concentration\ at\ Time\ i(O_i) - Predicted\ Concentration\ at\ Time\ i\ (P_i).$$

Second-by-second plots of modeled vs. observed emissions were created for each vehicle and test run for model validation. An example UDDS cycle is presented in Figure 5.12.

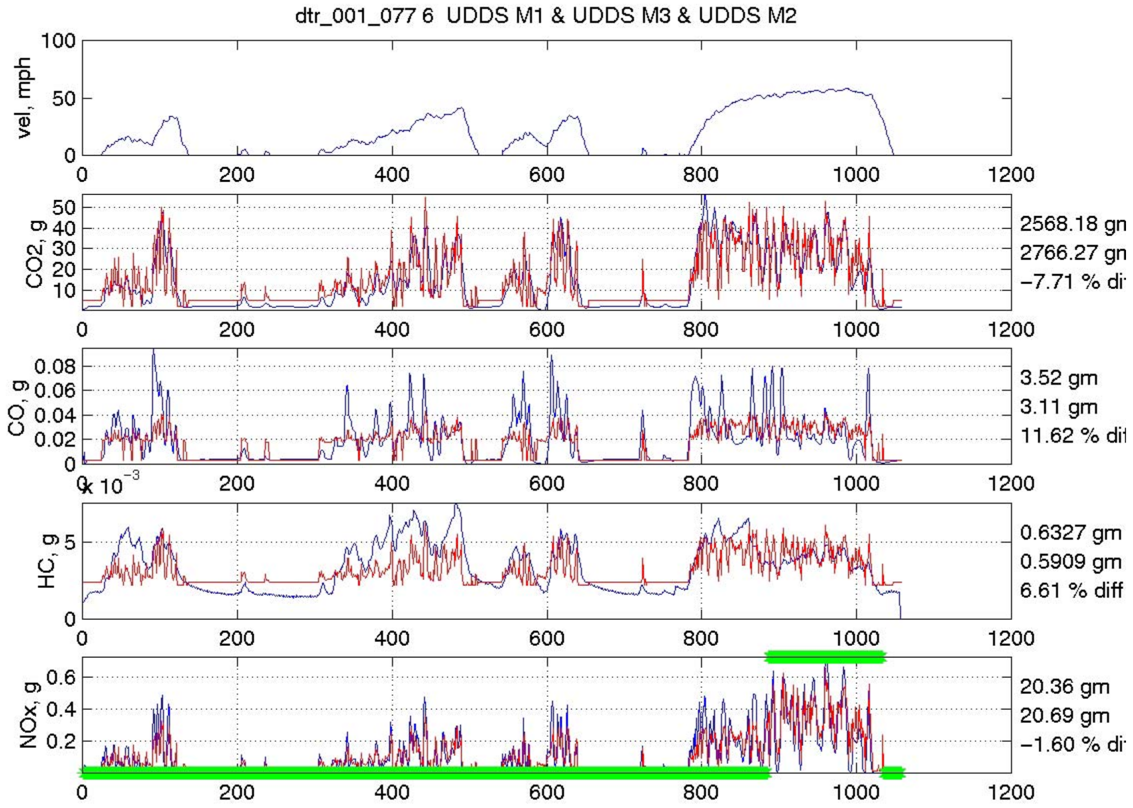

Figure 5.12. Observed emissions (blue) modeled emissions (red) and alternative control strategy (green).

5.4. 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).

5.4.1. Emissions Measurement Variability

There always exist a certain degree of inherent emission measurement variability. The instruments used in MERL were calibrated prior to each HDD vehicle test. Prior to all measurement programs, MERL underwent a very thorough test and calibrate phase. MERL was tested and compared against other emission measurement instruments at other laboratories (e.g., CARB testing laboratory). In nearly all cases, problems have been worked out where the emissions comparison always resulted in less than 5% error. Propane material balance tests resulted in 98+% match.

During previous testing at CE-CERT, sample measurements from identical instruments were made. There were very small time and exhaust mixture differences due to placement of the sample lines. The total grams measured by each instrument for steady-state cruise events 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 5.2.

Table 5.2. Standard Deviation and Precision of $D_{Instrument}$. and Precision $D_{Instrument}$(%).

	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%

5.4.2. Vehicle Driving/Operation Variability

In dynamometer testing for the development of the light-duty CMEM model, it was found that small differences in driving of the pre-specified driving cycles accounted for 5% to 10% variability in emissions. Following the driving trace on the pre-specified sections of the vehicle testing sequence was considerably more difficult because of external influences such as other vehicles on the road, road grade, wind conditions, and the need to pay attention to driving the vehicle in a safe manner. Repeatability of the slower and shorter driving cycles was still relatively good under on-road conditions. For example, Figure 5.13 shows 10 replicate runs of the CARB transient cycle during on-road conditions.

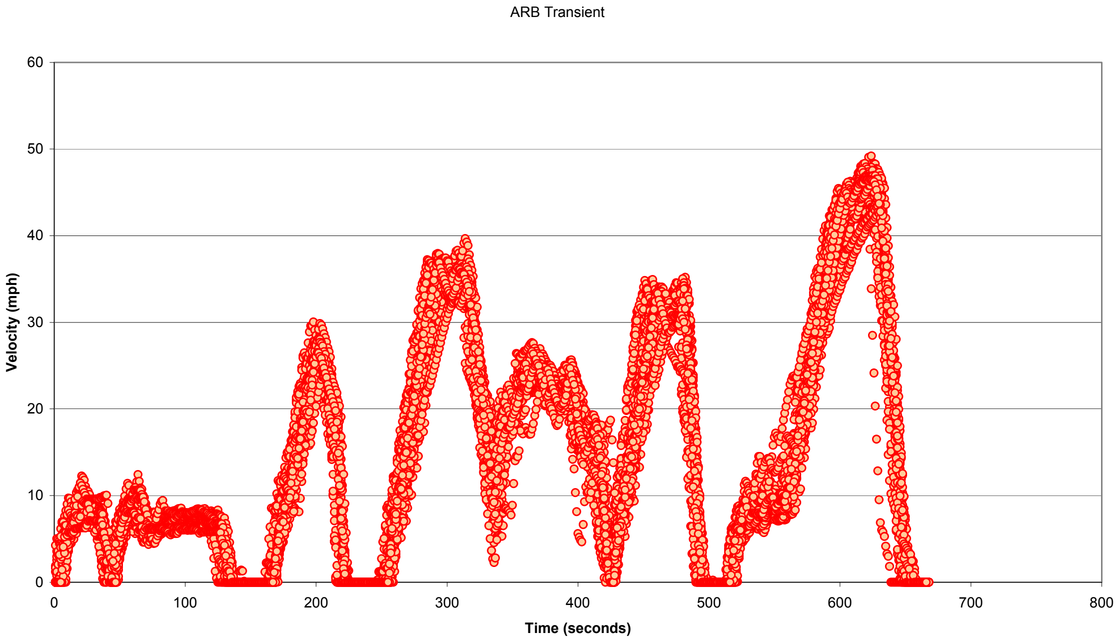

Figure 5.13. Ten replicate runs of the ARB Transient Cycle for vehicle 1.

For the HDD vehicles, driving and operational variability was not a significant factor in model uncertainty. This results from two main factors:

1. Model development was not dependent on pre-specified driving cycles. While the testing protocol included pre-specified driving cycles, they were not essential to the model building process.
2. The on-road data collection is subject to external factors such as wind and road grade that significantly affect emissions and thus increase the variability of the data far more than small deviations from the driving cycle.

5.4.3. Vehicle Sampling Variability

At present, there is little data available to estimate the vehicle-to-vehicle variability in on-road emissions. However, data available from dynamometer testing on power-curves by the California Air Resources Board do show considerable variability in emissions within model years, and within manufacturers [Chernich et al, 2003]. The power curve tests were run in the CARB's HDD lab in Stockton, California in 2002 and 2003. Average emissions for the vehicles did not appear to decline with model year, and variability within model years frequently ranged up to 400% as shown in Figure 5.14.

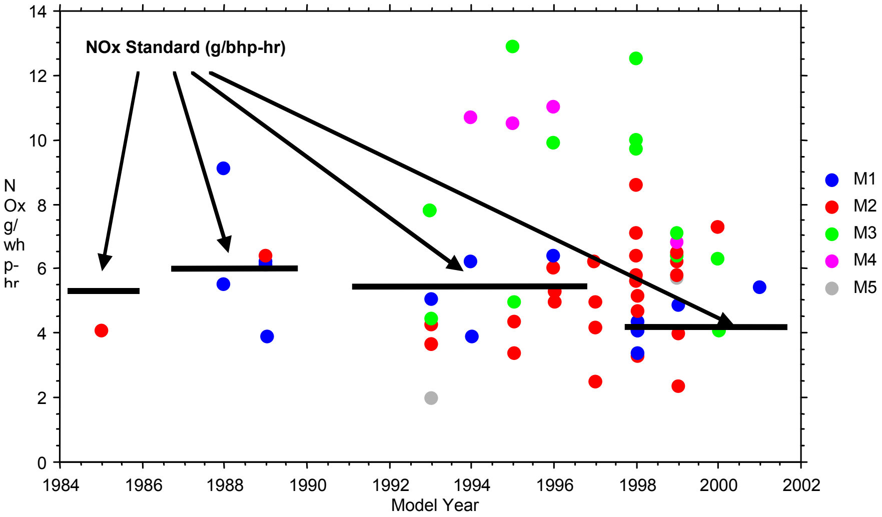

Figure 5.14. Power-curve average NOx (g/whp-hr) by model year for five manufacturers.

5.4.4. Parameter Estimation Variability

The alternative control strategy parameters are estimated from the data and are to some extent dependent upon the vehicles selected for testing. Sampling was designed to cover a representative sample of the manufacturers, however with the small samples available in this project it was not possible to assure coverage of the representative strategies in-use in the on-road fleet. In addition, the manufacturers do not provide information on any of the current strategies and it is not known how many variations exist or the fleet coverage of any particular control strategy. For this reason, the model version of the alternative control strategy is intentionally generic and is intended to simulate a fleet average switching time. Individual vehicles and families of vehicles may not follow the strategy in great detail, however the fleet as a whole is expected to be in the high NO_x mode at representative times and operating conditions.

Model parameters estimated by regression from the on-road data are subject to a number of sources of variation. For example, the slope of the upper and lower NO_x/fuel regressions varies from test run to test run as well as having uncertainty in the estimate from each data set. However, because of the large number of data points that are collected for each test run the 95% confidence limits for the slope of the fuel/NO_x regression are very narrow, as shown in Figure 5.15.

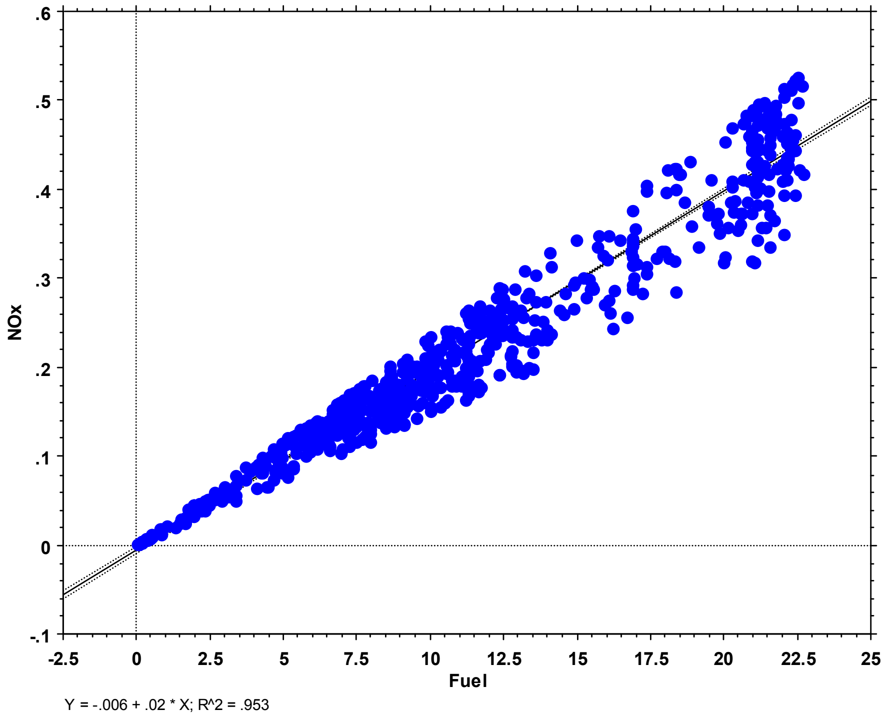

Figure 5.15. Example Fuel/NOx regression estimate of slope (solid line) and 95% confidence bands (dashed lines).

5.5. Supporting Data Analysis

Throughout the testing and model development, 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 key analyses are presented below.

Data analysis was conducted on two areas that support the model development: 1) Estimation of the slope of the emissions/fuel regressions, and 2) estimation of the switch timing for the alternative control strategy (ACS).

5.5.1. Emissions/Fuel Regressions

Estimation of the slope of the relationship between fuel (g/s) and CO_2, CO, HC, and NO_x (g/s) is a key element of the model. For each vehicle, the NO_x/fuel data were plotted and examined. Each vehicle had at least one test run that exhibited two modes as described in Section 4.5. For the data sets with two modes, linear regressions were run for the upper NO_x slope and the lower NO_x slope, as shown in Figure 5.16.

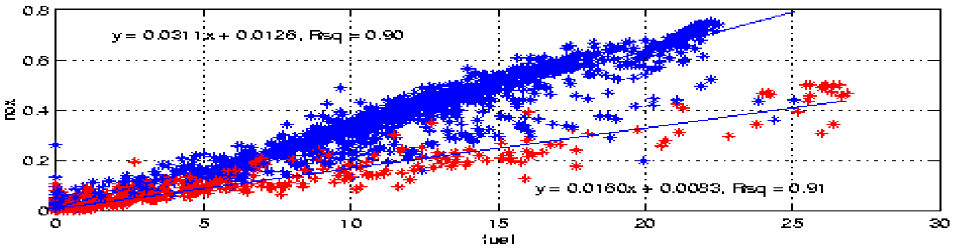

Figure 5.16. Example regressions of NOx and fuel with two operating modes.

All vehicles tested to date had at least two test runs with an apparent two-slope NOx result. Some of the vehicles did not switch modes on the majority of the test runs, while several did switch modes on quite a few of the runs. Slopes were fit to the data, including two slopes where it appeared necessary and the resulting slopes and intercepts are presented in Table 5.3. Additional data is available for estimation of the lower slope on tests that were not included in this initial analysis that focused primarily on test runs having possible two-slope effects.

Idle tests were not included in this initial analysis because the slope was consistently higher than the same vehicles high emission slope, but over a much more limited range of fuel values. One additional note is that the DDC motors exhibited curved NO_x/Fuel regressions on some of their test runs, as shown in Figure 5.17. The response was not consistently curved so a linear regression was used for these vehicles for all tests to enable comparison within vehicles and between vehicles. Some loss of accuracy in modeling of emissions would be expected under conditions where the true response was curved.

Table 5.3. Technology Group, Data source, and NO_x/Fuel Regression Slopes, Lower (ano) and Upper (anoh).

Pre-1991 Two-stroke

source	ano	anoh

Pre-1991 Four-stroke

source	ano	anoh
E55_2	0.0279	0.0176
E55_2	0.031	0.0236
E55_2	0.0243	0.0249
E55_2	0.0184	0.0255
E55_2	0.0236	0.0244
E55_2	0.0333	0.0274
E55_2	0.0122	0.014
E55_2	0.0203	0.0222
E55_2	0.0301	0.0338
E55_2	0.0419	0.0459
E55_2	0.0365	0.0374
Group	**0.0272**	**0.0270**

1991-1993 Mechanical FI

source	ano	anoh
E55_3	0.0196	0.0191
Group	**0.0196**	**0.0191**

1991-1993 Electronic FI

source	ano	anoh
E55_4	0.014	0.0231
E55_4	0.0188	0.0149
E55_4	0.0242	0.0252
E55_4	0.0216	0.0214
Group	**0.01965**	**0.02115**

1994-1997 Electronic FI

source	ano	anoh
CERT	0.0218	0.0439
CERT	0.0261	0.0483
CERT	0.0193	0.0318
CERT	0.0205	0.054
CERT	0.0221	0.0553
E55_5	0.032	0.0323
E55_5	0.0173	0.0198
E55_5	0.0302	0.0524
E55_5	0.0239	0.0416
Group	**0.024**	**0.042**

1998 Electronic FI

source	ano	anoh
CERT	0.0137	0.0376
CERT	0.0116	0.0408
E55_6	0.014	0.0326
E55_6	0.0344	0.0754
Group	**0.018**	**0.047**

1999-2004 Electronic FI

source	ano	anoh
CERT	0.0161	0.0316
CERT	0.0181	0.0629
CERT	0.0181	0.0629
CERT	0.0143	0.0312
E55_7	0.0165	0.002
E55_7	0.0223	0.0294
E55_7	0.0166	0.0197
Group	**0.018**	**0.037**

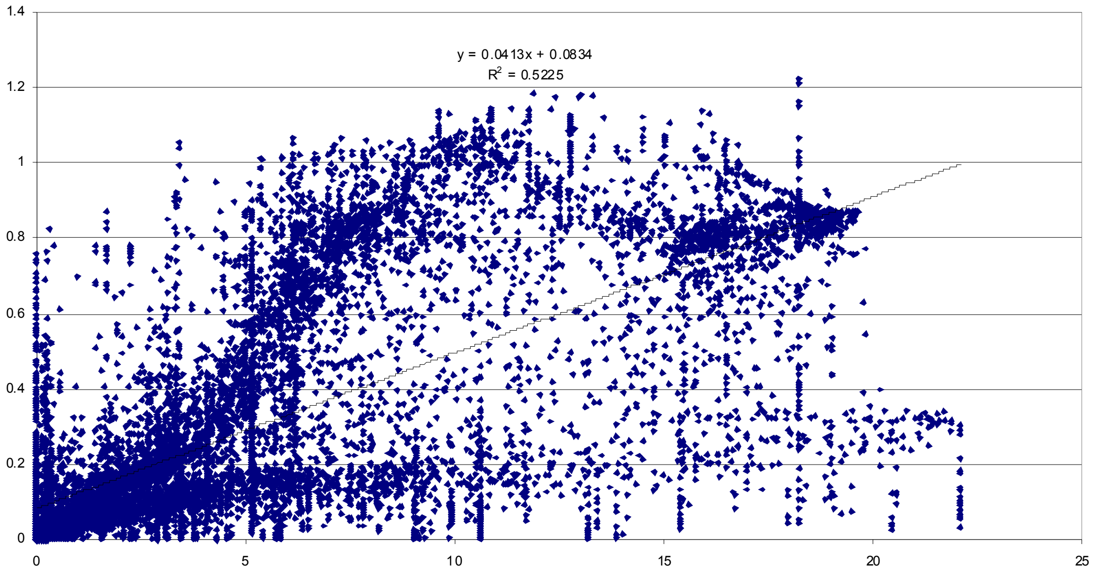

Figure 5.17. NOx/Fuel plot exhibiting curved response.

Upper and lower NO_x regression slopes were consistent within vehicles and no overlap was found between upper and lower slopes within vehicles for the newer electronic fuel injection motors. However, the average lower NOx slope and upper NOx slopes were very similar for the mechanical fuel injected motors, see Figure 5.18. The average of the slopes for each vehicle were used to represent the NO_x/fuel relationship for the vehicle.

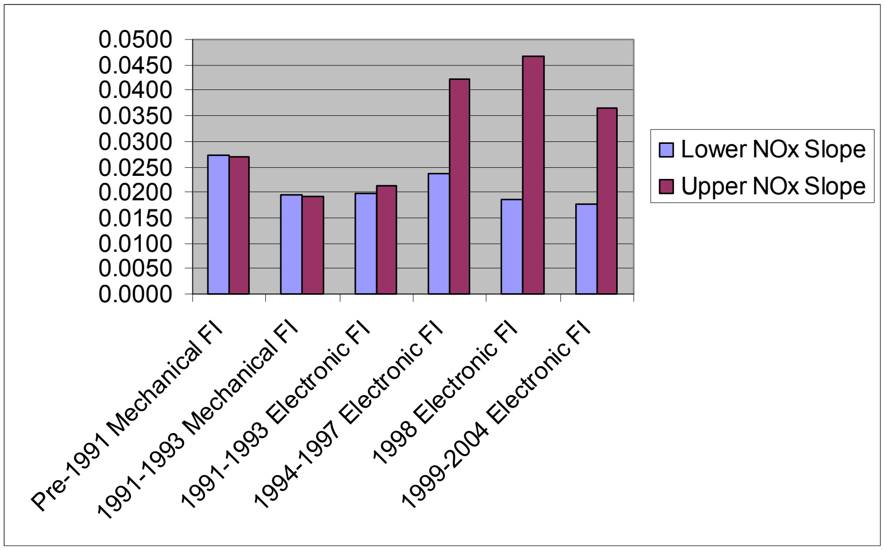

Figure 5.18. Upper and lower NOx/fuel regression slopes.

From these results it can be seen that the mechanical fuel injected vehicles and the oldest electronic fuel injected vehicles do not show large differences in NOx regression slopes for the upper and lower lines. It should also be noted that for the groups that exhibit two slopes the upper slope is considerably higher than the lower slope.

5.5.2. ACS Timing Estimation

A key component of the model is the timing of the alternative control strategy for NOx. Unfortunately the strategy is not easily identifiable and varies from manufacturer and model year to model year. In some cases the ACS is only activated at higher speeds (Figure 5.19a) while other vehicles exhibit ACS at a greater variety of speeds under higher loads (Figure 5.19b).

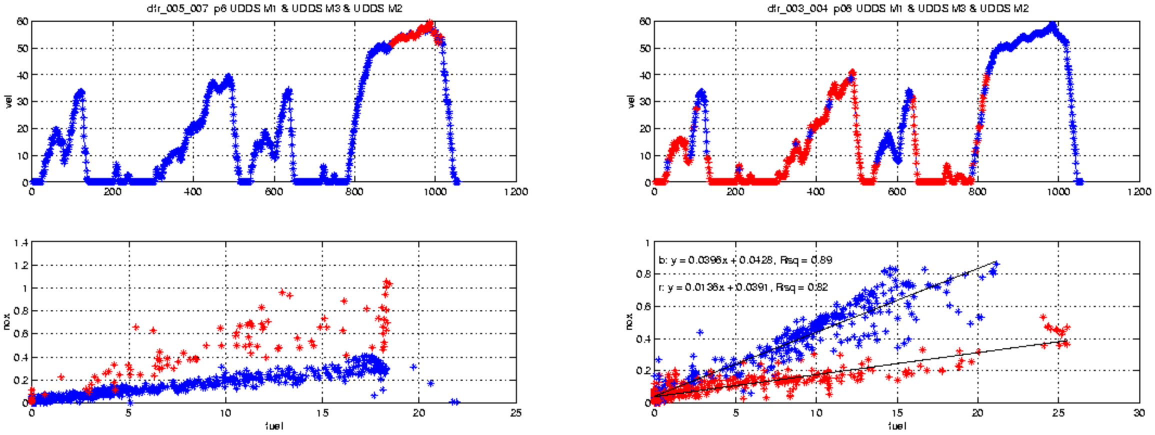

Figure 5.19. Differences in alternative control strategy between manufacturers a) Manufacturer 1, ACS only at higher speed, b) Manufacturer 2 ACS at slower speeds with harder acceleration.

6. Integration with Transportation Simulation Modeling Tools

As described in Chapter 1, the new HDD vehicle/technology categories are part of the larger comprehensive modal emissions (CMEM) modeling framework. The original design of CMEM allows it to be integrated with a wide variety of transportation models and/or transportation data sets in order to produce an emissions inventory. The final CMEM categories with the additional HDD vehicle sub-models is shown in Table 6.1. In this figure, the new HDD truck categories are highlighted in yellow.

Table 6.1. Vehicle/Technology modeled categories in CMEM, with HDD vehicle categories added. Note "blank" categories are user programmable from category #60.

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)
41	Pre 1991, 2-stroke HDDT
42	Pre 1991, 4-stroke HDDT
43	1991 to 1993, 4-stroke, Mech. FI HDDT
44	1991 to 1993, 4-stroke, Elect. FI HDDT
45	1994 to 1997, 4-stroke, Elect. FI HDDT
46	1998, 4-stroke, Elect. FI HDDT
47	1999 to 2002, 4-stroke, Elect. FI HDDT
	High Emitting Light Duty Vehicles
19	Runs lean
20	Runs rich
21	Misfire
22	Bad catalyst
23	Runs very rich

It is important to remember that the emissions estimation for each category is for an average *composite* vehicle within each category. Thus, when integrated with transportation models or datasets, two key issues must be considered:

Vehicle Fleet Distribution—when integrating, it is necessary to specify the vehicle fleet distribution in terms of the CMEM categories outlined in Table 6.1. 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—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 spacings (which may play a role with aerodynamic drag reduction if sufficiently small).

The comprehensive modal emission model (which includes the new HDD vehicle categories) has been set up to handle different fleet distributions and microscopic vehicle operational parameters. A detailed description on how to use CMEM is provided in a "CMEM User's Guide" [Barth et al., 1999]. Only a brief description is provided here.

CMEM was developed and is continually improved in a research environment, using MATLAB modeling/analysis tools. A "research" version of the model exists that is used to test new model changes and to carryout a variety of research applications. In addition, CMEM takes on additional forms:

Command-Line Executable Code—the command-line executable code allows a user to prepare an input control file and an input vehicle activity file and can process both single vehicle activity as well as fleet vehicle activity. This command-line executable program has been compiled on many computing platforms including UNIX, PC, and MAC environments. This form of the model is best suited for large batch processing with the user understanding how to manipulate the input control file and resulting output file.

CMEM Graphical User Interface—a more user-friendly version of CMEM exists, only for the PC environment. This version has a well developed graphical user interface (GUI) that allows the user to select various vehicle categories, modify various parameters, adjust the type of output, and even perform some basic emissions plotting. This version is better suited for small projects that require only a few CMEM runs.

CMEM Velocity/Acceleration-Indexed Lookup Table—CMEM can also take on the form of a velocity/acceleration indexed lookup table. This form is well suited for several traffic simulation models that currently use velocity/acceleration emission tables. The advantage of the lookup table-based emission model form is that it is straightforward to integrate, and the computational costs are very low. However, the lookup table method assumes that there is no time dependence in the emissions response to vehicle operation. This assumption is not true for many vehicle types when 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, oxygen storage in catalytic converter, HDD truck NOx timing strategies, etc.).

6.1. Simulation Model Integration

As part of our PATH HDD vehicle modeling project, we have integrated our emissions model with several transportation modeling tools to evaluate various automation scenarios. For this task, we have successfully integrated our model with:

1. a simple vehicle trajectory simulator;
2. SHIFT/SmartAHS simulator; and
3. PARAMICS, a state-of-the-art traffic simulator.

These integration tasks are described in more detail below.

In addition, our research-grade model has also been made available to Petros Iannou at USC for integrating with his ACC simulation work under PATH sponsorship. He is evaluating various ACC strategies for various performance measures, including emissions and fuel consumption. We are working with this USC team on a regular basis, providing up-to-date HDD model versions.

6.1.1. Integration with SHIFT/SmartAHS Tools

In order to evaluate the fuel and emissions impact of HDD vehicle movement, we initially developed a simple trajectory simulator in MATLAB. This allowed us to specify a desired HDD truck trajectory, and the simulator would then apply the appropriate kinematic equations to obtain realistic motion of the simulated vehicle. For example, if the desired trajectory ("Target" trajectory) had power requirements greater than what the HDD truck could achieve, the trajectory would be modified ("Actual" trajectory) so that the vehicle could best complete the desired movement. This simple simulator was later expanded from single vehicle operation to multiple vehicle operation so that issues such as platooning could be evaluated.

In parallel with this effort, we integrated our model with PATH's SHIFT/SmartAHS toolset. This stems from previous work that we carried out with PATH during the NAHSC Demo work in 1997 when we integrated our light-duty vehicle fuel and emission models with SmartAHS. For this task, we obtained the latest version of SHIFT/SmartAHS and completed the integration by setting up a "monitoring" function in the SHIFT/SmartAHS code that provided the appropriate vehicle operation parameters, such as velocity, acceleration, and following distance from any leading vehicle. As a SmartAHS simulation would run, the trajectory information would be captured, and subsequently the emissions and fuel consumption could be estimated. An example SmartAHS run is illustrated in Figure 6.1.

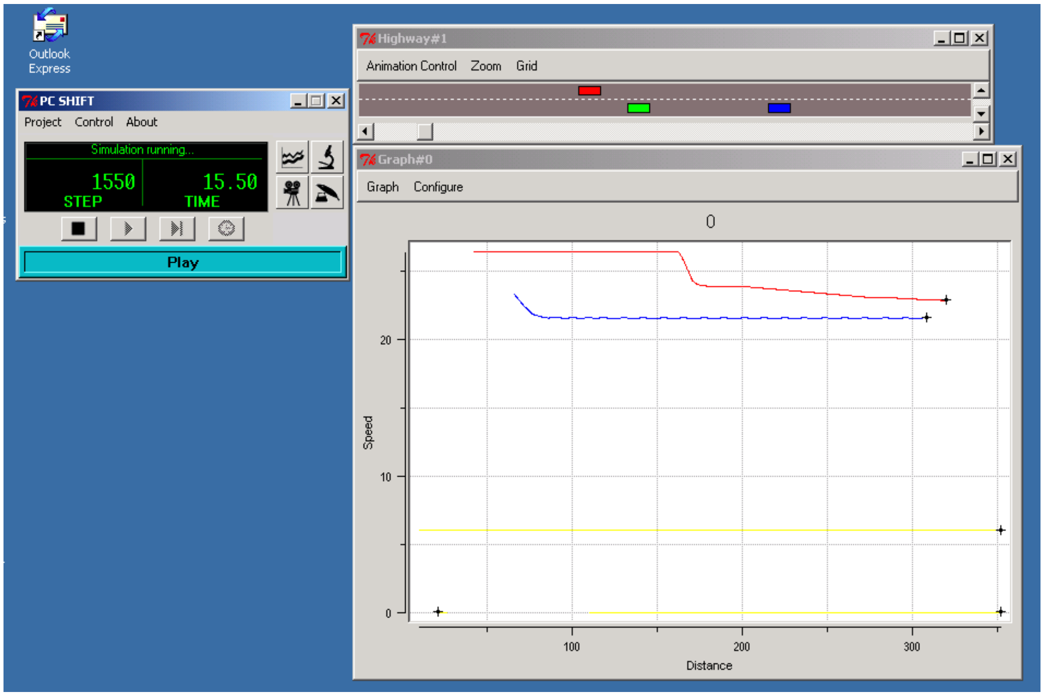

Figure 6.1. SHIFT/SmartAHS example run with the integrated model.

6.1.2. Integration with PARAMICS Traffic Simulator

In addition to the integration with SHIFT/SmartAHS, many researchers at PATH and Caltrans are using PARAMICS, a state-of-the-art microscopic traffic simulation tool. For this reason, it made sense to also integrate our HDD vehicle fuel consumption and emissions model with PARAMICS. This work was very similar to the work that was carried out in PATH MOU #381 where our light-duty fuel consumption and emissions model was integrated for a variety of ITS evaluation projects [Barth, et al., 2001].

PARAMICS is a suite of high performance software tools for microscopic traffic simulation. Individual vehicles are modeled in fine detail for the duration of their entire trip, providing very accurate traffic flow, transit time and congestion information, as well as enabling the modeling of the interface between drivers and ITS. The PARAMICS software is portable and scalable, allowing a unified approach to traffic modeling across the whole spectrum of network sizes, from single junctions up to national networks. The parallel computing high-performance approach used in PARAMICS allows for faster than real-time simulation of networks of any size with no loss of detail. Key features of the PARAMICS model include direct interfaces to macroscopic data formats, sophisticated microscopic car-following and lane-change algorithms, integrated routing functionality, direct interfaces to point-count traffic data, batch model operation for statistical studies, a comprehensive visualization environment, and integrated simulation of ITS elements [Quadstone, 2004].

In the default version, PARAMICS uses simple look-up tables of exhaust pollution and fuel consumption as a function of vehicle type, speed, and acceleration. In this version, there are only default tables for a single vehicle type. In order to make this a more powerful model, data sets for a variety of vehicles must be provided.

One major advantage that PARAMICS has is that it allows users to customize some critical parts of the PARAMICS core models. Through the use of an Application Programming Interface or API, traffic modeling researchers can override PARAMICS default behavioral models (such as car following, gap acceptance, lane changing or route choice) to better reproduce local driver and vehicle characteristics, or implement their own complementary traffic control strategies (such as signal optimization, adaptive ramp metering, incident detection, etc.). With this open architecture, it was possible to create a plug-in module that can calculate fuel consumption and emissions in-situ. This method is advantageous since it does not suffer from history effect problems when vehicle performance state information is stored. Further, there are no intermediate trajectory files to worry about, and the performance of the integrated model is quite satisfactory.

Thus, we were able to integrate our new HDD vehicle fuel consumption and emission models into PARAMICS by creating an API through the use of the PARAMICS Programmer utility. The PARAMICS Programmer utility is a framework that allows the user to access many of PARAMICS' features and variables as the simulation takes place. This API was written in C and revolves around two elements: 1) control functions and 2) callback functions. Control functions are functions that PARAMICS uses as part of its standard simulation. These control functions allow the user to override or add additional code to the simulation run. Callback functions allow the user to retrieve specific information from the simulation such as vehicle and network attributes. On UNIX systems, the plug-in is compiled as a shared object file (.so) and a path directing the PARAMICS simulation to the .so file is specified in the .plugin file. This allows PARAMICS to find and load the plug-in on opening.

This API for PARAMICS calls the emissions/fuel consumption function during the PARAMICS simulation in order to obtain calculated emission values for each vehicle at every second. This is done through the overloading of control functions, most notably the *vehicle_link_action*, which is where the emissions function call is located. This control function is called for every vehicle on every link at each time-step. During this function call, the current vehicle type, speed, acceleration and previous vehicle history are identified using callback functions and from previously stored values. This information is passed to the CMEM function which calculates emissions and fuel consumption for that vehicle type at that second and with that history. Updated vehicle history values are then stored for future events. Emission values are also stored at this point and can be cumulated and summarized at the end of the simulation or at given intervals during the simulation. Currently the API summarizes link emissions at every 15 minutes of simulation.

As an example evaluation of our integrated PARAMICS tool, we evaluated the emissions and fuel consumption impact of adding a separate truck climbing lane on the Moreno Valley freeway (I-215/SR-60, see Figure 6.2 and 6.3.

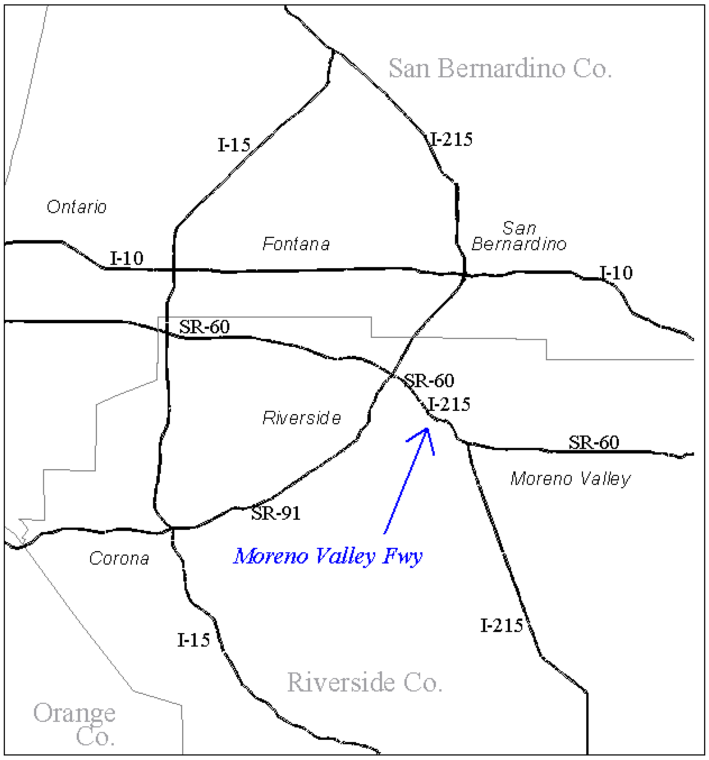

Figure 6.2. Location of the Moreno Valley freeway.

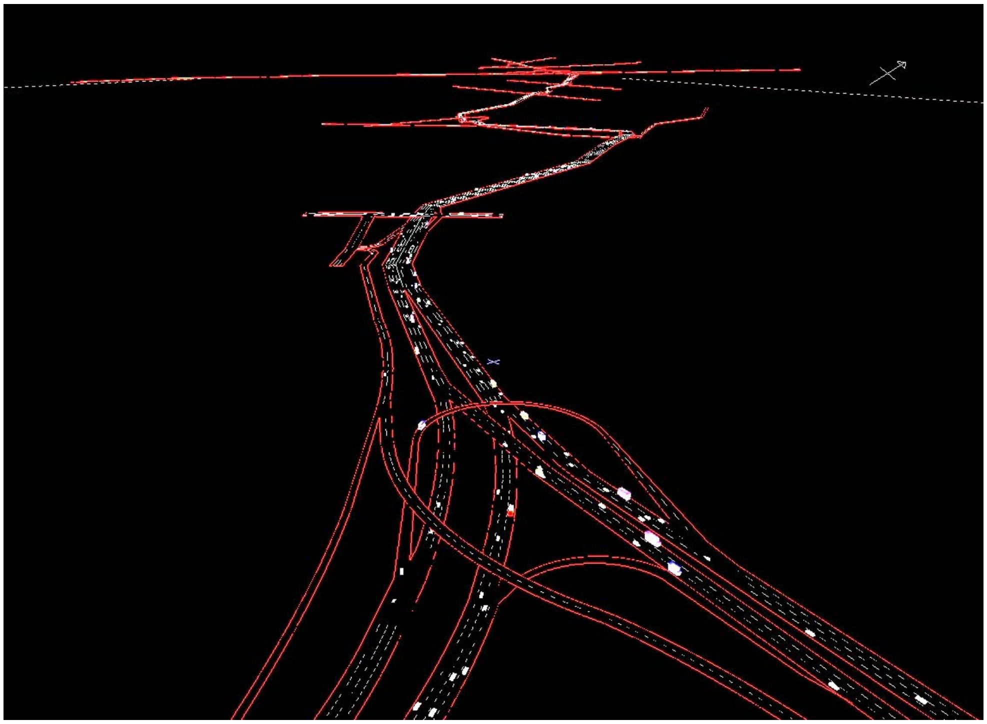

Figure 6.3. Snapshot of Paramics simulation of the SR-60/I-215 Moreno Valley Freeway corridor. Foreground is SR-60/I-215 split in Moreno Valley, background is the corridor climbing the grade from SR-91.

6.2. Automation Scenario Evaluation

Using the integrated tools described in the previous section, it was possible to carry out several evaluations of HDD vehicle operations, with an emphasis on automation impacts.

6.2.1. HDD Truck Speed Impacts on Fuel and Emissions

One of the first issues we wanted to investigate was the impact of HDD truck speeds on fuel consumption and emissions. In order to carry out comparisons, the following exercises were performed:

Steady-State Cruise at Different Speeds—using the PARAMICS simulator, we examined fuel consumption and emissions for steady-state cruise conditions at different speeds. As part of this exercise, we also examined the impact of controlling the off-cycle fuel injection strategies that many manufacturers use to save fuel at the expense of higher NOx emissions (see Sections 2.2 and 4.5). The steady-state cruise speeds were achieved by simulating conditions under freeflow with a specified maximum desired speed. The steady-state cruise conditions should give forth the lowest fuel consumption and emissions compared to other traffic conditions.

Congestion Modeling—using the simple vehicle trajectory simulator, we evaluated the HDD vehicle sub-models for different congestion drive cycles that were originally derived at the U.S. EPA [Sierra Research, 1997]. These "congestion" cycles represent typical traffic on freeways for different Levels-of-Service (LOS). In addition, we simulated freeway traffic under different levels of congestion using PARAMICS and obtained similar results. The resulting modeled fuel consumption and NOx emissions have been calculated at a variety of average congestion speeds.

CARB Mode Cycles—as described in Chapter 2, the California Air Resources Board created several driving cycles for HDD vehicles, which include an idle, creep, transient, and cruise section, with different representative speeds of traffic. These drive cycles were measured directly during the model development phase. Further, it was easy to simply take the same cycle and do a model prediction, using the vehicle trajectory simulator. In this way, both measured and modeled emissions and fuel consumption can be compared.

The results of these exercises are shown in Figures 6.4 – 6.6. In these figures, we show the fuel consumption versus speed and NOx emissions versus speed for the example categories 45, 46, and 47 (1994-1997, 1998, 1999-2002 4-stroke, electronic fuel injection HDD trucks, respectively).

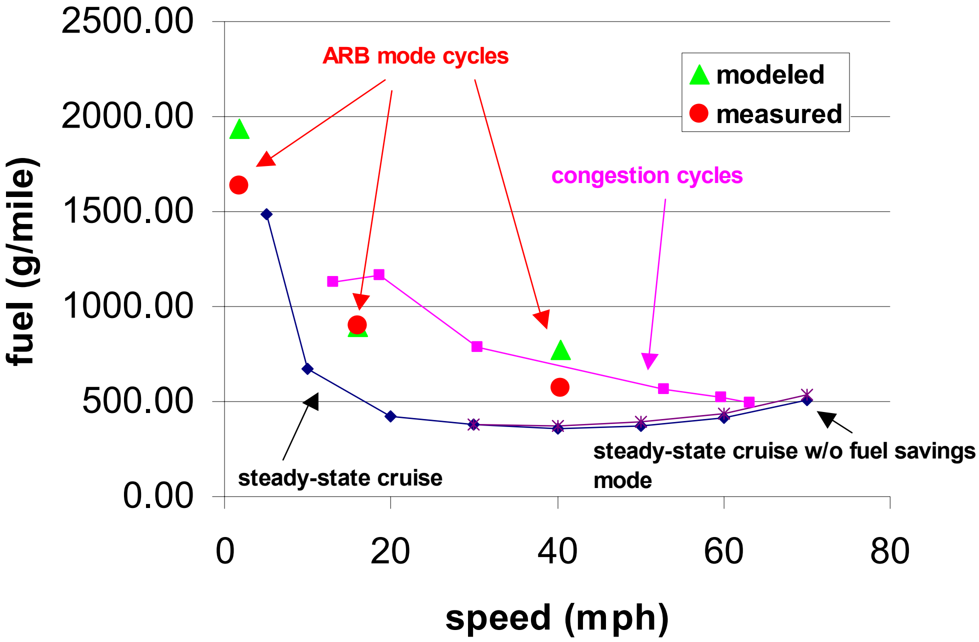

Figure 6.4a. Fuel consumption vs. average vehicle speed, for variable exercises, for CMEM category 45 vehicles (1994-1997 HDD trucks).

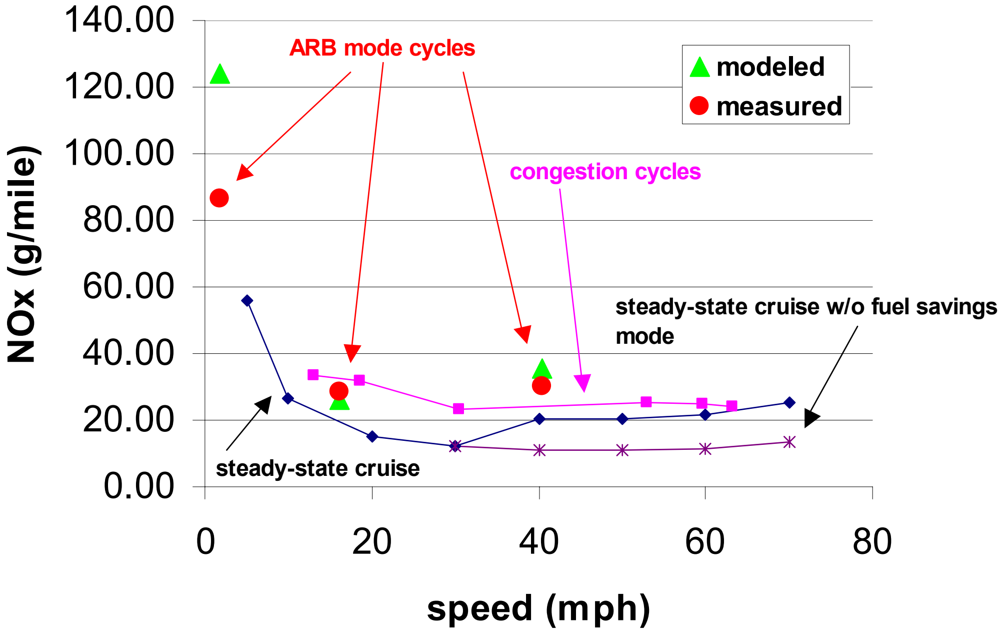

Figure 6.4b. NOx emissions vs. average vehicle speed, for variable exercises, for CMEM category 45 vehicles (1994-1997 HDD trucks).

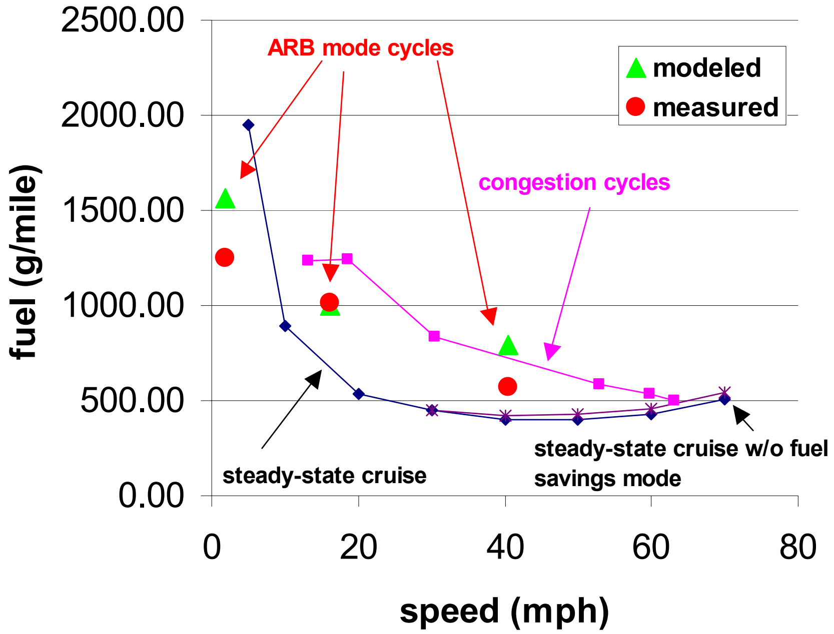

Figure 6.5a. Fuel consumption vs. average vehicle speed, for variable exercises, for CMEM category 46 vehicles (1998 HDD trucks).

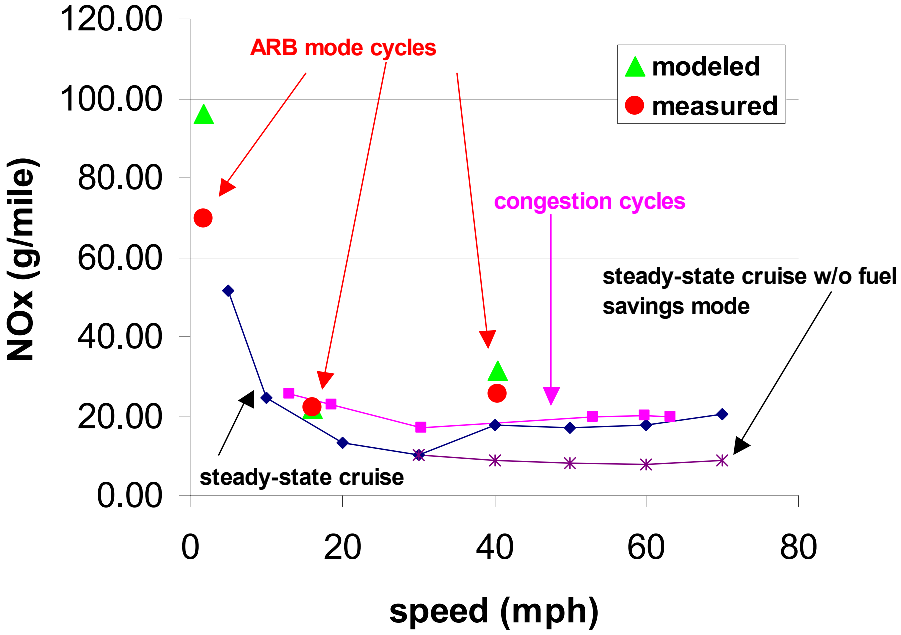

Figure 6.5b. NOx emissions vs. average vehicle speed, for variable exercises, for CMEM category 46 vehicles (1998 HDD trucks).

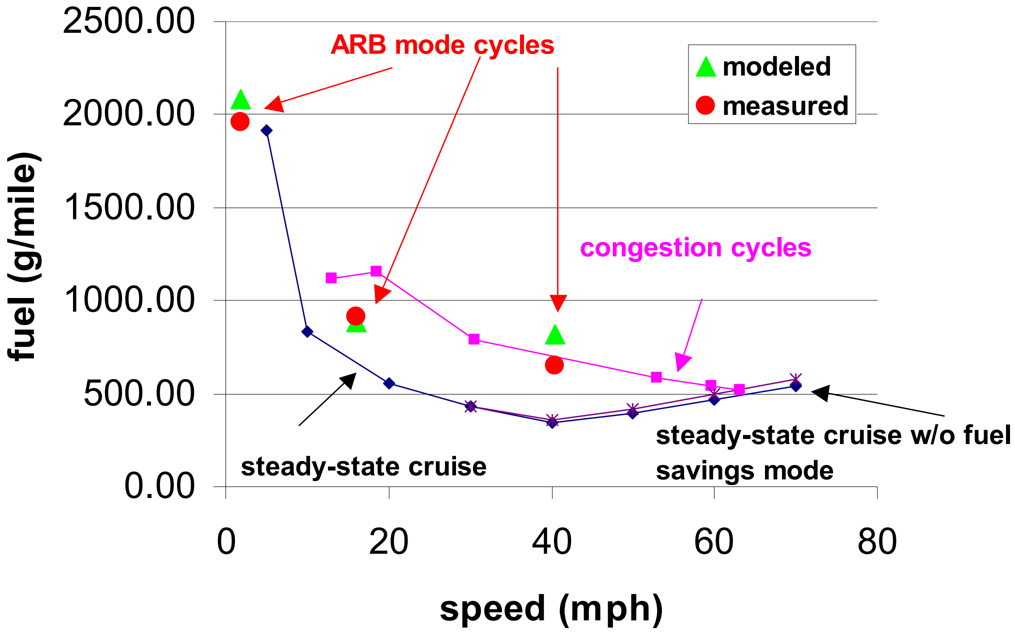

Figure 6.6a. Fuel consumption vs. average vehicle speed, for variable exercises, for CMEM category 47 vehicles (1999-2002 HDD trucks).

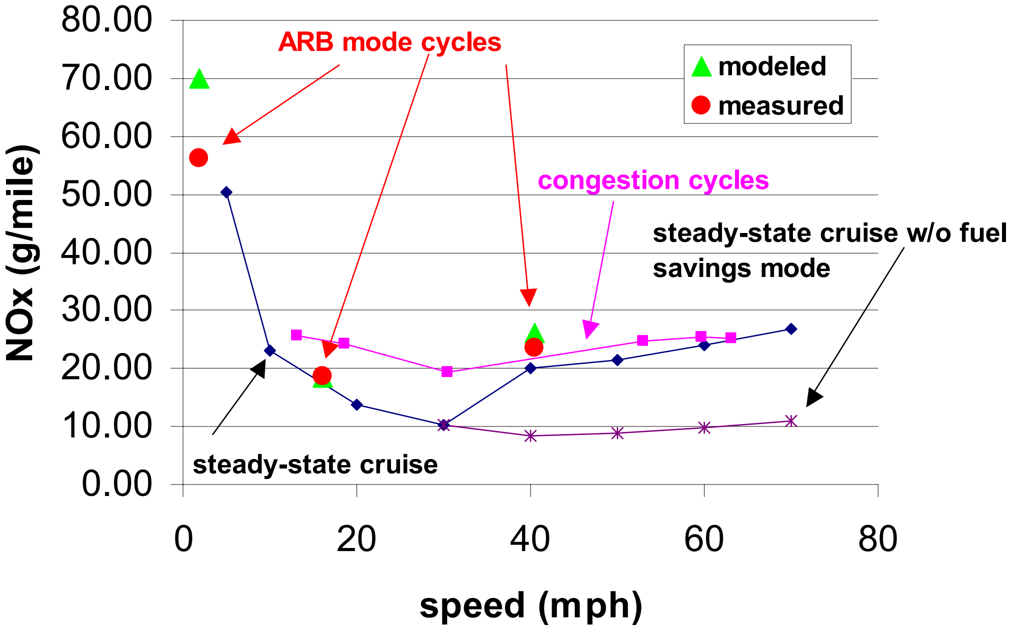

Figure 6.6b. NOx emissions vs. average vehicle speed, for variable exercises, for CMEM category 47 vehicles (1999-2002 HDD trucks).

Several conclusions can be made from these graphs:

- The steady-state cruise conditions do indeed provide the lowest fuel consumption and emissions. Since there are no strong acceleration/deceleration events during these steady-state conditions, there are no high power and thus high fuel consumption and emissions events;

- By comparing the fuel savings mode of operation versus controlled NOx mode (see a description of the dual modes in Section 4.5), a fuel savings of approximately five percent is typically gained at higher freeway speeds. This is shown in the fuel consumption graphs where both controlled vs. non-controlled fuel-savings mode conditions are plotted. Similarly, NOx emissions are shown for these two conditions, with NOx increases as great as 100% in some cases.

- The congestion fuel consumption and emissions are shown in purple. These conditions represent typical traffic on a freeway under different levels of congestion. These results are obviously higher than the steady-state conditions since there are a variety of acceleration/deceleration events as the vehicle moves with traffic. Under heavy congestion conditions, there are even cases where traffic occasionally stops, with a low overall average speed.

- Also plotted in these graphs are both the measured and modeled CARB HDD mode cycles, shown in red (measured results) and green (modeled results). In nearly all cases, it can be seen that modeled results matches fairly well with the measured results, with the exception of very low speed. At these low speeds, the model tends to over predict fuel consumption and emissions. Further, these CARB HDD mode cycle values should be fairly close to the modeled congestion cycles since they represent the same type of traffic conditions. In most cases, the do match well to the purple congestion line.

6.2.2. Modeled Platooning Effects on Fuel and Emissions

As described in Section 4.10, the model also incorporates the functionality of load reduction due to aerodynamic drafting effects when the HDD vehicles are traveling with close inter-vehicle spacings. To see the effect of this load reduction, we used our integrated modeling tools to simulate two trucks traveling in tandem at various steady-state cruise speeds and at different inter-vehicle spacings. The speeds include 5, 10, 20, 30, 40, 50, 60, and 70 miles per hour. For example category 45 (1994-1997 MY truck), the results are shown in Figures 6.7a (fuel consumption) and 6.7b (NOx emissions). In these graphs, the different truck spacings results are shown for spacings of 2, 3, and 5 meters, as well as the trucks not traveling in a platoon.

Overall, it can be see that at 60 mph cruise speed, platooning at spacings of 2 meters can give approximately a 15% fuel savings and potentially a 21% NOx savings. At greater spacings, these benefits are diminished: three-meters: 12% fuel savings, 18% NOx; five-meters: 8.4% fuel savings, 7.5% NOx.

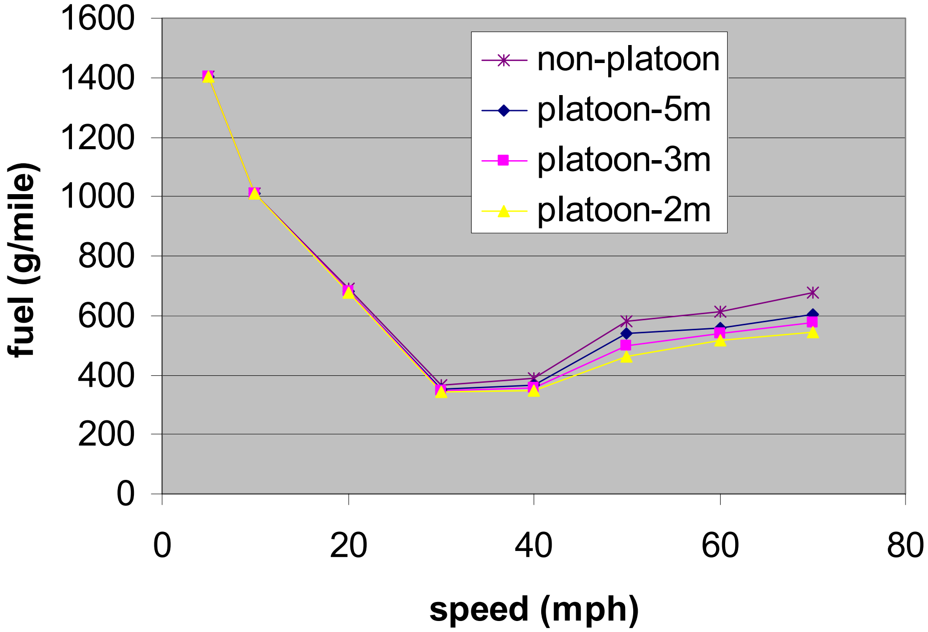

Figure 6.7a. Fuel consumption vs. vehicle speed, for non-platooning, and platooning with 5, 3, and 2 meter spacings.

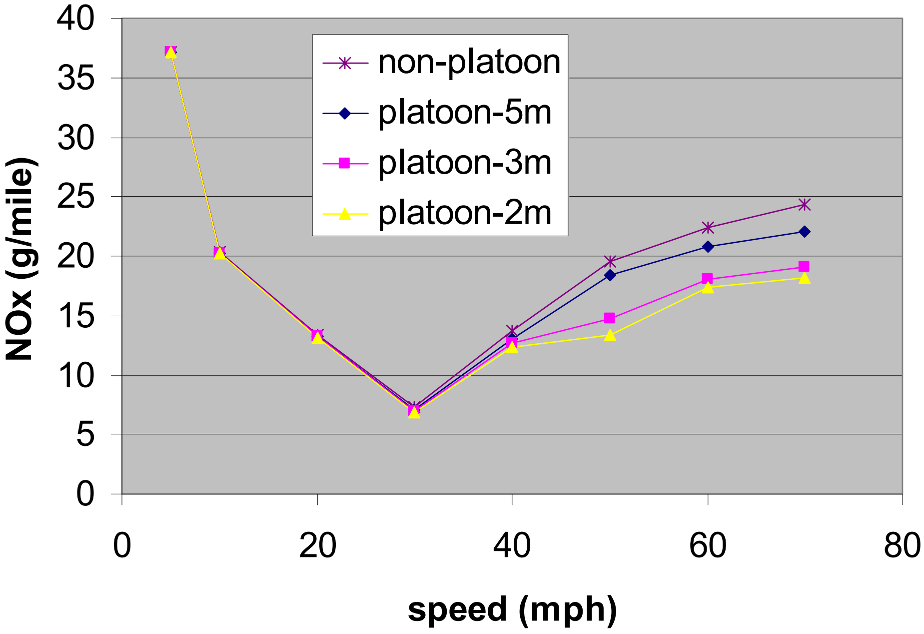

Figure 6.7b. NOx emissions vs. vehicle speed, for non-platooning, and platooning with 5, 3, and 2 meter spacings.

6.2.3. Modeling HDD Truck Maneuvers

As shown in the previous section, there are significant fuel consumption and emission benefits that occur when two or more HDD vehicles platoon, i.e., follow at relatively small vehicle spacings. Ideally, it would be advantageous to have as many trucks in a platoon, traveling for large distances. However, it will still be necessary for trucks to join into a platoon, and it will also be necessary for other trucks to drop out of a platoon. Specific *vehicle maneuvers* must be designed so that these transitions occur safely and so that they do not cause large perturbations to the traffic flow. Further, we want to design these maneuvers so that they do not have large impacts on fuel consumption and emissions. Since many of these maneuvers involve transient operations (i.e., accelerations/decelerations), high power events may induce higher fuel consumption and emissions.

In order to study these maneuvers and their impact on fuel consumption and emissions, we have carried out simulation modeling for several specific maneuvers.

The first such maneuver might be for a trailing truck wanting to join an existing platoon. The joining truck would have to accelerate up to the speed of the existing platoon and join slowly enough from behind to meet specific safety requirements. From a fuel consumption and emissions point of view, hard accelerations will induce greater power demand, resulting in high fuel consumption and emissions. However, a long drawn-out join procedure is also not desirable. Therefore the acceleration rate should be chosen so that the following vehicle can close in on a platoon in a reasonable amount of time, and yet not be overly aggressive such that high power events are minimized.

We can specifically examine a maneuver where one truck in a three-vehicle platoon will want to exit the platoon and exit the freeway. One such distance-time diagram may look like Figure 6.8. In this diagram, the lead vehicle is traveling at a constant speed (20 m/s), shown as a single line at the top of the distance-time diagram. The second vehicle is following at 5 meters spacing, followed by a third vehicle at the same spacing. In the middle of the plot, a platoon split maneuver occurs. In a platoon split, the platoon is divided at the vehicle that needs to exit. The upstream segment of the platoon decelerates as a whole, then accelerates back up to the nominal highway speed, leaving a sufficiently large safety gap between the two platoons. The leader of the upstream platoon (the vehicle that needs to exit) then changes lanes, and the second vehicle in the platoon becomes the new leader. The upstream platoon then performs a merge maneuver, rejoining the two segments.

In Figure 6.8, the rejoin acceleration is done very aggressively, using a constant acceleration profile. This is compared to another scenario where the join acceleration is done under a more relaxed constant power acceleration, shown in Figure 6.9. This is further compared to a longer join procedure where the vehicles again undergo a constant power acceleration, however at a reduced power level (Figure 6.10). The fuel consumption from these scenarios are shown in Figure 6.11.

Overall, we do not see tremendous differences in fuel consumption between the different scenarios. The aggressive constant acceleration method has the highest total fuel consumption, as expected. The moderate power scenario actually had less total fuel burned for the maneuver compared to the passive-power scenario. This is primarily due to the fact that the passive-power scenario was stretched out in time, and the cumulative fuel consumed ended up being slightly larger.

The overall conclusion is that there are not significant fuel consumption differences between how these maneuvers are performed in terms of accelerations and resulting power requirements. This is due to the fact that the diesel engines fuel consumption and emissions do not sharply increase between relatively high load power conditions. This is evident in Figures 6.4 – 6.6, where the slope of the fuel consumption and emission curves only had slight positive slope at the higher speeds. This is in contrast to some light-duty vehicles, that often have a non-linear response at higher load conditions, due to strategies that put the light-duty vehicle's emission control system into an enrichment mode (see [Barth et al., 1999]).

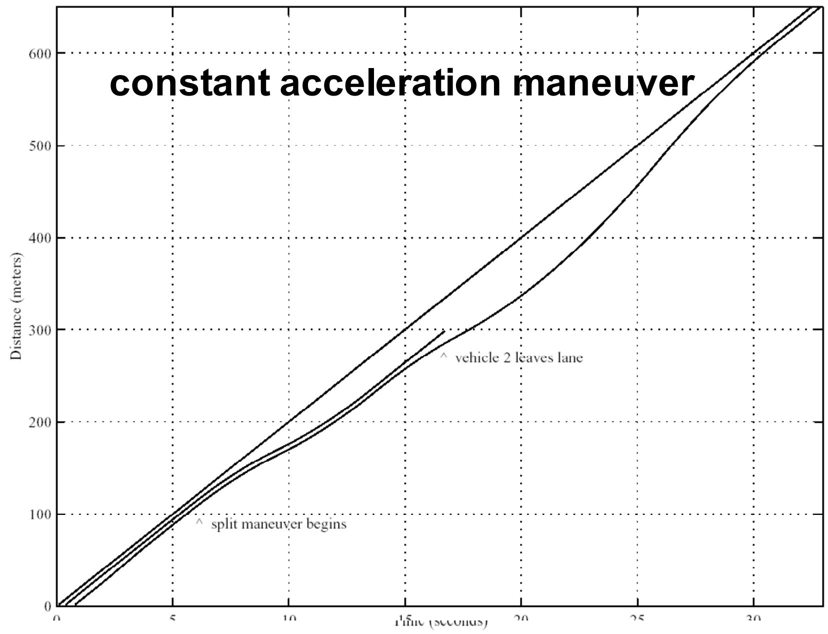

Figure 6.8. Distance-time diagram for a three truck platoon where the middle truck leaves the platoon, then the following truck catches up to the lead truck using a constant acceleration profile.

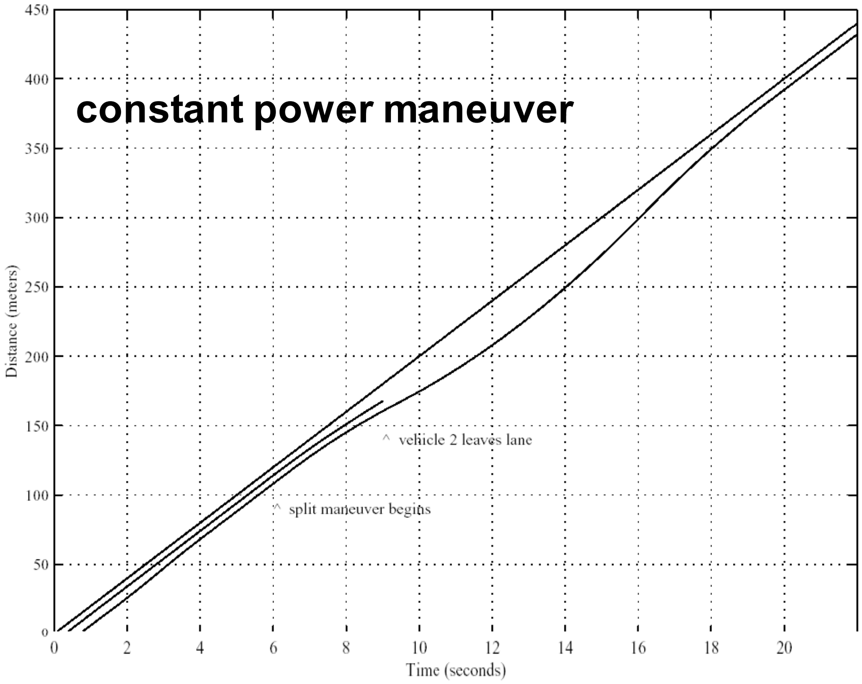

Figure 6.9. Distance-time diagram for a three truck platoon where the middle truck leaves the platoon, then the following truck catches up to the lead truck using a constant power profile.

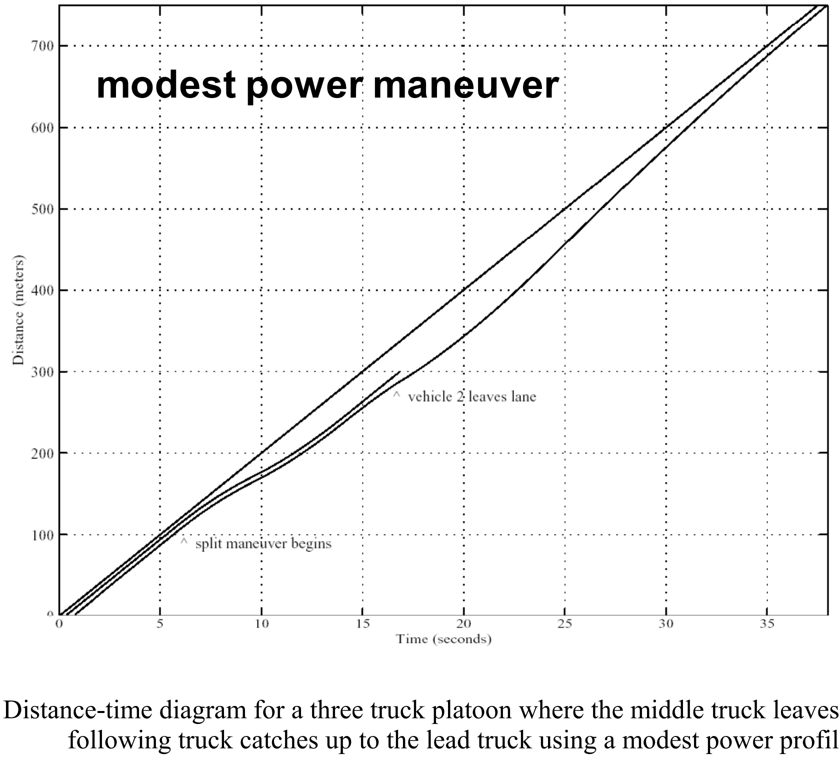

Figure 6.10. Distance-time diagram for a three truck platoon where the middle truck leaves the platoon, then the following truck catches up to the lead truck using a modest power profile.

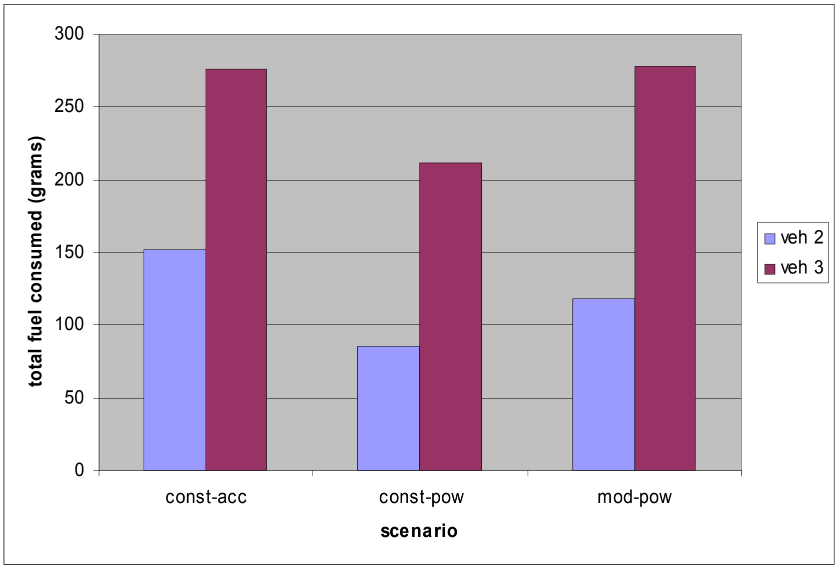

Figure 6.11. Cumulative emissions for trucks number 2 and 3 for the three scenarios.

7. In-Situ Testing with Platooning Trucks

In addition to the HDD vehicle modeling, this project also included a task to perform real-world testing along with other PATH investigators, examining fuel consumption and emissions effects of platooning trucks. In conjunction with Professor Fred Browand from the University of Southern California (USC) and PATH's HDD truck team, experiments were carried out with two identical Freightliner tractors pulling trailers and operating in tandem at close spacings. Fuel consumption and emissions were measured using MERL as one of the trailers in the experiments, operating at various speeds and spacings. The USC team has also reported on this experimentation in Task Order 4214 [Browand et. al., 2004].

These experiments were carried out at the Crows Landing airfield runway in the San Joaquin Valley of California. This airfield is no longer active, but is often used by PATH researchers to perform vehicle testing. The main runway (shown in Figure 7.1) is approximately 7875 feet long, oriented in a north-south configuration The runway has a very slight up-grade (0.45%) traveling southbound. To eliminate the effects of grade, experiments were conducted both in the north-bound and south-bound directions, and results were averaged.

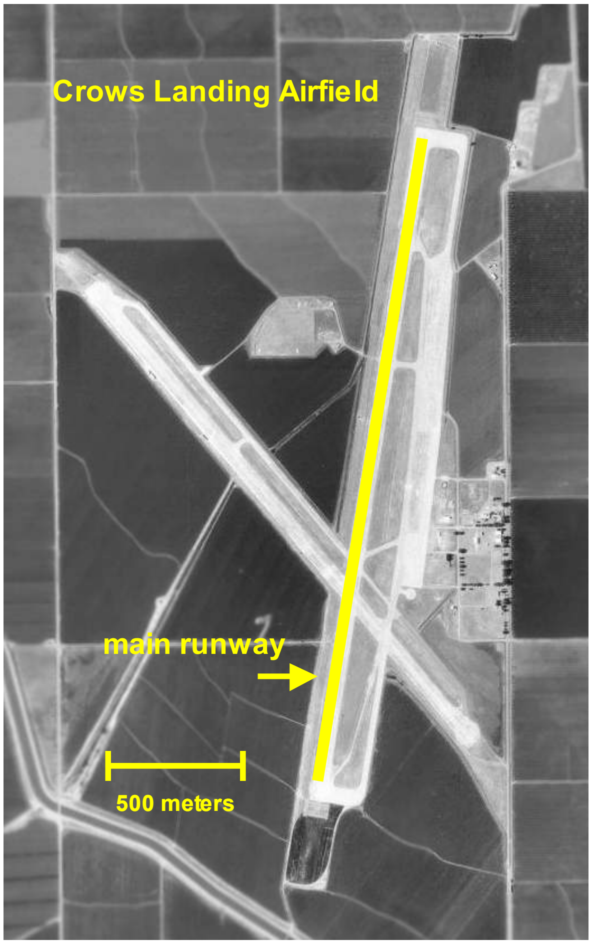

Figure 7.1. Crows Landing Airfield.

For the experiments, two Freightliner 2001 trucks were used, both powered by Cummins N14 engines rated at a maximum horsepower of 350 HP. The PATH HDD team has modified the engine controls to allow throttle and braking to occur via computer control. For the platooning experiments, a laser range finder is mounted on the front of the following truck, providing input to a control system that can maintain a fixed separation between the trucks. The accuracy of the control is on the order of a few centimeters. The PATH HDD team has also equipped these tractors with lateral control (i.e., steering), however in these experiments the lateral control systems were not used and steering was performed by licensed drivers.

The two trailers are standard 53-foot trailers that were nearly identical. The shapes were the same, they were mounted in similar positions, and the tire pressure was set equally among all tires (110 psi). MERL (see Section 3.1) served as one of the trailers during the experimentation. The vehicles were weighed at a truck weighing station. Table 7.1 provides the test weights. The two trucks are shown in Figure 7.2.

Table 7.1. Vehicle Test Weights.

Truck/Trailer	Test Weight
Tractor 1 (Gold Tractor)	18770 lbs
Tractor 2 (Blue Tractor)	18570 lbs
Empty Trailer	13851 lbs
MERL trailer	44906 lbs

Figure 7.2. Trucks during testing.

7.1. Testing Procedure

The testing took place in October 2003, when the temperature varied from a low of 48 degrees F to a high of 69 degrees F. The nominal temperature during testing was approximately 56 degrees, with relative humidity at 70%. The winds during the testing were generally light at 4 – 5 mph.

On one of the test days, there was light rain in the morning and those tests were not used in the analysis.

Because of the linear configuration of the runway, the vehicles simply had to travel down the runway, brake to a stop, then turn around travel the opposite direction. As a result, the test runs were constrained in the distance that could be performed. To start from 0 mph, get up to a steady-state velocity, then decelerate in time, it was possible only to maintain a steady-state velocity of approximately 50 mph for about 10 seconds.

For all of the experimental runs, the vehicles were completely warmed up and operated in hot-stabilized condition. Each run was made under closed-loop longitudinal control, where one truck was following the other at a prescribed distance. While the control system was running, data was being acquired from the engine control modules in both tractors, as well as on MERL. Later, the data sets had to be matched and time aligned so that the data could be properly analyzed.

Test runs were made at different spacings, including separate runs in isolation. The emissions trailer was put both in the lead and following position, and several runs were made for spacings of 10, 8, 6, 4, and 3 meters (along with ∞ meters for the isolated runs).

An example plot of a test run is shown in Figure 7.3. In this figure, the velocity is shown in purple, with the distinct acceleration, steady-state cruise, then deceleration events. The fuel consumption is closely related to the CO_2 emissions, which is plotted in dark blue. Also on this graph are NOx emissions, shown in green. Even with the data undergoing noise filtering, it is still possible to see the oscillations in the control system during the close spacing tests.

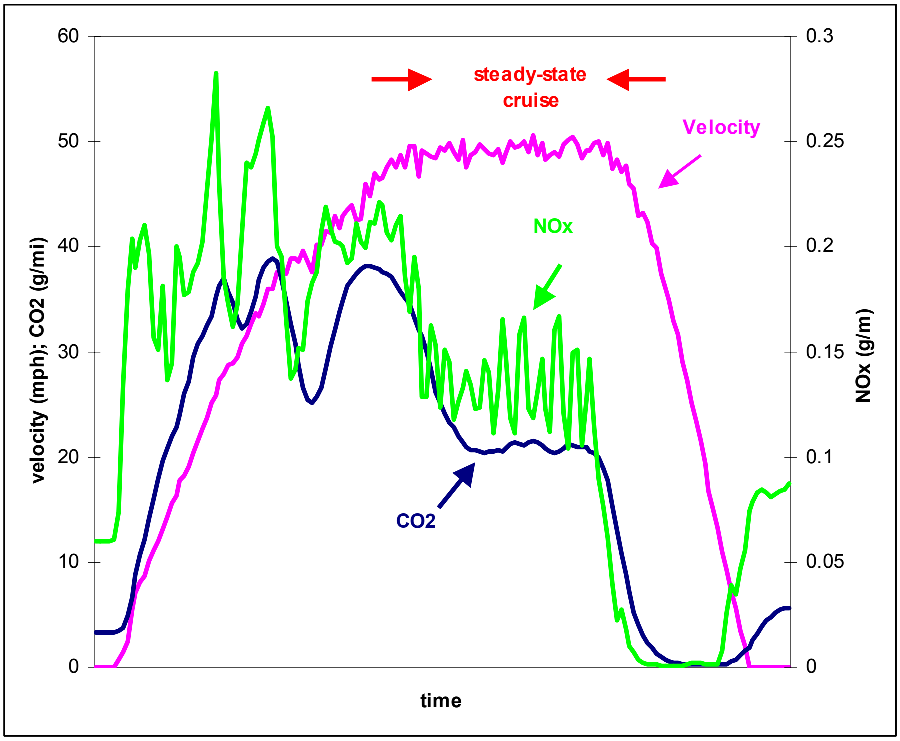

Figure 7.3. Typical Velocity, Fuel, and Emissions Profile for Test Truck.

7.2. Results

A thorough analysis of the data has shown that there is a high degree of variability in the results. The variability is due primarily to run-to-run variations with slightly different steady-state cruise speeds, speed fluctuations due to the control system, and other effects such as wind. The best way to eliminate this variability is to establish a much longer steady-state cruise period, longer than the 10 seconds, and use the data to determine a better average set of readings for all measurements.

Nevertheless, we have carefully extracted the NOx and CO_2 (i.e., fuel) data for the different steady-state cruise periods of each run. Both north- and south-bound results were averaged. The results are given below.

In Table 7.2a the average measurements for the *lead* vehicle are given. Table 7.2b shows the benefit for the lead truck when compared to a non-platoon situation.

Table 7.2a. Lead truck measurement data at different spacings.

Lead Truck Benefit (%) compare to no-platoon			
spacing	**CO2**	**NOx**	**fuel**
10 M	8.15	5.58	8.14
8 M	10.00	-2.18	9.98
6 M	1.29	1.01	1.28
4 M	11.28	4.38	11.26
3 M	15.54	7.60	15.49

Table 7.2b. Lead truck benefits when compared to a non-platoon situation.

Lead Truck raw data			
spacing	**Avg CO2 gm/s**	**Avg NOx gm/s**	**Avg fuel gm/s**
inf M	31.60	0.18	9.99
10 M	29.03	0.17	9.18
8 M	28.44	0.19	9.00
6 M	31.20	0.18	9.87
4 M	28.04	0.18	8.87
3 M	26.69	0.17	8.45

These results are plotted in Figure 7.4a, 7.4b, and 7.4c for CO_2, NOx, and fuel, respectively.

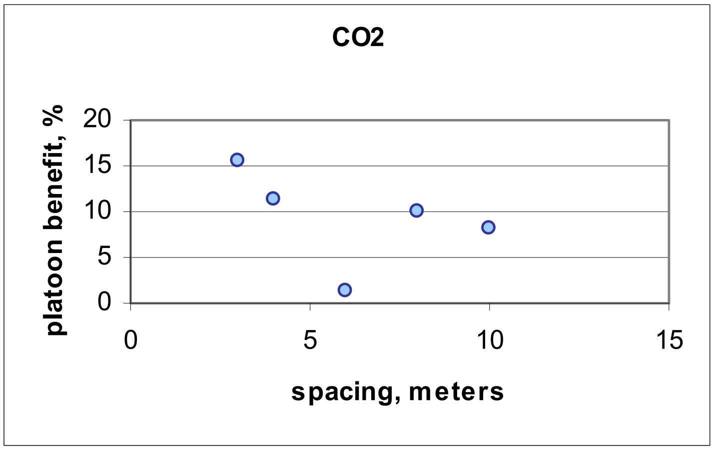

Figure 7.4a. Lead truck benefits when compared to a non-platoon situation, for CO2.

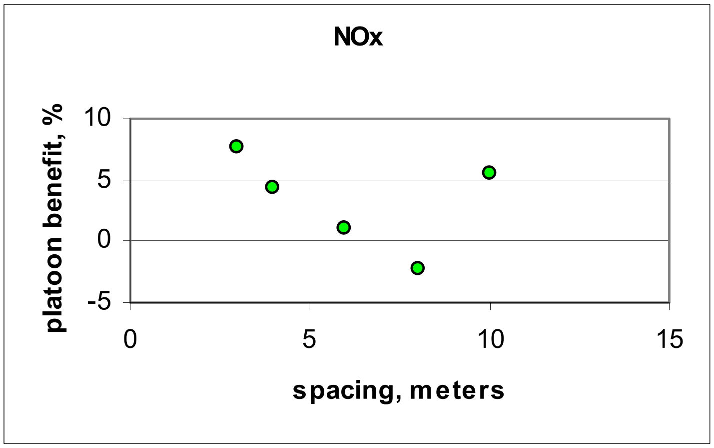

Figure 7.4b. Lead truck benefits when compared to a non-platoon situation, for NOx.

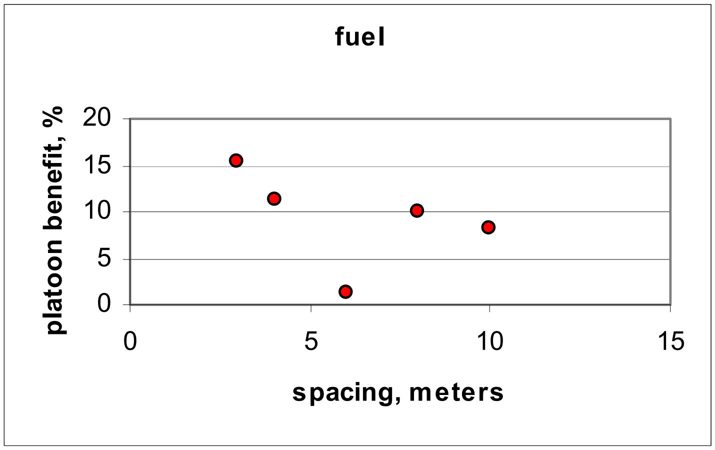

Figure 7.4c. Lead truck benefits when compared to a non-platoon situation, for fuel.

Similarly, Table 7.3a provides the average measurements for the *following* vehicle. Table 7.3b shows the benefit for the following truck when compared to a non-platoon situation.

Table 7.3a. Following truck measurement data at different spacings.

Follow Truck Benefit (%) compare to no-platoon			
spacing	**CO2**	**NOx**	**fuel**
10 M	7.56	1.42	7.49
8 M	7.93	3.26	7.87
6 M	11.55	3.88	11.49
4 M	17.74	1.08	17.66

Table 7.3b. Following truck benefits when compared to a non-platoon situation.

Follow Truck raw data			
spacing	**Avg CO2 gm/s**	**Avg NOx gm/s**	**Avg fuel gm/s**
inf M	33.44	0.2004	10.57
10 M	30.91	0.1975	9.78
8 M	30.78	0.1938	9.74
6 M	29.58	0.1926	9.36
4 M	27.50	0.1982	8.70

These results are plotted in Figure 7.5a, 7.5b, and 7.5c for CO_2, NOx, and fuel, respectively.

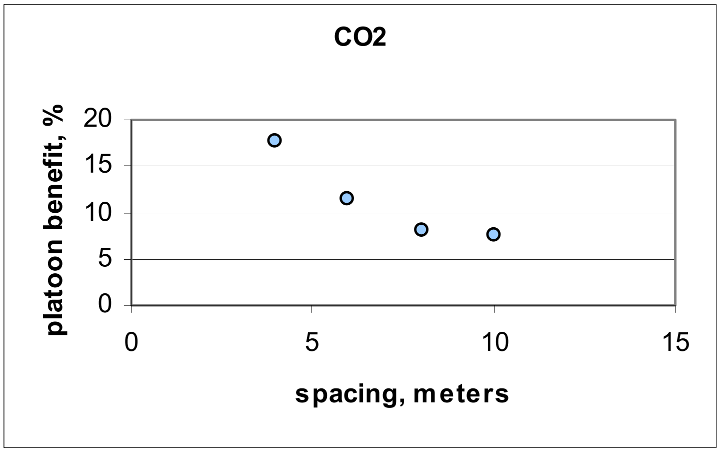

Figure 7.5a. Following truck benefits when compared to a non-platoon situation, for CO2.

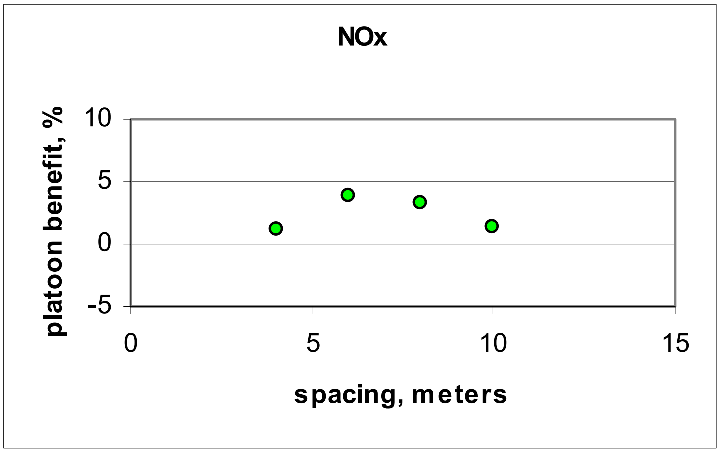

Figure 7.5b. Following truck benefits when compared to a non-platoon situation, for NOx.

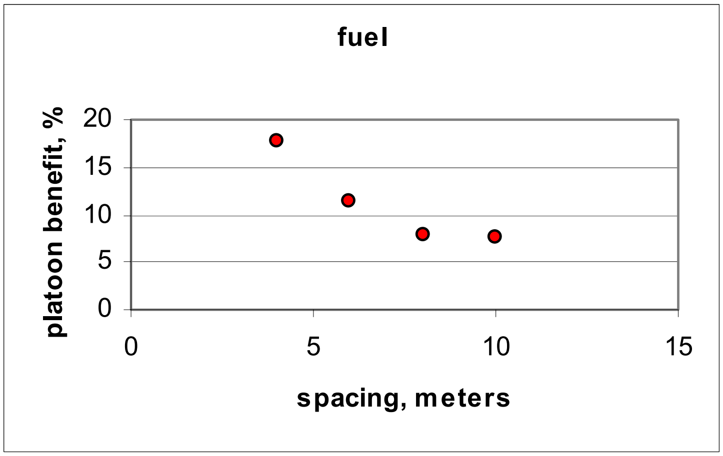

Figure 7.5c. Following truck benefits when compared to a non-platoon situation, for fuel.

It can be seen that there are moderate benefits for the lead vehicle: 1 – 15% in fuel and up to 7% in NOx emissions during platooning conditions. As expected, there is generally a larger benefit when the vehicle spacing is smaller. For the following vehicle, slightly better benefits can be seen: 5 – 16% in fuel and approximately 5% in NOx emissions. However, it is evident that there is a lot of variability in these results, stemming from the problem of such short (i.e., 10 seconds) measurement periods. It is nearly impossible to obtain consistent results during such short time periods when there are control system corrections, road surface perturbations, and slight wind shifts. It is also important to remember that these tests were carried out at approximately 50 mph; greater savings would be expected at higher speeds.

As a point of future work, longer steady-state data should be collected to average out the variations in the data. Further, the experiments were conducted with MERL operating with its rear door either open or closed, depending on whether it was the lead truck or following truck. It is thought that the aerodynamics change significantly with this rear door open or closed. Consistent testing should take place with the rear door closed if possible.

8. Conclusions and Future Work

HDD trucks play an increasingly important role in the overall emissions inventory since LDV emissions continue to decrease. In many microscopic transportation evaluations, it is important to have the ability to model second-by-second emissions of all vehicles. With the HDD vehicle models now in place, UC Riverside's CMEM program is now capable of simulating a wide variety of traffic scenarios.

The HDD truck models in CMEM are based primarily on testing carried out with UC Riverside's mobile emissions research lab. Vehicles will continue to be tested with MERL and the results will continually be added to the models. In addition, other HDD truck data are being collected from other programs and integrated into the CMEM models to provide further breadth.

The HDD truck emissions model described herein is based on a physical, power-demand approach. Because it is a physical model, it inherently handles fluctuations in power that may arise, such as changing road grade. Further, by modeling individual components of the physical process, it is possible to include emissions and fuel effects that arise from different control strategies. In this report, we have described the HDD model in detail and have provided our more recent results illustrating its effectiveness. We plan on using this model for evaluating a variety of traffic scenarios; in particular those that are associated with HDD trucks, such as continued work in truck climbing lanes and restricted truck lanes.

Also as part of this project, we have implemented the ability to evaluate ITS-related projects by combining the HDD vehicle fuel consumption and emission models with a variety of traffic simulation models. One of the key elements is the ability to model vehicle activity at close spacings, when aerodynamic drafting effects take place. We have built into the model the proper physical load reductions due to drafting based on data provided by the USC research team.

It has been shown that significant fuel emissions savings can be achieved when platoon vehicles travel with close inter-vehicle spacings. This was shown in simulation as well as with real-world experimentation. The real-world experimentation results showed benefits overall, however there was a large amount of variation in the data due to the nature of the test (i.e., the testing durations were too short).

When developing the HDD vehicle models, 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 these HDD emission models. 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. The advent of new emissions standards in 2007 are likely to force significant changes in total emissions and modal behavior of HDD trucks.

Additional Testing**—**The relatively small number of vehicles tested in this program need to be augmented with additional tests, particularly in pre-1994 model years.

Incorporation of Outside Data Sources**—**Additional HDD test data is available for HDD vehicles under EPA testing programs that are underway. Incorporation of these data into the model would greatly enhance the robustness of the model.

High Emitting Vehicles**—**In this project, high emitting vehicles were ignored. While it is likely that the high emitting HDD vehicles play a much smaller part in the total emissions of the fleet, they do warrant further investigation.

Additional On-Road Emission Testing**—**As stated above, additional testing should take place with HDD vehicles operating in tandem at close spacings. There is a large potential to save fuel and cut emissions, while maintaining safe operation.

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