Final Report

CRC Project E-68

ANALYSIS OF EPA'S DRAFT PLAN FOR EMISSIONS MODELING IN MOVES AND MOVES GHG

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BACKGROUND AND PURPOSE OF THE STUDY

EPA has proposed a new modeling method for on-road vehicle emissions called the Motor Vehicle Emission Simulator (MOVES). To date, the MOVES model is an effort to estimate emissions produced by on-road vehicles by more closely accounting for engine and after-treatment device response to vehicle operation. Important vehicle operating parameters have yet to be fully defined for all emissions, but include, at a minimum, engine load as calculated from speed, grade, and vehicle weight. The initial release of the MOVES model is scheduled for mid-2004; this version, called MOVE GHG, will address only greenhouse gas emissions, which are primarily due to fuel consumption. Later versions of MOVES to be released in the coming years will address regulated pollutant emissions (including hydrocarbon, carbon monoxide, nitrogen oxides, and particulate matter) for on-road and off-road vehicles.

This report reviews the overall MOVES model design and the approach to be implemented in MOVES GHG using the publicly available information and presentations provided by EPA through the end of 2003. It is important to note that at that time EPA had not finalized many of the details of the approach for regulated pollutants.

This study consisted of three main tasks: (a) a review of the overall MOVES approach for on-road vehicles; (b) a review of specific issues related to the modeling of greenhouse gases; and (c) a review of the portable emission monitoring system (PEMS), an innovative in-situ emission measurement method to be used in gathering future emissions data for MOVES. For this work, CRC provided a list of very specific questions; these are provided in Appendix A with brief responses indexed to the parts of the report addressing each question.

REVIEW OF OVERALL MOVES APPROACH

Our review of the overall MOVES design addresses the vehicle fleet definitions, vehicle activity parameters that affect regulated pollutant emissions, in-use emission adjustments, how activity data could be incorporated into regional emission estimates, and how bias and uncertainty will be incorporated into the model estimates. Key issues discussed in the report are:

Vehicle Fleet Definitions

- Differences between the fleet definitions used by EPA emission standards, transportation monitoring devices, and registration programs need to be resolved.
- EPA's original draft design document described too many vehicle types for practical models.
- Data gathering efforts need to focus more on light-duty and heavy-duty trucks.
- Remote sensing can and should be used to adjust for a potential selection bias when recruiting vehicles for emission testing; methods are outlined how this would be accomplished.

Effect of Vehicle Operation on Regulated Pollutants

- Vehicle specific power (ratio of instantaneous engine power and vehicle weight) for light-duty vehicles and vehicle power for heavy-duty vehicles are clear indicators of exhaust pollutant emissions.
- Other vehicle operating parameters (such as instantaneous load changes, vehicle speed, and other parameters) will be necessary to explain all emissions responses.
- The EPA plan to use operating parameter bin (such as a power range) averages instead of statistical regressions to describe emissions will reduce the applicability of the model in predicting specific situations and may bias the emission analysis.

In-Use Adjustments

- In-use adjustments for ambient conditions (including altitude, temperature, humidity and others) and fuel effects have been described to date using only test cycle (long stretches of driving activity) averages; efforts should be directed at determining adjustments for more specific vehicle activity modes, such as activity parameter bins.
- Adjustments should not be applied to data collected to date to avoid compatibility problems should these adjustments be improved in the future.

Use of Activity Data

- The MOVES draft design outlines an emissions modeling tool that is more advanced than the available activity information typically collected by transportation monitoring systems.
- New data should be collected in terms of distributions of vehicle weight, speed and acceleration by congestion conditions for all road types.
- On-road transportation networks will need to be more detailed by defining ever smaller road links in order to fully use the ability of the planned MOVES model.

Incorporation of Uncertainty

- EPA's most recent work evaluated the propagation of errors approach, as it may be computationally less demanding than the more rigorous Monte Carlo approach originally considered, but that work considered only more simplified functional forms than used in MOVES, and did not use any actual emissions data for the evaluation.
- To reduce the uncertainty in the predicted emission rates, EPA also needs to identify those bins with the largest and/or most variable emissions, and be sure to adequately populate those bins.
- EPA should also work with transportation planners to develop uncertainty estimates for the transportation modeling-based activity estimates.

SPECIFIC ISSUES RELATED TO THE MODELING OF GREENHOUSE GASES

In the MOVES GHG version, vehicle power is used to model fuel consumption, and therefore CO_2 emissions. This approach is shown to mostly explain the available data. EPA has been using a separate model called the Physical Emission Rate Estimator (PERE), which was developed as a tool to assist the MOVES fuel consumption modeling. PERE can be useful for filling or interpolating missing data ranges, but it is not a shortcut for a well-stocked and representative data set. The prediction of criteria pollutants using PERE requires an aftertreatment model, which is not yet available. EPA plans to incorporate Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation

(GREET) model, which addresses CO2 emissions from extraction, refining, processing, and delivery of the fuel, into its greenhouse gas estimates, but this report did not address GREET. Key issues arising from the review of the MOVES GHG modeling are:

- EPA should identify and explicitly determine the fuel parameters, especially the lower heating value, for test and in-use vehicles used to generate data for MOVES.
- If PERE is to be used to describe the vehicle power requirements, EPA needs to generate a great deal of information to estimate the engine efficiency and power requirements of vehicles for different engine and chassis technologies.
- Whether or not PERE is used, EPA needs to develop basic information about vehicle weight, rolling resistance, and aerodynamic drag, especially for heavy-duty vehicles, in order to estimate vehicle power distributions among vehicle types.
- EPA should fund projects to test whether remote sensing data can be used to check and adjust or extend the use of PEMS or laboratory data results.
- The correlation of CO_2 emissions and also regulated pollutants was improved by adding terms describing the rate change in power to a correlation using only the power demanded by the vehicle.
- Transportation sources are a minor source of methane emissions; methane emissions estimates should be indexed to criteria pollutants (likely total hydrocarbon) based on smaller studies designed for that purpose.
- Likewise, because of the lower importance to overall greenhouse gas emissions, N_2O should be indexed to criteria pollutants (likely NOx emissions) based on smaller studies designed for that purpose.
- If EPA is concerned about GHG from vehicles, they should account for all GHG generated by vehicles including particulates, refrigerants, and the GHGs generated in making and recycling vehicles. Of those emissions, MOVES would only be suitable for estimating particulate emissions. Some alternative GHG emission sources are addressed in the GREET model which may be incorporated into MOVES.

REVIEW OF THE PORTABLE EMISSION MONITORING SYSTEM (PEMS)

PEMS is a new method that allows emissions measurements during on-road vehicle operation. The advantage of PEMS is that emissions data can be collected more inexpensively than traditional laboratory methods, and that data can be gathered while drivers are operating their vehicle on surface roads rather than in the artificial laboratory environment on test cycles that may represent only some types of vehicle activity. The field data gathered by PEMS may also be used to represent in-use activity behavior in addition to gathering emissions data. Key issues arising from the review of the PEMS development through June 2003 are:

- Early versions of PEMS needed an independent means of determining exhaust flow without relying on the engines' computers; newer versions of the system have since included various methods of determining exhaust flow but still need validation.
- PEMS needs to be evaluated on malfunctioning and high emitting vehicles where on-board computers and sensors may not be functioning.
- EPA needs to determine an appropriate methodology to match the second-by second emissions measurements with vehicle operating parameters including load and other important variables.

- Laboratory and PEMS modal (second-by-second) measurements are not currently comparable at that fine a time scale, so data filtering methods (also called data smoothing) must be defined to resolve PEMS and laboratory data.
- However laboratory and PEMS measurements were comparable over longer time scales when emissions are averaged over time scales in excess of three seconds.
- PEMS can provide a wealth of activity information and emissions data at least as precise as laboratory measurements when proper data filtering methods are used.

1.0 INTRODUCTION TO MOVES DRAFT DESIGN

1.1 INTRODUCTION

This report reviews the current MOVES model design and approach to be implemented in MOVES GHG using the publicly available information and presentations provided by EPA through the 2003 calendar year. The primary focus of this report was to review exhaust emissions because the most revolutionary aspect of the MOVES model plan is to revise the method of estimating exhaust emissions using real-time driving behavior, especially power demands, to correlate emissions. EPA has intended to release the greenhouse gas (GHG) version of the model as the first version of MOVES approach, and GHG emissions are primarily tailpipe exhaust emissions. For these reasons, this report does not address any revised plans for evaporative emissions. Also, while off-road emissions are intended to be part of MOVES, the MOVES modeling approach as implemented for GHG has yet to address off-road sources.

The MOVES approach for modeling exhaust pollutants of interest, including HC, CO, NOx, and PM, is still developing, because these emissions are not a focus of the GHG version of the model. This report reviews the MOVES approach and data available through the end of 2003 for all exhaust emissions, acknowledging that EPA has not finalized it approach. The report provides a detailed review of the general structure of MOVES that will incorporate these exhaust emission estimates.

1.2 OVERVIEW OF MOVES GOALS

The stated goal of MOVES, quoted below, should also allow the user to apply the model for a variety of in-use situations. In order for MOVES to be successful in estimating mobile source emission inventories, predicting future emission inventories, and estimating control strategy future benefits, it must be able to incorporate data in the future which can be used to test its earlier predictions. The test of the model's success is the degree to which MOVES can satisfy its objectives, including providing a reasonable means to demonstrate and test the stated benefits of future control strategies.

> *"MOVES should encompass all pollutants (including HC, CO, NOx, particulate matter, air toxics, and greenhouse gases) and all mobile sources at the levels of resolution needed for the diverse applications of the system."*

The National Research Council published a thorough review of EPA's mobile source modeling program in 2000 (NRC, 2000). The NRC provided several recommendations for improving EPA's mobile source modeling tools, including:

(a) the development of a modeling system more capable of supporting smaller-scale analyses;
(b) improved characterization of emissions from high-emitting vehicles, heavy-duty vehicles, and off-road sources;
(c) improved characterization of particulate matter and toxic emissions;
(d) improved model evaluation and uncertainty assessments; and

(e) a long-term planning effort coordinated with other governmental entities engaged in emissions modeling.

MOVES must be able to predict emissions over a wide range of geographic and temporal scales. The range of geographic scales should be as small as for individual intersections and as large national estimates. The range of temporal scales could be as short as by individual driving event, such as acceleration from a traffic light, or as long as an annual estimate. It is expected that MOVES will require activity inputs provided from another source, typically transportation or local and regional planners, so MOVES must be compatible with the expected data sources or provide reasonable estimates for potential data gaps.

In this report, the review of MOVES focused on on-road mobile emission sources on a regional or macro scale because the first version of MOVES, the greenhouse gas (GHG) model, will predict emissions primarily affected by national and annual activity. Also, because MOVES GHG will be a more general model than subsequent versions, certain elements of future MOVES models have not been fully developed in terms of data or analysis approaches.

1.3 ORGANIZATION OF THE REPORT

The organization of the report follows the general MOVES method design (Section 2), specific issues related to the modeling of greenhouse gases (Section 3), and the portable emission monitoring system (PEMS) to be used in gathering future emission data for MOVES (Section 4). The report is outlined below with additional description to follow. Many of the subsections under Section 2 that describe and review the general implementation of the model in estimating all pollutants carry over in the implementation of MOVES GHG. So while Section 2 provides information about the general design, specific issues related to GHG are further developed in Section 3.

The CRC sponsoring committee for this report had a series of specific questions for which it desired answers. These questions are provided in Appendix A with short answers and point the reader to sections of the report where more discussion is available for that question.

1.3.1 Section 2: General Review of the Design And Approach for the MOVES Model

Because the MOVES model represents a significant departure from early methods based on limited but well defined laboratory generated data, the model deserves added scrutiny in terms of the basic method and structure, data needs, and quantifying the potential errors. Section 2 describes the vehicle fleet categorization and identification, how regulated pollutants respond to vehicle activity parameters, adjustments for ambient conditions and fuel types, incorporating and generating activity data, and estimating uncertainty and bias.

The purpose of Section 2 was to provide an overall review of the draft design of MOVES with regard to all emissions, both regulated pollutants (hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter) and greenhouse gases. This section is divided into five subsections: a description of the in-use fleet; the effect of driving activity on regulated pollutants; the incorporation of adjustment factors; consideration of incorporating activity information; and a discussion of uncertainty, bias, and accuracy.

1.3.2 Section 3: Issues Specific to MOVES GHG

There are specifics concerning MOVES GHG distinct of the overall framework of the general MOVES model for all emissions. Section 3 addresses issues unique to the implementation of the first version of MOVES, the greenhouse gas model (MOVES GHG). Section 2 reviews the plan, data gathering, and implementation of MOVES for emissions including regulated pollutants.

The MOVES GHG model, now planned for release in 2004, will estimate total carbon dioxide (CO_2) exhaust emissions [including all carbon species by also adding carbon monoxide (CO) and total hydrocarbon (THC)] from estimates of the fuel consumption rates. EPA plans to relate these fuel rates to the power demanded by the operation of the vehicles and to variables associated with the technology of the vehicles including factors affecting efficiency and other design elements.

Section 3 examines whether the 'first principles-based' PERE model or a more data-driven empirical approach based on relating the fuel rate to vehicle specific power (VSP) is a more suitable way to estimate CO2 emissions as a function of vehicle type, age, and activity. This report concludes that the PERE approach is useful either for interpolating empirical results or used directly and calibrated with data to more accurately reflect in-use efficiency, but its use is not necessary to produce an emission inventory model.

Whether PERE or a more empirical approach is used, VSP therefore is intended to be the basic correlating variable to estimate the fuel consumption rate for each vehicle. This assumption that VSP is the primary variable to explain fuel rate was tested with available data, and the data suggested that changes in VSP with time (such as during hard accelerations and decelerations and likely associated with different operational efficiency than other modes of operation), provide additional explanation of fuel consumption.

While the primary purpose of MOVES GHG is to accurately predict CO_2, other greenhouse gases including nitrous oxide (N_2O), methane (CH_4) or black carbon are also produced by mobile sources and will be accounted in the overall framework of MOVES but not within MOVES GHG. Refrigerants and other potential greenhouse gases can be emitted from vehicles, but are unrelated to fuel combustion and are not reviewed here.

The current plan for MOVES GHG is only practical for producing estimates of fuel consumption. A number of vehicle and technology types deserve additional study beyond the current information available for Tier 0 and Tier 1 light-duty vehicles and trucks. Either a data-calibrated PERE model or an empirical model can provide equally valid results provided all explanatory variables in addition to VSP and mass have been tested for significant improvement to the estimates.

1.3.3 SECTION 4: Review of PEMS Method And Design

This section reviews the PEMS measurement method and available confirmation data to determine if the measurements are valid for model development. The PEMS data gathering method does not appear to introduce more variability into the results, but may not be sufficient to address all in-use conditions. The PEMS method can also be used to generate vehicle driving behavior data to better represent in-use activity.

The review of the PEMS method required an evaluation of the results by comparing time resolved laboratory and PEMS results from the available data set. The laboratory testing identified areas of concern for future evaluations at the 1 Hz (second-by-second) time level, though the emissions averaged over a test cycle were comparable. It was unclear whether the modal laboratory measurement method or the PEMS results were more accurate at the 1 Hz time level.

In addition, field experiments may introduce added uncertainty through ambient (temperature, barometric pressure, humidity, etc.), road (surface roughness, snow or rain introduced wheel slip), or vehicle condition (leaking exhaust, aging transmission, or other functional tests). The PEMS data therefore requires additional tests to produce the same level of certainty that laboratory data do. The available data reviewed demonstrated that the ease of data generation more than compensated for the added uncertainty introduced from the field measurements. However, the range of vehicle driving behavior during field testing, especially high VSP conditions, is more limited than laboratory test cycles because drivers generally do not drive with the abandon of the more aggressive laboratory driving cycles.

ENVIRON provided an overview of the PEMS design to identify areas of continuing concern regarding the data. The quality of the data will be affected by the treatment of the raw measurements in terms of filtering and data quality screening methods. The concerns of PEMS data treatment include but are not limited to data time offset and treatment, accuracy of factory installed computer data, introduced noise, and other data gathering issues characteristic of field data.

2.0 REVIEW OF EPA MOVES DRAFT DESIGN

2.1 INTRODUCTION

The purpose of this section is to provide an overall review of the draft design of MOVES with regard to all emissions, both regulated pollutants (hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter) and greenhouse gases. This section is divided into five subsections: a description of the in-use fleet; the effect of driving activity on regulated pollutants; the incorporation of adjustment factors; consideration of incorporating activity information; and a discussion of uncertainty, bias, and accuracy.

Subsection 2.1 describes the considerations when defining the fleet of in-use vehicles. This includes a review of the vehicle class definitions showing inconsistency among the categorizations used by EPA, activity data collectors, and State registration databases of fleet vehicles. The current database that EPA is using for developing MOVES (as of September 15, 2003) includes vehicles only up to model years 2001, and included much fewer light and heavy-duty trucks than light-duty passenger vehicles. A continuing concern is the potential selection bias for lower emitting vehicles in studies included in the EPA database, and we discuss methods to identify the proper fraction of high emitters in the fleet through remote sensing.

Subsection 2.2 describes methods and considerations when identifying important activity parameters to describe regulated pollutants. This subsection includes a review and analysis of the emission response to vehicle power for light-duty (normal and high emitters) and heavy-duty vehicles. The analysis demonstrates that a number of additional vehicle driving parameters beyond vehicle specific power (VSP) could be important to explain the emission rates. The analysis shows that binning vehicle activity (VSP) may not be necessary to describe emissions rates.

Subsection 2.3 reviews the in-use adjustments for ambient conditions (altitude, temperature, and humidity) and fuel effects. The development of adjustments for these conditions deserves further study because the adjustments to date have been developed on test cycle total emissions rather than emissions under the variety of conditions to be modeled under MOVES, and in many cases (especially the effect of humidity) rely on studies performed in the 1970s. These adjustments have currently been applied to laboratory and PEMS field data, so the emissions gathered to date may need to be reconsidered in light of revision to the adjustment equations.

In Subsection 2.4, a review of the opportunities and challenges for the incorporation of activity data into MOVES is provided. The opportunity of the MOVES modeling method is to better describe emissions with actual vehicle operation on specific roadways and conditions, but the challenge is that it will require significant resources to improve the collection of activity information to make the emissions estimates relevant. EPA will need to generate default activity for a large variety of roadway types and conditions (congestion, signal timing, and many others); otherwise, local transportation planning organizations may be overwhelmed by the model requirements for appropriate activity inputs.

Section 2.5 discusses uncertainty, bias, and accuracy issues for the MOVES model. Following recommendations of the National Research Council (NRC, 2000), MOVES will be the first on-road mobile source emissions model that will include estimates of uncertainty, primarily to be used as a tool to guide EPA on how to improve the model. Sources of uncertainty and bias in the data underlying MOVES are discussed. We review the two approaches EPA is assessing for evaluating MOVES uncertainty, and discuss concerns with populating the very large number of bins proposed for the model.

2.2 VEHICLE SELECTION AND FLEET CHARACTERIZATION

2.2.1 Introduction

This section outlines the issues associated with vehicle definitions, reviews the available data to estimate emissions, and describes methods for identifying high emitter fractions among the in-use fleet.

EPA will need to define the vehicle fleet using individual vehicle types that provide sufficient categorization to explain different emission rates. EPA has historically defined vehicle categories by the applicable emission standards and gross vehicle weight rating (GVWR), but activity information from transportation agencies and registration databases distinguish between different sets of vehicle definitions than those currently used by EPA.

Table 2-1 provides the vehicle type definitions currently used within MOBILE6, which further delineates by model year to address the effect or expected effect of emission standards. The vehicle definitions therefore were a result of different emission standards by vehicle type and by gross vehicle weight rating (GVWR).

Table 2-1. Vehicle type classifications within MOBILE6.

Code	Vehicle Description
LDGV	Light-Duty Gasoline Vehicles (Passenger Cars)
LDGT1	Light-Duty Gasoline Trucks 1 (0-6,000 lbs. GVWR, 0-3,750 lbs. LVW)
LDGT2	Light-Duty Gasoline Trucks 2 (0-6,000 lbs. GVWR, 3,751-5,750 lbs. LVW)
LDGT3	Light-Duty Gasoline Trucks 3 (6,001-8,500 lbs. GVWR, 0-5,750 lbs. ALVW)
LDGT4	Light-Duty Gasoline Trucks 4 (6,001-8,500 lbs. GVWR, 5,751 lbs. and greater ALVW)
HDGV2b	Class 2b Heavy-Duty Gasoline Vehicles (8,501-10,000 lbs. GVWR)
HDGV3	Class 3 Heavy-Duty Gasoline Vehicles (10,001-14,000 lbs. GVWR)
HDGV4	Class 4 Heavy-Duty Gasoline Vehicles (14,001-16,000 lbs. GVWR)
HDGV5	Class 5 Heavy-Duty Gasoline Vehicles (16,001-19,500 lbs. GVWR)
HDGV6	Class 6 Heavy-Duty Gasoline Vehicles (19,501-26,000 lbs. GVWR)
HDGV7	Class 7 Heavy-Duty Gasoline Vehicles (26,001-33,000 lbs. GVWR)
HDGV8a	Class 8a Heavy-Duty Gasoline Vehicles (33,001-60,000 lbs. GVWR)
HDGV8b	Class 8b Heavy-Duty Gasoline Vehicles (>60,000 lbs. GVWR)
LDDV	Light-Duty Diesel Vehicles (Passenger Cars)

Code	Vehicle Description
LDDT12	Light-Duty Diesel Trucks 1and 2 (0-6,000 lbs. GVWR)
HDDV2b	Class 2b Heavy-Duty Diesel Vehicles (8,501-10,000 lbs. GVWR)
HDDV3	Class 3 Heavy-Duty Diesel Vehicles (10,001-14,000 lbs. GVWR)
HDDV4	Class 4 Heavy-Duty Diesel Vehicles (14,001-16,000 lbs. GVWR)
HDDV5	Class 5 Heavy-Duty Diesel Vehicles (16,001-19,500 lbs. GVWR)
HDDV6	Class 6 Heavy-Duty Diesel Vehicles (19,501-26,000 lbs. GVWR)
HDDV7	Class 7 Heavy-Duty Diesel Vehicles (26,001-33,000 lbs. GVWR)
HDDV8a	Class 8a Heavy-Duty Diesel Vehicles (33,001-60,000 lbs. GVWR)
HDDV8b	Class 8b Heavy-Duty Diesel Vehicles (>60,000 lbs. GVWR)
MC	Motorcycles (Gasoline)
HDGB	Gasoline Buses (School, Transit and Urban)
HDDBT	Diesel Transit and Urban Buses
HDDBS	Diesel School Buses
LDDT34	Light-Duty Diesel Trucks 3 and 4 (6,001-8,500 lbs. GVWR)

The vehicle classification used by the Federal Highway Administration (FHWA) in their traffic identification system (FHWA, 2001) is shown in Table 2-2. Automatic traffic recorders are used to identify the activity in terms of the numbers of vehicles passing a given site by these vehicle classifications at different roadway facility types around an urban area. This information then becomes the basis for determining the vehicle miles traveled (VMT) by vehicle classification. Mathematical algorithms are used to identify the number of axles and the spacing between axles to identify each vehicle's classification according to the definitions given in Table 2-2. There are obvious problems in matching the FHWA definitions with those used in MOBILE6. This is especially true for light-duty trucks and heavy-duty vehicles where the vehicle configuration in Table 2-2 does not necessarily match the GVWR as in Table 2-1.

Table 2-2. FHWA vehicle classifications.

FHWA Class	Traffic Monitoring Vehicle Type Description
1	Motorcycle
2	Passenger cars
3	Other 2-axle, 4-tire single unit vehicles
4	Buses
5	2-axle, 6-tire single-unit vehicles
6	3-axle, 6-tire single-unit vehicles
7	4+ axle single-unit vehicles
8	4 or less axle combination vehicles
9	5-axle combination vehicles
10	6+ axle combination vehicles
11	5-axle multitrailer vehicles
12	6-axle multitrailer vehicles
13	7+ axle multi-trailer vehicles
14	Unclassified
15	Unclassifiable

Many planning agencies (local and State transportation or air quality agencies) look to State registration data to resolve many of the vehicle definition problems between the activity information, found in the form of Table 2-2, and the requirements of the emissions modeling, as described in Table 2-1. However, many States have their own definitions of vehicle class that do not necessarily match either the MOBILE6 or the FHWA definitions. In Table 2-3 are samples of vehicle registration definitions for two States (http://www.dps.state.mn.us/dvs/MotorVehicle/txmanual/taxmanual.htm, www.ksrevenue.org/pdf/forms/02d.pdf) indicating that these vehicle definitions may not be readily associated with the GVWR categories used by EPA or by FHWA.

Table 2-3. Registration vehicle classifications for Minnesota and Kansas.

MN Commercial Vehicle (GVWR)	KS Commercial Vehicle (GVWR)	KS Passenger Vehicle (GVWR)
0 – 9,000 lbs	0 – 12,000	0 – 3,000 lbs
To 12,000	To 16,000	To 3,999
To 15,000	To 20,000	To 4,500
To 18,000	To 24,000	Over 4,500
To 21,000	To 26,000	
To 26,000	To 30,000	
To 33,000	To 36,000	
To 39,000	To 42,000	
To 45,000	To 48,000	
To 51,000	To 54,000	
To 57,000	To 60,000	
To 63,000	To 66,000	
And so on	And so on	

In order to resolve the differences, the three types of vehicle definitions have typically been matched in terms of fractions of vehicles under each definitional category. So for instance, the heavier trucks, HDDV8a and 8b, under the EPA definition might be matched to the larger trucks in the FHWA definition, classes 8 through 13, and the fraction of HDDV8a and HDDV8b would be estimated by using the relative registration distribution of trucks above and below 60,000 pounds GVWR for all trucks above 33,000 pounds GVWR. In this way, planning agencies define a crosswalk to identify the in-use fleet in the manner used by the emissions model.

EPA and FHWA should, therefore, pursue a better method to determine the in-use fleet by vehicle categories defined by different emissions rates. It has not been clearly defined by either EPA or FHWA how this is to be accomplished, and incorrect methodologies could lead to substantial uncertainty in model emissions.

2.2.2 Summary of Standards

In investigating the historical and future year emission of vehicles, it is helpful to have an understanding of the emission standards for each type of vehicle to discern vehicle groupings or bins. Below we provide a general overview of the emission standards for the four major groupings: light-duty passenger cars and trucks, and heavy-duty diesel and gasoline engines.

The basic low mileage (typically 50,000 mile) emission standards for light-duty vehicles are shown in Tables 2-4 and 2-5. (This summary does not include the emission standards promulgated for model years prior to 1972 because model years before 1972 are not expected to be a significant portion of the in-use vehicle fleet.) Many of these standards had a number of adjustments including small volume and special exemptions (especially during the 1982 through 1987 model years), phase-in of standards, high altitude standards, cold temperature standards, different and supplemental test procedures, changes to the useful life, warrantees, on-board diagnostics (OBD), and a number of other specific details for many model years. In addition to the 1996 Tier 1 emissions standards, the National Low Emission Vehicle (NLEV) and Clean Fueled Vehicle programs were implemented in the 1999 through 2003 model years for some regions of the county targeted mainly at reduced hydrocarbon emissions in the form of nonmethane organic gas (NMOG) but also including some NOx emissions reductions. The tables below are therefore, merely general groupings. Along with the regional differences in emission standards, the Tier 1 phase-in years 1994 and 1995 and future Tier 2 emissions standards phased-in from 2004 through 2009, where emissions averaging is a feature, will require that EPA give more consideration to vehicle selection to ensure that the emissions estimates are derived on an appropriate mix of vehicle models that represent typical in-use vehicle activity.

Table 2-4. Federal emission standards (up to 5 years or 50,000 miles) for gasoline light-duty passenger cars.

Model Year	Emission Standard (g/mile)			
	HC	CO	NOx	PM
1972	3.4	39	---	---
1973–1974	3.4	39	3.0	---
1975–1976	1.5	15	3.1	---
1977–1979	1.5	15	2.0	---
1980	0.41	7.0	2.0	---
1981	0.41	7.0	1.0	---
1982–1986	0.41	3.4	1.0	0.60
1987–1993	0.41	3.4	1.0	0.20
1994 (40% phase-in)	*0.41*	*3.4*	*0.4*	*0.08*
1995 (80% phase-in)	*0.41*	*3.4*	*0.4*	*0.08*
1996–2003	0.41	3.4	0.4	0.08
2004 and later	Tier 2; Fleet average of 0.07 g/mile NMOG and NOx at 120k miles by 2009			

Table 2-5. Federal emission standards (up to 5 years or 50,000 miles) for gasoline light-duty trucks.

Model Year	Emission Standard (g/mile)			
	HC	CO	NOx	PM
1972	3.4	39	---	---
1973–1974	3.4	39	3.0	---
1975–1978	2.0	20	3.1	---
1979–1981	1.7	18	2.3	---
1982–1983	1.7	18	2.3	0.60
1984–1986	0.80	10	2.3	0.60
1987	0.80	10	2.3	0.26 LDGT1 0.50 LDGT2
1988–1993	0.80	10	1.2 LDGT1 1.7 LDGT2	0.26
1994 (40% phase-in)	<u>NMHC</u>	3.4 LDGT1	0.4 LDGT1	0.08

Model Year	Emission Standard (g/mile)			
	HC	CO	NOx	PM
1995 (80% phase-in)	0.25 LDGT1	4.4 LDGT2	0.7 LDGT2	(effectively for all trucks)
1996–2003 (100% phase-in)	0.32 LDGT2 0.32 LDGT3 0.39 LDGT4	4.4 LDGT3 5.0 LDGT4	0.7 LDGT3 1.1 LDGT4	
2004 and later	Tier 2; Fleet average of 0.07 g/mile NMOG and NOx at 120k miles by 2009			

Table 2-6 provides a summary of the emission standards for heavy-duty diesel engines, those vehicles with gross vehicle weight ratings (GVWR) greater than 8,500 lbs. Because of averaging, banking, and trading provisions in the heavy-duty engine regulations, the emission standards in Table 2-6 do not necessarily result in a proportional effect on each model year grouping.

Table 2-6. Federal emission standards for heavy-duty diesel engines.

Model Year	Emission Standard (g/hp-hr)					Smoke* (Opacity)
	HC	CO	NOx	HC + NOx	PM	
1970–1973	---	---	---	---	---	**A:40%; L:20%**
1974–1978	---	40	---	**16**	---	**A:20%; L:15%; P:50%**
1979–1984	1.5	25	---	**10**	---	**A:20%; L:15%; P:50%**
1985–1987**	1.3	15.5	10.7	---	---	**A:20%; L:15%; P:50%**
1988–1989	1.3	15.5	10.7	---	0.6	**A:20%; L:15%; P:50%**
1990	1.3	15.5	6.0	---	0.6	**A:20%; L:15%; P:50%**
1991–1992	1.3	15.5	5.0	---	0.25	**A:20%; L:15%; P:50%**
1993	1.3	15.5	5.0	---	0.25 truck 0.10 urban bus	**A:20%; L:15%; P:50%**
1994–1995	1.3	15.5	5.0	---	0.10 truck 0.07 urban bus	**A:20%; L:15%; P:50%**
1996–1997	1.3	15.5	5.0	---	0.10 truck 0.05 urban bus	**A:20%; L:15%; P:50%**
1998–2003	1.3	15.5	4.0	---	0.10 truck 0.05 urban bus	**A:20%; L:15%; P:50%**
2004–2006	---	15.5	---	2.5 combined NMHC + NOx***	0.10 truck 0.05 urban bus	**A:20%; L:15%; P:50%**
2007 and later	0.14 NMHC		0.20	---	0.01	**A:20%; L:15%; P:50%**

* A = Acceleration; L = Lug; P = Peaks
** Emission test cycle changed from a 13 mode steady-state to a transient
*** Emission test adds a not-to-exceed standards for higher power level groups

Table 2-7 outlines the general emission standards for heavy-duty (>8,500 GVWR) gasoline engines. The late model (2005 and later) emission standards include averaging and banking emission standards, and many manufacturers have already been producing vehicles effectively meeting this emission standard, so a dramatic emission reduction with the 2005 model year may not be readily apparent.

In addition, EPA has changed the definition of greater than 14,000 pounds GVWR heavy-duty passenger vehicles; these were formerly considered heavy-duty vehicles and are now classified as sport-utility trucks and passenger vans, to be included under the Tier 2 light-duty emission standards and expected to reach emission rates of 0.075 (g/mile) THC and 0.07 (g/mile) NOx (EPA, 2001a).

Table 2-7. Federal emission standards for heavy-duty gasoline engines.

Model Year	Emission Standard (g/hp-hr)				
	NMHC	CO	NOx	NMHC + NOx	PM
1974–1978	---	40	---	16	---
1979	1.5	25	---	10	---
1980–1983	1.5	25	---	10	---
1984	1.3	15.5	10.7	---	---
1985	2.5	25	10.7	---	---
1986	2.5	25	10.7	---	---
1987–1989 GVWR <14,000 GVWR >14,000	1.1 1.9	14.4 37.1	10.6 10.6	---	---
1990 GVWR <14,000 GVWR >14,000	1.1 1.9	14.4 37.1	6.0 6.0	---	---
1991–2004 GVWR <14,000 GVWR >14,000	1.1 1.9	14.4 37.1	5.0 5.0	---	---
2005 and later GVWR <14,000 GVWR >14,000	---	14.4 37.1	---	1.0	---
2007 and later	0.14	---	0.2	---	---

2.2.3 MOVES Vehicle Bin Definitions

Using vehicle definitions and emission standards, EPA (2002a) has outlined the vehicle type bins that they intend to consider to distinguish between vehicle types in their emission modeling. These vehicle definitions are shown in Table 2-8. It clearly indicates that EPA has given consideration to both the GVWR and the FHWA vehicle definitions, vehicle emission standards, with additional categorical considerations for the use or owner type, technology type, mileage accumulation, and emitter class. However, defining the vehicle type bins by this large number of classifications will unduly burden the data collection efforts.

Table 2-8. Proposed MOVES On-road vehicle classification scheme.

Activity Classifications		Emission Classifications Examples (Source Bins)					
HPMS Class	**Use Type**	**Weight Range (pounds)**	**Fuel Types**	**Standard Groups**	**Techno-logies**	**Mileage Range**	**Emitter Class**
Passenger Cars	Passenger Cars	< 4,000 > 4,000	Gas, Diesel, CNG, LPG, M85, E85, EV, HEV, FCV	Pre-control, Tier 0, Tier 1, NLEV, Tier 2	No catalyst Oxidation catalyst 3-way catalyst Carbureted Fuel injection EGR secondary air	Low Medium High	Normal High Super
Other 2-axle / 4-tire Vehicles	Passenger Trucks (Pick-up, Mini-van, SUV)	< 4,000 < 6,000 < 10,000					
	Work Trucks	< 6,000 < 10,000 < 14,000					
Single Unit Trucks	Service Trucks	<14,000 <16,000 <19,500 <26,000 <33,000 <60,000	Gas, Diesel	Gas: Pre-control, 1987, 1988, 1991, 1998, 2004, 2007 Diesel: Pre-control, 1985, 1988, 1990, 1991, 1994,[1] 1998, 2004, 2007			
	Local Delivery Trucks						
	Short-Haul Delivery Trucks						
	Motorhomes						
Buses	Interstate Buses		Gas, Diesel, CNG, LPG, M85, E85, EV, HEV, FCV				
	Urban Buses						
	School Buses						
Combination Trucks	Long-Haul Delivery Trucks	< 33,000 < 60,000 > 60,000	Diesel				
Motorcycles	Motorcycles		Gas, EV				

1 EPA did not suggest 1994, but an emission standard changed for this model year.

The potential benefit for defining the use type (or owner type) is that each may have different activity and emissions characteristics. For instance, the differences between long-haul and delivery trucks will be significant in terms of typical activity (in-use driving behavior), age (registration distribution and mileage accumulation rates), and potentially emission deterioration rates (different levels of maintenance and effects of in-use duty cycles).

The emission standards prompted the use of various technology types, which could be important variables in addition to the effect of the emission standards themselves. In past versions of MOBILE additional technology type definitions, such as carbureted, throttle-body (TBI) or port fuel injected (PFI) for light-duty vehicles, have been used. While it may be possible to disaggregate several vehicle designs within each category, each vehicle category definition should be justified on the basis of the available data and whether the result provides a better understanding of the emissions or activity without introducing unnecessary complexity.

The mileage accumulation and emitter class definitions will most likely be important considerations in the final emissions model because of the effects deterioration and malfunction for vehicles with emission control devices that may degrade or fail in use.

The major difficulty with defining so many vehicle type bins is that the data requirements (most especially the numbers of vehicles representative of each bin) may be substantially increased. For instance, the numbers of bins described in Table 2-8 could total nearly 10,000 for passenger vehicles and 20,000 for light-duty trucks depending upon the number of model years and mileage bins used to describe the fleet. However, MOBILE6 implicitly included a number of similar bin descriptions for five types of light-duty gasoline vehicles and trucks (LDGV, LDGT1, LDGT2, LDGT3, and LDGT4), additional descriptions for diesel and CNG vehicles, similar types of technology groupings as described above, model years, and emitter groups, but MOBILE6 estimated age and mileage through analytic expressions determined through data regressions defining roughly 1,500 distinct vehicles types. The MOVES draft design proposed to add vehicle application ("Use Type" in Table 2-8), mileage, and age bins likely increasing the number of vehicle type bins, if the other vehicle types already defined in MOBILE6 are maintained. If the number of vehicle bins in MOVES is substantially increased, then attention must be paid to gathering representative numbers and types of vehicles to describe the vehicle fleet for each bin describing the range of activity (VSP and other parameters of interest). As we discuss under Section 2.5, EPA will need to specifically define the appropriate numbers of vehicles to describe the emission within each defined vehicle bin. Combined with the number of bins outlined above, the emissions data requirements could be substantial. EPA proposed in the December 2, 2003 MOVES Federal Advisory Committee Act (FACA) Modeling Workgroup meeting to continue to review the need for any increase in number of vehicle bin descriptions, and expects to have no more bin descriptions than were already defined in MOBILE6.

Therefore, it will likely be necessary to combine many of these vehicle classification bins to reduce the data requirements. For instance, most of the technology groups defined in Table 2-8 were originally used to describe the phase-in of fuel injection technologies into light-duty vehicles beginning in 1981, primarily with the introduction of the Tier 0 standard and phased-in throughout the 1980s and 1990s. However the technology differences might expected to be less important with future model years, so it may no longer be necessary to divide the in-use fleet into so many categories especially when model year will also be a consideration. Also, one of the benefits of the proposed modeling approach is that emissions will be described as a function of the vehicle behavior, so it may be possible to combine the emission response for many types of vehicles. This is especially true for heavy-duty vehicles where engines are certified to similar emission standards, so vehicle weight and configuration (i.e., number of axles, frontal area, and aerodynamics) combined with typical driving behavior may be the only consideration when distinguishing the emission rates between many vehicle types.

2.2.4 Current Database of Modal Emissions

A review of EPA's Mobile Source Observational Database (MSOD, dated September 15, 2003) was performed to investigate the numbers of vehicles available for emissions estimation. The number of vehicles may be more important than the number of tests performed on each vehicle provided each had a sufficient range of activity to describe in-use emissions. The MSOD includes data available to EPA from a range of emission studies including laboratory evaluations, inspection and maintenance programs, and field (with a dynamometer or a portable system) testing. The data included testing on vehicles using either on a number of test cycles (driving traces) or on a single cycle. It is not possible to review here every study included in the MSOD, but EPA is performing a number of quality assurance and review procedures on this data that should be provided to reviewers at a later date.

Table 2-9 shows the number of light-duty vehicles with modal (second-by-second) data currently (as of September 15, 2003) available to EPA in their MSOD. The number of vehicles is relatively low for the higher weight trucks, LDGT2, and for late model vehicles. Because sales of all trucks (LDGT1 and LDGT2) have become equivalent or higher than that for passenger cars (LDGV) more emphasis on gathering data for these vehicle types is warranted. Also, because the primary value of the emissions model will be to project future year emissions, more emphasis should be given to recruiting late model vehicles with appropriate technology types.

Table 2-9. Passenger vehicles with modal (second-by-second) data available in EPA database as of September 15, 2003.

Vehicle Class	Weight (lbs)	Precontrol ~ (<1980)	Tier 0 ~ (1980 – 1995)	Tier 1 ~ (1996 – 2001)
LDGV	All	2,237	35,088	1,643
LDGT1	<6,000[1]	86	4,691	663
LDGT2	>6,000	37	249	5
LDDV	Any	7	30	1
LDDT	Any	0	18	0

[1] Many entries had no weight estimate.

The total number of tests on the 44,759 light-duty vehicles is 98,984. However, it is more important to determine if these tests completely cover all the operational modes of activity. For instance, as described in Section 2.4 of this report, if a large fraction of the light-duty vehicles have been tested only on the IM240 test cycle, then almost no data are available for vehicle specific power (VSP) above about 19 kW/tonne. It was unclear from the database parameters if there could have been selection bias in recruiting vehicles under the studies included here. If there was a risk of a selection bias, then more consideration should be given to adjusting the emission rates or the population of vehicles in each, yet undefined, emitter class bin.

The definition of a high emitter needs additional scrutiny, with a discussion of the issues in defining a high emitter provided below. However, to provide an idea of the data availability, the EPA database was searched for vehicles that produce either high (>2 g/mile) THC or NOx emissions from gasoline passenger vehicles on any test in the database. The results are shown in Table 2-10. The higher number of higher emitting vehicles for older model years is a function of less stringent emission standards and more mileage or age accumulation at the time of the test. Table 2-10 shows that there are very few late model vehicles with high emissions rates in the MSOD. If the MSOD has a selection bias with an under representation of high emitters, this could create a significant under prediction of future year emissions. It is possible that these vehicles had not aged enough to produce high emissions by the time of testing, and that the lower emission standard for these vehicles was sufficiently stringent to reduce the chance that deterioration or minor failures result in as high emissions as those vehicles where the emission standard was closer to the ad hoc high emitter criteria defined here.

Table 2-10. High emitter gasoline passenger vehicles available in EPA database as of September 15, 2003 (Criteria of THC or NOx emissions >2 g/mile).

Vehicle Class	Weight (lbs)	Precontrol ~ (<1980)	Tier 0 ~ (1980 – 1995)	Tier 1 ~ (1996 – 2001)
LDGV	All	599	1072	2
LDGT1	<6,000[1]	39	294	0
LDGT2	>6,000	11	20	0

[1] Many entries had no weight estimate.

The number of heavy-duty vehicles in the database is shown in Table 2-11. There are significantly lower numbers than for light-duty vehicles, which may make the emissions estimates considerably less certain. This table highlights the areas of weakness in the dataset from which to estimate emissions. In particular, the numbers of light heavy-duty diesel vehicles are quite low for all model year types, and ENVIRON demonstrated (CRC E-64) that the emissions for these types of vehicles varied greatly by manufacturer and model year. It should be relatively easy to generate more data because the testing on light heavy-duty diesel vehicles can be performed on light-duty chassis dynamometers, so more research groups are available to test these types of vehicles compared with heavier trucks where specially designed dynamometers are required. Another weakness in the data are estimates for engines meeting the 2004 diesel engine emission standards; engines of this type are already being introduced into the market because of a consent decree. How these late model engines behave, with the use of exhaust gas recirculation (EGR) or other aftertreatment devices, and deteriorate or malfunction could have an important effect on the future year in-use emission rates.

Table 2-11. Heavy-duty vehicles with modal (second-by-second) data available in EPA database as of September 15, 2003.

Model Year	Heavy-Duty Gasoline Engines (<11,000 GVWR)	Light Heavy-Duty Diesel	Medium Heavy-Duty Diesel[1]	Heavy Heavy-Duty Diesel	Diesel Buses
<1985	0	0	4	14	2
1985 – 1987	0	0	5	7	1
1988 – 1989	10	4	2	6	2
1990	6	0	2	5	0
1991 – 1993	23	3	6	4	2
1994 –1997	35	6	16	9	35
1998 – 2003[2]	4	7	5	9	7
2004 – 2006	---	---	---	---	---
2007+	---	---	---	---	---

[1] 10 trucks (all 1996 and later) were in the GVWR range of 15,000 to 19,000 lbs, so were technically light heavy-duty trucks, but the reported engine displacements (>10 l) were more indicative of and therefore included as medium duty vehicles.

[2] Consent decree engines meeting the 2004 emission standard were produced starting October, 2002. In addition, 21 CNG and LNG Heavy heavy-duty vehicles were in the database.

The data for emission measurements for heavy-duty trucks was limited to maximum test weights for heavy-duty vehicles of 62,900 pounds; the vehicles in-use range to over 130,000 lbs. in rare cases, so testing should include vehicle weights above 62,900 pounds. Emission estimates for larger vehicles, therefore, need to be extrapolated to these higher weights from the test data where the effect of vehicle weight had been incorporated in the test plan. It may not be entirely accurate to use a simple regression (or the PERE model estimates) to project emissions estimates to higher weight trucks. One consideration for projections to higher in-use weights may be that the VSP levels could be limited by the installed power of the truck, so that while VSP may be higher during typical driving, peak VSP may not be higher.

It is clear that little data are available to discern issues associated with advanced technology vehicles for either light or heavy-duty vehicles. Additional vehicle type groups may need to be considered including hybrid-electric or other load leveling (e.g., continuously variable transmissions (CVT), or actuated valve or injection timing) vehicle designs, but because these vehicle types have just come on the market within the last few model years very few if any have yet been tested for emission response especially with sufficient aging to properly represent the emission response in the field.

2.2.5 Defining High Emitters

EPA has yet to determine the criteria to define high emission vehicles, yet defining high emitters will be a critical element to determine vehicle selection for emission measurements. There are a number of different methods for defining high emitting vehicles based on a given measurement procedure, whether remote sensing, inspection or other emission test. These methods include two basic approaches where high emitting vehicles are defined either on the basis of relative emissions compared to their original certification standard or on the basis of the absolute emission level. The first method is more common and is typically associated with the model year of the vehicle in question. The second method is more in line with the air quality goals of a given region, and will likely preferentially identify older model year vehicles, originally certified to a lower standard, as high emitting vehicles.

The definition of a "gross polluting vehicle" in California that requires it to be tested in a special station can be found at: http://www.smogcheck.ca.gov/ftp/pdfdocs/asm_ph31.pdf. This describes a series of cutpoints based on the vehicle type, model year, and test weight on the acceleration simulation mode (ASM) test. This definition is based on the emission standard for which the vehicle was originally certified.

Denver's Regional Air Quality Council (RAQC) defined high emitters from approximately the top 10 percent of the vehicle fleet in terms of emission rate, so the high emitter definition was not necessarily associated with the emission standard on which the vehicle was originally certified.

> *"For the strategy analyses contained in this report, it is important to estimate the number of high emitters by category that might be found in the Denver metro area. Overall, the gasoline powered vehicle fleet in the Denver region is estimated to be approximately 2,000,000 vehicles. RAQC staff estimates that 240,000, or 12%, are high-emitters. Of this total, an estimated 140,000 are gas phase-only high-emitters, 40,000 are particle phase-only high-emitters, and 60,000 are vehicles that could be both particle and gas*

phase high-emitters. RAQC staff used a number of data sources to determine the contribution of these high-emitters to mobile source pollution in the Denver metro area. The contribution of these vehicles to PM2.5, HC, and CO is estimated to be 46%, 35%, and 39%, respectively. The Work Group based its definition on this research which defines any vehicle that falls in the highest emitting 10% of the fleet as a gas phase high-emitter."
(http://www.raqc.org/high%20emitter%20work%20group/Findal%20RAQC%20Report.PDF)

In MOBILE6, high emitters were defined as those vehicles that emit HC or NOx at levels more than two times their 50,000-mile certification level, or CO at more than three times the certification standard. Average emission rates for high emitters were estimated from FTP data as a simple average (by vehicle class, model year group, and technology type). There was very large variability in the emission rates for the high emitters.

The NCHRP 25-11 report (Barth et al., 2000) characterized high emitters as outlined below where high emitters were identified using a defined series of cutpoints of emissions on the hot running emissions as measured on the certification cycle, or similar to the approach used in MOBILE6.

"4.13.1 Characterizing High Emitters
As specified in Chapter 3, suspected high-emitting vehicles were recruited and tested based on a number of different methods. Based on their FTP bag emission results, the vehicles were classified either as high emitting or normal emitting using a set of cutpoints. …….

For this particular analysis, we define high emitters as vehicles, which exceed FTP bag 3 emissions cutpoints in grams per mile (gpm)……….. With the chosen cutpoints, high emitters exceed the emissions of typical properly functioning MY 1990-1993 vehicles [reprised in Table 2-12] *by more than a factor of about 2.5. These are rather low cutpoints for 'high emitters'; we choose them because MY90 and later high emitters proved hard to recruit for testing."*

Table 2-12. Emissions (g/mile) from properly functioning cars at 50,000 miles in three studies: FTP Bag 3. (Barth et al., 2000)

	MYs	Number	CO	HC	NOx
NCHRP	1990-3	24	2.7	0.22	0.35
FTP-RP	1991-4	23	1.5	0.16	0.33
AAMA in-use	1991-2	57	2.5	0.21	0.22

Because heavy-duty engines are certified on the basis of the output of the engine and the fuel efficiency of such engines typically does not vary by model year, cutpoints based on the ratio of pollutants and fuel consumption (or CO_2) could be defined to identify heavy-duty high emitters. In CRC E-55 (Gautam et al., 2002), the authors suggested a variety of such cutpoints for NOx/ CO_2 and PM/ CO_2 based on the original certification of the engine. PM emissions are often associated with high CO emissions in diesel engines, so CO may be used as a surrogate for PM emissions. Measuring these ratios in this work was accomplished through dynamometer testing, but a remote sensing site might be used to describe such ratios provided the practical concerns of exhaust systems placement and other interaction of the exhaust plume with the vehicle configuration are addressed.

2.2.6 Use of Remote Sensing to Define High Emitter Fractions for Light-Duty Vehicles

One of the questions when estimating emissions, especially for vehicles with emission control devices that may fail in use, is to determine the fraction of the fleet that could be classified as high emitters. Because of the potential selection bias for lower emitting vehicles when recruiting vehicles for emission testing, remote sensing has been suggested as an unbiased means to identify the higher-emitting fraction of the fleet.

As discussed above the definition of a high emitter is not straightforward. Some vehicles have extremely high emissions; for instance a small percentage of vehicles convert more of their gasoline to carbon monoxide than to carbon dioxide. Some vehicles have much higher emissions under certain driving conditions and driving history. Some vehicles have high emissions due to intermittent failure of engine controls or emission control devices. If high emitters are defined according to the multiple of an emission configuration standard, more categorization is required because of the range of the emission standards as described above. If high emitters are defined as multiples of their emission standard, remote sensing is unlikely to be useful at identifying high emitting vehicles originally certified with a low emission standard such as a super-ultra low emission vehicle (SULEV) because it will be difficult for remote sensing to measure emissions at that low an emission rate.

This section demonstrates the usefulness of second-by-second dynamometer data to better understand the limitations of a single remote sensing reading for identifying high emitters and to illustrate possible methods to improve the use of remote sensing for high emitter identification. Vehicles and dynamometer data for this analysis were compiled from the 346 vehicles in the NCHRP 25-11 data set (Barth et al., 2000). The descriptions of the vehicles selected and their emissions on the three driving cycles are shown in Appendix B.

The usefulness of remote sensing as a tool to understand vehicle emissions has improved because the vehicle load can now be estimated to associate by vehicle specific power (VSP). Further improvement may be possible by describing remote sensing sites in terms of other vehicle driving behavior, such as defining cruise, acceleration, or other modes. Indices for driving behavior include traffic density, speed, acceleration, change in load with time, and change in acceleration with time. More recent versions of remote sensing instruments acquire more speed and acceleration measurements. This offers additional opportunities for describing vehicle behavior. Future work should consider analyzing for the driving behavior and its effect on emissions from the large remote sensing data sets covering multiple sites in Missouri, Colorado, and Virginia, but these were beyond the scope of the current work.

Remote sensing to identify particulate matter high emitters (beyond what can be seen with the eye, e.g., fine particulates) is also outside the scope of the current work. Techniques to measure fine particulate matter with remote sensing equipment are currently under development.

Remote sensing is a proven technique to identify high emitting vehicles. This has been demonstrated in a number of studies where vehicles with high remote sensing readings were pulled over and given dynamometer tests to confirm their high emitter status (CBAR, 2001;

NRC, 2001; Walsh, 1996). These studies were confined to identifying high emitters from vehicles with tailpipes near the road. Remote sensing has monitored heavy-duty diesel vehicles with raised exhaust exits, but the measuring equipment must be adjusted in height to capture the plume. Hybrid vehicles operating on electrical power would not have a plume and would be missed by a remote sensor.

When high emitters are estimated from remote sensing measurements two types of errors may be made. False Positive [FP]: A normal emitting vehicle may be identified as a high emitter. False Negative [FN]: A high emitting vehicle may be classified as a normal emitter. The higher the cutpoint criteria used to define a high emitter, the less chance a FP error will be made, but the more chance a FN error will be made, and fewer high emitters will be identified.

An ideal remote sensing site will ensure that no vehicles have cold catalysts, the vehicles are under moderate load but not at high speed, there is high traffic density without congestion, vehicles are representative of the fleet in the area, and the site is safe to operate.[1]

The better the remote sensing sites chosen, the more remote sensing measurements per vehicle that are used to make the judgment, and the more VSP and speed filtering of the data prior to deciding which vehicles are high emitters, the less chance either a FP or a FN error will be made, and the higher the cost per high emitter identified and the lower the coverage of the fleet.

Quantifying these uncertainties would be very expensive to do by confirmatory roadside dynamometer tests. An alternative approach is to base the analysis on second-by-second dynamometer data [SBSDD] or PEMS data.

2.2.6.1 Defining a High Emitter for Remote Sensing

Before discussing the second-by-second results, it is worth commenting on the question of what is a high emitter. In addition to emissions variability observed in repeated dynamometer tests of high emitting vehicles (Knepper et al., 1993; Bishop et al., 1996), vehicle emissions of criteria pollutants depend on driving cycles and on driving modes within a driving cycle. As discussed previously, the definition of a high emitter is unclear, and the definition will affect the design of a remote sensing program to identify such high emitter fleet fractions.

Wenzel and Ross classified some early 1990's vehicles in the NCHRP 25-11 data set based on their emissions from FTP Bag 3 as shown in Figure 2-1. Three vehicles, Vehicles 113, 125, and 136, were classified as "Type 2: Operates Rich at Moderate Power" because of the difference between their engine-out and tailpipe-out CO emissions (Wenzel and Ross 1998). Vehicle 277 would also have been categorized the same way except that it also had strong catalyst deterioration so it fell into a different high emitter category.

On the basis of the Federal Test Procedure (FTP) emissions, seven other early 1990's vehicles were selected as normal emitters, Vehicles 117, 229, 242, 250, 270, 293, and 334. In addition three 1980's vehicles were chosen with high FTP CO emissions, Vehicles 097, 205, and 300.

[1] It is important to note that remote sensing sites chosen in the pullover studies were not at ideal remote sensing sites. Pullover sites had to meet other criteria. Vehicles had to be safe for pullovers and the transportable dynamometer needed room to operate and have access to auxiliary power.

All of these vehicles can be ranked and classified by their FTP CO composite emissions. However, as is shown in Figure 2-1, the ranking and classification becomes confused when CO emissions of the MEC or US06 test cycles are used. The "normal" emitters become indistinguishable from the "high rich" emitters and one of the "rich" emitters behaves like the "high" CO emitters from the early 1980's vehicles.

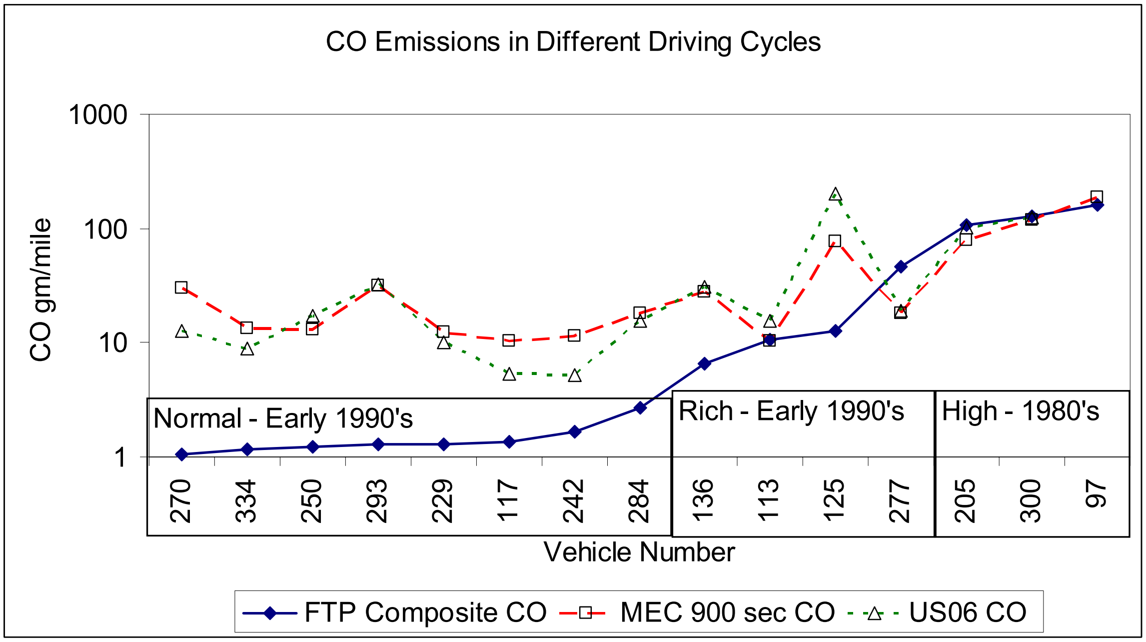

Figure 2-1. CO emissions on different driving cycles for various NCHRP 25-11 vehicles defined as high emitters.

In order to classify vehicles as high emitters, the definition of a "high emitter" will require further consideration given that the emission rates of "normal" emitters can be high using certain driving cycles as shown in Figure 2-1. While the three 1980's vehicles can be easily identified as high emitters, the early 1990's vehicles' classification will depend on the driving conditions under which the emissions are measured. So in designing a remote sensing program to identify the high emitter fleet fraction, site selection should consider limiting the vehicle driving activity to the VSP (and other important emission parameters) levels typically experienced on the FTP.

2.2.6.2 Remote Sensing Concentration Units

Remote sensing measurements are gas concentrations in the exhaust plume, and are typically reported as calculated ratios of criteria pollutants to carbon dioxide. Although the concentrations seen by the remote sensor decrease as the plume disperses, the relative concentrations of the criteria pollutants and carbon dioxide stay constant. Measurements are made many times in less than a second as the plume disperses. The uncertainty of the measurement is reduced by using the slope of a plot of the changing concentrations of pollutant and CO2.

The remote sensing measurements can be converted to grams of pollutant per gallon or kilogram of fuel (Pokharel et al., 2001). A fuel based criteria pollutant emission inventory based on gasoline sales and remote sensing measurements has been made for Los Angeles (Singer and

Harley 2000). A fuel-based emission inventory can be used to estimate the uncertainty of an emission inventory estimate based on vehicle activity and grams/mile emissions from an emissions model provided an accurate source of information about fuel sales and use can be determined.

Using a relationship between VSP and fuel rate, such as those developed in Section 3 where fuel consumption estimation methods are reviewed, grams of emissions per kilogram of fuel can be converted to grams per mile for individual vehicles (Slott, 2003).

Because vehicles have been certified by grams/mile, emissions measured in grams/kilogram of fuel might be expected to show a bias against more fuel-efficient vehicles. However, this difference is small compared to the difference in emissions between normal and high emitters. Vehicle 229, a Honda Civic LX, and Vehicle 293, a Plymouth Voyager, have nearly identical FTP composite emissions but quite different fuel economies[2] as is shown in Table 2-13. The emissions of the two vehicles expressed as grams/kilogram of fuel versus VSP by driving mode are quite similar as is shown in Figures 2-2a, 2-2b, and 2-2c. Vehicle 125, a high CO emitter on the FTP, is also plotted in Figures 2-2a, 2-2b, and 2-2c. In Figure 2-2a, the high CO emitter is easily distinguished by its CO gm/kg of fuel emissions from the two normal emitting vehicles with fuel efficiencies that differ by about 50 percent.

Table 2-13. Comparison of FTP composite emissions for vehicles 125, 229, and 293.

Vehicle Number	125	229	293
Make	Dodge	Honda	Plymouth
Model	Spirit	Civic LX	Voyager
Year	1990	1993	1994
Engine Size (liters)	2.5	1.6	3
List Weight (lbs)	3,125	2,625	5,200
Odometer (miles)	183,392	61,032	80,722
Rated Power (hp)	150	125	155
Tier Type	0	1	1
Vehicle Type	car	car	Truck
State	CA	CA	CA
FTP Composite CO (g/mile)	12.58	1.28	1.28
FTP Composite HC (g/mile)	0.50	0.10	0.14
FTP Composite NOx (g/mile)	0.46	0.23	0.21
Fuel Economy CITY	21	27	19
Fuel Economy HWY	29	34	23

[2] http://www.fueleconomy.gov/feg/findacar.htm.

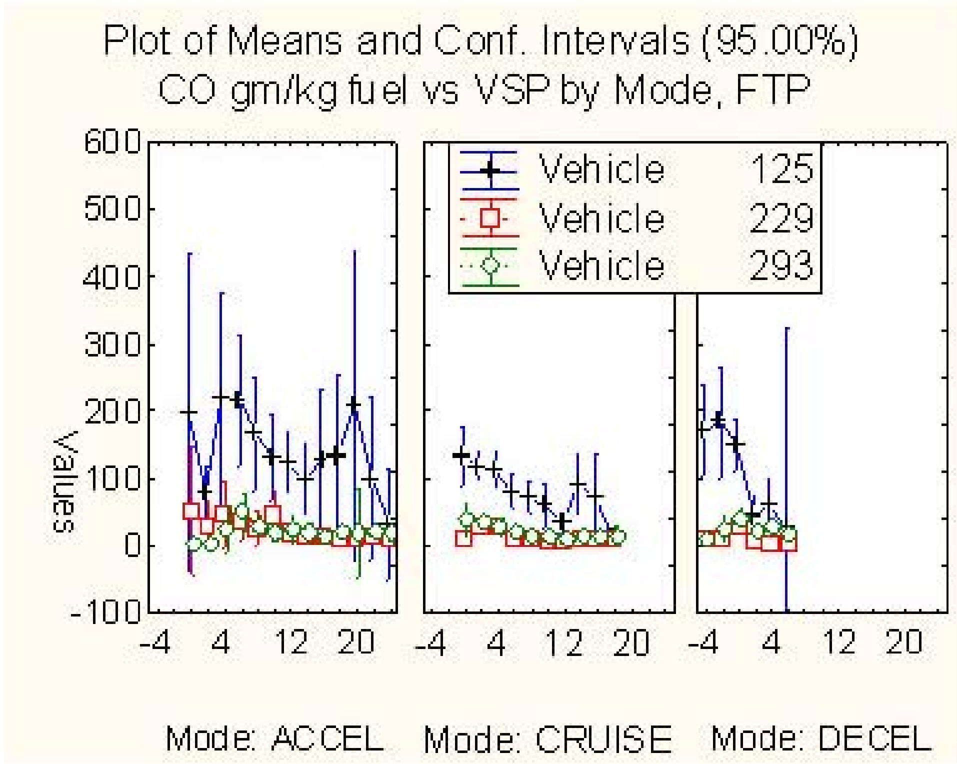

Figure 2-2a. FTP Composite CO for three vehicles from NCHRP 25-11.

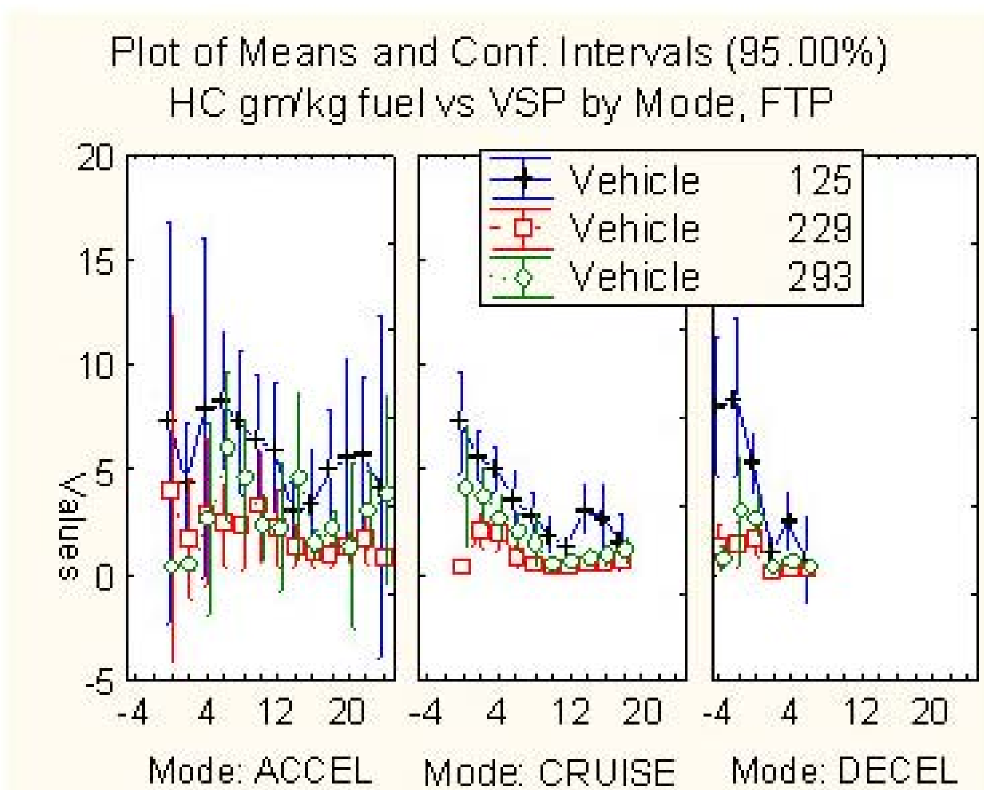

Figure 2-2b. FTP Composite HC for three vehicles from NCHRP 25-11.

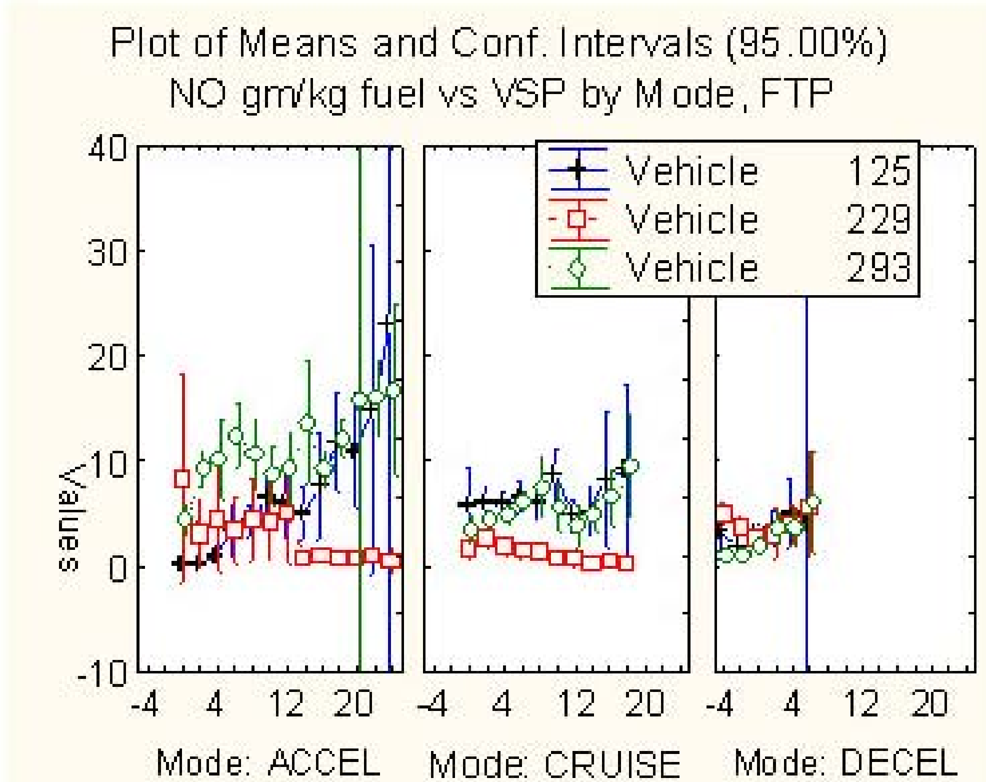

Figure 2-2c. FTP Composite NO for three vehicles from NCHRP 25-11.

2.2.6.3 Finding High NO Emitters

NO emissions are sensitive to load even when emissions are in concentration units. To examine under what conditions NO high emitters could be detected with remote sensing, Vehicle 298, a high NO emitter, was compared with all the normal emitters on all three driving cycles. The results in Figures 2-3a, 2-3b, and 2-3c show less aggressive driving cycles make the high NO emitter easier to identify in all driving modes. Going to higher VSP values for the MEC or US06 cycles did not help distinguishing the high emitting vehicle, and Vehicle 270, a normal NO emitter on the FTP, becomes a high NO emitter on the MEC and the US06.

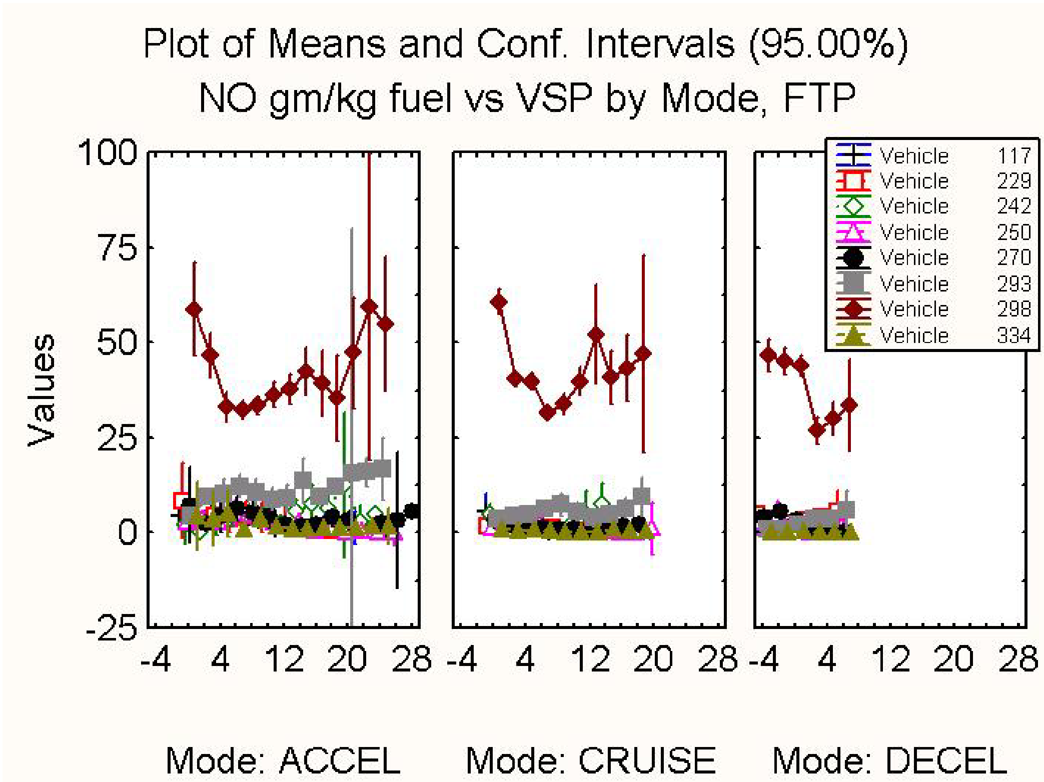

Figure 2-3a. Distinguishing a high NO emitter from a series of normal emitters, FTP.

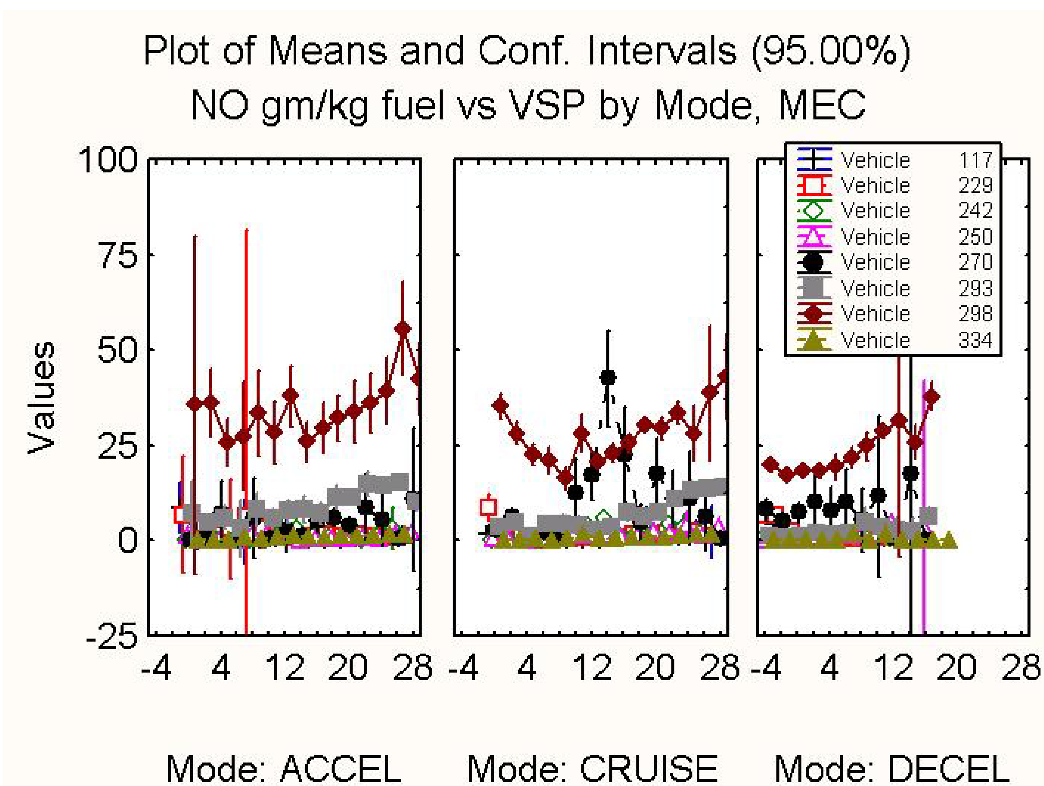

Figure 2-3b. Distinguishing a high NO emitter from a series of normal emitters, MEC.

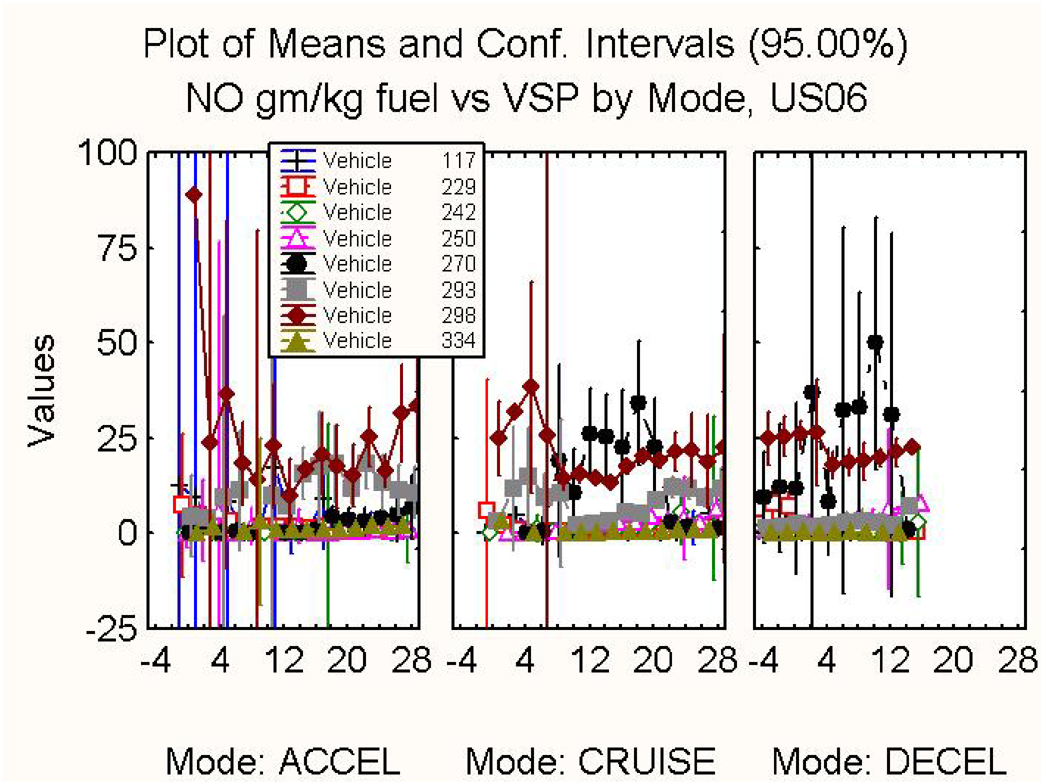

Figure 2-3c. Distinguishing a high NO emitter from a series of normal emitters, US06.

2.2.6.4 Finding High CO and HC Emitters

A very high CO and HC emitting vehicle, Vehicle 205, is easily distinguished under all driving cycles and all driving modes as is shown in Figures 2-4 and 2-5. However, the more marginal CO high emitters, Vehicles 113, 125, and 136, show variable high emissions and are much less resolved even in the FTP, shown in Figure 2-6a. In the MEC, Vehicle 125 had high emissions in all modes, shown in Figure 2-6b.

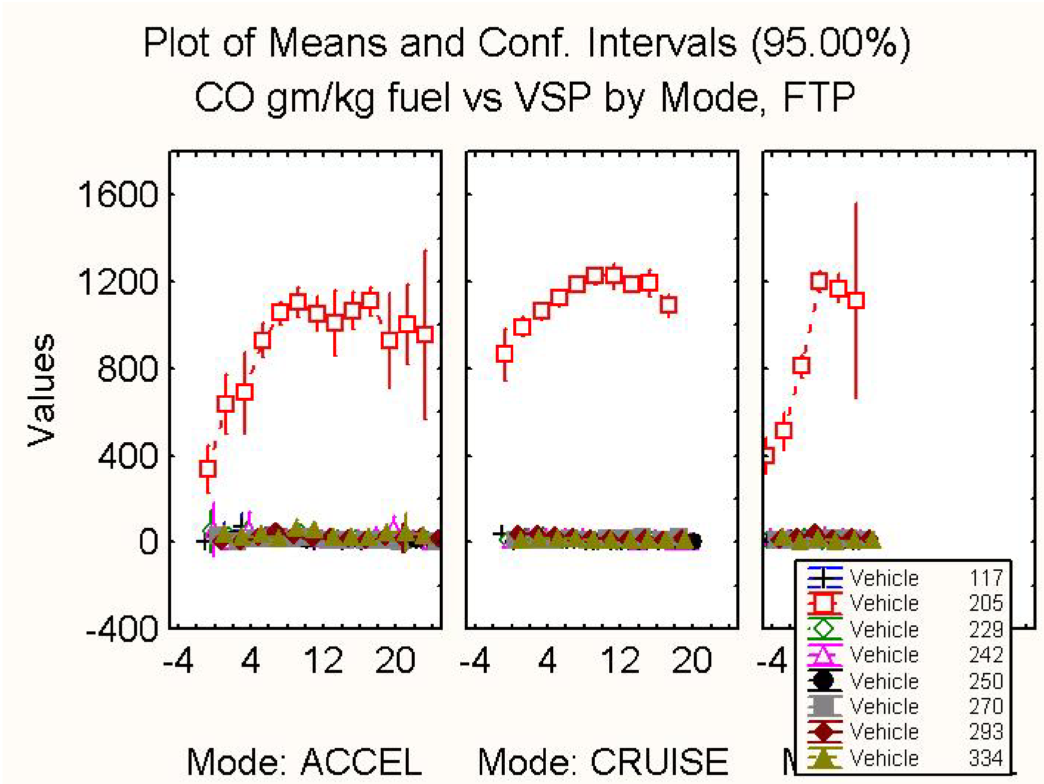

Figure 2-4a. Distinguishing a high CO emitter from a series of normal emitters, FTP.

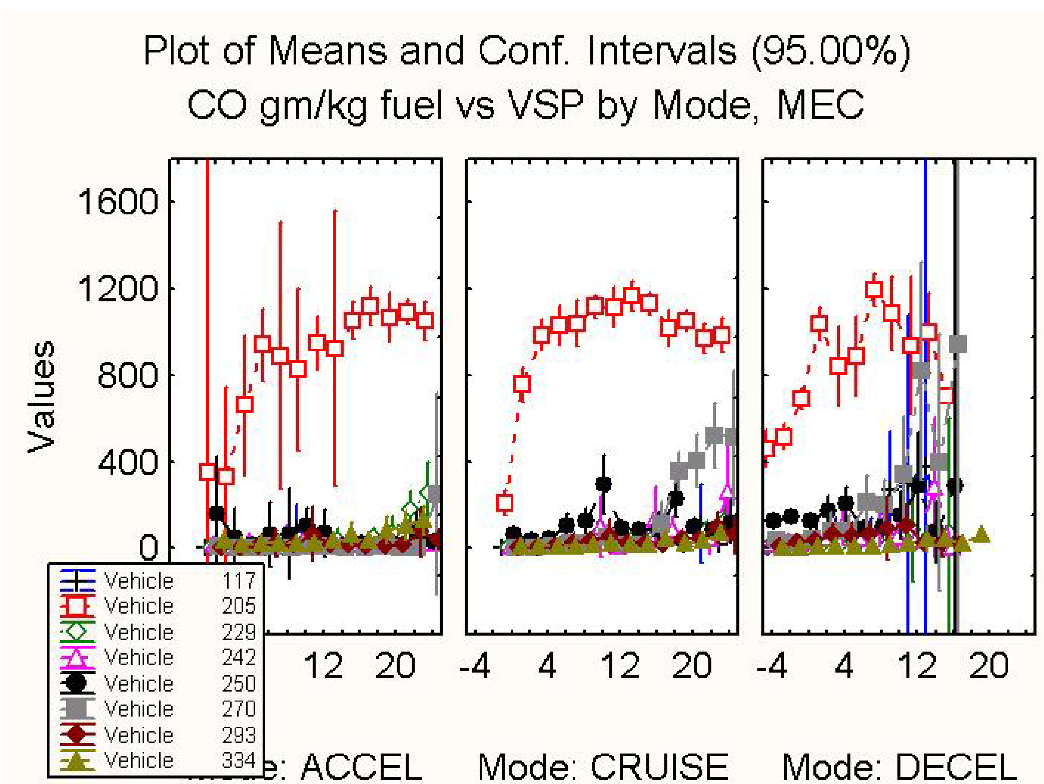

Figure 2-4b. Distinguishing a high CO emitter from a series of normal emitters, MEC.

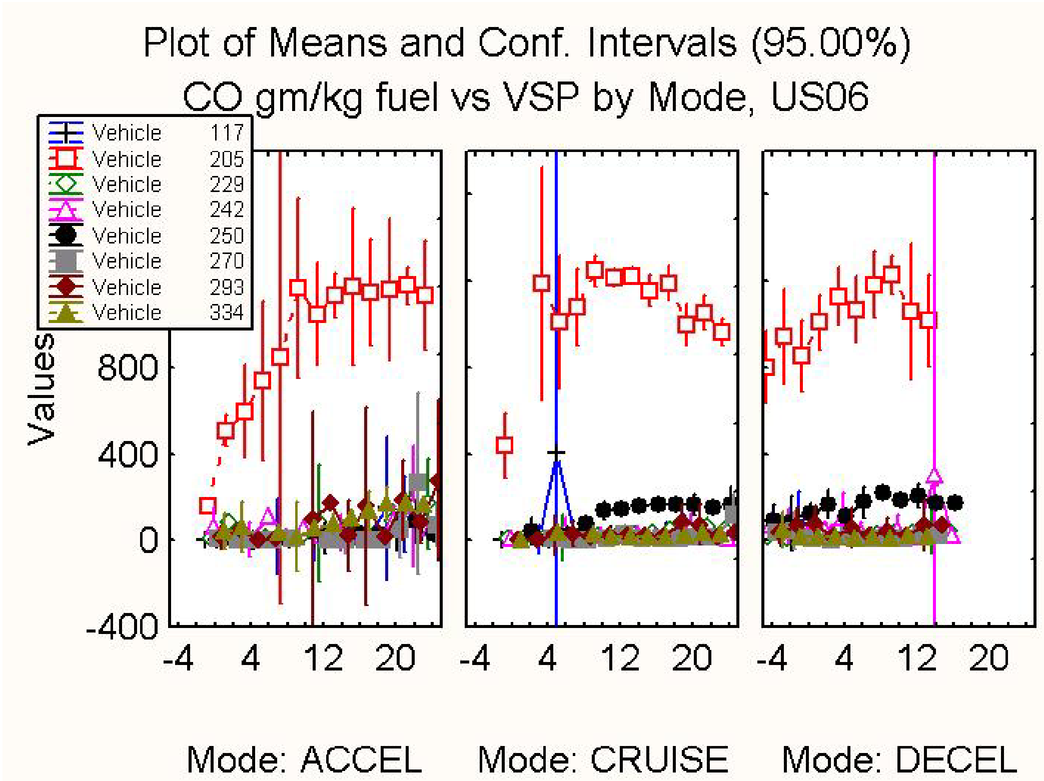

Figure 2-4c. Distinguishing a high CO emitter from a series of normal emitters, US06.

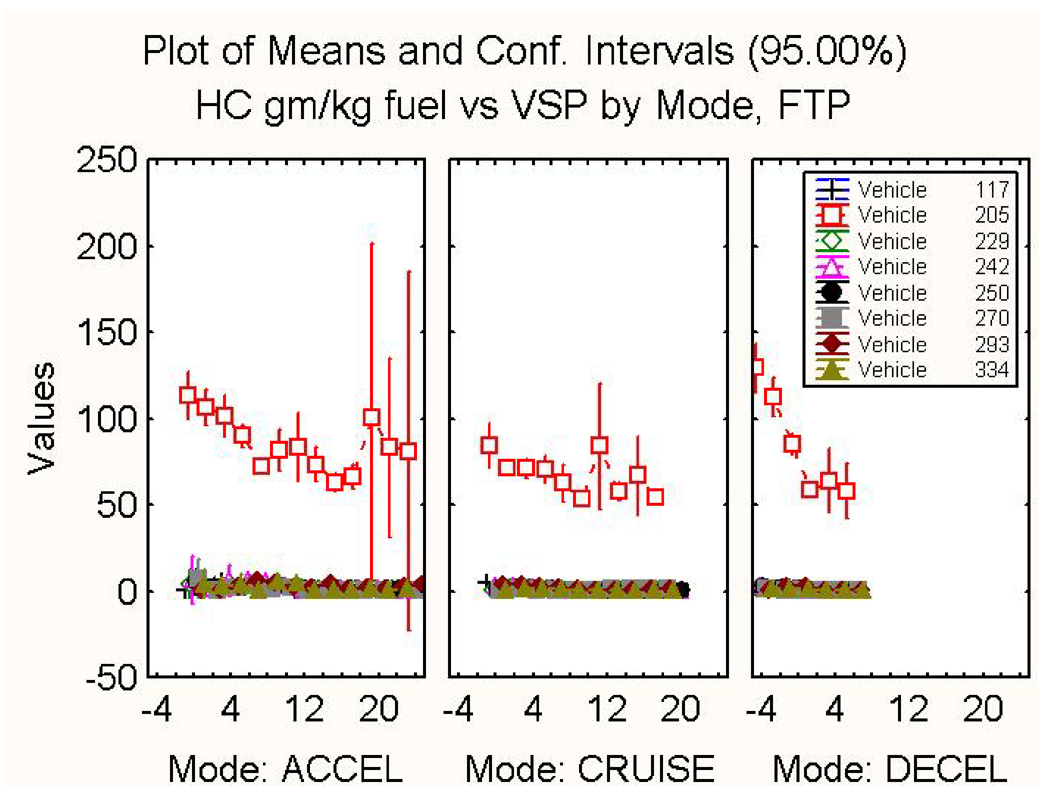

Figure 2-5a. Distinguishing a high HC emitter from a series of normal emitters, FTP.

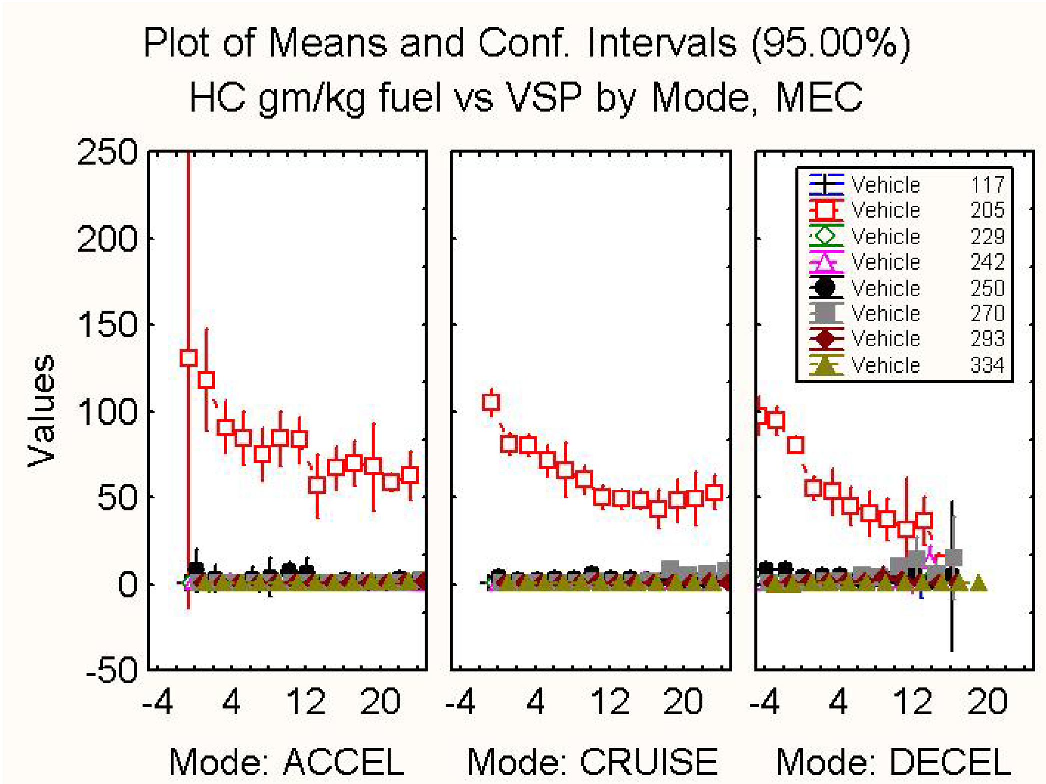

Figure 2-5b. Distinguishing a high HC emitter from a series of normal emitters, MEC.

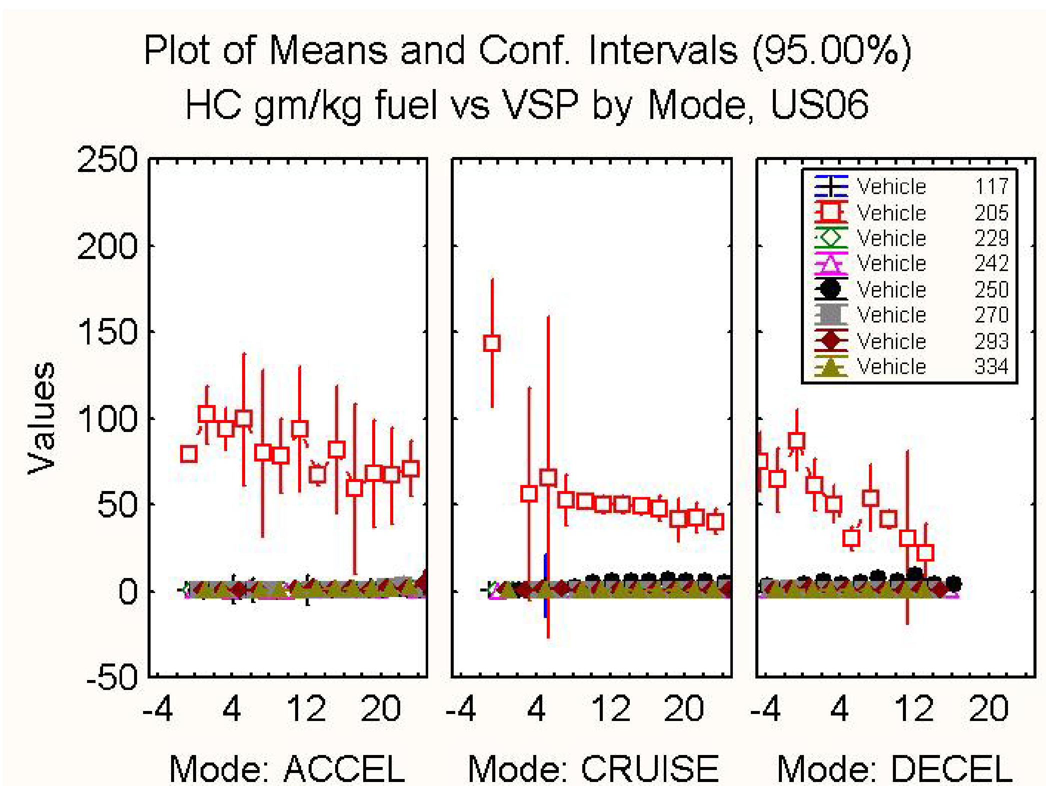

Figure 2-5c. Distinguishing a high HC emitter from a series of normal emitters, US06.

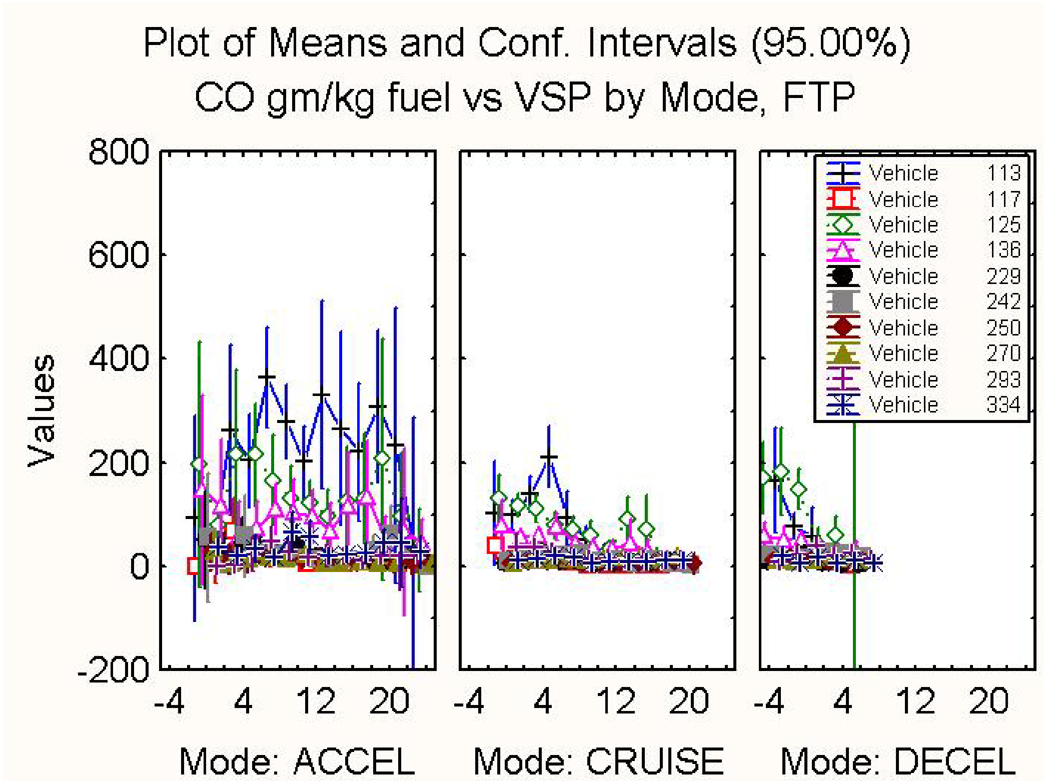

Figure 2-6a. Distinguishing a moderately high CO emitter from a series of normal emitters, FTP.

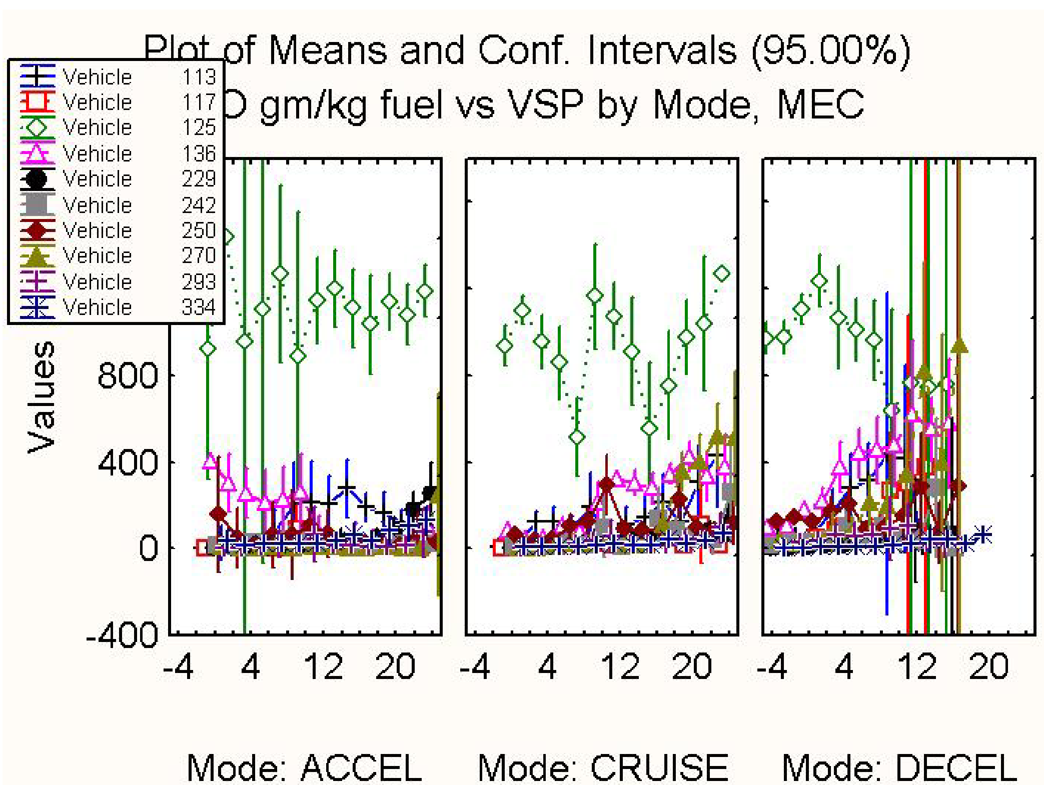

Figure 2-6b. Distinguishing a moderately high CO emitter from a series of normal emitters, MEC.

2.2.6.5 Remote Sensing Site Driving Conditions and Data Treatment

Remote sensing data were obtained at sites in a variety of VSP ranges. Some VSP and driving mode distributions for remote sensing sites are shown in Appendix C, where VSP distributions are given for all CRC E-23 remote sensing sites.[3] In general for these sites, remote sensing driving was more aggressive than the FTP and less aggressive than US06.

VSP filters were used to eliminate high load and heavy decelerating vehicles. Some vehicles were designed to go into fuel enrichment at high load (above the FTP limit of 23 kW/t). If these vehicles were not to be classified as high emitters, the remote sensing data need to be filtered to eliminate these higher VSP values. Some older vehicles continued to emit HC when in deceleration at low load. If these vehicles are not to be classified as high emitters, the remote sensing data need to be filtered to eliminate these low VSP values. Still, high HC emissions during deceleration may be an indication of a high emitting vehicle (see Vehicle 300).

Clean vehicles, especially Tier 0 vehicles, often appeared to be high emitters if their catalyst has not come up to temperature. This cold start condition can be eliminated by site selection if the site is chosen such that to reach that site vehicles must have driven on a high speed road for some distance (i.e., a freeway off ramp). At other sites, methods have been devised to filter remote sensing data from the time of the day where significant numbers of vehicles may be in cold start. In the Virginia remote sensing study, data were removed at sites and hours when site/hour combinations had high percentages of new vehicles with high emissions (after VSP filters were applied) (ESP, 2003).

A bias in remote sensing readings has been observed for HC channels. The bias has been eliminated by one investigator by setting the remote sensing readings of the cleanest new vehicle models to zero and adjusting the remote sensing HC readings of the other vehicles by the same number (Pokharel et al., 2001).

2.2.7 Vehicle Selection and Fleet Characterization Summary

In this subsection, we have outlined the considerations when estimating emissions for the in-use fleet. We have identified several areas of continuing concern as summarized below.

One area of concern is that the definitions of vehicle types have not been completely standardized in terms that EPA and users of MOVES can use to identify emission and activity rates. This was a concern for both light and especially heavy-duty trucks where available information confounds the classification of vehicles by EPA emission standard, vehicle configuration, or gross vehicle weight category. This concern exists currently with the use of MOBILE6, but should be addressed by MOVES in terms of vehicle selection and model structure.

Late model emissions standards, which include phase-in and averaging of the emission standards, will present a challenge to EPA both in terms of vehicle selection to avoid bias and with the modeling structure. More vehicle types and model years may need to be defined putting

[3] See http://www.crcao.com/ for the CRC website. Reports and data available at http://www.feat.biochem.du.edu/reports.html.

added burden on the data collection efforts to address the phase-in and averaging by preventing the combination of several model years and vehicle types into fewer bins.

EPA provided only a general outline about how they propose to define vehicles types. The EPA outline did not address specifically how the vehicle types would be defined for emissions and activity purposes, and provided little identification of technology of concern especially how newer technology groupings might be defined or combined. Further work should target emission testing to determine if technologies used in modern vehicles are distinct and sold in significant numbers to justify additional technology groupings.

The numbers and types of vehicles selected for emission testing to date has included light-duty and heavy-duty vehicles covering model years only up to 2001. The data included very low numbers of test vehicles for light-duty and heavy-duty trucks, and has not included much data for later model years for all vehicles. For a MOVES release date in 2005, much more emphasis in the coming year should be placed on gathering data for all types of late model vehicles including Tier 2 light-duty and 2004 certified heavy-duty vehicles. There were considerably fewer higher emitting vehicles in the later model years (because the cutpoint was too lax or the vehicles had not sufficiently aged), which either needs to be confirmed from an in-use analysis, such as through remote sensing, or more late model high emitters need to be measured for emissions.

High emitting vehicles have continued to be targeted as a disproportionally large fraction of the emissions for an urban area; however, a consistent definition for these high emitters has not gained general agreement. EPA will need to provide a definition for high emitters consistent with most regions' efforts and with their modeling approach.

Lastly, we provided a discussion of how remote sensing could be used to identify the high emitter fleet fractions. This analysis provides the basis for remote sensing site selection by choosing sites with vehicle activity less likely to misidentify high emitters, and provides an analysis of how cutpoints could be determined by the in-use behavior of the vehicles during remote sensing. By identifying the high emitter fleet fraction through remote sensing, EPA could avoid or ignore selection bias in their available emissions data. Emission testing programs could then target high emitters at lower cost without comprising their emission modeling from a vehicle selection bias.

2.3 REGULATED POLLUTANT MODELING ISSUES

2.3.1 Introduction

The MOVES design for on-road emissions estimation combines emission rates for the dominant vehicle types, binned (in yet undefined bin ranges) by Vehicle Specific Power (VSP), with populations and activities specific to road facilities from the micro- to macro-scale. This ambitious approach has the potential power of being able to construct facility specific emissions that reflect time of day, vehicle populations, traffic, ambient conditions, control strategies, and more. Critical to this methodology is the sufficiency of the VSP (or other parameter) bins to capture the range of conditions with a significant effect on emissions. Most data, experience, and interest in which the VSP model has evolved addressed regulated gaseous tailpipe emissions (HC, CO, and NO_x). This subsection addresses whether the VSP binning model can be used to estimate these regulated emissions.

In Section 3, a review of the MOVES implementation for greenhouse gas emissions, the correlation of VSP is established as a reasonable indicator of fuel consumption at least for light-duty vehicles. The correlation of fuel consumption could be improved by adding a term describing the instantaneous change in VSP [d(VSP)/d(t)] to address vehicle efficiency during acceleration. In this section, it is demonstrated that VSP can also be used to describe fuel consumption in heavy-duty diesel trucks as well as NOx emissions and influences hydrocarbon and carbon monoxide emissions, which is a likely indicator of particulate emissions response.

The driving history, defined here as the past use of the vehicle prior to the instantaneous emissions measurement, can have an effect on emissions and has not typically been an issue in past versions of MOBILE where fixed driving cycles were used. The most obvious example of this effect is observed with start emissions where the longer the soak, the higher the emissions. But other history effects may be observed depending upon the ambient conditions and in-use activity such as extended idling or cruises. For instance, in its study for EPA, ENVIRON (2002) found emissions to partially correlate with the most recent operating history of the vehicle. If inspection and maintenance data are to be used, these data may have uncertainties associated with the condition of the vehicle prior to the test. The length of the time the vehicle has been waiting, the ambient conditions while the vehicle was waiting, and the driving history of the vehicle prior to the test all could influence the test data and are often unknown.

The purpose of this subsection was to investigate if the plan for MOVES will be appropriate for regulated pollutants. An investigation of the impact of vehicle behavior on exhaust emissions of regulated pollutants is provided in this subsection. Specifically addressed in this section is if the primary measure of vehicle behavior, VSP, will describe the regulated emissions of HC, CO, and NOx as well as it appears to for fuel consumption. In addition, potential additional variables are suggested to better describe the regulated pollutant emissions rates.

2.3.2 Light-Duty Vehicles

While VSP may be a good predictor of fuel consumption rates for individual light-duty vehicles and is further discussed in Section 3, VSP by itself will not necessarily be a good or the only predictor for tailpipe criteria pollutants emissions.

Vehicles and dynamometer data for the analyses presented in Section 2.1.6 were from the 346 vehicles in the NCHRP 25-11 data set (Barth et al., 2000). This data set was chosen because three different driving cycles were used on most of the vehicles, there were a large number of high emitting vehicles, and the data were in the public domain. The descriptions of the vehicles selected and their emissions on the three driving cycles are shown in Appendix B.

From this data set, it was observed that high emitting vehicles have different second-by-second emissions that may be affected by both the driving mode and the driving cycle in addition to the emissions response to vehicle load as measured by VSP. The emissions may be highly variable within VSP bins defined within a 2 kW/tonne range for certain conditions, but not for other conditions. For instance, the grams per second emissions rates may correlate with VSP for normal emitters, or if a variable high emission vehicle, emissions may correlate with a function of both VSP and the change in VSP [d(VSP)/dt].

The driving modes used were the same as those defined in the "PERE" report (EPA, 2003a). These driving modes were: Idle: speed <2 mph; Deceleration: acceleration < -0.2 mph/s; Cruise: -0.2 mph/s > acceleration < 1 mph/s; Acceleration: acceleration > 1 mph/s. Other driving mode definitions may lead to better resolution and to restricting emissions variability, when it occurs, to a more limited range of driving conditions.

Driving cycles were generally used to simulate typical on road driving on a dynamometer. The FTP was the EPA's vehicle emission certification driving cycle for the 1980's and 1990's vehicles. The acceleration and speed ranges in the FTP were mild. It is not surprising that 1990's vehicles, which were normal CO emitters on the FTP, had much higher CO emissions on the more aggressive driving cycles. These vehicles were only required to have low emissions on the FTP. EPA has added the US06 test cycle for certification of more recent model year vehicles so that more of the aggressive driving observed on the road is included in the certification test. The NCHRP 25-11 study vehicles had a FTP and a US06 test and a third driving cycle, the modal emission cycle (MEC) developed specifically for Barth et al., (2000), which included higher speeds and decelerations, for emission model verification. VSP distributions for the three driving cycles are shown in Appendix D.

Modal (gram per second) emissions of some NCHRP 25-11 vehicles were binned by VSP for the different driving modes. In Appendix E, a number of comparisons of emissions and VSP are provided for normal and high emitters. Appendix E shows charts with emissions in gram per second as a function of VSP and driving mode for these vehicles. This demonstrates when the driving mode (acceleration, deceleration, cruise, or other) may be an important consideration in addition to changes in VSP.

Vehicle 284, a Tier 1 normal emitter, had low emissions on all three driving cycles, but the HC and CO emissions appeared to be higher under acceleration modes in US06 test cycle. This indicates that an acceleration mode (independent of VSP) may be an important additional variable to describe emissions under all conditions.

High emitters often behave differently from one another. For instance vehicle 300, a Tier 0 high CO and HC emitter, emitted especially large amounts of CO and HC during deceleration in MEC and US06. Vehicle 205, also a high CO and HC emitter, emitted increasing CO and HC as VSP increased for all driving cycles. Vehicle 277, a high CO emitter and moderate HC emitter, and 97, a very high CO and HC emitter, became extremely variable during US06 and MEC cycles, respectively.

As a test of additional explanatory variables, an additional parameter describing the change of VSP with time [kW/tonne/second and labeled "d(VSP)/dt)"] dramatically improved the correlation of the highly variable HC and CO emissions with VSP for Vehicle 97 as shown in Appendix E. The high variability of emissions as a function of VSP observed in some vehicles during certain driving modes is consistent, at least in part, with repeated remote sensing measurements seen in some high emitting vehicles ("flippers"). But the improvement in the explanation of the emission response with this additional parameter should continue to be investigated.

Therefore, additional vehicle driving parameters will be needed to adequately describe regulated emissions. Additional driving parameters could be either a single additional parameter for power increases, or driving modes (acceleration, deceleration, or cruise) may need to be defined.

It is also clear from this analysis that VSP bins do not provide more confidence in describing emissions behavior because the emissions could be better described through regression of the data. However, the VSP bins were useful for investigating emission response.

2.3.3 Heavy-Duty Vehicles

To analyze heavy-duty vehicle emissions, three of the most recent models available in EPA's database, described in Table 2-14, were chosen to review important considerations when estimating emissions. Recent models were chosen to better reflect the latest technology likely to be employed in future versions of engines. The vehicles were chosen from the most recent CRC E-55 dataset as the data appeared in EPA's MSOD database provided to ENVIRON on September 15, 2003. The test cycles chosen were the ARB transient and cruise test cycles, which were run back to back. During the testing, two runs of these cycles occurred each day, and, to eliminate any influence of a cold start, the second run (considered here as a hot start) of these cycles was used in the analysis below.

Table 2-14. CRC E-55 vehicles used to analyze heavy-duty truck emissions.

Vehicle ID	CRC-4	CRC-5	CRC-11
MSOD ID	1HSHCATR6YH696992	1FUYDDYB01PG95265	1FUBAHA861PH45722
Model Year	2000	2000	2000
Engine Type	Caterpillar C-10	Cummins N-14	Cummins ISM-11
Vehicle GVWR	52,000 lbs.	52,000 lbs.	Not Available
Test Weight	56,000 lbs.	56,000 lbs.	56,000 lbs.
Test Condition	Hot	Hot	Hot
Time Matching Adjustments			
VSP Delay	19 sec.	13 sec.	12 sec.
NOx Delay	11 sec.	6 sec.	3 sec.
ARB Hot Transient (g/mile)			
THC	0.60	2.08	1.19
CO	9.18	9.23	3.46
NOx	29.1 \ 28.9	36.6 \ 37.6	16.9 \ 17.1
CO2	2707	3096	2274
PM	0.85	0.88	0.45
ARB Hot Cruise (g/mile)			
THC	0.20	0.69	0.42
CO	4.28	3.89	1.22
NOx	16.9 \ 17.4	24.0 \ 24.2	14.2 \ 14.1
CO2	1477	1638	1301
PM	0.22	0.24	0.12

The vehicle speed was converted to VSP through the use of the wheel load calculation as follows in the equation below. [For these trucks in the analysis here, the VSP was defined as the power in kilowatts rather than in kilowatts per tonne of vehicle weight because the applicable emission standard was based on the engine specific power (gram per horsepower-hour) rather than in terms of the specific vehicle (gram per mile) like light-duty vehicles and all these trucks were tested at the same weight of 25.4 tonnes.]

$$Power_1 = (a + b * Speed_1 + c * Speed_1^2) * Speed_1 + 0.5 * Mass * (Speed_1^2 - Speed_0^2) + Mass * g * grade * Speed_1 + Auxiliary\ Power$$

The coefficients a, b, and c for a transit bus were supplied by West Virginia University (2000), as shown in Table 2-15. A transit bus is not necessarily a perfect representation of the behaviors of these trucks given the different vehicle configurations, but because this analysis was a qualitative review of the emissions behavior it was considered reasonable for investigating important explanatory variables.

Table 2-15. Road load coefficients for a bus (WVU).

Source	a (Hp/lb$_m$/(ft/sec))	b	c (Hp/(ft/sec)^3)
WVU (2000)	1.68985E-05	0	0.000130600

The data available in EPA's MSOD for these tests required that the emissions and vehicle behavior to be matched in time to better compare VSP with the regulated emissions. The time was matched by adjusting the peak VSP (and vehicle speed) to correspond with the peak CO2, but the peak NOx still appeared to be offset, so a separate NOx adjustment was made. These adjustments from the raw data are shown in Table 2-14. The THC and CO emissions were not explicitly adjusted and expected to correspond in time to the CO2 signal.

The importance of the time matching is critical to accurately reflect the emissions with vehicle behavior, and deserves considerably more analysis than can be investigated here. Time lag adjustment is a complex function of engine exhaust flow, sampling systems, and gas analysis systems. The constant time lag used in this work is a first approximation of an adjustment. The time lags with heavy-duty vehicles are much longer than with light-duty vehicles, which suggests that they are largely associated with the vehicle's exhaust system, both in terms of the distance between the exhaust port and the sampling location and the sampling lengths. The lag time associated with this flow is inversely proportional to the exhaust flow rate and, roughly, the engine power or VSP both surrogates for exhaust flow rate, so the time adjustment should vary by power level. The scatter in the emissions versus VSP charts described below could be due to inaccurate time matching. Any remaining offset may lead investigators to the wrong conclusions about the importance of each explanatory variable.

Figures 2-7 through 2-12 show the time traces and the emissions response to VSP for these three vehicles. The time trace demonstrates an issue with the CO signal where the emissions rate was clipped at 0.1 gram per second. Otherwise, the time traces demonstrate a correspondence of emissions and VSP. The correspondence of CO_2 and NOx with VSP demonstrates that the vehicle load explained much of the emissions response. THC emissions from these vehicles were very low, so the THC emission response to engine load was less certain. For all emissions (but especially so with CO_2 and NOx emissions) there is no demonstrable reason for the use of VSP bins to estimate emissions. An analytical expression derived through regression of the data will explain the emissions behavior more accurately than segmenting the activity into VSP bins.

The diesel engines in these tests do not include the most recent technologies, including exhaust gas recirculation (EGR), expected to be widespread with the 2004 heavy-duty diesel emission standards but already introduced for some models. When emission controls, including aftertreatment devices, begin to be implemented, the emission response to VSP may become less certain as the emission control devices are introduced. As an example of the peculiar effects of vehicle or engine design, Gautam et al., (2002) under CRC E-55 demonstrated, for vehicle number 10, that the driving mode (transient or cruise) could have an effect on the NOx emissions in addition to response to vehicle load.

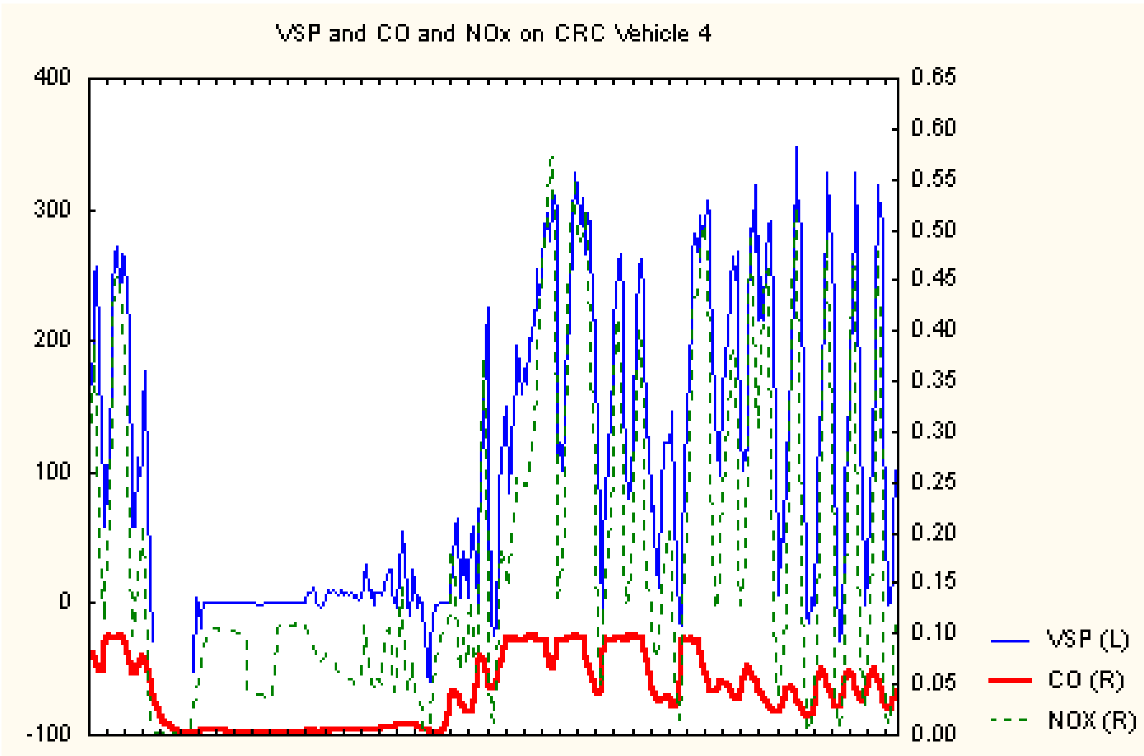

Figure 2-7. Time matched VSP (kW) and emissions (g/sec.) for vehicle number 4 from CRC E-55.

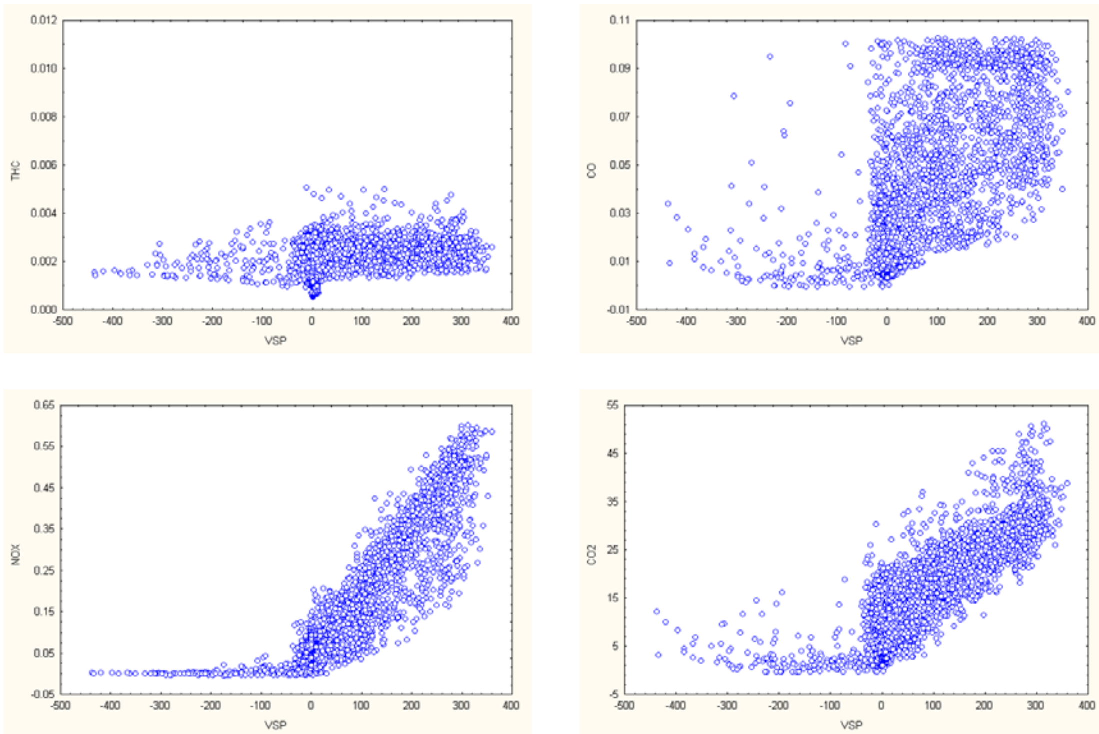

Figure 2-8. Emissions (g/sec) by VSP (kW) from vehicle number 4 from CRC E-55.

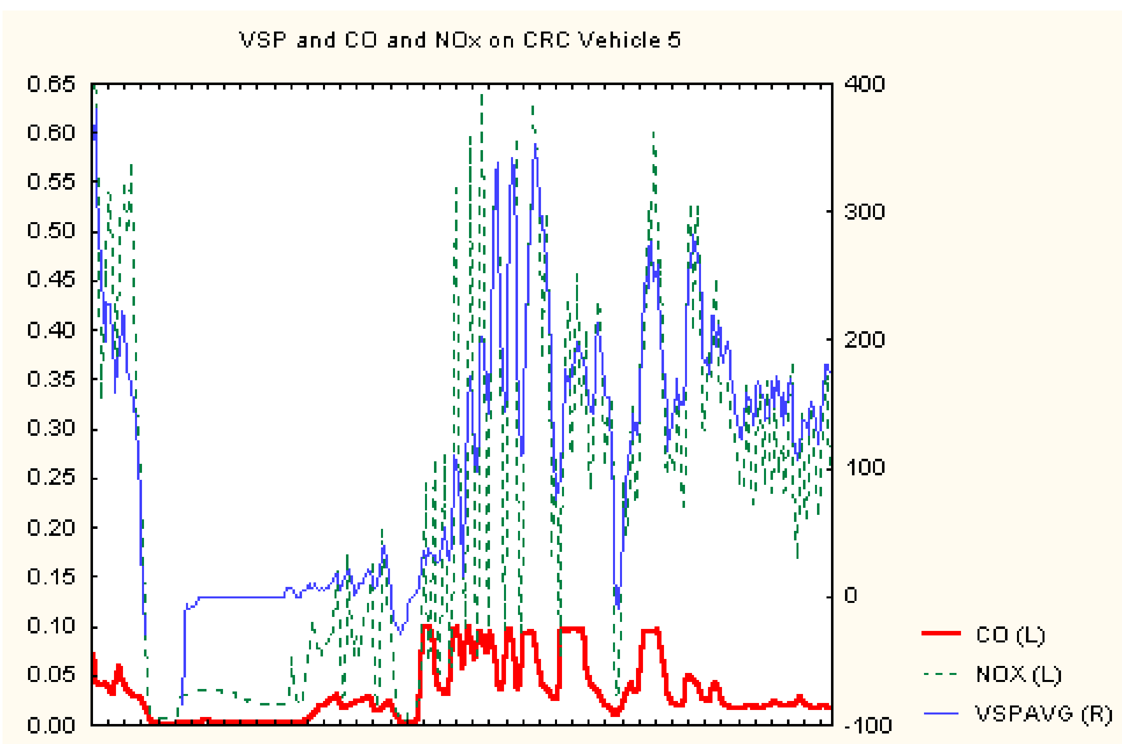

Figure 2-9. Time matched VSP (kW) and emissions (g/sec.) for vehicle number 5 from CRC E-55.

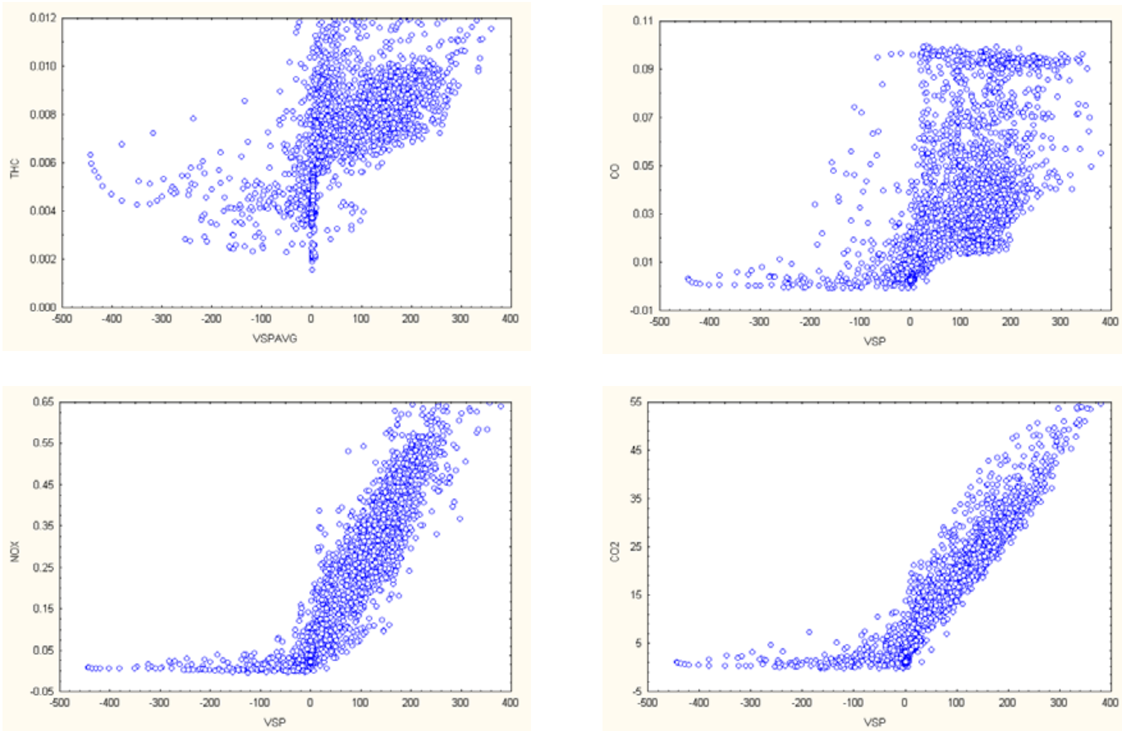

Figure 2-10. Emissions (g/sec) by VSP (kW) from vehicle number 5 from CRC E-55.

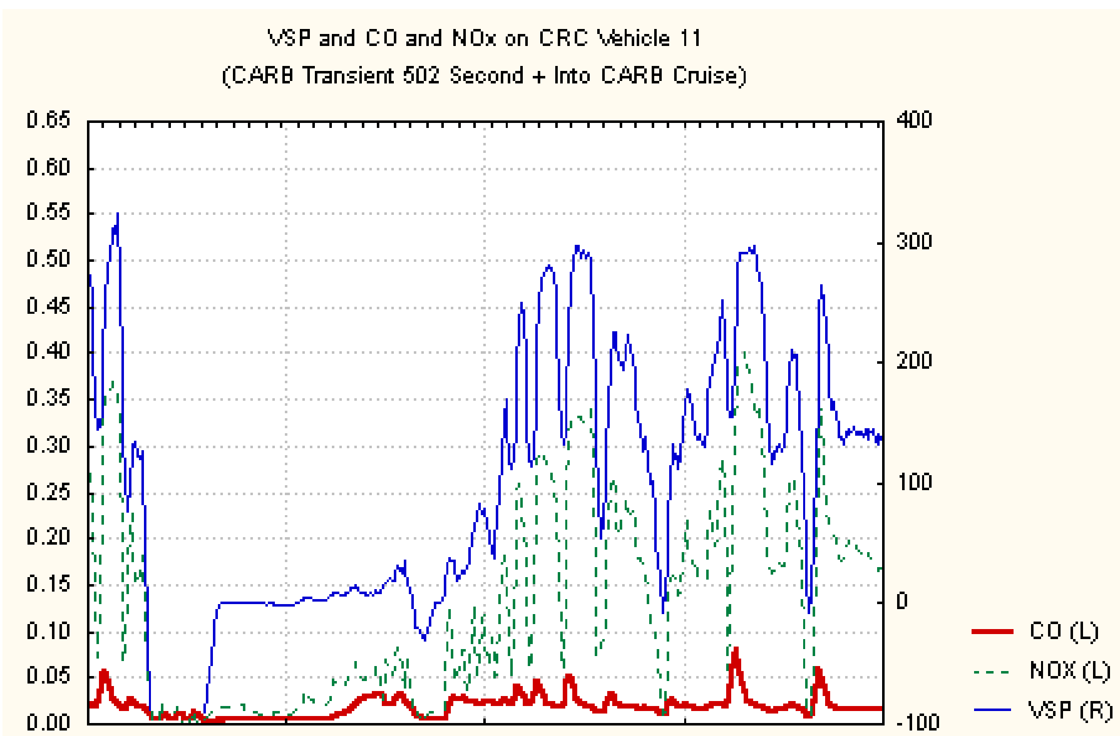

Figure 2-11. Time matched VSP (kW) and emissions (g/sec.) for vehicle number 11 from CRC E-55.

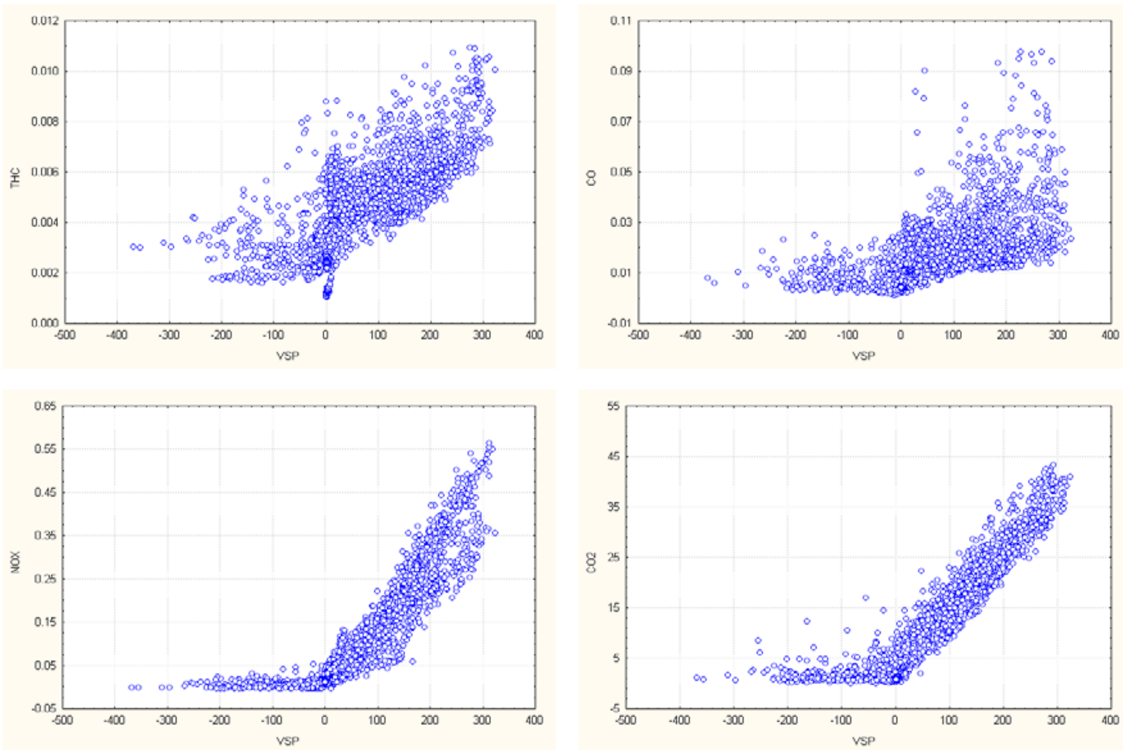

Figure 2-12. Emissions (g/sec) by VSP (kW) from vehicle number 11 from CRC E-55.

Because of the larger scatter in the CO emission rates, a qualitative investigation of other potential explanatory variables was undertaken. THC emissions also show scatter, but THC emissions were an order of magnitude lower than CO emissions, so the scatter was more likely due to noise in the measurement. Also, CO emissions are potentially more important because CO emissions have been reported to correlate with PM emissions (Wang et al., 2000). The effect of vehicle parameters was addressed only for CRC Vehicle 11 because the CO emission peaks for Vehicles 4 and 5 appear to be clipped at about 0.10 gram per second and are probably erroneous. Vehicle 11 CO emissions were always below this level, so there was no interference with the measurements, however the low emissions rate may introduce measurement noise into this analysis. (Vehicle number 1 also demonstrated this effect, so it was endemic with this study's results as it appears in EPA's database.)

An investigation was performed to investigate if other parameters could be important in describing CO emissions. The other parameters investigated here include vehicle speed, the instantaneous change in VSP per second (labeled DELVSP), and the previous 5-second average positive (negative VSP reset to 0) VSP prior to each data point (labeled VSPPRPOS). The DELVSP variable is used to describe rapid increases in VSP and meant to represent engine behavior such as turbocharger lag when undergoing acceleration possibly resulting in lower instantaneous air-fuel ratios. Negative DELVSP are included in the analysis but lumped with DELVSP equaling zero in the figures described below. The VSPPRPOS variable is used to describe the effect vehicle history, in this case the previous five seconds of activity, to describe events when engine is ramping up from a lower load or down from higher loads to describe differences in engine condition prior to the event.

Figures 2-13 and 2-14 provide multiple scatter plots for three variables at a time. In Figure 2-13, CO is described as a function of VSP, Speed, and DELVSP, and in Figure 2-14, as a function of VSP, Speed, and VSPPRPOS. Each of the smaller plots within the figures is a plot of CO versus VSP, the primary variable. The effect of vehicle speed is visualized by comparing the plots in the rows with one another. The effect of either DELVSP in Figure 2-13 or VSPPRPOS in Figure 2-14 is demonstrated by comparing plots in the columns with one another. Each plot within the figures could be considered a bin describing the vehicle behavior.

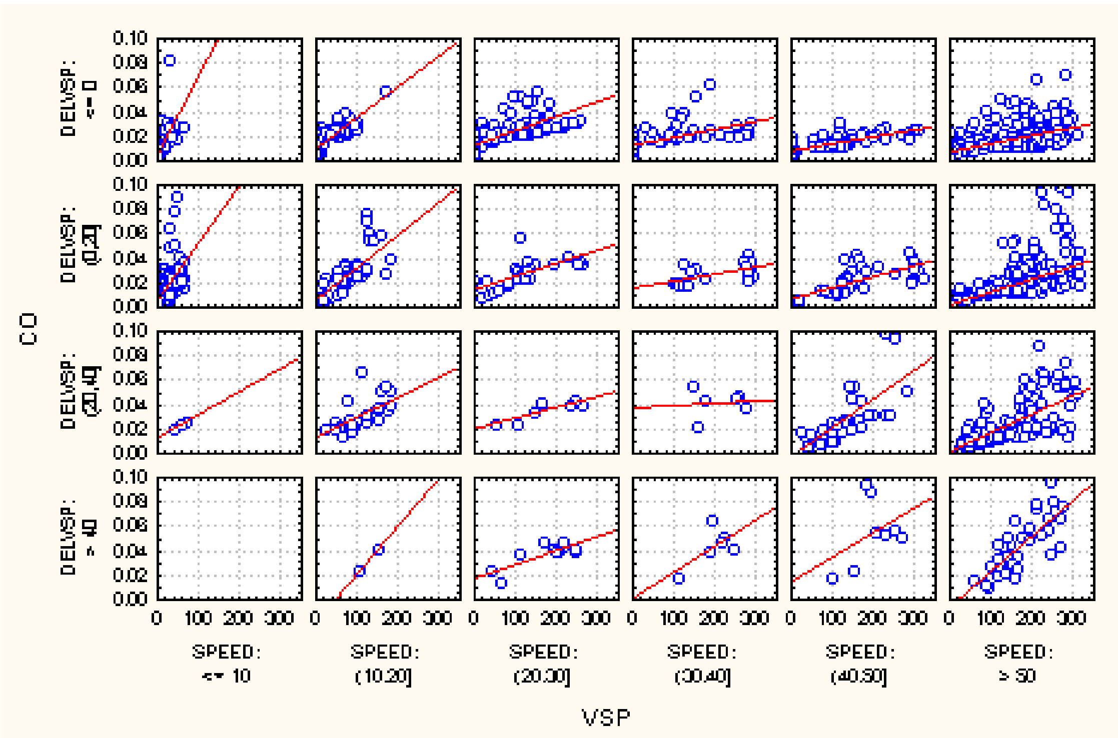

Figure 2-13. Comparison on CO emissions (g/sec.) as a function of VSP (kW) under different speed (mph) and load changes (kW/sec).

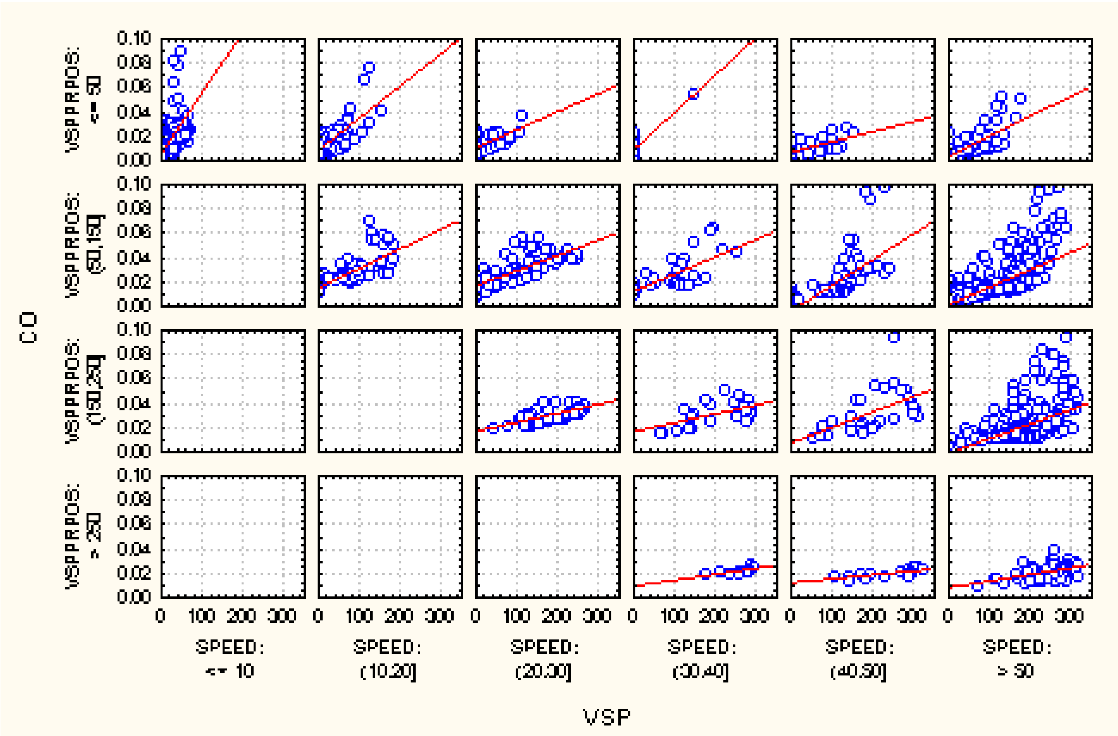

Figure 2-14. Comparison on CO emissions (g/sec.) as a function of VSP (kW) under different speed (mph) and previous load (kW).

In addition to the general trend of CO emissions and VSP, vehicle speed, change in VSP, and the previous 5-second VSP all appear to have an influence on the CO emission rate under certain conditions. A more extensive analysis is warranted to determine which variables and how many bins need to be defined to describe emissions. Because the data on these test cycles do not equally represent each bin, the number of bins defined should be minimized to only those that demonstrate large differences in the fitted parameter to improve the correlation. In Figures 2-13 and 2-14, for the bins where the data were sparse, the correlation could be unnaturally influenced by individual data points, so the fits within those bins with little data should be viewed with skepticism.

For both Figures 2-13 and 2-14, the vehicle speed appears to have an effect on the emission for vehicle speeds below 10 mph and perhaps 20 or 30 mph where sufficient data exist. For vehicle speeds above 30 mph, the effect is much less apparent. Understandably, the VSP in the lower speed bins was limited to lower VSP ranges. So while the correlation for CO and VSP in the lower speed bin appears to be substantially different than for other speeds, the emission rates within the applicable VSP range are not as dramatically different than for other speed bins as the correlation makes it appear.

In Figure 2-13, there may be an indication that DELVSP can improve the description of CO emissions, best observed comparing the plot in the last two columns. Comparing the lower plots, those with higher DELVSP, with the plots above, one may discern a trend toward higher emissions with higher DELVSP. However, the trend is not clearly obvious.

In Figure 2-14, the previous VSP (5 seconds was arbitrarily chosen) may have influenced the CO emissions response to VSP. This is best represented by comparing the lowest row of plots, those for VSPPRPOS >250, with the rows above where the higher previous VSP (VSPPRPOS) corresponded to lower CO emissions. Again, CO emission behavior is of interest because it may be predictive or correlate with particulate emissions. Appropriate second-by-second data on PM emissions have not been available that would allow a direct analysis of the adequacy of VSP binning for PM emissions prediction.

2.3.4 Conclusion

The correlation of regulated emissions with VSP is more complicated than the correlation of fuel consumption with VSP that is demonstrated for light-duty vehicles in Section 3 and here for heavy-duty vehicles. This has important implications for data collection in that more explanatory variables will be required to describe the regulated pollutant emissions from vehicles. The analysis performed here included only a handful of vehicles, so it was difficult to draw firm conclusions based on this limited analysis.

Light-duty vehicles, and high emitters especially, were demonstrated to respond differently to vehicle power, change in power, and driving modes. At a minimum, the change in VSP with time was demonstrated as an important additional explanatory variable for one high emitter. However, there were also indications that the driving mode could be important for some vehicles.

For heavy-duty vehicles, the emission response to VSP was clearer for NOx; however, CO emissions, probably a good indicator of PM emissions, demonstrated much more complex behavior where a number of additional variables could be important to explain the emissions response.

EPA conceptual design describes binning the vehicle activity; however, the analysis here did not demonstrate that the effect on emissions of vehicle behavior falls neatly into bins of activity. The effect on emissions often can be described by analytical expressions of emissions as a function of vehicle operation. In many cases, the test cycles used to generate emissions estimates populate information selectively by bins, so binning the data may reduce the amount of data in certain bins creating the possibility that outlier data points would unduly influence the estimates within that bin. The concept of activity bins needs further analysis especially compared with an approach that uses analytic (regressions) to the vehicle operational parameters. Binning may then be used as an intermediate step to investigate and demonstrate the importance of a given parameter on the emissions before preparing the best analytical expression to describe the data.

2.4 IN-USE ADJUSTMENTS

2.4.1 Introduction

When using field (such as using PEMS) or laboratory dynamometer data, the emission rates measured have been adjusted from the testing conditions to a standard condition. EPA (2002a) describes that the in-use adjustments will likely include adjustments for ambient conditions and fuel use. These ambient and fuel adjustments have been used in reporting data from testing as well as in the model itself and so should be consistent. A single adjustment has been made for the effects of cold start where cold start has been considered to be a separate operating mode. Other adjustments have accounted for mileage accumulations and age but these have been addressed as separate variables when defining vehicle bins or as an analytic expression for estimating emissions as discussed in Section 2.1.

Ambient conditions have been shown to affect emission rates, so conditions occurring at the time PEMs measurements are recorded could be important. This could be important for a greenhouse gas model, where predictions are intended for all seasons compared with pollutants associated with just the ozone season. A list of potentially important ambient conditions includes temperature, humidity, cloud cover, wind speed, and barometric pressure or altitude. The effects of all of these ambient conditions except wind are estimated in MOBILE6, and the EPA (2002a) describes that MOVES will likely include these adjustments in a similar fashion as was programmed into MOBILE6.

Fuel effects could include a number of obvious parameters (e.g., oxygen and sulfur content) as well as other effects including volatility (by time of year) or other parameters. Most concerns about fuel parameters have focused on gasoline, but there may be important diesel fuel parameters including the California and Texas reformulated diesel fuel requirements, the winter use of lighter diesel fuel in northern climates, or newer formulations such as gas to liquids (GTL) diesel mostly produced using the Fischer-Tropsch process. If the model uses adjustments to account for these parameters, then the in-use data (such as collected using PEMS) must address the fuel effects either through corrections or in-use measurements for all types of driving.

2.4.2 Ambient Conditions

The ambient conditions can have a marked effect on the emissions predicted, and current adjustments are made in MOBILE6 for altitude, cloud cover, temperature, and humidity. These adjustments are made to reflect the in-use conditions, but are also used to adjust the emissions data according to the test conditions.

Humidity and temperature are conditions most often manipulated according to the in-use conditions when ozone or carbon monoxide exceedance ambient modeling and planning exercises have been performed. Higher humidity has been shown, as described below, to reduce NOx emissions, and typically higher temperature results in higher NOx emissions when the combustion parameters are held constant.

Emissions under laboratory conditions are adjusted according to the Code of Federal Regulations (CFR) such as CFR 86-144-90 for light-duty gasoline vehicles and CFR 86-345-79 for heavy-duty engine dynamometer testing. For light-duty vehicles the primary adjustments for temperature and altitude correct the volumetric flows for the exhaust emissions calculations but otherwise do not correct emissions based on the testing conditions. EPA and others using the CFR to correct light-duty NOx emissions according to the humidity using equation (1), while the heavy-duty gasoline engines used an alternative humidity correction factor in equation (2). The adjustments for diesel engine NOx emissions include corrections for both temperature and humidity, as shown in equation (3).

Light-duty vehicles

$$K_H = NOx_{adjusted} / NOx_{test} = 1 / [1 – 0.0047 (G – 75)] \quad (1)$$

Heavy-duty gasoline engines

$$K_H = 0.6272 + 0.00629G – 0.0000176G^2 \quad \{K_H = 1 \text{ when } G = 75\} \quad (2)$$

Heavy-duty diesel engines

$$K_H = 1 / [1 – A (G – 75) + B (T – 85)] \quad (3)$$

where

G is humidity in grains/pound of dry air
A = 0.044 (f/a) – 0.0038
B = -0.116(f/a) + 0.0053
(f/a) = fuel air ratio
T is inlet air temperature in Fahrenheit

The correction factor for light-duty vehicles was based on work performed by Manos, et al. (1972). The correlation is in the form to correct the test conditions (NOx_{test}) to an adjusted baseline condition ($NOx_{adjusted}$). The adjusted emission rate has been used as the condition for developing the basic emission factors (BEF) for emissions models.

For the correction factor for gasoline-fueled heavy-duty engines during certification, EPA (Code of Federal Regulations Part 86.345-79) presents a correction factor for NOx based on the humidity of the inlet air. This correction factor was established based on the work of Krause (1971). The correlation shown in equation (2) was developed to use when reporting test results from the certification test cycle for heavy-duty gasoline engines.

The SAE correction factor for heavy-duty diesel engines was based on work performed by Krause, et al., (1973). The relationship, presented as Equation (1), includes the effects of both temperature and humidity, and is referenced to standard conditions of 85°F (29.4°C) and 75 grains/lb (10.71 g/kg) humidity, where (f/a) is the fuel-to-air ratio by mass. The SAE standards J177 and J1003 that reference this correction procedure were recently cancelled on October 1, 2002 with the comment that these procedures were no longer required. This correction factor was also, and continues to be, used as part of the EPA standards CFR title 40 Part 86. When the test condition is with higher temperatures, the emissions would be corrected to lower emission estimates to the baseline conditions.

EPA revised the light-duty vehicle humidity correction equation for MOBILE6 to incorporate the basic premise of the Manos correlation, but truncated the effect to limit the uncertainty of the estimates for high and low humidity, as shown in equation (4). This adjustment is separate of the interaction of humidity on air conditioning loads, where humidity affects the calculation of heat index used to estimate the air condition loads and described in more detail below. This relationship (Figure 59 of EPA, 2002b and reprised in Figure 2-15) is comparatively similar to the Manos correlation and reflects that when the humidity is higher than 75 grains per pound of dry air the in-use NOx emissions are predicted to be lower, according to the historic understanding of the effect.

$$NOx_{\text{in-use}} / NOx_{\text{BEF}} = 1 / K_H = \begin{cases} 1.2 & \text{if } G \# 20 \\ (-0.004\,G + 1.28) & \text{if } 20 < G < 120 \\ 0.8 & \text{if } G \$ 120 \end{cases} \qquad (4)$$

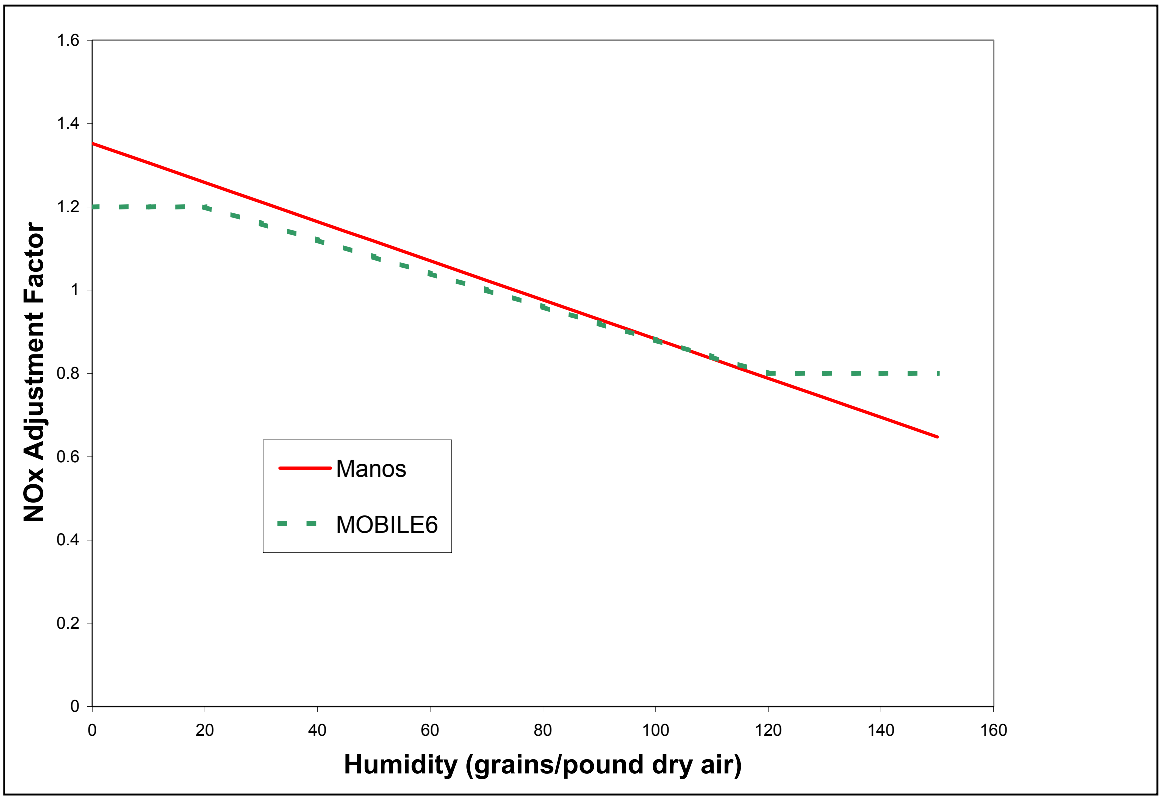

Figure 2-15. Comparison of adjustment factor.

The other primary adjustment has been that used for altitude corrections to reflect the lower barometric pressures found at higher altitudes. To date, the only correction that has been applied is for high altitude where Denver area testing was compared with lower level testing performed in places such as Michigan, Indiana, or Phoenix. In Table 2-16, are a comparison of the altitude corrections in MOBILE6 for various vehicle types. For open loop light-duty vehicles, the corrections vary by model year and separately adjust zero-mile (ZM) emission factors and deterioration factors (DF). Closed loop air fuel controls largely eliminate the problems with changing barometric pressure as experienced at altitude.

Table 2-16. Emission effect of altitude as a ratio (high/low).

Vehicle Type	THC	CO	NOx	PM
1979-1980 Open Loop LDV	2.07 ZM 0.95 DF	4.11 ZM 1.10 DF	0.53 ZM 0.97 DF	---
1979-1980 Open Loop LDGT1	2.08 ZM 1.09 DF	3.66 ZM 1.02 DF	0.53 ZM 0.96 DF	---
1979-1980 Open Loop LDGT2	1.25 ZM 0.66 DF	2.53 ZM 0.70 DF	0.56 ZM 1.02 DF	---
HDGV	1.86	3.18	0.82	---
HDDV	2.05	2.46	1.02	1.47

Temperature has long been a variable in estimating emissions from on-road vehicles. In MOBILE6, solar load and cloud cover combined with temperature and relative humidity within a heat index were found to affect the time that the air conditioning compressor was running (EPA, 2001b). The added load of the air conditioner affects emissions through increase engine load to run the air conditioning compressor. In MOBILE6, the correlation of emissions demonstrates an increase with the use of the air conditioning compressor. With MOVES, similar adjustments could be used because the time that the compressor was on and the effect on emissions were determined for a number of modal conditions. At lower temperatures, the temperature affects the emissions during the cold start by delaying the time for which the engine and catalyst can reach operating temperature, effectively increasing the start emissions. In-use measurements, such as developed using PEMS, should be able to account for and provide additional evidence of the effect of air conditioner loads.

The ambient adjustment factors have been developed using studies, especially those investigating heavy-duty vehicles, where the studies date to the early 1970s, with vehicles unrepresentative of the latest technology. Also, in large part the adjustments were developed using cycle total data rather than modal data, so are inconsistent with the modal emissions approach in MOVES. Further investigations on modal emissions rates need to determine if the effects of ambient conditions are consistent for all types of driving.

2.4.3 Fuel Effects

The fuel effects incorporated to date have also been incorporated as adjustment based on the effect on cycle total emissions. The typical fuel adjustments (such as those included in MOBILE6) have focused on gasoline properties; especially oxygen and sulfur content, fuel volatility as measured by RVP, and a combination of fuel parameters represented by reformulated gasoline. It may also be necessary to consider diesel fuel parameters such as oxygen content, use of biodiesel, or the use of reformulated diesels (such as those mandated in California and Texas) that affect cetane, aromatic, density, and other parameters that affect emissions rates. The adjustments to date have been to emissions in total, but the emission response to fuel parameters may not affect emissions equally under each vehicle driving condition. Therefore, the effect of gasoline fuel parameters will depend upon both the vehicle and test conditions tested.

For instance, a functioning late model Tier 1 vehicle with fuel air control may not be sensitive to small changes in the fuel oxygen except during conditions of enrichments such as might be experienced during cold start conditions or under high load conditions. Tier 1 normal emitters begin to have significantly higher emissions above 20 kW/tonne VSP, as shown in Section 4. For a malfunctioning vehicle, the effect of added fuel oxygen would likely primarily affect emissions under conditions where fuel air control was not functioning, which could be either under specific circumstances such as decelerations (as demonstrated for vehicle 300 in Appendix E) or with a similar effect for all driving behavior. However, a limited analysis of the effect of fuel oxygen content on CO emissions did not indicate a different response for modes of operation (Heirigs, 1998). This type of analysis could be expanded to include emission response under all operating conditions not just the start and hot running emissions rates.

Fuel sulfur has long been known to increase emissions during hot running conditions because of catalyst poisoning. During cold start when the catalyst has not attained operating temperature, it might be expected that fuel sulfur would have little impact; however, lower fuel sulfur likely reduces the time for the catalyst to attain its operating temperature, so lower fuel sulfur likely reduces the overall increase in emissions during cold start. Still the effect of fuel sulfur will likely be different depending upon whether the vehicle is operating under cold start or hot running conditions (EPA, 2001c). The effect of fuel sulfur may become a moot issue, as all on-road gasoline will need to maintain a low sulfur level so the fuel will not vary much in the field.

2.4.4 Summary and Conclusions

The humidity and temperature corrections (other than air conditioning effects) for the tailpipe emissions refer to studies from the 1970s, so EPA must revisit these adjustments. These dated adjustment equations have already been used to adjust the field and laboratory data, so any revised relationships will need to consider how they affect the emissions in the EPA's database. While most of the ambient and fuel effects could be adjusted, it should be a special consideration when converting in-situ data (such as collected using PEMS or portable dynamometer) to a base condition where the conditions during testing may be significantly different than the base conditions compared with laboratory conditions, which are usually modified to be close to the base condition.

When adjusting emission factors in the MOVES model, it will be necessary for EPA to consider adjusting emissions based on the effects under all operating conditions. EPA therefore needs to determine whether the adjustments should affect all vehicle operating (VSP or others) activity (such as each bin) to an equal extent, or if the ambient or fuel conditions affect emissions from certain vehicle operation to disproportional extent compare with other operation.

2.5 INCORPORATION OF ACTIVITY DATA

2.5.1 Introduction

The interaction of MOVES with in-use activity estimates will be important to estimate all pollutants but perhaps will be even more important for models subsequent to MOVES GHG. Where issues are more regional (defined by EPA as meso-scale) or micro-scale rather the macro-scale of the entire national emissions estimates, the burden will be greater for the modeling to describe emission rates for more types of activity. These finer scale model efforts may be of interest for MOVES GHG where small-scale projects may affect fuel consumption, but modeling the finer scale emission rates will be essential to evaluate the impact of regulated pollutants. Preparing emission estimates using emission factor models, such as the proposed MOVES or the current MOBILE6 models, activity estimates must be generated that correspond to the variables proposed by the models. The MOVES model and its estimates combined with the activity information will be used for national (macro-scale), regional (meso-scale), and project (micro-scale) planning and analysis. The project analysis could encompass as small a spatial area as an individual intersection or specific segment of roadway.

With current MOBILE6 modeling, there are a number of variables that must be estimated including vehicle type (both vehicle size and fuel type), registration and mileage accumulation, average speed, and others. The use of MOVES will demand additional information about the driving behavior besides average parameters such as used in MOBILE6 where average speed is the critical parameter of interest. Because of the opportunity to describe more vehicle specific parameters, it could be possible to estimate emissions using distributions of activity instead of single averages. However, this opportunity increases the burden on data collection and for EPA to provide reasonable typical vehicle behavior for a larger number of situations (vehicle types, road facilities, time-of-day or congestion levels, and other conditions) than is currently used to describe emission rates.

2.5.2 Activity Estimates

The activity estimates used for planning purposes use a range of information sources varying in specificity by the spatial scale of interest. More specific information is required as the analysis proceeds from larger to smaller scales of interest. In all cases, estimates of the numbers of vehicles traveling on each roadway have been used directly or converted to vehicle miles travel (VMT) estimates and average speeds and combined with mobile source emission rates estimates to provide total emission estimates by the temporal averages of annual, seasonal, monthly, weekly, day-of-week, or hourly.

2.5.2.1 Macro-scale

Macro-scale analysis usually relates to State and national total emissions analysis where VMT estimates generated from general information using the data derived from the Highway Performance Monitoring System (HPMS) have been used with MOBILE emissions models to estimate total annual or other average conditions (FHWA, 1999). The HPMS is a combination of sample data (such as using traffic recorders) on the use and physical characteristics of road facilities functionally classified as shown in Table 2-17. The traffic counts include estimates for all public roads within each State.

Table 2-17. HPMS roadway functional classifications.

Code	Classification Description
Rural	
1	Principal Arterial – Interstate
2	Principal Arterial – Other
6	Minor Arterial
7	Major Collector
8	Minor Collector
9	Local System
Urban	
11	Principal Arterial – Interstate
12	Principal Arterial - Other Freeways or Expressways
14	Principal Arterial – Other
16	Minor Arterial
17	Collector
19	Local System

The general travel within a state has been calculated as a product of the annual average daily traffic (AADT) and the centerline length of the section for which the AADT was reported. For the most part, travel for the rural minor collector and rural/urban local functional systems was calculated by the States using their own procedures and are provided in HPMS on a summary basis. Some States used supplemental traffic counts outside of the HPMS procedures; others employ estimating techniques, such as fuel use, to determine travel on their systems. In general, these methods have been used in both rural and urban areas, including the areas ringing the urban cores of nonattainment areas, to estimate activity for comparing emissions with the Clean Air Act requirements (FHWA, 1999).

EPA (2002c) allocated the State level VMT estimates from FHWA (1999) to individual counties through allocation indicators of rural mileage and urban population for the rural and urban road facilities. In this manner, EPA allocated the general State estimates to the counties using a generalized approach.

2.5.2.2 Meso-scale

For regional and smaller scale analysis, such as for air quality models or for local transportation plans, a more sophisticated approach is necessary. Travel demand modeling (TDM) is used to generate estimates of travel on specific roadways at specific times of day. The typical approach is outlined below, but there is also feedback/adjustment with actual field measurements and ground truth methods to ensure the predictions are accurate and can be used for planning. The outcome of the model is then VMT predictions on all roadways by time of day.

Travel Demand Modeling Method

1. Trip Generation
2. Trip Distribution
3. Mode Split
    a. Intermodal (heavy-duty vehicle activity)
    b. Non-motorized
4. Roadway Assignment
    a. Micro Simulation

b. Feedback Loops
c. Continuous Validation/Calibration

In addition, the travel demand model may then provide average speed, congestion levels, and other activity modes of operation. The importance of these estimates is to provide MOVES the activity by roadway type and under what condition. For instance, the average vehicle speed is a function of the congestion level where free flowing (unencumbered by traffic congestion) speed will be adjusted according to the congestion level, but average vehicle speed will not be sufficient for developing emission estimates using MOVES. MOVES will require generation (or provide default estimates) of vehicle activity (vehicle specific power) and preferably this should be a distribution of activity rather than a single estimate. If the emission rates are not linearly dependent upon the parameters of interest, then applying emission rates to a distribution of activity will not produce the same result as applying emission rates to average activity. NCSU (2002) found that emissions could be associated with higher order fits to various parameters. So it will be safer to provide a distribution around average activity rates. This would also facilitate uncertainty estimation.

One parameter of interest for emission modeling will be for activity estimates to better characterize trip starts and ends to properly apportion cold start exhaust and hot soak evaporative emissions. Many regions have begun to consider spatially and temporally allocating start emissions to specific locales by time of day.

TDM modeling to date has largely ignored the vehicle mix between heavy-duty and light-duty vehicles on all roadways, so that, for example, the proportion of VMT for heavy-duty vehicles is the same on freeways as it is on local roadways. However, for heavy-duty vehicles, there has been a great deal of interest in generating specific trip generation for commercial vehicles (Cambridge Systematics, 2003). The mix of vehicle types is particularly important for emission modeling because heavy-duty vehicles emit at significantly higher rates than light-duty vehicles. This could be important when considering vehicles whose trips begin and end outside of the area of interest including most significantly line haul trucking. Automatic traffic recorder (http://www.fhwa.dot.gov/ohim/tmguide/index.htm) measurements of vehicle types by time-of-day and day-of-week have made on a limited (limited both by number of sites and days of observation) basis and compiled by the Federal Highway Administration (http://www.fhwa.dot.gov/ohim/ohimvtis.htm). However, even these limited measurements have been used to adjust the vehicle mix on local roadways to better reflect the relative activity rates of heavy and light-duty vehicles.

In most cases, the travel demand models (TDM) provide the VMT and other activity estimates by roadway link. A sample of a small roadway link is provided in Figure 2-16. Typically the link is longer than shown but can range from about 0.02 to 5 miles. The TDM provides vehicle traffic estimates on each link including numbers of vehicles in each direction as well as free flowing speed and congestion level for each hour of day. The MOVES emission model demands of the TDM link level analysis that it estimate additional activity modes including acceleration, braking, idle, as well as cruise conditions within each link or to increase the number of links to address these different activity modes. Superimposed on the chart of the link in Figure 2-16 is an example of the relative VSP activity rates on the IM240, which might be representative of a surface street (collector or arterial) including idling, acceleration, and cruise conditions through two or more intersections; the speed-time trace in Figure 2-17 for the IM240 shows 2 braking events.

So the link definition may represent activity more typical of a driving cycle reducing the usefulness of added features and specificity that the MOVES method could provide by averaging activity and emissions over these longer time/geographic scales.

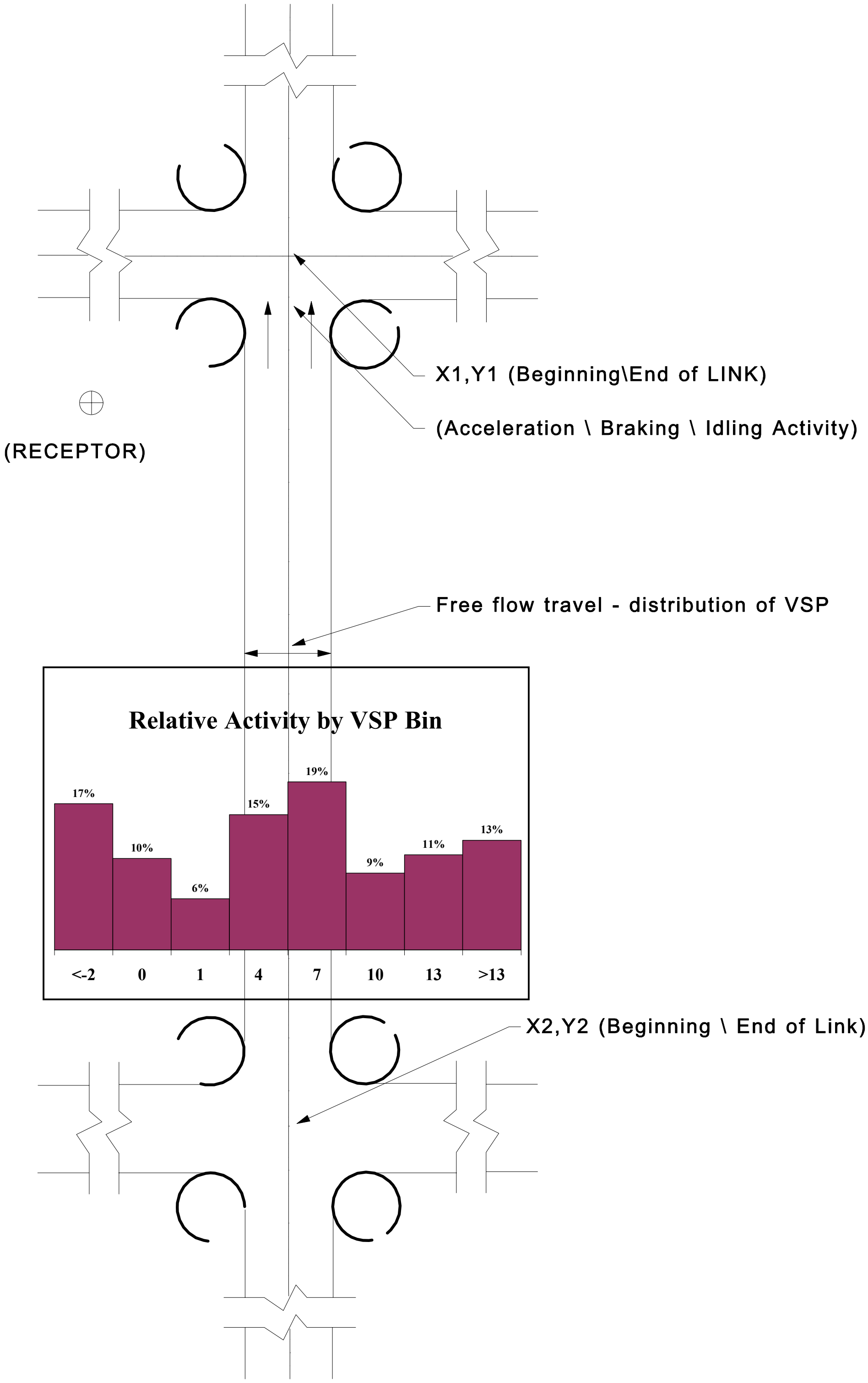

Figure 2-16. Example of a small link with IM240 VSP activity rates superimposed as an example of the activity that might be found on such a surface link (Adapted from EPA, 1995).

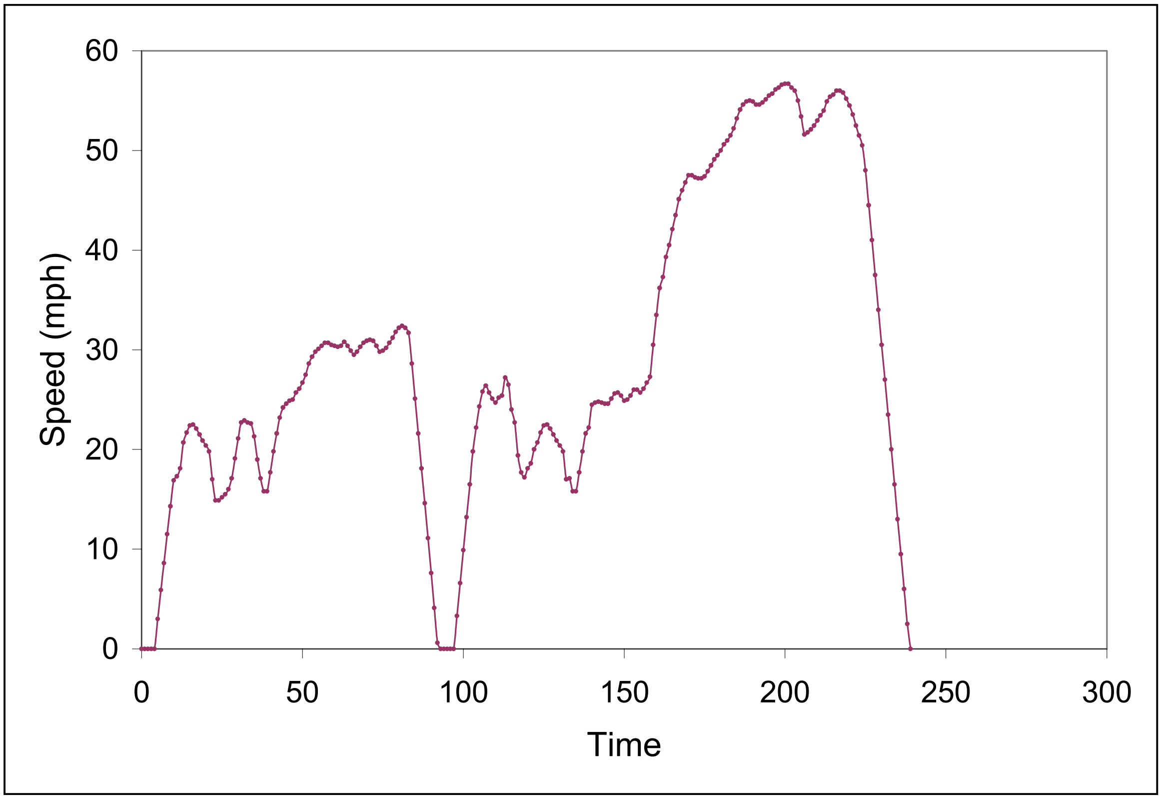

Figure 2-17. Activity on the IM240 driving cycle.

The use of MOVES will therefore encourage or demand more data gathering of actual activity rates (VSP but other variables considered important) on each link during all conditions (commuting periods, mid-day, over night, weekend, etc.). The opportunity of the MOVES modeling framework may encourage transportation modeling to size link lengths so that intersections may become distinct from the rest of the roadway or other modification to their existing network definitions or the model estimates may be divided in such a manner consistent with the current link definitions. The MOVES model will also permit the calculation of emissions as a function of road grade or wind speed through the power parameters defined in the modeling. TDM or other activity modeling would need to provide travel by direction on the specific roadway links that have a grade or prevailing winds. The mapping of roadway links will then require additional fields (grade, signal timing, and other such parameters) to describe each link. The MOVES approach will then burden transportation planners by requiring more local activity information to be collected, or the planners will be faced with using the national default information that EPA will need to provide.

This progression to smaller and smaller links is a natural outcome of the modeling approach and follows the progression from MOBILE5 to MOBILE6 where different roadway facilities including on-ramps of freeways were first addressed as separate entities. This approach recommended by CE-CERT (2002) follows the development of the Comprehensive Modal Emissions Model (CMEM) where trip based emissions could be successively divided into many different driving modes to provide the level of specificity required of the estimates. One concern with using modal emissions independent of the total trip emissions is that as the estimates are more finely distinguished, such as at the 1 Hz rates, the aggregate emissions of trips is lost. This is mostly a cause for concern if the effects of the driving history are important, for instance, if the prior experience of the vehicle will greatly affect the emissions. The effect of the vehicle history is clearly important for cold start emissions, but it is unclear how important other types of driving history are to emission rates. ENVIRON (2002) found that the recent historical engine load (typically for the previous 20 – 50 seconds) affected the emissions rates with higher historical load associated with lower emission rates even when cold start effects had been eliminated. So by ignoring the trip history, modal emission estimates may not accurately reflect in-use emission rates.

The importance of defining activity levels within each bin for each link will require that data describe vehicle behavior (VSP at a minimum but all variables deemed to be important in estimating emissions) on each link under all travel conditions. In looking at the distribution of activity levels within each VSP bin for a given link, the activity may be widely dispersed especially if a link is a long section of a roadway that passes through several intersections where acceleration, braking, idling, and cruise conditions may be represented. For illustrative purposes, the activity rates on the IM240 test cycle were calculated for a selection of VSP bins defined by NCSU (2002) and the results are shown in Table 2-18. Using the IM240 test cycle likely does not reflect vehicle behavior on a specific link, however it demonstrates that the vehicle behavior on a given link could span several bin definitions.

Table 2-18. Example of sample VSP bins and fraction of activity on the IM240[1].

VSP Mode Bin	Definition	Time in Bin
1	VSP<-2	17%
2	-2<=VSP<0	10%
3	0<=VSP<1	6%
4	1<=VSP<4	15%
5	4<=VSP<7	19%
6	7<=VSP<10	9%
7	10<=VSP<13	11%
8	13<=VSP<25	13%

[1] VSP will not be the only parameter of interest and the IM240 test cycle may not be representative of any particular roadway.

The emissions calculated for each link will be sensitive to the relative time-in-bin activity rates. These relative rates will be especially important for high VSP bins where emission rates are typically higher as shown in Figure 2-18. As shown the activity distribution used to generate the emissions estimates will not always be compatible with the actual activity distributions (such as suggested by the actual activity estimates provided in Table 4-5) within each bin and this will have an effect on the emission estimates. In Figure 2-18, for instance, if the highest VSP bin lumps all activity above a certain VSP level together, then the emission rate calculated for that bin will depend upon the test cycle used to generate the average emissions level. Because the average emission rate typically increases with increasing VSP level, the emission rate calculated for a lumped high VSP bin will be higher using the FTP+US06 than the IM-240 test cycle. This is because there is more activity at the highest VSP levels using FTP+IM-240 test cycle. If activity binning is used in MOVES, then the highest VSP bin will show the greatest bias because the emission estimates within that bin will be the most sensitive to the activity distribution. So when the MOVES estimates for the bin above 13 VSP are calculated, the data used to estimate emissions must reflect the activity rates above 13 VSP. In other words, in this example, the distribution of VSP (or any important parameter) for all bins when calculating emission rates should reflect the distribution of VSP in each bin for all roadway links at all times of day. This will reflect the situation best when bins are defined with infinitesimally small ranges.

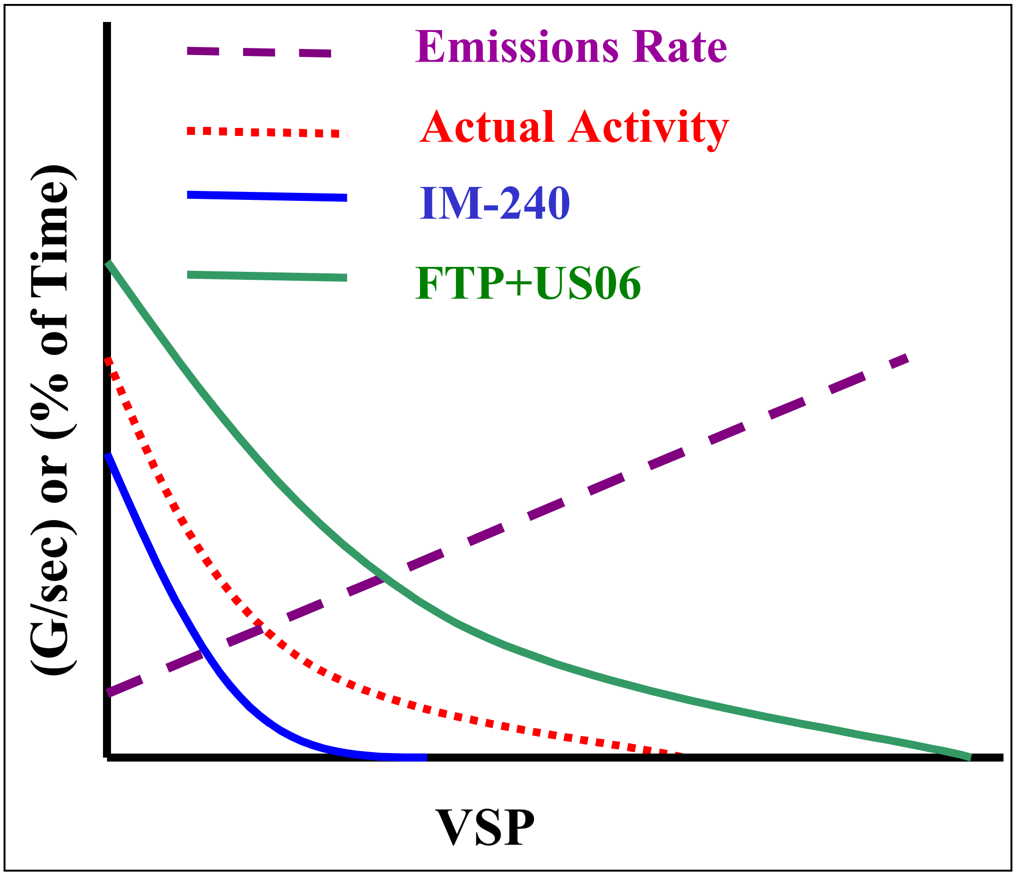

Figure 2-18. Example of activity and emissions distributions for the highest VSP bin.

A better approach than using activity bins would be to use functional relationships between emissions and vehicle driving parameters of interest. Then the activity rate distributions on specific roadways and time of day can be used directly rather than forcing it into activity rate bins that may not be compatible with the activity rates used to define the emission rates. In this manner, the distribution of activity rates for each link could be mapped to an emission level for all parameters of interest. Or this approach could be combined in a hybrid fashion with the bin approach where functional relationships could be defined within each bin in a piecewise fashion.

2.5.2.3 Micro-scale

Micro-scale analysis involves individual transportation or planning projects that may affect local air quality. The best example of a typical micro-scale analysis is the requirement that many projects undergo an analysis of air quality near affected intersections (EPA, 1992). This guidance suggests using the CAL3QHC model to estimate air pollution concentrations at receptor locations near the intersections of interest. The CAL3QHC model currently allows only the input of idling and driving modes. With the MOVES model, emissions could be generated for several different modes of operation including idling, acceleration, braking, creeping, and cruising conditions leading to more accurate emission estimates than the MOBILE model previously provided.

Also, similar but more general than CAL3QHC model, the CALINE3 or CALINE4 models allow the analysis of emission near highways and other roadways using emissions estimated along the roadway link along with meteorological variables to describe air pollution concentrations at different receptor locations near roadways. The emissions along the link would need to be estimated for both lanes of travel under normal driving conditions. By modeling the emissions for specific situations, MOVES should provide more accurate estimates than MOBILE6 or earlier versions of MOBILE. MOBILE models adjusted emissions according to the speed and ambient conditions. By determining the actual vehicle behavior, such as VSP and other import parameter distributions, along each roadway, the emission estimates should become significantly less uncertain than previous models for this micro-scale condition. A recent example of such specific estimates is included in Kean et al., (2003), where emissions were much better defined by estimated vehicle power than by vehicle speed especially when road grade is a factor.

Micro-scale analyses will likely be the more difficult situations to model emissions accurately. Because of the critical need to place emissions in time and space appropriate to each receptor, the emissions and activity must be accurately placed. As discussed in Section 4 of this report, it is difficult to exactly match the emissions and vehicle activity in time at the 1 Hz rate for vehicles accelerating from a stop. Filtering and other data manipulations improved the overall fit between different emission measurement methods, but will obscure the instantaneous understanding of emissions.

It will also be important to accurately reflect the distribution of activity for micro-scale analysis. This will include the relative rates of acceleration, driving speed, and driving history if considered to be sufficiently significant to include in the modeling.

2.5.3 Summary

The MOVES modeling approach will demand additional activity information in terms of power demand and other variables deemed to be important rather than average vehicle speed as is now required by MOBILE6. The importance of specific emission rates in MOVES will increase as the geographical extent of the modeling moves from macro to micro-scale. As the emission rates need to be estimated by roadway link by time of day, MOVES will need to provide emission rates for the entire distribution of activity along each link, and EPA will need to provide planning agencies with national averages for the activity parameters of interest.

Average activity rates will likely be only valid for modeling efforts where specific emission estimates are not required. It would be better to provide distributions of activity rather than average activity rates along each link by time of day or congestion level. For instance, along any given link at any given time, a fraction of vehicles will be accelerating, cruising, braking, idling, and other modes, and even if all vehicles are cruising, there will be a distribution of speeds and acceleration rates.

2.6 UNCERTAINTY, BIAS, AND ACCURACY

Accuracy in MOVES refers to its ability to correctly estimate the true value of emissions. Bias is the tendency for estimates to be consistently higher or lower than the true values. Uncertainty is the variability (or scatter) in MOVES' prediction about the actual emissions. MOVES will be accurate, for example, if it predicts the correct emissions factors for the fleet of on-road vehicles, and if it predicts the actual changes that result from mobile-source emissions control programs such as inspection and maintenance (I/M). Uncertainty and bias in MOVES will arise from many sources, primarily from the data used to construct the model, and from errors in analyses and assumptions leading to model formulations (discussed further below). Uncertainty and bias in MOVES will be difficult to assess because of the complexity of the model, the uncertainty in the underlying emissions data and model formulation, the uncertainty in the input data, and the difficulty in obtaining accurate measures of real-world emissions (e.g., from analyzing ambient data).

The National Research Council, in its review of the EPA's mobile source modeling, recommended that EPA "include a rigorous study of uncertainties and bias in all model components and in the data used to develop model parameters and relationships." (NRC, 2000). In response, EPA (2002a) in the MOVES design document stated, "We have adopted most of the NRC's recommendations as our objectives in designing MOVES. The MOVES design objectives include . . . addressing model validation and the calculation of uncertainty. . ." To date EPA has expended considerable effort evaluating approaches for estimating model uncertainty, and that is the focus of the discussion below. Concerns about potential sources of bias are also addressed.

Accuracy can only be determined through validation with other independent estimates of emissions. These independent evaluations of MOVES estimates should include, but not be limited to, field observations, including tunnel studies; remote-sensing measurements; source-receptor modeling (chemical mass balance); roadside pullovers; vehicle emissions testing data from vehicle I/M programs; and other vehicle emissions tests. These validation techniques may only address individual or partial emission estimates in MOVES rather than all the parameters and variables; since we cannot directly measure total fleet emissions from all vehicles and all emissions modes, no one validation technique will be able to assess overall model uncertainty.

2.6.1 Uncertainty

MOBILE6 and all previous versions of MOBILE have generated emission factor estimates without any indication of uncertainty, although it is likely that there is a significant amount of uncertainty in the model predictions. Some limited analyses have been done on the uncertainty in components of the MOBILE5 model (e.g., Frey and Zheng, 2002), but there have not been any quantitative estimates of MOBILE6 uncertainty.

Uncertainty estimates can serve two purposes:

- They can provide information to model developers on which portions of the model have the larger contributions to overall model uncertainty, and hence can be used as a guide on where to expend resources to improve the model (e.g., where additional test data is needed).
- They can be provided to decision and policy makers to assist in decisions.

Providing uncertainty estimates to policy/decision makers can be problematic, who are used to point estimates that allow for simple yes/no comparisons to target levels. If emissions estimates were provided with uncertainty bounds, that would create questions such as what to include in air quality modeling for State Implementation Plan (SIP) development, and how to treat the uncertainty in conformity budgets. For example, if the MOVES model generated emissions results that are above a transportation conformity budget, but the uncertainty in the model was such that the conformity budget was within the uncertainty of the predicted emissions, then is the budget considered to be met or not? EPA, however, has stated that any uncertainty estimates for MOVES would be used for the first purpose only, "to help focus efforts to upgrade the model." (Tierney, 2003).

2.6.1.1 Sources of Uncertainty

There are many sources of uncertainty in the MOVES model. These include:

- Uncertainties arising from selection of a biased and/or non-representative vehicle sample. An important example is high emitters, which have more variable emissions than normal emitters, and which may not be properly represented in the underlying databases that are primarily from recruited vehicles.

- Uncertainties arising from use of an incorrect physical/engineering model to describe the physical process. An example here would be not including a factor that is significant in explaining emissions in a given bin. Another example is extrapolating from one bin to another in the absence of emissions test data.
- Uncertainty arising from using an incorrect statistical model. An example here would be a linear regression where the relationship is non-linear.

- Uncertainty in the fitted statistical model. An example here is using a binning approach instead of the simple linear relationship between VSP and fuel rate. But even if binning is appropriate, there is variability in the data in each bin.

- Uncertainties in the available test data. Emissions for similar vehicles — i.e., same model year, manufacturer, make, and mileage — on the exact same driving cycle, can be dramatically different for a variety of reasons, including vehicle maintenance and driver habits. Also included here is test to test variability, though that is relatively small compared to other sources of variability.

- Uncertainties in model inputs. Most significantly here, there are uncertainties in the model's activity estimates. There are also uncertainties in meteorological inputs, though these are likely unimportant relative to other sources of uncertainty.

One of the most important sources of uncertainty and potential for bias in MOVES likely occurs in vehicle selection where emission and activity estimates are based largely on test data from in-use vehicles that are selected for instrumentation. The selection process is, by necessity, voluntary introducing a potential for bias. Recruited vehicles have serious bias issues because high emitters and tampered vehicles as well as expensive luxury vehicles are less likely to be voluntarily submitted for testing. Very high emitting vehicles are a relatively small fraction of the on-road vehicle fleet, but they contribute a very large fraction of total vehicle emissions. Emissions from high-emitting vehicles are much more variable than emissions from normal emitters, and thus require a large sampling fraction to obtain reasonably accurate estimates of their emissions (and to estimate the affects of control programs for their emissions). It is thus critically important that such vehicles be appropriately represented in emissions testing programs. If emissions from high emitters are not properly characterized, then MOVES emissions factors can be seriously flawed.

In Section 2.2.2, we provided data showing a Tier 0 high CO and HC emitter that emitted especially large amounts of CO and HC during deceleration on the MEC and US06 driving cycles. If vehicles such as this one occur only one or two percent of the time, they could have a large effect on fleet emissions, but they would be difficult to capture for testing programs. If they are not captured, and/or if the fraction of the fleet that they represent is incorrectly estimated, then the model's results could be significantly biased.

Another major concern is the very large number of proposed bins, as discussed in Section 2.1.3 and shown in Table 2-8. The number of bins currently proposed is in the tens of thousands. While that allows for finer resolution and specificity of emissions, it also means that all of these bins have to be populated, and the data requirements for the model are hence enormous. The numbers and types of vehicles must be representative of the vehicle fleet, and representative within each bin, considering the range of activity in terms of VSP and other parameters of interest. EPA will need to populate each bin so that the emissions within each bin are adequately described, and the distribution or summary statistics (mean, variance) for each bin can be adequately characterized for the uncertainty analysis.

Particular focus should be paid to adequately populating bins where the emissions are high and account for a significant fraction of the fleet, especially such bins as have high variability in the emissions. Two important examples are:

- High emitting vehicles contribute substantially to fleet emissions. For light-duty vehicles, typically the highest ten percent emitters account for about half of the fleet emissions.
- Heavy-duty vehicles contribute a significant fraction of fleet NOx emissions, but there is relatively little data available on modal emissions for heavy-duty vehicles, as shown in Table 2-11.

The available data can be analyzed to determine how many vehicles/tests are needed to obtain estimates of the average emissions in each bin within a desired level of uncertainty. Such an analysis was done for CRC project E-55 by Warren White (2000). He used analysis of variance techniques to review the West Virginia University database of heavy-duty vehicle chassis dynamometer data. He evaluated vehicle-to-vehicle variability, variability across different tests for the same vehicle, and replicate tests on the same vehicle (measurement error). As has been seen for light-duty vehicles, White found that measurement error proved a negligible contributor to observed variability for all pollutants, "vehicle-to-vehicle variability was larger for NOx emissions, and within-vehicle (across time) variability was larger for PM emissions." Based on the available data, he calculated the number of vehicles that would need to be tested as a function of desired levels of uncertainty. Once the binning structure is completely defined, EPA should perform similar analyses to determine where more data need to be collected to populate the MOVES model.

The MOVES model outputs either emissions mass per unit time (g/sec) or emissions mass per unit distance (g/mile). In either case, the MOVES estimates are then multiplied by activity data generated outside the model. On the macro scale, the g/mile emission factor estimates would be multiplied by vehicle miles traveled (VMT) estimates from HPMS or some other data source, as is currently done with MOBILE6. On the micro scale, the g/sec estimates would be multiplied by speed estimates on a link basis, which are in turn estimated from transportation demand models. Both of these types of external activity estimates have uncertainty as well. EPA should work with transportation planners to develop uncertainty estimates from these activity estimates, so that an overall estimate of the uncertainty of predicted emissions can be developed.

2.6.1.2 Approaches for Estimating Uncertainty

There are two main types of approaches for estimating uncertainty in a model such as MOVES: Monte Carlo and propagation of errors. The Monte Carlo approach is a computer-intensive approach that uses extensive repeated sampling and calculations. Essentially the approach is to assume parametric distributions for the model inputs and variables, and to randomly draw samples from those distributions and perform the model calculations with those samples. An example would be to fit a normal (or lognormal or other) distribution to the emissions within VSP bins and repeatedly sample from those assumed distributions. The primary disadvantages of this approach are that the assumed distributions may not be correct, or may be poorly characterized with bins that have very little data, and it will require a great deal of computing time. However, most users will probably not be running the model in the uncertainty calculations mode, so the computer resources issue may not be an important one.

An approach that is similar to Monte Carlo but does not require distributional assumptions is known as the Bootstrap, a term coined by Bradley Efron (1979). In the bootstrap approach, samples are randomly drawn from the observed data, and the statistic of interest is calculated for each new set of data, yielding what is referred to as the bootstrap distribution for the statistic. By repetitive resampling observations from the observed data, the process of sampling observations from the population is mimicked. The key assumption in using this method, though, is that the observed data are representative of the underlying population. The Bootstrap approach has the same computationally intensive demands as the Monte Carlo approach.

Propagation of errors is an uncertainty estimation approach that also relies on assumed distributions in the data underlying the model. Specifically, propagation of errors assumes that the underlying distributions are all normal (or lognormal). Propagation of errors is an analytical procedure using partial derivatives that calculates the uncertainty in a mathematical function of several variables or inputs using the mean and variance of each input. It is simplest if the function is linear, and can get quite complex with more complicated functional forms that involve products and ratios; in the latter cases approximations are often made. There are several types of methods that can be used in propagation of errors; these are described with some examples for the MOVES context in Frey (2003).

The advantages of the propagation of errors approach are its relative simplicity from a programming point of view, and it does not require the intensive computing resources required by Monte Carlo approaches. One of the disadvantages is that it relies on only the mean and variance of the model inputs, and not on their distribution. An assumption must be made about the distribution of the model output, whereas in the Monte Carlo approach the distribution of the inputs is used to determine the distribution of the model output.

2.6.1.3 EPA Proposals and Assessments of Uncertainty Approaches for MOVES

The MOVES draft design plan (EPA, 2002a) suggests that limited Monte Carlo analyses would be incorporated into the model to assess some of the uncertainty in the model predictions, using the estimated emission rate distributions. The plan says that in the future the approach could be extended to incorporate distributions in activity data, meteorological factors, and other model parameters. However, at the MOVES workshop in late 2002, EPA discussed and said they were evaluating both the Monte Carlo and propagation of errors approaches (Bailey, 2002).

Frey (2003) performed some evaluations of the propagation of errors approach for consideration in MOVES. He compared Monte Carlo simulation results with the propagation of errors approach for several different kinds of functional forms (additive, multiplicative, quotient, and more complicated additive/multiplicative combinations), normal and lognormal input distributions, and different assumptions for input variable standard deviations. All of the evaluations assumed statistical independence of the inputs; correlations in the inputs makes the analytical solution much more complex. His simulation results showed that the propagation of errors approach is reasonably accurate in its estimate of uncertainty when the variance of the inputs is small, and more and more inaccurate as the variance of the inputs is larger. However, if only a few of the inputs have relatively large variance, and most of the inputs have relatively small variance, then the propagation of errors approach was reasonably accurate in its estimate of uncertainty compared to the Monte Carlo simulations. With simple linear models, the propagation of errors approach is very accurate, but with more complex models, especially those involving quotients, it can be very inaccurate especially with inputs with large variance. This is of particular concern with higher emitter bins, as high emitters have much larger variability than normal emitters.

While the work is informative, these comparisons and analyses need to be redone when the functional forms of MOVES are defined, the variances of the input variables can be estimated, and the correlations in the input variables can be assessed. The largest range of uncertainty in Frey's evaluation was for input variables with plus or minus 100 percent uncertainty. But emission rates in some bins may well be significantly larger. So while the propagation of errors approach may be preferred for its relative computational ease, it is not yet known how reliable it is in estimating MOVES output uncertainty. And, as Frey notes, "Although the potential advantage of the analytical method is a lower computational burden compared to a numerical simulation method, such an advantage may or may not be realized in practice depending upon the functional form of the model."

Whatever approach is used to estimate MOVES uncertainty, it must be kept in mind that the resulting uncertainty estimates are a *lower bound* on the actual overall uncertainty, because there are some sources of uncertainty that cannot be quantified. Uncertainties arising from the use of an incorrect model functional form and from selection of biased and/or non-representative samples cannot be estimated. Uncertainties in activity data are likely unknown as well.

3.0 REVIEW OF MOVES MODEL DESIGN SPECIFIC TO GREENHOUSE GASES

3.1 INTRODUCTION

The overall purpose of this project is to review EPA's plan for the MOVES model. Section 3 addresses issues unique to the implementation of the first version of MOVES, the greenhouse gas model (MOVES GHG). There are many specifics elements of MOVES GHG distinct of the overall framework of other subsequent MOVES models that will incorporate estimates for other pollutants. Section 2 reviewed the plan, data gathering, and implementation of MOVES for emissions including regulated pollutants.

The MOVES GHG model, now planned for release in early 2004, will determine total carbon dioxide (CO_2) exhaust emissions [including all carbon species by also adding carbon monoxide (CO) and total hydrocarbon (THC)] from estimates of the fuel consumption rates. EPA plans to relate these fuel rates to the power demanded by the operation of the vehicles and to variables associated with the technology of the vehicles including factors affecting efficiency and other design elements.

In specific, this section examines whether the 'first principles-based' PERE model or a more data-driven empirical approach based on relating the fuel rate to vehicle specific power (VSP) is a more suitable way to estimate CO2 emissions as a function of vehicle type, age, and activity. This section examines the PERE model and concluded that the PERE approach is useful either for interpolating empirical results or used directly and calibrated with data to more accurately reflect in-use efficiency, but is not necessary to produce an emission inventory model.

Whether PERE or a more empirical approach is used, VSP therefore is intended to be the basic correlating variable to estimate the fuel consumption rate for each vehicle. This assumption that VSP is the primary variable to explain fuel rate was tested with available data, and the data suggested that changes in VSP with time (such as during hard accelerations and decelerations and likely associated with different operational efficiency than other modes of operation) provided additional explanation of fuel consumption.

While the primary purpose of MOVES GHG is to accurately predict CO_2, other greenhouse gases including nitrous oxide (N_2O), methane (CH_4) or black carbon are also produced by mobile sources and will be accounted in the overall framework of MOVES but not within MOVES GHG. Refrigerants and other potential greenhouse gases can be emitted from vehicles, but are unrelated to fuel combustion so are ignored for this review effort but are under investigation by others (Siegl et al., 2002)

The current plan for MOVES GHG is only practical for producing estimates of fuel consumption. A number of vehicle and technology types deserve additional study beyond the current information available for Tier 0 and Tier 1 light-duty vehicles and trucks. Either a data-calibrated PERE model or an empirical model will provide equally valid results provided all explanatory variables in addition to VSP and mass have been tested for significant improvement to the estimates.

3.2 ASSESSMENT OF THE PHYSICAL EMISSION RATE ESTIMATOR (PERE) FOR FUEL RATE (CO_2 AND OTHER EMISSIONS)

The Physical Emission Rate Estimator (PERE) is a concept developed and reported by E.K. Nam (2003). Vehicle behavior described by the time variation of velocity and grade plus vehicle characteristics (rotational inertia, rolling resistance, aerodynamic drag parameters, accessory loads, and mass) are used to calculate vehicle specific power (VSP) [kW/tonne]. In fact, if the accessory loads and transmission efficiency are included, this calculation yields the required engine specific power. The tie to engine out emissions is through the predicted fuel consumption that, in turn, depends on engine efficiency and fuel characteristics. The required parameters for the calculation are vehicle, engine, and fuel specifications although generic values are proposed that would apply to all or large groups of vehicles. Such a generic VSP relation (eqn. 2 from Nam's report) is:

$$VSP\ [kW/tonne] = v * (1.04 * a + 9.81 * grade\ [\%] + 0.132) + 0.00121 * v^3 \qquad (1)$$

Because acceleration is derived from the time rate of change of velocity, this simplified expression for VSP depends only upon velocity (as a function of time) and grade.

The brake power required of the engine is the product of VSP, vehicle mass, drivetrain efficiency (η_d):

$$P_b\ [kW] = VSP * m * (\eta_d) \qquad (2)$$

The issue of whether accessory loads (for example, air conditioning, power brakes, power steering, alternator, water pump, oil pump, radiator fan, and others) are assigned to the vehicle or to the engine is largely a matter of definition. The first three loads are vehicle operational requirements. The last three are engine requirements. The alternator provides electrical needs of both the vehicle and engine. Sometimes engine friction and engine inertia are treated as engine loads. The definition and assignment of the various loads affects the definition of engine efficiency. Hence, a variety of different physical models of the vehicle and engine are possible and appear in the literature. We follow the definitions as used by Nam, which are taken from Ross (1997), as follows. The thermodynamic efficiency,

$$\eta_t = (P_b + P_{fric}) / (FR*LHV) \qquad (3)$$

where (P_b+ P_{fric}) is total power, which consists of output or brake power, P_b, and internal friction power, P_{fric}, FR is the fuel rate, and LHV is the lower heating value of the fuel. The mechanical efficiency is the fraction of the total available power from the combustion process that is delivered by the engine to the transmission:

$$\eta_m = P_b / (P_b + P_{fric}) \qquad (4)$$

and the overall engine efficiency:

$$\eta_{eng} = \eta_t * \eta_m = P_b / (FR*LHV) \qquad (5)$$

giving for the fuel rate:

$$FR = P_b / (\eta_{eng} * \eta_d * LHV) \quad (6)$$

The challenge with the use of this equation lies in accurately estimating the engine efficiency, which is highly variable, especially for gasoline engines for which engine efficiency is load dependent. As an approach to this challenge, Nam suggests use of a more complex expression for fuel rate, taken from UC Riverside Comprehensive Modal Emissions Model (CMEM) (Barth et al., 2000). This more complex expression is presented later in this section as equation (7). The critical question is the variability of the terms in this equation among vehicles and operating conditions, that is, how much new data will be required to apply the PERE model.

3.2.1 Relating Tailpipe Emissions To Fuel Rate

To estimate emissions, first engine out emissions are related to the fuel rate calculated from the PERE or whatever approach is chosen. This relationship is straightforward for total carbon dioxide emissions as demonstrated in Section 2.4 where vehicle power highly correlates with emissions, but is more complex for the criteria pollutants (hydrocarbons, carbon monoxide, oxides of nitrogen, and particulate) and even more difficult to determine for non-criteria pollutants (toxics and greenhouse emissions including methane, nitrous oxide, and black carbon). Because in the MOVES modeling approach the tailpipe emissions are of interest, a model of exhaust aftertreatment is required for these other pollutants but not necessarily for total carbon dioxide (sum of carbon dioxide, carbon monoxide, and total hydrocarbon all eventually oxidized to carbon dioxide in the atmosphere) where fuel consumption rate can be used to estimate the total carbon dioxide emissions. Other greenhouse gases such as refrigerant greenhouse emissions and others associated with vehicle components are unrelated to engine or exhaust emissions, or to the fuel consumption rate.

3.2.2 Utility Of PERE

PERE is proposed as an approach to fill data gaps, through interpolation and extrapolation. Since it describes the behavior of individual vehicles, it should be particularly useful at the microscale and for the examination of the effect of specific technologies and traffic management schemes (such as low rolling resistance tires, friction reducing lubricants, on-ramp metering, signal timing, tunneling and road cuts for reduced grade, grade separation and other road alignment projects, and speed limit enforcement).

The ability of PERE to predict mesoscale, fleet average emissions will depend on an extensive database of vehicle parameters that are representative of the in-use fleet. Fleet averaging would require binning by vehicle and engine technologies to be discussed in greater detail under Section 2. Assessment of the utility of PERE must include an assessment of the relative data requirements of characterizing the fleet for PERE modeling versus characterizing the fleet emissions.

For medium and heavy-duty vehicles, vehicle mass is highly variable, even for a single gross vehicle weight rating (GVWR) type, and must be part of the database needed to implement the

PERE model. The distribution of GVW for the on-road medium and heavy-duty fleet is becoming available through weigh-in-motion monitors. Also the aerodynamic coefficient and frontal area estimates needed for estimating the average aerodynamic drag relationships require further investigation because the data for these components are only known for the few specific coast down tests that have been performed to date. Until EPA or others conduct more coast-down testing, it is unknown how variable aerodynamic drag is for heavy-duty vehicles. If this testing demonstrates that aerodynamic drag is significantly variable and affects VSP estimates, then EPA will need to determine appropriate vehicle types within vehicle weight rating classifications.

3.2.3 PERE For Greenhouse Emissions

The greenhouse emissions of interest are CO_2, CH_4, N_2O, refrigerants, and black carbon. Note that carbon emissions in the form of hydrocarbons and carbon monoxide are oxidized in the atmosphere to carbon dioxide. Hence all carbon emissions, with the exception of black carbon, which is truly a small fraction of total carbon emission, are equivalent to CO_2 on a carbon basis. Hence fuel consumption and resulting atmospheric CO_2 are equivalent on a carbon basis though the effects of other emissions (especially CH_4) are considered to be greater prior to their oxidization in the atmosphere.

The ability of PERE to predict carbon emissions will be as good as the data used to develop the predictions. The primary uncertainty arises from the estimation of the thermodynamic efficiency during the operation of the vehicle and engine. Because of the close relationship between fuel consumption and ultimate (all carbon species once oxidized) carbon dioxide emissions and a large database, selecting an appropriate thermodynamic efficiency is straightforward for a given technology and driving cycle, at least at the mesoscale where emissions are averaged for a full range of power levels. Because thermodynamic efficiency is a strong function of engine torque and speed (percent of maximum power) the ability of the model to predict CO_2 emissions at the microscale using a single thermodynamic efficiency is unlikely.

The accurate estimate of efficiency is more of a problem for gasoline engines than for diesel engines. Throttled gasoline engines have low efficiencies at low power and higher efficiency at higher power. The efficiency of diesel engines, because they are unthrottled, does not vary as much with power. Partially throttled gasoline engines, such as lean burn homogeneous charge and direct injection stratified charge engines, have an efficiency dependency on power between those of conventional gasoline and diesel engines. Engine technologies such as turbocharging, variable valve timing, and cylinder deactivation also affect efficiency. Drive train technologies affect engine efficiency by better matching the engine to the vehicle (allowing the engine to operate in a higher efficiency mode). These include 5- and 6-speed automatic transmissions, continuously variable transmissions, and hybrid electric drives. Emerging technologies for the reduction of accessory power through electric drive and computer control also improve efficiency. Emission control technologies applied to diesel engines, such as exhaust gas recirculation, retarded injection timing, and exhaust traps likely reduce engine efficiency. Computer controlled engine management algorithms have been shown to affect emissions and fuel efficiency, especially those used on some late model heavy-duty diesel trucks and add another level of complexity. Therefore, using a single constant fuel efficiency estimate is problematic as it varies with technology and with load (driving cycle). The solution to this lies in incorporating binned variation of engine efficiency, a more complex engine model with its own parameters likely binned by operating mode, or a combination of the two approaches.

The prediction of methane (CH_4) can be determined, as it is now, from a fixed fraction of the hydrocarbon emissions, and likewise for nitrous oxide (N_2O) from oxides of nitrogen (Jimenez, et al., 2000); however, the dependence of the emission rates for these components on engine/aftertreatment and vehicle driving deserves additional investigation. Existing and evolving databases can be examined for the dependence of the fixed fractions on technology, fuel, and vehicle age. The ability of PERE to predict CH_4 and N_2O emissions, therefore, derives from an evaluation of the approach used to predict hydrocarbons and oxides of nitrogen addressed in Section 2. PERE is not appropriate to the modeling of refrigerant loss emissions because these are engine load independent. Black carbon is most directly related to particulate emissions, which are not presently treated by PERE.

3.2.4 Other PERE Issues

EPA plans to use a data driven, binning approach to model motor vehicle emissions in the MOVES model. The number of bins chosen will be a tradeoff between model accuracy and data availability. PERE, a parametric approach, offers a means to reduce the data needs of MOVES by introducing physical modeling of emissions, and offers the potential to “fill-in” or interpolate operating modes with missing data. Nam (2003) provided a list of the advantages and disadvantages of each approach, reproduced below.

BINNING vs. PARAMETERIZED APPROACH QUALITATIVE COMPARISON (Nam, 2003)	
Advantages	*Disadvantages*
BINNING (MOVES)	
1. Simple 2. Data driven: each bin relates real data 3. Bins can be sized to optimize fit 4. Can fit analytical form to bin heights 5. Does not require constant recalibration 6. Easy to implement 7. Easy to update 8. Consistent across scales 9. Uncertainty can be quantified	1. A LOT of data must be taken 2. Difficult to interpolate gaps accurately 3. Nearly impossible to extrapolate gaps beyond scope of data 4. Difficult to incorporate data from many sources (true for all approaches) 5. Can end up being a “black box” of statistics without a theoretical basis 6. Difficult to disaggregate to analytical approach if needed
PARAMETERIZED (PERE)	
1. Fits interpolate excellently 2. Fits can extrapolate outside the bounds of data to some extent 3. Data needs are fewer, due to above two cases (cost is less) 4. Comprehensible/explainable mathematical trends 5. Can populate data bins or cells—can aggregate to bin approach is needed 6. Easy to implement 7. Easy to update 8. Consistent across scales Uncertainty can be quantified	1. Value is fitted thus may not necessarily reflect measurement at any given values 2. Difficult to incorporate data from many sources 3. Requires recalibration with each data set 4. More calculation intensive (may reduce software efficiency) 5. The model may be more complicated, and require additional training for users

The primary issue then in implementing PERE is to determine the data requirements and whether the claim that "data needs are fewer" is in reality true. Because the PERE model at this stage (as implemented in MOVES GHG) does not include or need to include the evaluation of exhaust aftertreatment, a full assessment of the data needs for versions of MOVES is not yet possible, and will be addressed in Section 2. PERE is well suited to predicting fuel rate and, therefore, carbon dioxide at the microscale, provided that the required data to evaluate fuel efficiency over the driving cycle and vehicle types are available.

While addition of PERE to the MOVES model increases complexity and data requirements, the potential advantages of interpolation and less clear potential advantages and possibility for extrapolation need to justify the increased data requirements. There also remains the uncertainty associated with PERE's capability to predict lesser tailpipe greenhouse emissions and in later versions of MOVES to predict criteria and non-criteria tailpipe emissions.

While providing a thorough analysis of the data needs of PERE is beyond the scope of this report, the most important parameters to predict total carbon emissions (fuel consumption) are:

- engine efficiency as a function of or binned by
    i. engine technology
    ii. drivetrain technology
    iii. power level (percent maximum) or perhaps engine speed and load (torque)
- vehicle mass
- vehicle frictional characteristics
    i. roll down characteristics
    ii. aerodynamic drag
- vehicle accessory load
    i. air conditioning on/off
- fuel characteristics
    i. lower heating value
    ii. H/C ratio
    iii. oxygen concentration

Extending PERE to other emissions requires a model for the exhaust aftertreatment pass fraction and additional data such as treatment technology, warm-up status, ambient temperatures, and fuel characteristics.

3.3 ALTERNATIVE APPROACH TO PERE FOR CO_2 EMISSION ESTIMATES

A more straightforward approach to estimate CO_2 emissions uses an empirical framework rather than the more involved and theoretical PERE model. This section reviews the use of VSP information to estimate the instantaneous fuel rate. One objective of investigating this approach is to allow the use of remote sensing data as input into MOVES or as a verification tool.

Remote sensing data have a number of advantages for use in the MOVES model. There is less vehicle selection bias in remote sensing data because almost all vehicles going past a remote sensing site will be measured. Sample selection bias, usually an unavoidable uncertainty in any volunteer vehicle program, does not occur in remote sensing. Large quantities of remote sensing data are available at no cost to EPA. St. Louis (Missouri, 2002) has been using remote sensing in their I/M clean screening program generating millions of remote sensing records each year; Denver is just about to start an RSD-based clean screen program as well. Remote sensing data can help to measure local control strategies such as I/M program effectiveness (NRC, 2001). Local fleet information can also be sampled by remote sensing measurements at low cost.

However, remote sensing data does have a number of shortcomings because of the nature of the measurement technique. Because the measurement occurs across a single lane for a short period of time, the driving mode measured is limited. Also, data capture is best performed when the vehicles are under light to moderate acceleration. Therefore, site selection is important, and good remote sensing sites are limited. Sites currently require single lane traffic where very few if any vehicles are in cold start or deceleration. Sites also need to be situated to ensure the safety of the equipment and operators. Use of a good measurement protocol, with modern equipment capable of measuring speed, acceleration, and using quality control and quality assurance practice, is also important. Previous remote sensing measurement campaigns did not always operate in this manner.

Another drawback to remote sensing data is that emissions have only been available on a fuel specific basis. If vehicle activity data used to prepare emissions inventories is only presented in terms of miles and time (instead of gallons of fuel used per activity) such as from travel demand modeling or HPMS, the remote sensing data need to be converted from grams/kilogram of fuel to grams/mile.

It was for the purpose of this conversion that Slott (2003) investigated extending the observation made by Jimenez (1999) that fuel rate and VSP were linearly related and independent of driving cycle when VSP>0. Fuel rate was independent of VSP, and not equal to 0 when VSP<=0. Following this reasoning, sample correlation coefficients were used in the VSP equation as an alternative method of estimating fueling rate.

Remote sensing devices usually record the speed, acceleration, and road grade at the point where tailpipe emissions are measured. Jimenez (1999) noted that the VSP parameters should be measured and compared to when emissions are generated in the engine rather than when the emissions exit the tailpipe. However, Slott (2002) showed that HC and CO emission measurements were very slightly affected by this difference in measurement location under typical remote sensing conditions. Based on data from two remote sensors in the CRC Project E-23, Phoenix 2000 Campaign, for VSP between 7.5 and 27.5 kW/tonne, the relationship between HC and CO tailpipe emissions and VSP was very slightly affected by whether the VSP was calculated based on speed and acceleration values measured at the position where the emissions exited the tailpipe or 10 meters before that point, approximately where those emissions were formed in the engine. In this project, VSP was calculated using two methods. One method was to use the speed and acceleration from the remote sensor where the emissions were measured (the downstream remote sensor, the usual case). The other method was to calculate the VSP using the speed and acceleration from the remote sensor that was 10 meters in front of the remote sensor where the emissions were measured. From the speed and load of the vehicles, the 10 meters upstream remote sensor location was estimated to be the correct position to associate the measured load from speed and acceleration to the emissions as they were formed in the engine though emitted from the tailpipe later. However, it made little difference whether the load at the upstream or downstream location was used to compare the emissions measured from the downstream remote sensor. While more differences were observed in the NO emissions than for HC or CO, the NO relationship was not significantly affected by the VSP estimate.

The correlation of VSP with fuel rate allows the use of remote sensing data to be used to estimate the grams per second if the vehicle weight and vehicle fuel are known. For remote sensing data to be used the fuel and weight of the vehicle would have to be known or estimated. To obtain accurate vehicle weights remote sensing should be done in lanes equipped with weigh-in-motion sensors. If these sensors are not available, vehicle weights need to be estimated from the vehicle model obtained from through the observed license plate. Vehicle weight and fuel considerations also apply to extending MOVES. Therefore remote sensing is a useful method to compare or augment estimates from other test methods while substantially reducing the potential vehicle selection bias. EPA and/or others should therefore fund such combined remote sensing and vehicle weight measurements and estimates to determine if this approach is feasible and provides equivalent information to on-board emissions measurements. If the estimates provided a reasonable approximation to the weigh-in-motion weights, much more extensive use of remote sensing data would be useable and would provide data for many more vehicles than would be possible with on-board emissions and laboratory measurements.

3.4 CORRELATION OF VSP AND FUEL CONSUMPTION RATE

Regardless of whether the PERE or some other approach is used to estimate the vehicle power under in-use conditions, EPA will use VSP as the primary correlating variable to explain emission rates. Therefore, it is necessary to investigate if VSP can be used to model the fuel (consumption) rate to understand if this variable indeed explains much of the relationship between driving and fuel consumption.

In Figure 3-1, the fuel rate in grams/second of carbon is plotted against VSP for dynamometer measurements in Bag 3 of the FTP. The data come from the NCHRP 25-11 project carried out at UC Riverside (2000). The vehicle was a 1995 Honda Civic, a normal emitter with 43,000 miles, vehicle number 45 in the UC Riverside data set.

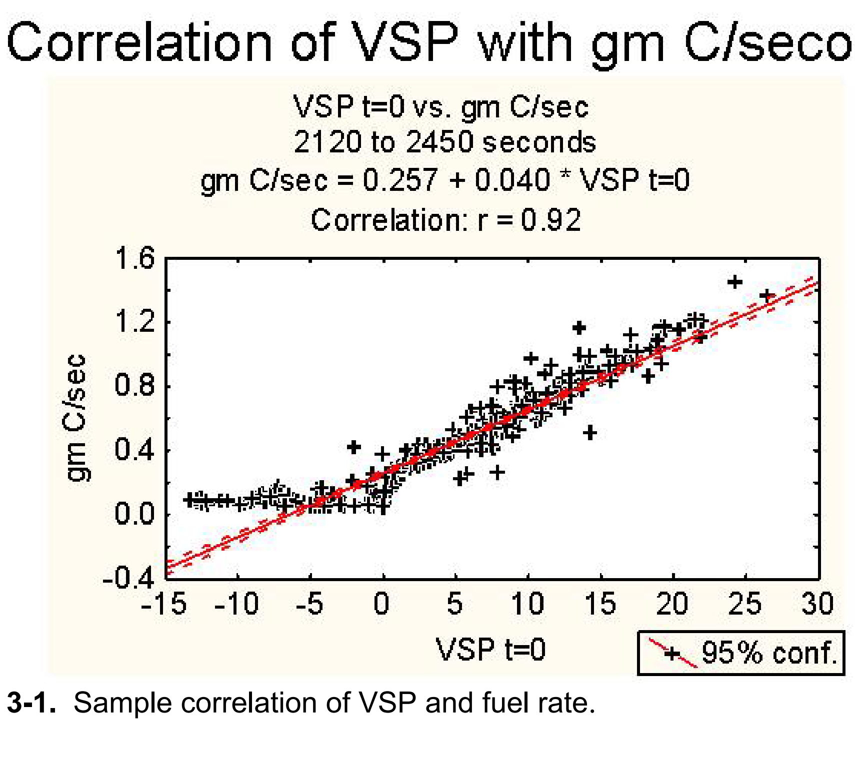

Figure 3-1. Sample correlation of VSP and fuel rate.

Figure 3-1 shows two linear sections; for VSP greater than 0 kW/tonne, the fuel rate increases linearly with VSP. Where VSP is equal to or less than 0 kW/t, the fuel rate is not a function of VSP, but it also is not equal to zero. The form of the relationship between fuel rate and VSP is similar to what was observed by Jimenez (1999) on the 1994 Jeep. The form of the relationship of VSP and fuel rate also holds true for a high emitter as shown in Figure 3-2, where fuel rate and VSP > 0 are plotted for a 1992 Toyota Tercel, a high emitter with 64,000 miles, vehicle number 77 in the UC Riverside data set.

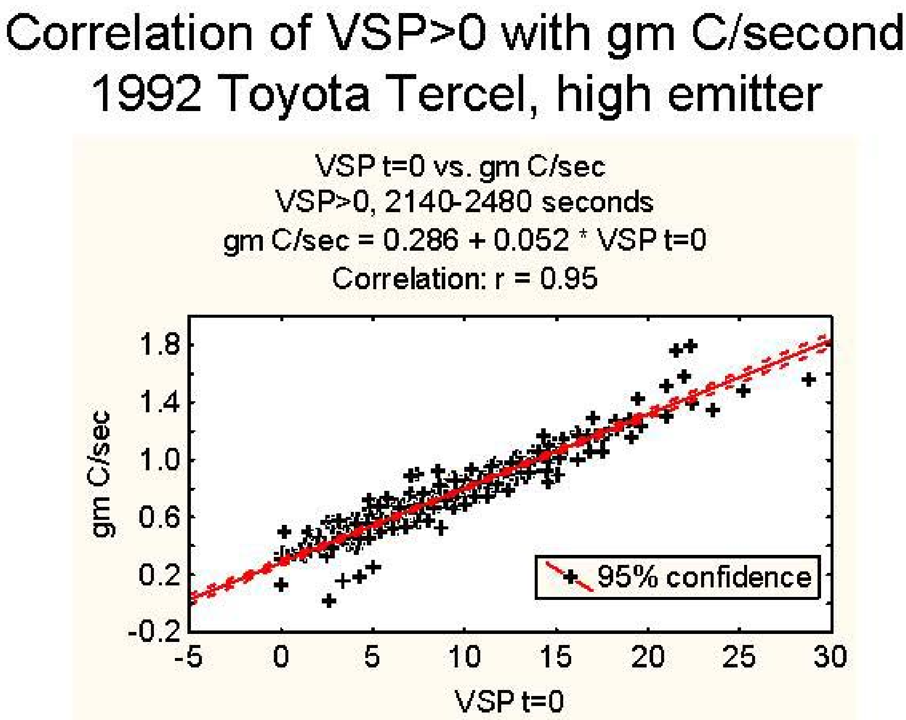

Figure 3-2. High emission vehicle correlation of fuel rate and VSP.

Similar relationships between fuel rate and VSP were found for 25 other vehicles from the NCHRP data set. These vehicles included both cars and trucks, fueled by both gasoline and diesel, ranging in model year from 1979 to 1996, in weight from 1750 to 8000 pounds, in engine size from 1 L to 7.5 L, and with Bag 3 emissions from 0.3 to 120 grams CO/mile. The slope and intercept of the fuel rate versus VSP are shown in Table 3-1 along with the correlation coefficient, Pearson r-values from correlating fuel rate and VSP for VSP>0.

Table 3-1. Correlation of fuel rate and VSP for various vehicle types.

Vehi. #	MYR	Brand	Model	Inertia Weight	Eng L	Type	FTP Bag3 gm/mile					gm C/sec = a + m x VSP t=0		
							CO2	CO	HC	NOx	CO/CO2	a	m	r
183	1985	Chevy	Sprite	1750	1.0	Car	170	19.0	3.7	1.9	11%	0.256	0.040	0.95
303	1991	Geo	Metro	1875	1.0	Car	226	5.3	0.7	3.0	2%	0.270	0.047	0.94
306	1991	Geo	Metro	1875	1.0	Car	222	3.2	0.8	2.7	1%	0.228	0.048	0.95
45	1995	Honda	Civic	2250	1.5	Car	189	0.5	0.0	0.2	0%	0.206	0.047	0.95
77	1992	Toyota	Tercel	2250	1.5	Car	235	7.0	1.0	1.5	3%	0.268	0.052	0.95
277	1992	VW	Fox	2500	1.8	Car	295	29.4	1.8	1.2	10%	0.503	0.047	0.94
13	1991	Toyota	Celica	3000	2.4	Car	305	17.7	4.2	2.2	6%	0.363	0.069	0.95
200	1979	Ford	Mustang	3000	2.3	Car	333	120.0	3.6	0.4	36%	0.746	0.100	0.88
34	1996	Buick	Lasabre	3500	3.8	Car	345	4.6	0.3	0.7	1%	0.251	0.082	0.94
96	1996	Cadillac	BHM	4500	5.7	Car	519	0.4	0.2	0.8	0%	0.396	0.118	0.96
205	1985	Dodge	Caravan	2750	2.2	Truck	232	95.6	6.6	0.4	41%	0.610	0.072	0.89
175	1988	Dodge	Caravan	3625	3.0	Truck	409	6.9	1.0	1.5	2%	0.425	0.086	0.94
182	1989	Dodge	Caravan	3750	3.0	Truck	386	5.0	0.5	1.4	1%	0.304	0.094	0.93
310	1989	Dodge	Caravan	3750	2.5	Truck	374	11.0	0.3	0.8	3%	0.343	0.093	0.95
209	1994	Dodge	Caravan	3875	3.0	Truck	422	12.2	2.0	0.1	3%	0.363	0.110	0.95
121	1995	Toyota	4Runner	4000	3.0	Truck	460	0.8	0.0	0.3	0%	0.555	0.093	0.94
150	1992	Dodge	Dakota	4000	3.9	Truck	448	8.8	1.9	2.7	2%	0.497	0.095	0.92
251	1994	Chevy	1500	4250	4.3	Truck	505	2.9	0.2	0.5	1%	0.427	0.122	0.97
181	1994	Chevy	SUV	4750	5.7	Truck	581	2.6	0.2	0.4	0%	0.574	0.128	0.95
402	1990	Dodge	250 D	4750	5.9	Truck	411	1.4	0.9	1.8	0%	0.523	0.077	0.83
408	1986	Ford	F350 D	4750	6.9	Truck	569	1.1	0.6	7.0	0%	0.800	0.098	0.92
412	1989	GMC	Sierra	4750	7.4	Truck	849	4.8	0.4	2.7	1%	1.200	0.127	0.87
407	1996	Ford	F350 D	5000	7.3	Truck	452	1.0	0.4	4.1	0%	0.629	0.078	0.91
410	1996	Ford	F350	5000	7.5	Truck	795	1.0	0.0	0.1	0%	1.001	0.140	0.95
215	1980	Ford	Superwagon	5250	6.6	Truck	711	16.8	2.2	2.4	2%	0.967	0.139	0.89
411	1997	Dodge	Ram	5500	5.9	Truck	626	0.3	0.0	1.2	0%	0.554	0.142	0.94
38	1995	Ford	Van 95	8000	5.8	Truck	780	6.9	0.1	0.1	1%	0.077	0.272	0.95

This type of data can be used to assist in preparing and verifying estimates provided by the PERE model. Because the PERE model estimates total fueling rate from in-use power demand and efficiency estimates, data can be used to provide estimates for many parameters or can be used to verify those parameters. From equation (6) in the PERE Report, shown below, VSP is related to fuel rate and vehicle properties (Nam, 2003).

$$FR = \varphi * [K(N)*N(v)*V_d + P_b(m,v,a)/\eta + Pacc(T,N)/\eta] / LHV \qquad (7)$$

φ: is the fuel air equivalence ratio (mostly =1)
K(N): is the power independent portion of engine friction, dependent on engine speed.
N(v): is the engine speed
V_d: is the engine displacement volume
η: is a measure of the engine indicated efficiency (~0.4).
Pacc(T,N): is the power draw of accessories such as air conditioning. This is a function of ambient temperature, T, and humidity (and engine speed for AC). Without AC, it is some nominal value ~ 1kW.
LHV: is the factor lower heating value of the fuel (~44kJ/g)

The PERE report points out that, "Fuel rate is relatively insensitive to K. Then engine efficiency, η, is relatively constant from car to car and from model year to model year.

KNV_d is a friction term, which has less of an effect on emissions than the tractive, or brake power term (the inertial acceleration term dominates along with aero drag at higher speeds). As a result, it is not crucial to model these terms with as much care." (Nam, 2003) Therefore, a simplified version of Nam's equation (6) is written as:
Fuel Rate = [(fuel air ratio)/(LHV)][VSP*(mass)/(engine efficiency) + other terms] (8)*

where:
LHV is the fuel's lower heating value
mass is proportional to the inertial weight.
engine efficiency was assumed to be a constant by PERE.
air fuel ratio was assumed to be 1.0 by PERE except when predicted or found to be different.

The natural logarithms of the slopes, ln(slope), (the correlating coefficient between fuel rate and VSP) from each vehicle from Table 3-1 were correlated using the following methodology: Multiple regression was performed with the following variables: ln(inertia weight), ln(engine size), ln(rated HP), ln(fuel (gasoline or diesel)), and ln(age = test year - model year + 1). Variables that did not show a significant correlation at the 0.05 level were dropped and the multiple regression was re-run. This procedure was continued until only variables with significant correlation remained. Fuel type was treated as a fuel efficiency term; gasoline was set at 100, diesel at 125, an approximate estimate based on the mid-point of the range of relative fuel consumption (miles per gallon) estimates by Schaeffer (2002) adjusted for a fuel density ratio of 1 to 1.13. The only statistically significant parameters found were inertia weight and fuel efficiency (or fuel type). The correlation from 27 very diverse vehicles with these two parameters gives a high degree of correlation, as is shown in Figure 3-3, with a Pearson r of 0.968. From the Beta values, the inertia weight is about three times more important than the fuel efficiency in the multiple regression.

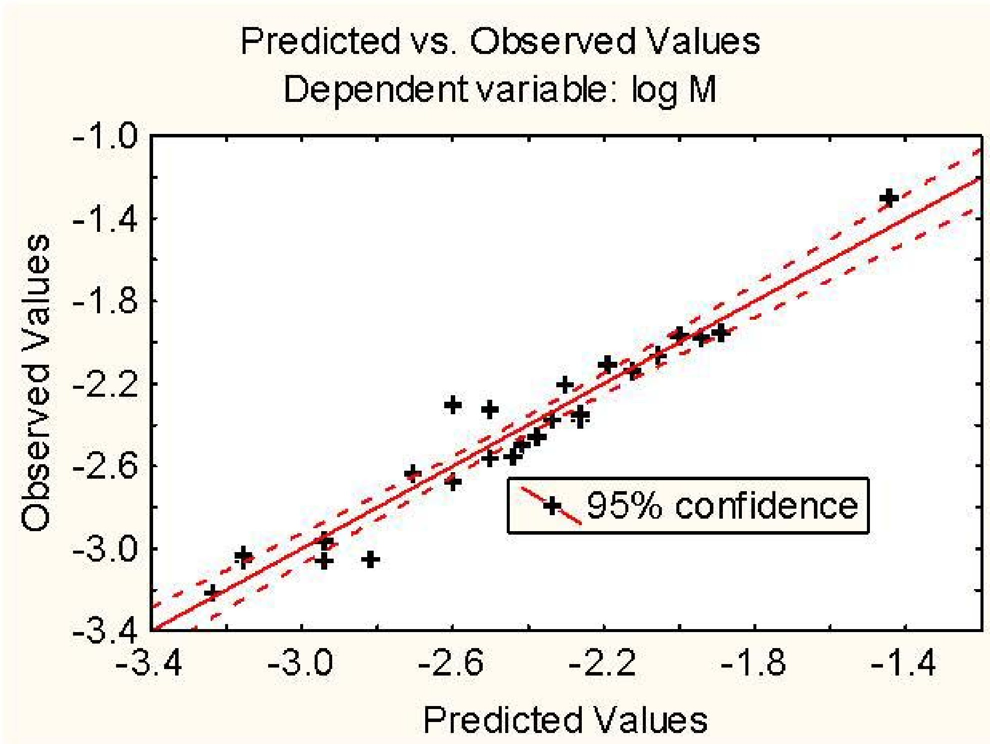

Figure 3-3. Correlation of empirical and predicted relationship of the slopes.
(Where the slope is the coefficient of the relationship of fuel rate to VSP for each vehicle.)

Using the coefficients from multiple regression, the equation resulting from the correlation is

$$Slope = 0.0530 * [inertia\ weight]^{1.18} / [fuel\ efficiency]^{1.98} \quad (9)$$

This is similar in form to the slope in the simplified version of 'PERE equation (6)' where 'mass' is identical to 'inertial weight' and 'fuel air ratio' and 'engine efficiency' combine to compare with 'fuel efficiency':

$$Slope = [(fuel\ air\ ratio) / (LHV)] * [(mass) / (engine\ efficiency)] \quad (10)$$

Thus, the PERE physical model and the fuel rate & VSP linear correlation arrive at a very similar relationship for how vehicle characteristics and fuel influence the change in fuel rate with change in VSP. Both (fuel air ratio) and (engine efficiency) in the PERE approach need be combined to be compared with the (fuel efficiency) variable in the empirical approach presented here.

We have demonstrated that a vehicle responds to a change in vehicle specific power by increasing or decreasing the fuel to the engine. The amount of the fuel rate change depends on vehicle weight and fuel parameters. However, during fast transient operation, it has been suggested that the vehicle response lags when vehicle specific power is changing rapidly. (EPA, 2002d)

Thus, the correlation between fuel rate and VSP should improve and does for the examples below if an additional term ΔVSP/Δtime is included in the correlation. To test the effect of ΔVSP/Δtime the two linear regression models shown below were compared:

$$Fuel\ Rate = a + m * VSP \quad (11)$$

$$Fuel\ Rate = a + m_1 * VSP + m_2 * \Delta VSP/\Delta time \quad (12)$$

In Figure 3-4, the correlation between Fuel Rate and VSP, taking into account the change of VSP with time, was better (higher 'r' values) than the correlation between Fuel Rate and VSP alone for a 1985 Chevy Sprite, vehicle 183 in the NCHRP 25-11 data set, for both the FTP Bag 3 and the US06 driving cycles. The additional term was found to be statistically significant with a 'p' level value less than 0.005.

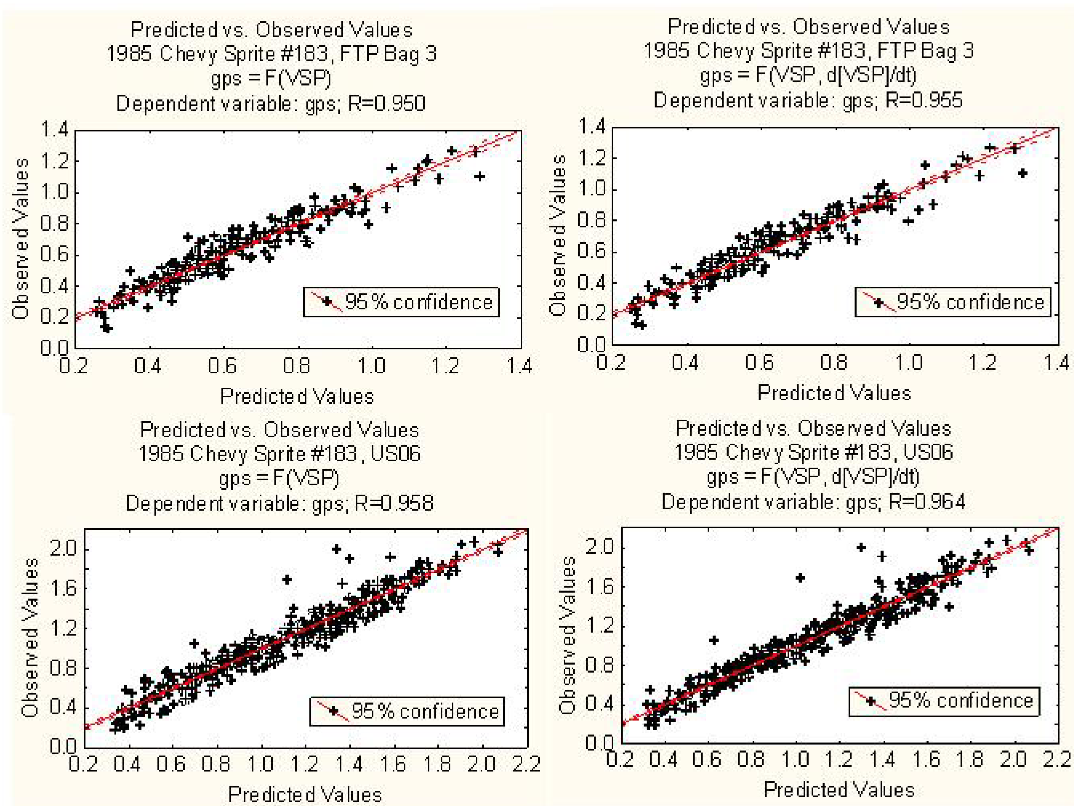

Figure 3-4. Effect of adding the variable (ΔVSP/Δtime) to the correlation of grams per second Carbon with VSP for a 1985 Chevy Sprite.

In Figure 3-5 the same improvement in the correlation is noted for a high CO emitting 1995 Dodge Caravan, on both the FTP Bag 3 and the US06 driving cycles. CO emissions for this vehicle were about 100 gram/mile for FTP, US06, and MEC (UC-Riverside, 2000) driving cycles. The additional term was found to be statistically significant with a 'p' value lower than 0.005.

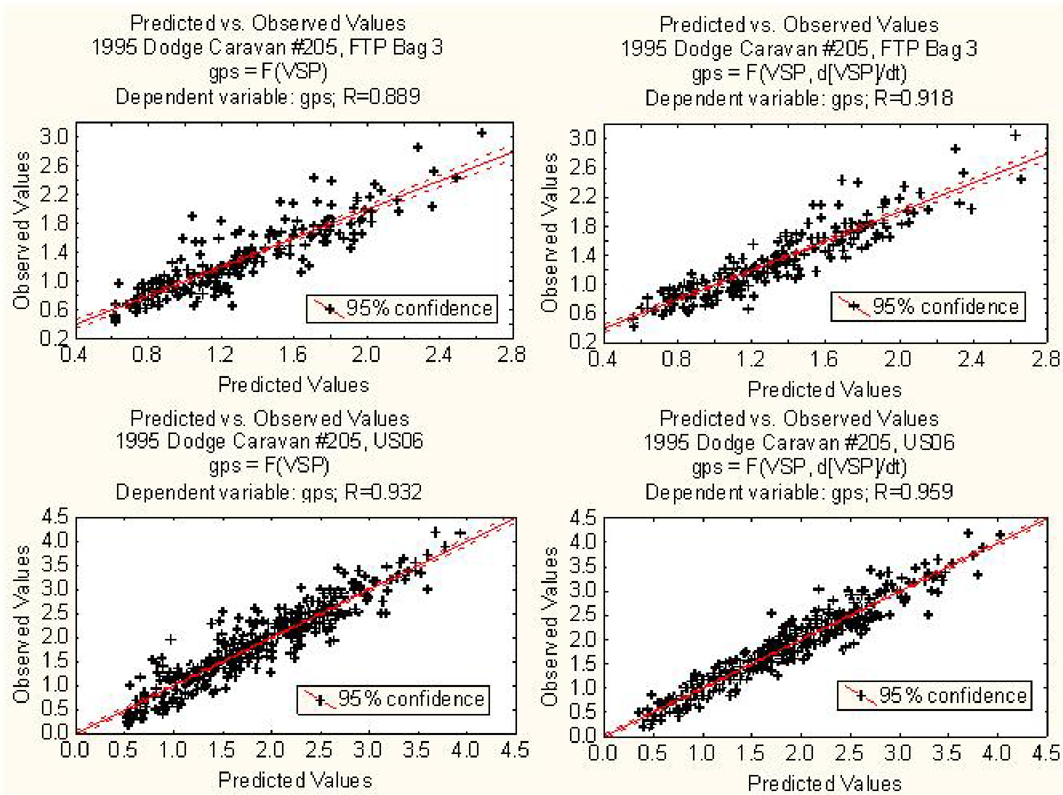

Figure 3-5. Effect of adding the variable (ΔVSP/Δtime) to the correlation of grams per second Carbon with VSP for with a high emission vehicle.

The value [ΔVSP/Δt] would be estimated from remote sensing data by multiplying the term [ΔVSP/Δdistance] by the average speed, [Δdistance/Δt]. [ΔVSP/Δdistance] can be determined if a sufficient number of speed measurements are made and the distance between them is known. The average vehicle speed usually changes very little over a short distance. So remote sensing is a tool to provide better in-use estimates including the [ΔVSP/Δt] correlating variable. This [ΔVSP/Δt] variable was shown in Section 2 to be more important for regulated emissions than for CO_2.

3.5 TREATMENT OF OTHER GREENHOUSE GASES (N_2O, CH_4, AND BLACK CARBON)

The initial planned release of MOVES, MOVES GHG, intends to assess greenhouse gas (GHG) emissions of automobiles. EPA plans to have MOVES-GHG map CO_2 emissions and possibly other greenhouse gases, N_2O, CH_4, and PM, into various vehicle operation bins defined by each of several variables including at least vehicle specific power (VSP). The national annual CO_2 emission estimates by on-road and off-road mobile sources to be predicted by MOVES-GHG should and are expected to be verified from the amount of fuel sold. A number of models and studies have related the CO_2 emissions used in the extraction, refining, processing, and delivery of the fuel, and MOVES plans to incorporate Argonne National Laboratory's GREET model into its greenhouse gas estimates.

One purpose of this report was to review the structure of the MOVES-GHG model which, in addition to providing national GHG emission estimates, is intended to provide information on possible GHG control strategies (EPA – G. Tierney, 2003b). The overall estimates of MOVES-GHG should be verified because the CO_2 emissions used in vehicle operation would be directly related to the amount of fuel sold. Vehicle operating conditions and emissions data are being accumulated from a number of data sources (EPA, 2002e). The plan is to interpolate and extrapolate these data using the concepts developed by PERE, a physically based engine load model that is designed to predict the fuel rate to the engine as a function of vehicle characteristics and operating conditions.

Although EPA has not yet but may produced or collected sufficient data to estimate CO_2 emissions to be ready in time for the now planned draft release of MOVES GHG for early 2004 (EPA, 2003b), other greenhouse gases would likely not be ready at that time. An earlier EPA (2003c) notice had indicated that a draft version of MOVES GHG was planned for September, 2003 as was described along with the overall release plan for the MOVES model as shown below.

> *"An internal version of MOVES (planned for September 2003) will be used for validation, to benchmark against fuel consumption estimates. The initial release (planned for December 2003) will focus on the policy evaluation components of the model, including well-to-pump emission estimation instead of the 1990-2002 inventory numbers, and the scope will be initially limited to inventories for calendar year 1999 and forward. Data will be linked to the TRENDS and NEI (National Emission Inventory) processes. A full on-road release will replace the MOBILE6 model in Fall 2005. Prior to that, MOVES will be limited to on-road greenhouse gases (GHG, such as CO_2, CH_4, N_2O). Mr. Koupal acknowledged that this represents a change in the scope from that of the planning documentation and the November 2002 mobile source models workshop. The off-road release, planned for 2006, will replace the NONROAD model."*
> (EPA – J. Koupal, 2003c)

The use of PERE for predicting engine-out emissions will likely work well in predicting total CO_2 generation, but requires much more data and as yet undeveloped catalyst pass algorithms to account for N_2O, CH_4, and PM emissions. From a practical point of view, devoting time to estimating CH_4 and possibly N_2O emissions at the level required for MOVES GHG in a detailed spatial and temporal map is a waste of resources. Gasoline and diesel vehicles emit very little CH_4, representing less than 1% of the CH_4 inventory. Even a natural gas vehicle emits about 20 times less methane in operations than a single cow (Lawson, 2003). It is possible to index CH_4 and N_2O to one or more criteria pollutants with sufficient accuracy, and it is appropriate and recommended to wait until the data on the criteria pollutants are incorporated in MOVES rather than to attempt to include these gases in MOVES GHG.

Black carbon has been claimed by Mark Jacobson (2001) of Stanford University to be 15 to 30 percent as much a contributor to global climate forcing as CO_2. Although John Seinfeld (2003) and James Hansen endorse the significance of black carbon as a greenhouse agent, the United Nations Intergovernmental Panel on Climate Control (IPCC), has not yet agreed (Seinfeld, 2003). However, if black carbon is as important a greenhouse gas emission as has recently been claimed, and because its effect is local rather than global, efforts to track it are warranted, if not in the initial release of MOVES GHG, then soon after. This will not be easy because the definition of black carbon is not clear, and the emission measurements have not yet been standardized (Chameides and Bergin, 2002).

While EPA's intends (see quote above) that MOVES GHG be limited to on-road greenhouse gas emissions, automobiles and trucks contribute to global warming by generating a number of greenhouse gases in use and in manufacture. The largest is CO_2, formed primarily from the burning of fuel in use, but also from the energy used to produce the fuel and in the vehicle life cycle, including manufacture, scrap, and recycle of parts. Other gases, N_2O and CH_4, are formed primarily, but not exclusively, from catalyst-equipped vehicles. Black carbon is formed mainly from diesel vehicles. CFC's are emitted from air conditioning systems as fugitive emissions and released when A/C systems are vented during recharging and when scrapped. SF6 was used by at least one tire manufacturer to reduce the leak rate and help maintain tire pressure, but this use was projected to end by 2002 (Smythe, 2000).

Greenhouse gases differ in their intensity of global climate forcing and their lifetimes. Whether an individual component of vehicle emissions is important will depend upon the forcing function described below and the emission rates of each component. According to the EPA (2003d) draft greenhouse inventory:

> "*Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, and other ambient air pollutants (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SOx products and black carbon), however, vary spatially, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.*
>
> *Table S-1: Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) of Greenhouse Gases (FCCC, 1996)*

Gas Component	*Atmospheric Lifetime*	*100-year GWPa*	*20-year GWP*	*500-year GWP*
Carbon dioxide (CO_2)	*50 - 200*	*1*	*1*	*1*
Methane (CH_4)b	*12 ± 3*	*21*	*56*	*6.5*
Nitrous oxide (N_2O)	*120*	*310*	*280*	*170*
HFC-23	*264*	*11,700*	*9,100*	*9,800*

Lave et al. (2000) estimated the impact of transportation sources through a life cycle analysis of CO_2-equivalent GHG emissions (not counting black carbon). A substantial amount of GHG (associated with gasoline and diesel fueled vehicles) is generated during the fuel preparation. "GHG … generated by the life-cycle of vehicles fueled by gasoline and diesel is large (e.g., approximately 100,000 kg for the reformulated gasoline port injection option). …. GHG emissions resulting from fuel production are 20-30% of those resulting from vehicle operation."

Substantial reductions in GHG emissions could be obtained in private transportation if motorists were willing to pay the price and incur less convenience, particularly in the range and size of their vehicles. Lave et al. (2000) noted the GHG emissions savings possible for vehicles having the same range, but different fuels. "Compared to the gasoline baseline vehicle, the greater efficiency of the diesel engine results in lower energy use and 25% lower global warming potential." The life cycle emissions from the Prius HEV were estimated to be about 50% of that from a typical vehicle fueled by reformulated gasoline.

The EPA (2003d) inventory of greenhouse gas emissions and sinks provided estimates of the 2001 CO_2-equivalent GHG for transportation for each of the gases except black carbon, as shown in Table 3-2. CO_2 itself was seen to be the predominant greenhouse gas and the transportation contribution to CO_2 generation was estimated to be a substantial fraction of total CO_2 emissions. On the other hand, the contribution of transportation to CH_4 is very low. Although the transportation contribution to N_2O is significant, the contribution to greenhouse gas CO_2-equivalents of N_2O is low. (Becker et al., 2000) The transportation share of HFCs emissions was not specified, but the total contribution from this source is expected to be low. Overall as shown in Table 3-2, the CO_2 emissions from transportation sources were overwhelmingly more (nearly two orders of magnitude high) important than other components in vehicle emissions therefore EPA should prioritize their efforts according to the relative importance of these emissions and focus primarily on CO_2 emissions for MOVES GHG.

Table 3-2. CO_2-equivalent (teragrams or %) greenhouse gases in the US in 2001 (EPA, 2003d).

Component	Transportation		All Sources	Component as a % of Total	Transportation Component as % of Total
Total	1,870	27%	6,938		
CO_2	1,781	36%	4,958	71%	26%
CH_4	4	0.7%	606	9%	0.1%
N_2O	55	13%	425	6%	0.8%
HFC's			111	2%	Negligible

Black carbon, on the other hand, was not tabulated, though the contribution to black carbon from transportation may yet be found to be a substantial and important source of greenhouse gas emissions. The CO_2 equivalency of black carbon has not been estimated so the impact of transportation generated black carbon on overall greenhouse gases cannot be estimated at this time. However, because the stated intention of MOVES is to estimate particulate emissions EPA should prepare to estimate the black carbon fraction of those emissions as a greenhouse gas.

3.6 SUMMARY AND RECOMMENDATIONS

In summary, the approach for MOVES GHG using the vehicle power to model fuel consumption (and therefore eventual CO_2 emissions assuming all CO and hydrocarbon emissions eventually oxidize in the atmosphere) is a sound approach and largely explains the data. It is not necessary to use the PERE model, but it is appropriate to use PERE calibrated with data or use PERE to inform an empirical approach. The PERE model requires its own data set, the most important, but not only data, being the vehicle mass. A strictly empirical approach informed by the physical parameters of load and efficiency as described by the PERE model was shown to describe the fuel consumption well. PERE can be useful in filling in or interpolating for missing data, but it is not a shortcut to bypassing a well-stocked and representative data set. The prediction of criteria pollutants using PERE requires an aftertreatment model, which is not yet available. Remote sensing can be used in conjunction with the MOVES modeling framework to supplement laboratory and PEMS test data and improve fleet characteristics, especially with regard to selection bias of malfunctioning vehicles typically cited with laboratory studies. Lastly, eventual CO_2 emissions are by far the most important, but not only, greenhouse gases emissions from vehicles in operation.

The recommendations that derive from this work are as follows:

1) We recommend that EPA identify and explicitly determine the fuel parameters, especially the lower heating value, in test vehicles and is an important consideration and a data need for model estimates.

2) If PERE is used to describe the vehicle power requirements, we recommend that EPA generate a great deal of information to estimate the engine efficiency and power requirements of vehicles for different engine and chassis technologies.

3) Whether PERE is used or not, we recommend that EPA develop basic information about vehicle weight, rolling resistance, and aerodynamic drag especially for heavy-duty vehicles in order to estimate vehicle power distributions among vehicle types.

4) We recommend that EPA fund a project to test whether remote sensing data can be used to check and adjust or extend the use of PEMS or laboratory data.

5) We recommend that the term [d(VSP)/dt] be used to improve the correlation of CO_2 emissions. We showed that this term improved correlation of regulated pollutants as part of Section 2.

6) Transportation sources are a minor source of methane emissions. We recommend that methane emissions be indexed to criteria pollutants (likely total hydrocarbon) based on smaller special studies designed for that purpose.

7) Likewise, because of the lower importance to overall greenhouse gas emissions, we recommend that N_2O be indexed to criteria pollutants (likely NOx emissions) based on smaller special studies designed for that purpose.

8) If EPA is concerned about GHG from vehicles, they should account for all GHG generated by vehicles including particulates, refrigerants, and the GHG's generating in making and recycling vehicles. Of those emissions just listed, MOVES would only be suitable for estimating particulate effects.

4.0 REVIEW OF PORTABLE EMISSIONS MONITORING SYSTEMS METHOD AND DESIGN

4.1 INTRODUCTION

The portable emissions monitoring system (PEMS) is an innovative technology that will assist EPA in gathering sufficient data to move mobile source emissions modeling in a new direction. The advantage of PEMS is that much more emissions data can be collected than traditional laboratory methods, and that data can be gathered while drivers are operating their vehicle on surface roads rather than in the artificial laboratory environment on test cycles that may represent only some types of vehicle activity. The field data gathered by PEMS may also be used to represent in-use activity behavior in addition to gathering data for emissions estimates.

The PEMS method is a device designed to measure emissions and activity *in situ* with the vehicle operated by the owner/operator. The system is an add-on device requiring less time or cost than traditional laboratory measurements. Using global positioning systems and the vehicles' on-board computers or sensors, vehicle speed, road grade, and other road load variables can be measured while the vehicle is in operation. Ambient temperature and humidity can also be gathered during the sampling. The emissions will be gathered from instruments mounted on-board, in the back of the vehicle, by sampling the exhaust and determining the exhaust flow. EPA (2002f) conducted an initial evaluation of the method, and has since written specifications and is taking delivery on second-generation models of the instruments. Evaluation data are not yet available for these second-generation instruments. A more detailed description of the PEMS instruments is provided in Section 4.4.

The PEMS system does not, however, evaluate evaporative emissions, perform fuel analysis, or (in the current versions) measure particulate and toxics emissions and other emissions such as those explicitly mentioned as greenhouse gases. Therefore, emissions generated from evaporative sources will still need to be measured in laboratory settings. Toxic and particulate emission measurements may be adapted for measurement in the PEMS system or be apportioned or indexed to measured pollutants, typically either CO or THC. Greenhouse gases other than CO2 may also be apportioned or indexed to the measured emissions, could require an additional measurement method, or rely on laboratory evaluation.

The PEMS instruments are likely to be important to generate sufficient data at low cost for the planned revisions to the next generation emission factor models, now called MOVES. As described in the draft MOVES design and implementation plan, the data generated by PEMS are expected to be subdivided into operating mode bins defined by vehicle specific power (VSP), the ratio of road load to vehicle weight, and/or other variables both in terms of activity and emissions rates (EPA, 2002g). The PEMS system will be used to determine activity distributions and emissions in each of several VSP bins by collecting field data on both. In order to estimate overall regional or local emissions, activity rates will still be generated by travel demand modeling and other transportation planning tools in terms of vehicle counts, and average speed or congestion level by transportation link, where a link is usually a short section of road way such as on a freeway between two exit ramps. Therefore, the collection of activity data by transportation link is of interest.

This section reviews the PEMS method using laboratory correlation data as part of EPA's initial evaluation of the PEMS method on normal emitting Tier 1 light-duty vehicles (EPA, 2002f). The laboratory methods included both the bag analysis and modal (second-by-second) systems allowing comparisons of both the cycle totals and second-by-second emissions. Using the PEMS, field data were collected to compare with laboratory measurements in terms of emission estimates by road load category or bin. Diesel bus data were collected, but no chassis confirmation testing of the method was performed. Laboratory evaluations of the diesel PEMS method using engine dynamometer testing showed good correlation with the laboratory measurements (EPA, 2002f), but this testing is removed from the intended purpose of the PEMS, and so was not reviewed here.

4.2 LABORATORY COMPARISONS

During the initial evaluation of the PEMS (EPA, 2002f), laboratory correlation testing was performed with the PEMS method, the official certification bag collection method, and an EPA laboratory modal system (made by Horiba) all operating on the standard Federal Test Procedure (FTP) with a US06 driving trace. These measurements allowed a one-to-one comparison of the two modal measurements (1 Hz or second-by-second responses) using PEMS and EPA laboratory-modal, and a comparison of test cycle totals using official certification bag samples and cycle totals of the modal systems.

4.2.1 Overall Cycle Totals

Summary information provided in the EPA evaluation report demonstrated that over the course of the test cycles, the PEMS methods (an early version of SEMTECH-G), EPA bag, and EPA modal results were comparable, as long as a flame ionization detector (FID) was used for the hydrocarbon measurements. Tables 4-1 and 4-2 reprise the EPA (2002f) summary tables of all valid and complete tests that show general agreement among all three measurement methods.

Table 4-1. Comparison between Modal and Bag Measurements on FTP (g/mile) (EPA, 2002f).

Car	MODEL_NAME	Year	Exh. Flow Meas. Type*	Semtech-G					EPA Bag results				EPA Modal Results			
				CO2	CO	NO	HC	HC FID	CO2	CO	NO	HC	CO2	CO	NO	HC
1	LUMINA LS	1998	2	398	2.396	0.243	0.138		377	2.275	0.239	0.184	392	2.344	0.179	0.096
2	TAURUS GL	1997	3	419	5.120	0.797	0.154		392	4.750	0.795	0.244	397	4.535	0.719	0.247
3	SABLE LS	1996	3	412	2.889	0.434	0.179	0.355	381	2.882	0.444	0.362	384	2.813	0.486	0.335
6	MALIBU LS	1999	2	386	2.432	0.369	0.152		381	2.270	0.362	0.190	392	2.250	0.379	0.183
7	SATURN	1999	1	299	1.283	0.736	0.074	0.136	298	1.283	0.701	0.137	289	1.219	0.733	0.148
8	ESCORT	1999	3	273	0.936	0.181	0.063		290	0.946	0.189	0.100	279	0.974	0.192	0.088
9	ESCORT	2000	3	292	0.680	0.061	0.057	0.060	280	0.699	0.066	0.061	276	0.635	0.067	0.064
11	TAURUS SE	1998	3	401	2.35	0.260	0.121	0.202	386	2.224	0.289	0.209	389	2.224	0.297	0.222
12	Escort	1997	3	349	1.71	0.342	0.072	0.125	355	1.685	0.347	0.133	356	1.651	0.360	0.133
13	Sable	1998	3	408	1.562	0.107	0.086	0.137	392	1.460	0.107	0.163	404	1.428	0.112	0.175
14	TAURUS WAGON	1998	3	457	0.91	0.20	0.15	0.28	460	0.955	0.207	0.260	495	0.993	0.216	0.297
16	CHEVY CAVALIER	1998	1	353	10.517	0.483	0.116	0.237	351	9.890	0.493	0.276	365	10.272	0.522	0.325
18	Ford Taurus	1996	3	387	3.651	0.626	0.172	0.220	384	3.434	0.606	0.231	405	3.542	0.614	0.261

Car	MODEL_NAME	Year	Exh. Flow Meas. Type*	Semtech-G					EPA Bag results				EPA Modal Results			
				CO2	CO	NO	HC	HC FID	CO2	CO	NO	HC	CO2	CO	NO	HC
All Vehicle Average				372	2.80	0.37	0.11	0.19	363	2.67	0.37	0.20	371	2.68	0.38	0.22

* See below in Section 4.4 for a description.

Table 4-2. Comparison between Modal and Bag Measurements on US06 (g/mile) (EPA, 2002f).

Car	Model	Year	Semtech-G					US06 Bag results				US06 Modal Results			
			CO2	CO	NO	HC	HC-FID	CO2	CO	NO	HC	CO2	CO	NO	HC
1	Lumina LS	1998	402	10.95	0.217	0.063		385	13.91	0.210	0.150	383	8.57	0.168	0.108
2	Taurus GL	1997	370	15.09	1.079	0.084		371	19.24	1.024	0.224	368	14.78	1.073	0.145
6	Malibu LS	1999	386	4.56	0.400	0.075		389	6.85	0.393	0.116	384	4.29	0.403	0.082
8	Escort	1999	279	4.38	0.715	0.032		299	6.33	0.769	0.045	293	4.73	0.933	0.037
9	Escort	2000	294	12.85	0.142	0.045	0.094	296	13.30	0.162	0.104	292	9.69	0.207	0.082
11	Taurus SE	1998	386	11.97	0.348	0.099	0.191	396	16.05	0.390	0.209	391	12.43	0.417	0.150
12	Escort	1997	317	32.38	0.966	0.082	0.225	340	34.78	0.894	0.268	338	31.33	0.993	0.296
13	Sable	1998	369	6.44	0.180	0.018	0.063	382	7.00	0.211	0.076	373	4.94	0.223	0.062
14	Taurus Wagon	1998	425	4.76	0.230	0.025	0.081	443	5.01	0.242	0.087	442	3.11	0.162	0.06
16	Cavalier	1998	347	17.62	0.880	0.134	0.197	371	21.26	0.974	0.206	367	18.68	1.024	0.225
18	Taurus	1996	364	16.75	0.639	0.097	0.260	389	24.35	0.673	0.280	390	18.29	0.706	0.203
All Vehicle Average			**358**	**12.52**	**0.53**	**0.07**	**0.16**	**369**	**15.28**	**0.54**	**0.18**	**366**	**11.89**	**0.57**	**0.15**

Regression analysis was used to estimate bias in the measurements. In the first set of comparisons between the bag results and PEMS data, unconstrained regression analysis was done to determine if the intercept was different from zero (i.e. to check for an absolute bias). In all cases, the intercept was not statistically different from zero at the 90% confidence level. A second set of regressions were then performed with the intercept set to zero, shown in the equation below, so that the slope can be used to check for a constant relative bias. The results of these constrained regressions are shown in Table 4-3. Table 4-3 shows little consistent bias, though the PEMS measurements were generally higher than bag measurements (slope < 1) on the FTP test cycle and lower than the bag measurements (slope > 1) on the US06 test cycle.

$$\text{Bag Result} = \text{Slope} * (\text{PEMS Result}) \qquad (1)$$

For the FTP cycle, the PEMS method measured the emissions no worse than within 6% (worst case: PEMS CO emissions were 6% higher than bag measurements). And on the US06 test cycle, the PEMS generally underpredicted emissions with the worst case being CO emissions where the PEMS CO emissions were 16% lower than the bag measurements. Note, however, that the vehicles tested here showed less range in emissions rates than will be found for all vehicles operating because all vehicles tested under this program met Tier 1 emission standards and were in reasonable working order; i.e., the bias may be larger or smaller with malfunctioning and/or high emitting vehicles.

Table 4-3. Correlation of bag results and PEMS.

Emission	Approximate Range (g/mile)	FTP – Test Cycle			US06 – Test Cycle		
		N	Slope	R^2	N	Slope	R^2
CO2	300 – 450	13	0.975	0.932	11	1.029	0.903
CO	1 – 10 FTP 5 – 35 US06	13	0.944	0.999	11	1.184	0.944
NOx	0.1 – 1.0	13	0.991	0.996	11	1.008	0.978
THC-FID	0.05 – 0.35	9	1.034	0.961	7	1.105	0.968

Test measurements are notoriously variable vehicle to vehicle and test to test, so a more extensive correlation effort may reveal that the results indicated by Table 4-3 were due to test variability, unrelated to the operation of the vehicle in these side-by-side tests, rather than any consistent measurement bias. However, no repeat tests were available to test this hypothesis. To illustrate this, the PEMS measurement was compared to the EPA laboratory modal test method in Table 4-4; there is less difference and less consistent difference between the two methods than shown in Table 4-3.

Table 4-4. Correlation of EPA modal and PEMS.

Emission	Approximate Range (g/mile)	FTP – Test Cycle			US06 – Test Cycle		
		N	Correlation	R^2	N	Correlation	R^2
CO2	300 – 450	13	0.999	0.913	11	1.019	0.903
CO	1 – 10 FTP 5 – 35 US06	13	0.960	0.997	11	0.970	0.968
NOx	0.1 – 1.0	13	0.992	0.972	11	1.085	0.957
THC-FID	0.05 – 0.35	9	1.096	0.881	7	0.981	0.775

4.2.2 Modal (Second-by-second) Analysis

The ability of the PEMS to gather emissions and activity data at 1 Hz (second-by-second) is the basis for the proposed modeling approach for MOVES, so a comparison of modal measurements is also an important component of the evaluation of the PEMS method. Table 4-4 shows that the two modal methods produce very similar emission measurements aggregated over the test cycle, so differences in second-by-second emissions rates may be expected to be due to the measurement method employed.

A laboratory modal method was used to provide a basis for comparison of the PEMS method using an EPA testing laboratory method. The EPA gas concentrations were determined using the standard gas measurement methods (chemiluminescence's for NOx, FID for hydrocarbon, and NDIR for CO and CO_2). EPA used a modal emission measurement method where the gas concentration was multiplied by an estimate of the exhaust flow using a smooth approach orifice method. The smooth approach orifice method determines the total dilute (exhaust plus dilution air) flow rate and the flow of the make-up (dilution) air using the pressure drop across a smooth approach orifice, a standard method to verify steady state gas flow rates. The flow measurement used in the EPA laboratory is an important distinction from the PEMS instrument used because it did not depend upon information from the electronic control module (ECM) of the vehicle. However, the exhaust flow measurement was calculated as a difference between the total dilute air flow at the constant volume sampler (CVS) and dilution make-up air using smooth approach orifices to measure instantaneous flow. This flow measurement is particularly uncertain at low exhaust flows, where the difference between the CVS and make-up air is small. In addition, the response of this flow measurement may be sensitive to rapid pressure changes as might be caused by rapid changes in exhaust flow. The CVS pressure may therefore experience short-term increases and decreases influencing the exhaust flow calculation.

To review the modal PEMS emissions estimates, data collected at 1 Hz from the EPA and PEMS modal test methods were compared in time with vehicle specific power (VSP, measured in kW/tonne) estimates for several vehicles. The VSP was calculated for the laboratory estimates using the Jimenez-Palacios (1999) simplified method of determining this parameter with the vehicle speed information provided in the raw data. This method does not take into account differences in specifics about the vehicle tested such as different drag and other resistance coefficients. To simplify the analysis, negative VSP values (coast down) were reset to 0, and idle condition was set to 0.1 to distinguish idle from coast down conditions.

To directly compare the estimates, the raw modal emissions data were time adjusted to the VSP by manually fitting the CO2 emissions to the last five high VSP events in the US06 because these sharp peak events allowed for a fine adjustment of the time alignment. An example of the raw (unadjusted) and time adjusted driving trace and emission estimates are shown in Figures 4-1 and 4-2. No formal criteria were used to perform this time adjustment and EPA suggested none, but EPA should develop a time adjustment methodology that is universally applicable when larger numbers of tests are performed. For instance, Ramamurthy and Clark (1999) have used a more rigorous method of time alignment accounting for the instruments' individual axial dispersion, and they perform the time alignment by minimizing the error between the NOx or CO2 signals and the power demanded. However using the Ramamurthy and Clark approach was more involved requiring specific information about the experimental setup, and was outside of the scope of this study. By matching emissions rates and VSP, the emissions response to the VSP can be compared between the EPA modal and PEMS modal measurement methods.

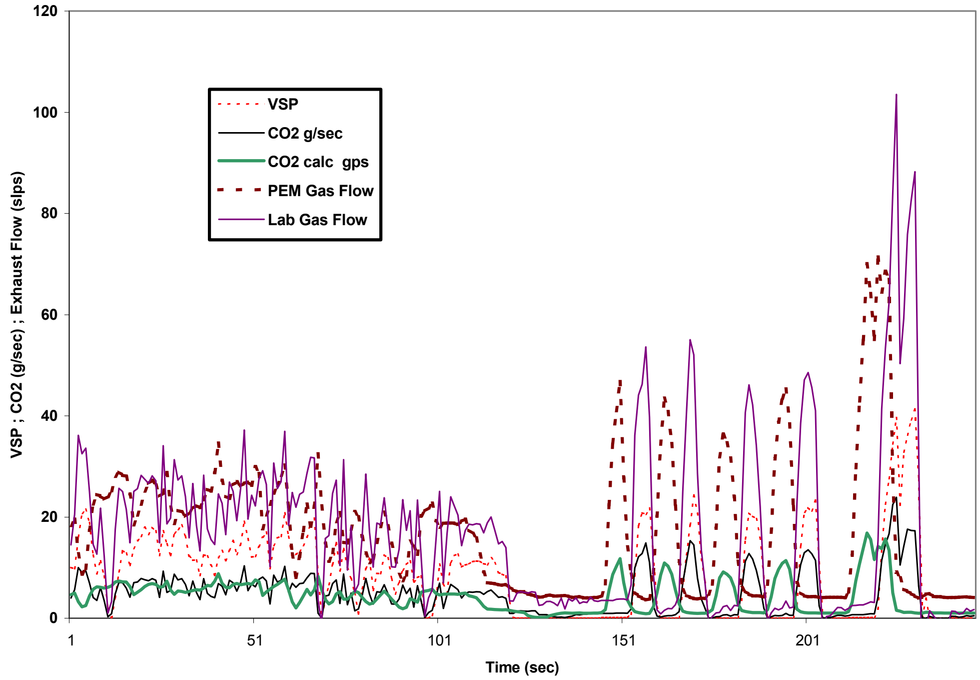

Figure 4-1. Vehicle 18 CO2, exhaust flow, and VSP modal data, unadjusted.

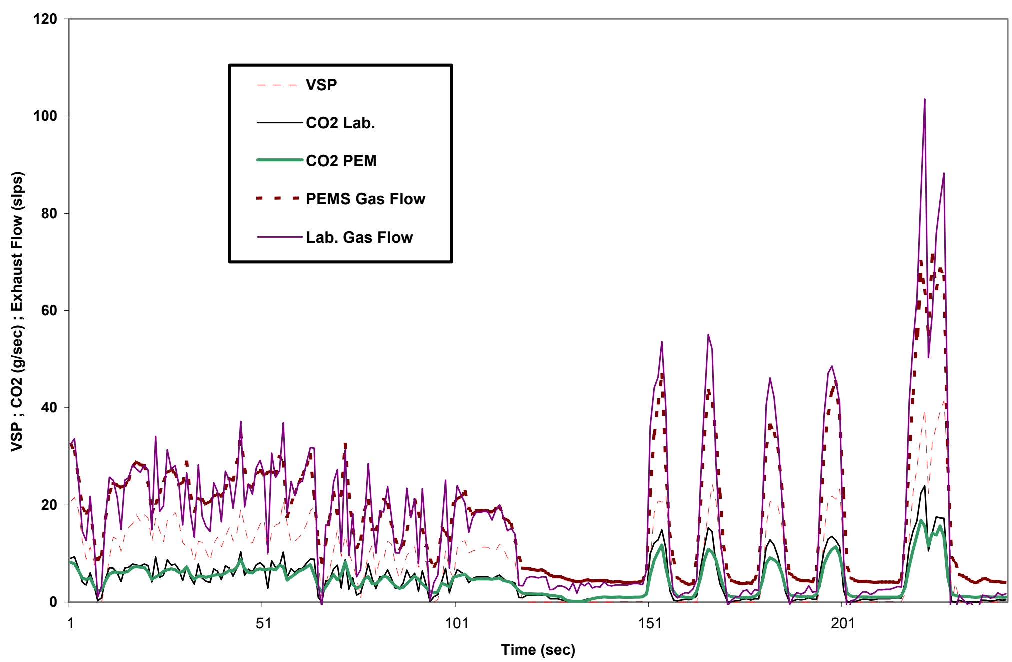

Figure 4-2. Vehicle 18 CO2, exhaust flow, and VSP modal data, time adjusted.

In Figure 4-2, it can be seen that the peak CO2 emissions level from the PEMS method was lower than the comparable EPA ("Lab.") method during the high VSP events. This phenomenon was observed for all vehicles tested on the US06 test listed in Table 4-2.

Another graphical method that can be used for evaluating bias is to compare emissions by VSP. Figures 4-3 through 4-6 show boxplot comparisons of PEMS and laboratory CO2, CO, THC, and NO_X emissions for vehicle 18 by VSP bins; similar graphs for other vehicles are in Appendix F. The figures show emission estimate average (means) for each of several VSP bins as point estimates (connected with lines). Around each mean the box marks the standard error of the point estimates, and a "whisker" (the blunt ended thin line) shows 2 times the standard deviation of each point estimate. Outliers (defined for these plots as greater than 3 times the box width above and below the box) and extreme (defined for these plots as greater than 6 times the box width above and below the box) values for each VSP bin are also shown on each plot for both the "LAB" (EPA modal) and "PEM" modal method.

These graphs demonstrate that PEMS measurements are clearly lower at high VSP for both the CO2 and CO compared to that measured by EPA method, while both methods estimate comparable THC and NOx emissions for all VSP bins. Because the average VSP is less than 5 kW/tonne on the combined FTP and US06 test cycles, the cycle totals could be similar while the high VSP bin estimates could be biased.

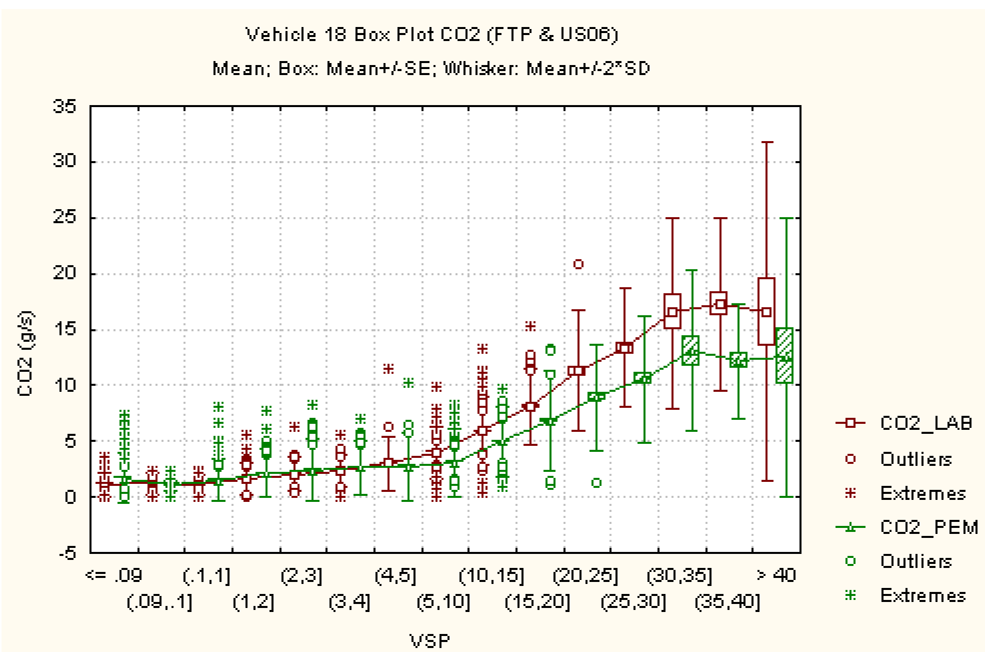

Figure 4-3. Vehicle 18 CO2 emissions by VSP bin.

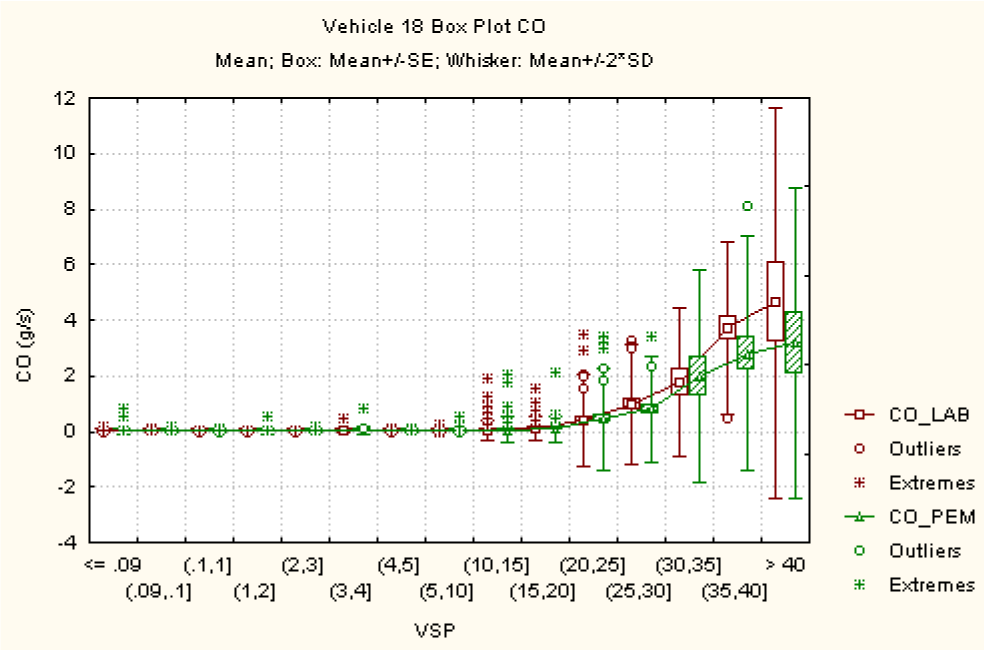

Figure 4-4. Vehicle 18 CO emissions by VSP bin.

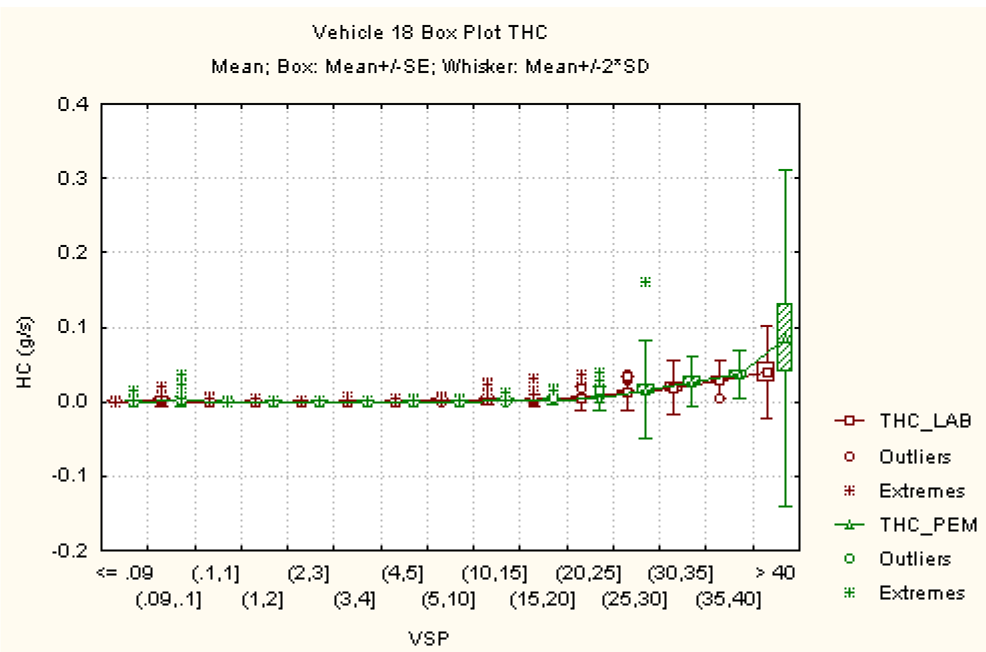

Figure 4-5. Vehicle 18 THC emissions by VSP bin.

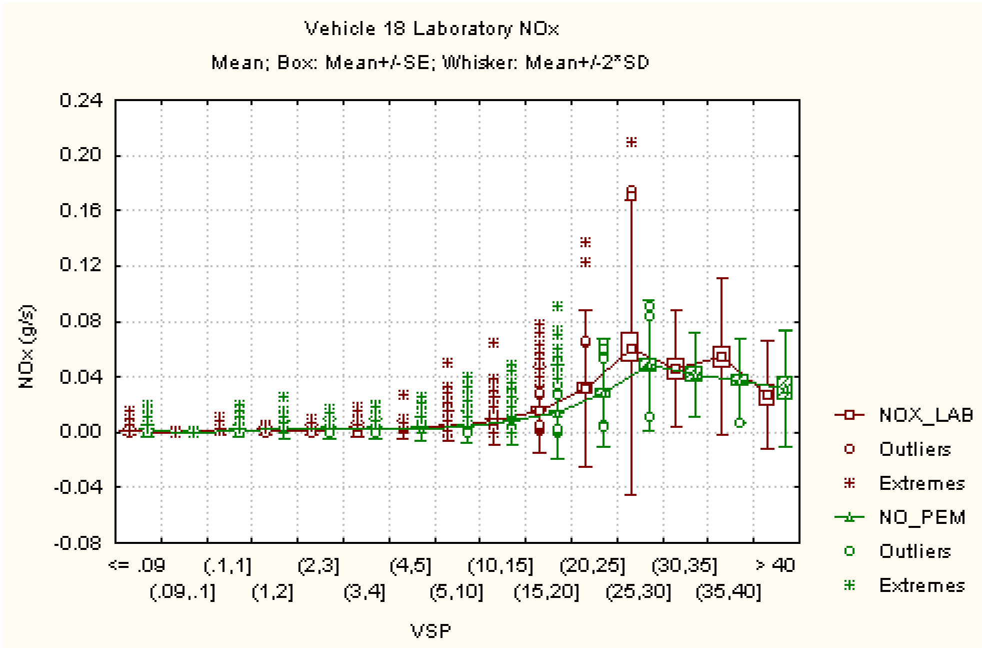

Figure 4-6. Vehicle 18 NOx (NO) emissions by VSP bin.

The bias at high VSP between the raw (second-by-second) laboratory and the PEMS modal analysis for high VSP is likely due to averaging or peak broadening within the PEMS emission signal or peak sharpening with the EPA modal system. The high VSP bias (low emission readings by PEMS) exhibited by PEMS was reduced by filtering (or smoothing) the laboratory modal data using a three-second rolling average, one of the simplest filters. This is demonstrated in Figures 4-7 and 4-8, which show the difference between the measurements without and with filtering, respectively, and indicate a lower intercept and a less pronounced slope; similar plots for other vehicles are in Appendix F. Figure 4-8 shows smaller differences after filtering, especially at higher VSP.

Filtering methods for the second-by-second data may be appropriate, but should be exercised with caution. While a filter (such as a three-second rolling average) might be justified on the basis of the data variability (such as because of difficulty in assigning the correct offset or noise in the signal), the filter may render it more difficult to perform a microanalysis (such as at an intersection). Because the higher VSP conditions in the test cycles are short-term events, the filter will reduce the data in the higher VSP bins. In addition, because the high VSP peaks in this data were typically of short duration, the emission estimates in the high VSP bins will be reduced with filtering because the highest VSP conditions will be accompanied by lower VSP conditions before and after. The effect of filtering would therefore lower the overall emission estimates at the higher VSP conditions, if emissions response to the VSP condition were not proportional.

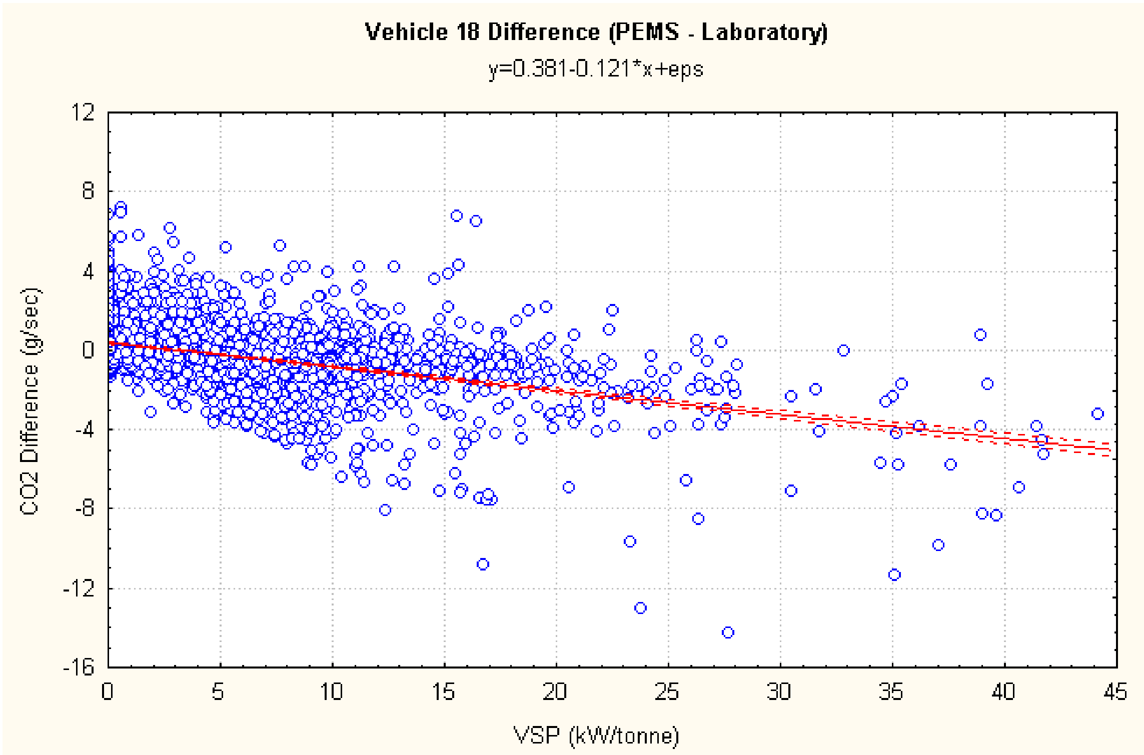

Figure 4-7. Vehicle 18 CO2 emissions: PEMS – EPA modal.

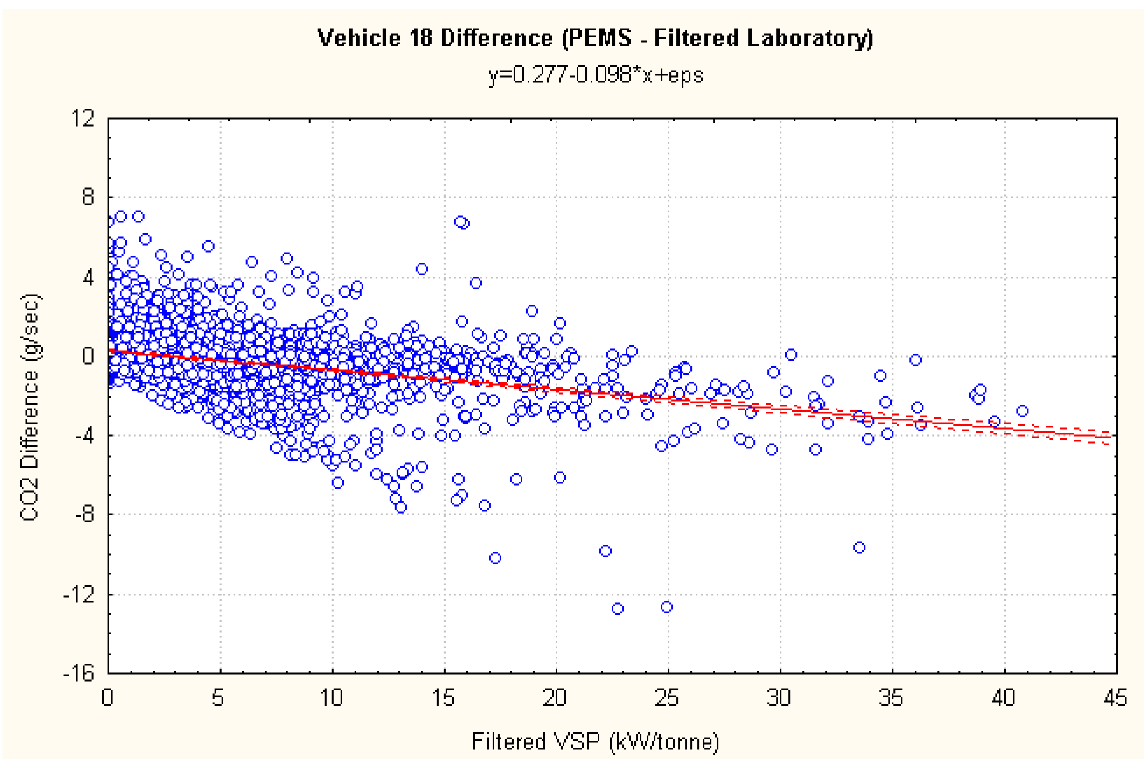

Figure 4-8. Vehicle 18 CO2 emissions: PEMS (raw) – EPA modal (3 second rolling average).

4.3 FIELD MEASUREMENTS

Field measurements were available to compare with the laboratory measurements in terms of the emissions and the activity generated. The VSP in the field now includes grade and auxiliary loads (air conditioning) as well as inertial, rolling resistance, and wind resistance estimates. The VSP was calculated using vehicle curb weights and drag coefficients supplied by EPA as described in an early investigation of these vehicles (ENVIRON, 2002) as:

$$Power_1 = (a + b * Speed_1 + c * Speed_1^2) * Speed_1 + 0.5 * Mass * (Speed_1^2 - Speed_0^2) + Mass * g * grade * Speed_1 + Auxiliary\ Power$$

In general, the driving behavior in the field data was not as aggressive as that used to generate laboratory data, especially the US06 test cycle. Table 4-5 compares field data with the combined FTP & US06 laboratory activity in terms of VSP bins. The proportion of time in high VSP bins (above the 15 – 20 kW/tonne VSP bin), is much lower when these vehicles were driven on the road by owner/operators as compared to the US06. Laboratory data to assess the vehicle response to high VSP ranges may therefore be needed to supplement field data.

Table 4-5. Sample time-in-mode activity results for field data as compared to FTP & US06.

Vehicle*	% of Time in Vehicle Specific Power (kW/tonne) Bin											
	< 2	2 – 3	3 - 4	4 - 5	5 – 10	10 - 15	15 – 20	20 - 25	25 – 30	30 - 35	35 – 40	>40
1	55	7	6	5	18	8	2	0.4	0.1	0.0	0.0	0.0
2	43	4	4	4	19	17	7	2.0	0.2	0.0	0.0	0.0
18	72	9	4	3	7	4	1	0.4	0.4	0.0	0.0	0.0
FTP & US06	51	5	6	4	16	9	4	2.0	0.9	0.3	0.5	0.2

* Data vary somewhat by operator and vehicle including the FTP & US06 results.

An interesting comparison is to look at the emissions generated in the field and the laboratory to see if the emissions rates are consistent in the VSP bins. This informs whether the method could be supplemented with laboratory data while maintaining consistency between the two types of driving behavior. Figures 4-9 through 4-12 show the vehicle 18 PEMS field measurements for CO2, CO, THC, and NO_X, respectively, for comparison with the laboratory PEMS measurements shown in Figures 4-3 through 4-6. The mean values from laboratory and field measurements shown in these two set of graphs are provided in Table 4-6. The field data show similar mass emission rates within each bin where there are sufficient data, predominately below 15 kW/tonne as shown in Table 4-5. Differences between the field and laboratory data can be attributed to many factors such as different vehicle operators, different driving traces (field data was normal driving by the owner and was characterized by lower VSP and generally less aggressive driving and less instantaneous change in VSP than the combined FTP and US06 driving traces) grade changes with field data, and many other potential factors. As shown by comparing Figures 4-3 through 4-6 with Figures 4-9 through 4-12, the field measurements tend to be less variable, likely because driving behavior is less aggressive, and because there is more data generated in the field, one of the most significant advantages in using the PEMS method.

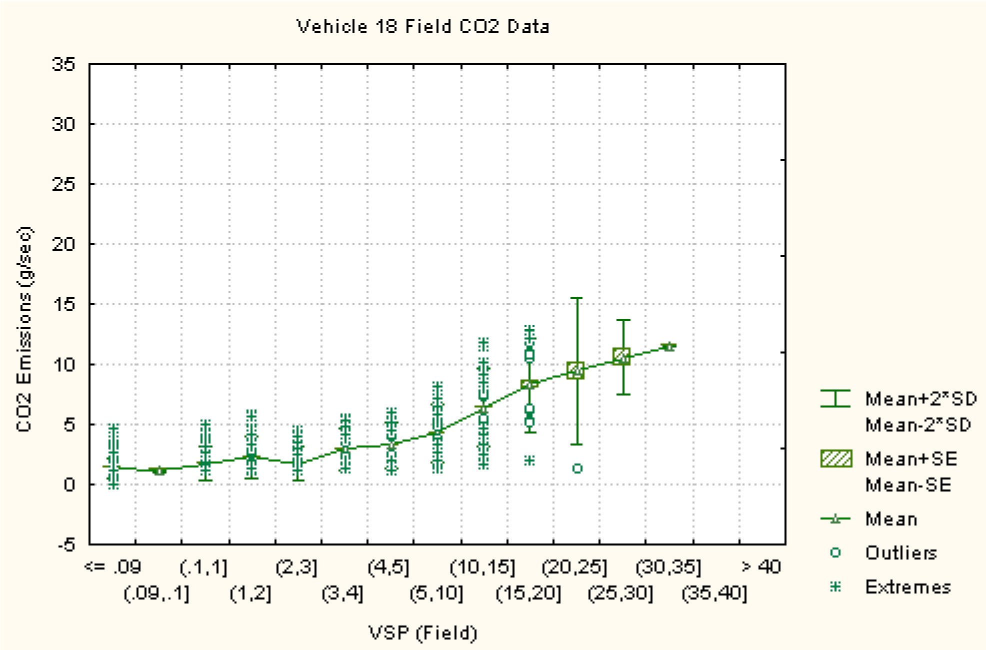

Figure 4-9. Vehicle 18 CO2 emissions by VSP bin from field data (for comparison to Figure 4-3).

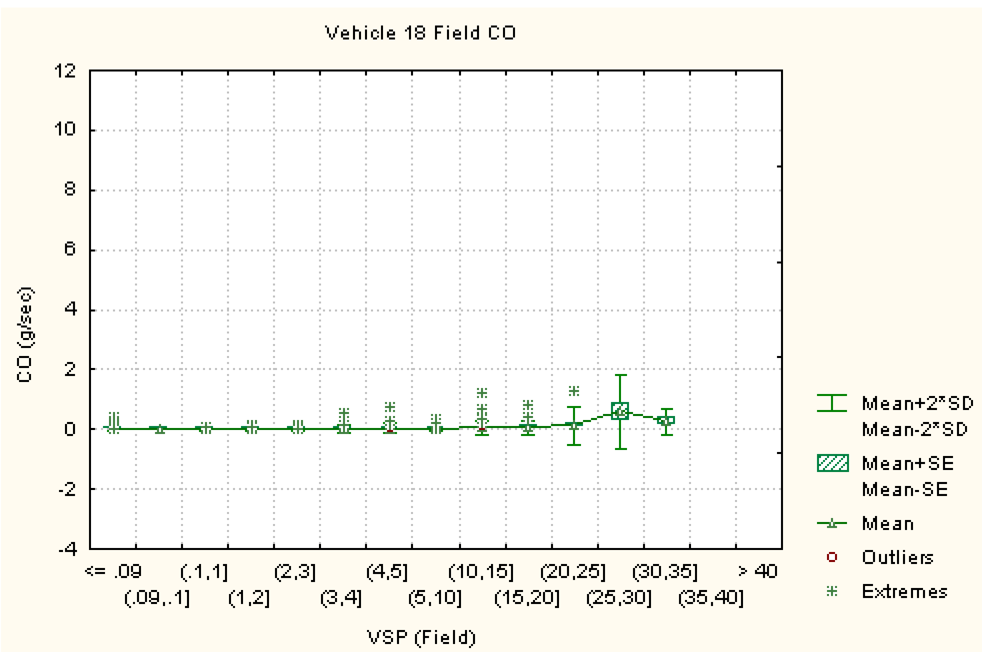

Figure 4-10. Vehicle 18 CO emissions by VSP bin from field data (for comparison to Figure 4-4).

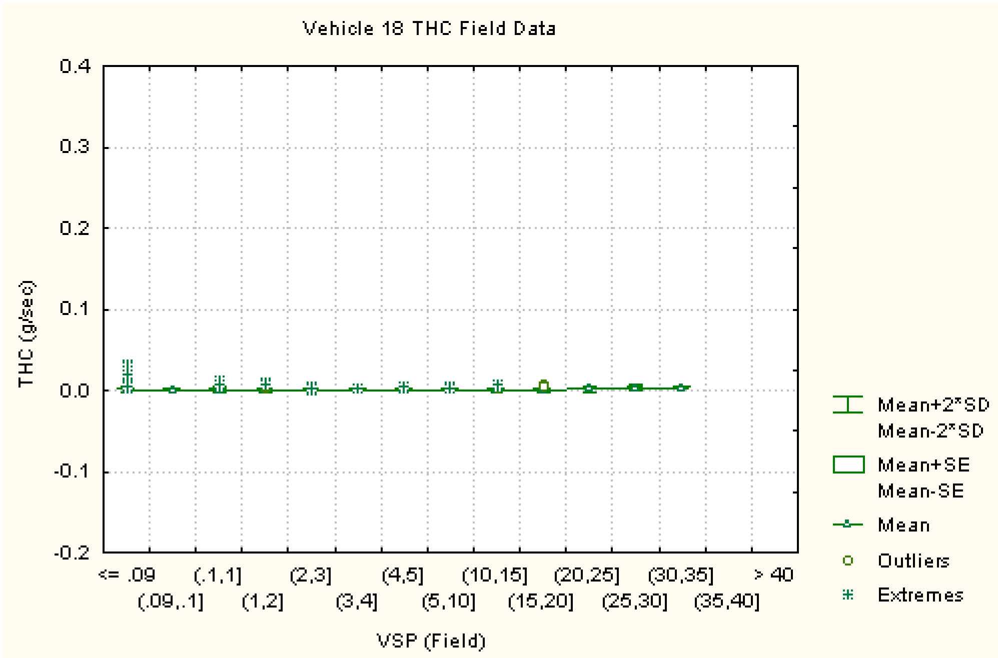

Figure 4-11. Vehicle 18 THC emissions by VSP bin from field data (for comparison to Figure 4-5).

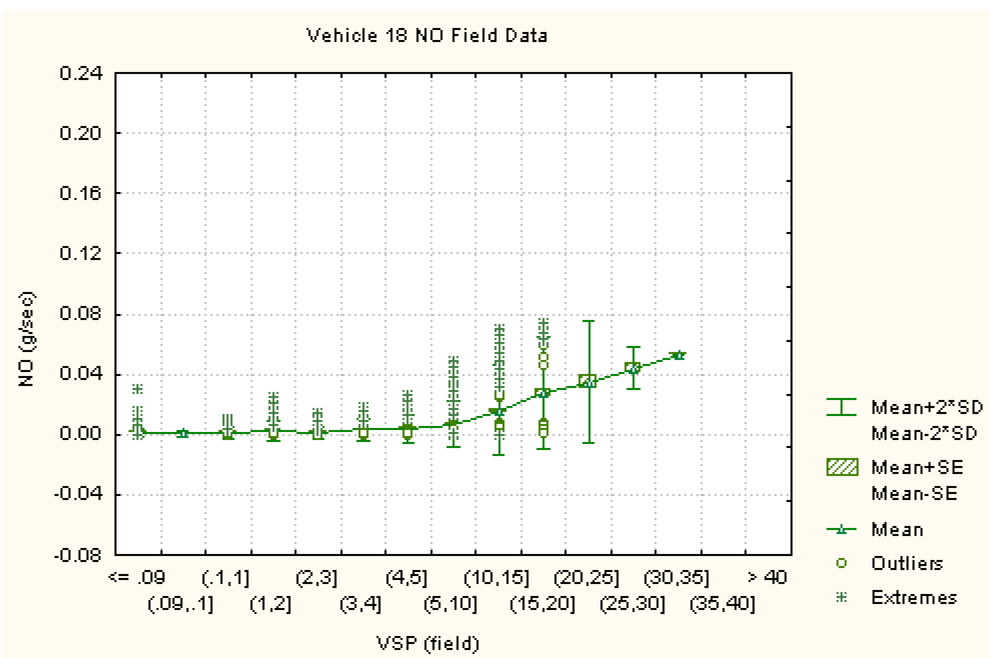

Figure 4-12. Vehicle 18 NOx emissions by VSP bin from field data (for comparison to Figure 4-6).

Numerical estimates of the mean values in each VSP bin from Figures 4-3 through 4-6 and Figures 4-9 through 4-12 are shown in Table 4-6, but differences between the measurements include differences in the fraction of time in cold start as well as other driving differences between the field and laboratory (combined FTP & US06) driving behavior. Overall emission estimates between laboratory and field data for this vehicle were generally similar, but more investigation is needed to determine if the field measurements show any bias compared with laboratory measurements and if the measurement method or the type of driving behavior caused those biases. One suggested method would be to use VSP (converted to speed)/time traces generated when the field data was collected as driving test cycles to perform in the laboratory.

Table 4-6. Emission rates (g/sec) by VSP bin for laboratory (FTP & US06) and field PEMS measurements with Vehicle 18.

VSP Bin (kW/tonne)	CO2		CO		NOx		THC	
	Lab	Field	Lab	Field	Lab	Field	Lab	Field
< 0.09	1.69	1.28	0.02	0.01	0.0021	0.0006	0.0010	0.0007
0.09 – 0.1	1.04	1.21	0.01	0.01	0.0001	0.0004	0.0013	0.0002
0.1 – 1	1.53	1.73	0.01	0.01	0.0009	0.0013	0.0007	0.0012
1 – 2	2.17	2.30	0.02	0.02	0.0034	0.0026	0.0009	0.0008
2 – 3	2.43	1.72	0.03	0.01	0.0045	0.0011	0.0018	0.0003
3 – 4	2.65	2.92	0.03	0.03	0.0034	0.0030	0.0009	0.0006
4 – 5	2.73	3.28	0.03	0.03	0.0032	0.0041	0.0015	0.0006
5 – 10	3.09	4.32	0.03	0.03	0.0043	0.0067	0.0013	0.0007
10 – 15	4.97	6.41	0.06	0.05	0.0073	0.0159	0.0009	0.0012
15 – 20	6.80	8.32	0.08	0.07	0.0167	0.0273	0.0014	0.0012
20 – 25	8.97	9.46	0.43	0.14	0.0268	0.0349	0.0045	0.0015
25 – 30	10.57	10.58	0.77	0.60	0.0463	0.0441	0.0154	0.0032
30 – 35	13.10	11.48	1.97	0.27	0.0413	0.0533	0.0267	0.0026
35 – 40	12.17	NA	2.81	NA	0.0374	NA	0.0372	NA
>40	12.54	NA	3.17	NA	0.0315	NA	0.0852	NA

4.4 PEMS FUNCTIONAL REVIEW

The PEMS method uses vehicle operation information and matches it to the emissions measurements. The emissions measurements combine the gas concentrations with exhaust flow measurements to estimate mass emissions. These mass emissions are then time adjusted to vehicle behavior (vehicle power), measured using speed and grade signals derived vehicle sensors (speed and distance) and/or global positioning system measurements.

The PEMS method uses gas concentration measurement methods similar to laboratory methods for regulated pollutants. These include non-dispersive infrared (NDIR) for CO2 and CO, and a flame ionization detector (FID) for total hydrocarbon (THC). Earlier versions of the device included an NDIR method for THC, but because a FID could be used for these measurements and shows less bias than NDIR, a FID will likely be used for future versions of the PEMS instruments. The one major difference in the laboratory methods and the PEMS was the use of a non-dispersive ultra-violet (NDUV) detector for NO and NO_2 instead of the established technique using a chemiluminescence detector. There were some operational reasons for the use of NDUV; based on the results of the initial tests and other laboratory evaluations, the method is an accurate alternative. The initial version of the PEMS measured only the major NOx component, NO, but could be adapted to measure NO_2 in addition so as to eliminate any question of bias in the measurement method. The detection limits and signal noise of these analyzers are the key factors for limiting the use of PEMS instruments for measuring high emitters and low emission vehicles. The lower detection limits of the PEMS analyzers are the same as current laboratory limits, though raw undiluted exhaust at higher emission concentrations is measured, so the method will have lower detection limits below that of certification methods that use dilute exhaust. As an example of the PEMS limits, the NOx analyzer detection limits range from 1 to

3000 ppm, which roughly translate to limits between 0.006 and 17 g/mile for light-duty vehicles. Likewise, CO and CO2 detection limits range from 50 ppm to 8% or from 0.2 to 300 g/mile for CO, and 0.3 to 500 g/mile for CO2. EPA (2002f) did not report the hydrocarbon detection limits, but the data indicate a lower detection limit of no more than 10 ppm translating to a lower detection limit of about 0.02 g/mile. Ensfield (2003) reported the upper detection limit of hydrocarbon at 10% or greater than 150 g/mile. The 'gram per mile' estimates here are very approximate and depend upon the vehicle operational modes, air-fuel ratio, and other factors. The lower limits indicate the level at which clean vehicles, such as might be found with those light-duty vehicles meeting Tier 2 and ULEV emission standards, can be measured and the upper limit provides the range at which high emitters can be measured. These measurement ranges are considerably wider than the emission standards for vehicles in operation.

One of the critical elements of the overall emissions monitoring system is the exhaust flow estimate. In the original version of the PEMS, a number of exhaust flow estimate methods were used but all relied on signals provided by the on-board computer. The methods employed either inlet air (for light-duty vehicles) or fuel (for diesel buses) flow estimates to calculate the exhaust flow, combined with the emissions gas concentrations to calculate the emissions rates. For all the vehicles tested in the original evaluation, the computer system and accompanying sensors needed to be accurate and in working order.

For the tests involving light-duty cars, exhaust flow measurements relied on a measure of the engine speed, assumptions of volumetric efficiency, and proprietary Ford estimates. The first measurement method, Type 1, relied on the current engine speed and volumetric efficiency to estimate the overall inlet air flow to the engine to calculate the exhaust flow. The second measurement method, Type 2, relied on a flow measurement using a load factor relative to exhaust flow conditions at a reference engine speed, discovered to be the rated speed of the engine. Type 3, a proprietary Ford method, was reported to be similar to Type 1 with Ford volumetric efficiencies specific to the engine speed. Table 4-1 shows the PEMS method used for each light-duty vehicle in the evaluation study.

For the diesel buses, the emission rate estimates were made using a carbon balance method where the fuel flow was recorded and associated with the measurements of all carbon species in the (CO_2 minus ambient CO_2, CO, and hydrocarbon). The emissions at any time then matches the fuel flow estimate with the exhaust species concentrations to calculate exhaust flow rates. The fuel flow measurement method appeared to work well compared to the laboratory method as reported by EPA (2002f), but reliance on the engines' computers, using a proprietary method that is likely a measure of fuel injection volume, could be subject to maintenance issues (injector wear or leakage) or other conditions unrelated to the actual exhaust flow.

The reliance of the on-board computer has been recognized as a limitation of the method, especially for measuring emissions of malfunctioning vehicles where a number of problems may be encountered. Besides a complete malfunction of the computer, individual sensors could malfunction (or, in the case of the fuel flow measurement method, leaking or deteriorating injections), engine blowby, leaking valves, and wide variability in volumetric efficiency could make overall estimates difficult because the exhaust flow could be miscalculated. The EPA (2002f) report of the initial evaluation noted that the mass airflow (MAF) sensor could be used. In the more recent models of the PEMS, an airflow measurement using a hot wire anemometer has been installed to provide a method completely independent of the on-board systems, but this next generation system has not been evaluated to date. (Ensfield, 2003) An additional exhaust flow measurement could be used directly if determined to be accurate and with sufficient response rate, or it could be used verify the calculated exhaust flow estimate.

For field activity data, one element of the PEMS may provide typical in–use behavior on different road facilities. Vehicle speed and road grade can be translated to road load or VSP, and if matched with the road facility type and average speed or speed limit might provide better typical field activity. The benefit of the PEMS could be to translate average behavior [speed, traffic counts, vehicle miles traveled (VMT)] to road load (VSP) and road load distribution across the fleet. The distribution of the VSP could be important if the emission response to VSP is nonlinear. Another difficulty in using this PEMS activity data is that the vehicle behavior will depend upon the congestion level in addition to the road facility, speed limit, or other factors. The PEMS system will need additional data gathering (road congestion by time of day and road link) to provide this type of data.

The global positioning system (GPS) may provide an alternative to the vehicles' wheel sensors for speed measurements but will certainly be used to determine road grade. In the first version of the PEMS method, EPA (Koupal, 2001 or ENVIRON, 2002) had recommended that the GPS grade (altitude) signal be (rolling) averaged over five seconds because of the noise in that signal. By averaging or filtering any signal, some specificity may be lost, making a microscale analysis more difficult. The GPS signal may be improved in future versions to provide more temporal specificity, such 1 Hz (or second-by-second) readings. In addition, many transportation planners want to be able to collect VSP distributions by road facility types (freeway, arterial, etc.); however, the data derived on earlier versions of GPS used to date have experienced difficulties matching the activity to the facility type (Maldonado, 2002). Additional work needs to be performed to match the GPS to the road facility type or link during the activity gathering and to combine that information with the links' congestion level or average speed.

4.5 SUMMARY

The PEMS method can be used to provide a wealth of vehicle activity and exhaust emissions data. The first generation of these instruments proved that overall emissions could be measured accurately in the laboratory and in the field with a self-contained portable unit. The ability and opportunity to collect more data with PEMS should more than compensate if field measurements are more variable than comparable laboratory measurements. This promises the opportunity to gather much more information than traditional laboratory methods.

Based on information to be gathered using the PEMS method, EPA plans to dramatically change the manner in which emissions are modeled. The plan calls for emissions to be modeled on the basis of instantaneous (1 Hz or second-by-second) road load and other variables as gathered by PEMS. The efficacy of the approach will depend in part on the validity of this PEMS data.

Based on the data available from an initial EPA evaluation, the PEMS method was consistent with approved laboratory methods over longer time scales than the second-by-second recorded measurements as long as several data handling issues were addressed. Therefore the PEMS method is acceptable and comparable to laboratory methods for longer than 1-second time scales until the data averaging/filtering issues are resolved. This section demonstrated that though 3-second averaging improved the demonstrated bias in short-term high power events, it did not eliminate the bias. Field and laboratory measurements with PEMS appeared to produce similar emission estimates even though driving conditions may have been significantly different between the two tests. Field data can be collected in much greater quantities than laboratory data making emission estimates more precise for each vehicle.

Some issues associated with the PEMS method or the comparison laboratory measurements were discovered with short duration high power events, which require additional work to resolve. When these high power events occurred, the PEMS method measured lower CO2 and CO emissions than laboratory comparison methods. Further work to resolve the differences should include comparing measurements under sustained high power events with those measured with short-term transient high power events.

4.6 RECOMMENDATIONS

In addition to resolving the high VSP bias shown here, several areas for additional work remain to make the PEMS method universally appropriate for vehicles in the field.

The PEMS method needs an independent means of determining exhaust flow especially for failure vehicles without relying on the engines' computers. EPA reportedly has taken delivery on such a system, but the evaluation of this latest generation system is just beginning. Once an independent means of exhaust flow is determined, the PEMS will need to be evaluated on malfunctioning (and presumably high emitting) vehicles.

The time adjustment in matching emissions to vehicle operation has not been fully described by EPA. EPA needs to determine an appropriate methodology and document how this will be accomplished with larger data sets.

This newer emission monitoring system needs to be compared for short duration high VSP conditions noted here. The response rate of any system should be measured against the response rates of other systems to determine if the PEMS method is adequate at the time scales (1 Hz) suggested by the reported data.

Heavy-duty diesel vehicles should be compared using the PEMS and chassis laboratory methods similar to the comparison conducted for light-duty vehicles. The heavy-duty systems would be expected to be similar to the light-duty systems; however, longer sampling tube lengths may be experienced with heavy-duty vehicles due to the physical dimensions of the vehicle. Longer sampling tube lengths may lead to additional peak broadening, and so should be investigated.

The global positioning system (GPS) may provide more data than were developed during the initial evaluation phase, but may also have limitations with respect to the use of the data for modeling especially at the micro-scale level. The GPS signal information was not used to evaluate typical driving conditions for each of several roadway links because it was beyond the scope of the initial work; however, the GPS could be used to place vehicles on individual transportation links to generate vehicle behavior (VSP, VSP transients, and other information) previously unavailable to emissions modeling. This data could be extremely useful to move emission modeling from using a single mean (such as average speed) behavior to model emissions to allowing distributions of activity around a single mean value. The use of distributions is important when the emissions are not proportional to the vehicle behavior (for example the primary indicator, VSP) such as is associated with command enrichment events.

Earlier work to date has noted difficulties in matching the GPS signal to individual roadway links making the activity data collected less useful. Additional work may resolve the problem of determining the functional roadway type and therefore allow activity data collection corresponding to each of several roadway types.

Also, the GPS altitude signal has not been considered by EPA to be reliable at the 1 Hz time scales. Additional work to resolve the altitude adjustment may provide better instantaneous estimates of grade, a potentially important component of the VSP calculation.

Data filtering methods may be used in conjunction with the data gathering. However, the data handling should be exercised with the understanding that some filtering may already be incorporated in the raw data with the PEMS method. Micro-scale analyses will be most sensitive to whatever data filtering methods are employed. There may be different filtering used with PEMS and laboratory methods to provide comparable estimates. Therefore combining data from different modal measurements needs additional scrutiny. This work demonstrates that the raw data from all modal methods are not comparable at all time scales (especially at 1 second) intended for emissions estimates.

Micro-analysis modeling will continue to be a challenge regardless of whether or not developments in the PEMS method can correct (or confirm the accuracy of) the peak broadening observed in the data collected during the first PEMS evaluation. With the advent of hybrid-electric vehicles and regenerating PM traps and NOx adsorbing catalysts, the emissions rates may become less dependent upon the instantaneous VSP driving conditions. Depending upon the scale (in time and space) of the modeling, it may not yet be feasible to determine individual emissions and activity rates on the scale (1 Hz) implied by the emission measurement method. However, the initial planned version of MOVES, the greenhouse gas model, is only a macro-scale model and therefore any minor bias in the PEMS system at the micro-scale level for CO2 estimates will not be critical to the overall estimates.

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Appendix A

Index of Specific Questions Raised by CRC

Overall Assessment – Model Implementation:

(1) Are there significant shortcomings under the MOVES GHG or criteria pollutant modeling proposals that bring into question whether the model should be implemented at this time (Note: release of GHG.1 is expected by Fall 2003)?

The release data for MOVES GHG is now expected for late spring 2004 and will focus primarily on a fuel/energy consumption model. Section 3 addresses specific elements associated with the implementation of MOVES-GHG, and concludes that a fuel consumption model using VSP as the primary correlating parameter will accurately estimate emissions on a given vehicle. The ENVIRON team suggested an additional correlating variable for light-duty vehicles that marginally though significantly improved the fit (change in VSP per time), though EPA contends it is correlated with with vehicle speed, the additional variable that EPA will use.

Two remaining areas of concern with implementation of the model are the amount of data available to make estimates and the use activity binning when correlating emissions to VSP or other driving activity behavior. As described in Section 2.2.4, the amount of data available as of September 2003 shows that light and heavy-duty truck data deserves attention prior to the release of the MOVES-GHG. The potential for bias when using VSP bins is discussed; a limited numbers of bins can skew the average emission rates within the bin (Section 2.5.2.2).

(2) Will MOVES GHG provide significant additional information that is not already contained or accessible by other available analytical tools?

The ENVIRON team sees the MOVES GHG model as a test case for later versions of MOVES that will incorporate regulated pollutants, as quoted in the EPA Draft Design "*Choosing a greenhouse gas model as the first implementation of MOVES allows us to start with a small scope relative to all of the considerations that go into modeling of ozone-precursor and criteria pollutants.*" Its use will likely be limited to research efforts and performing ad hoc evaluations of projects or vehicle designs. Annual and national fuel consumption estimates from MOVES GHG can be verified with fuel sales and other approaches.

2. Issues specific to MOVES GHG

The contractor is asked to provide comment on the specific elements of the proposed emission analysis plan for MOVES GHG, in the form of responses to the following questions:

Data*:*

(3) Are the data quality criteria and data sources proposed for use in developing the MOVES GHG emission rates appropriate?

Section 4, subsection 4.2.2, raises a number of concerns with 1 Hz data in that time matching, data filtering, and other data handling procedures have not been well documented or completely considered. These issues were found to have the largest effect at high VSP levels.

(4) Is the methodology proposed for weighting different data sources appropriate?

Besides the issues of data handling (time matching and data filtering) discussed in Section 4.2.2, emissions data need to be matched with the available activity discussed in Section 2.5. In Section 2.5 several data gaps have been identified.

(5) Is the proposed treatment of historical bag data appropriate?

As far as the Draft Design for MOVES, there is no distinct treatment of historic bag data; however, bag will need to be used for in-use adjustments, as discussed in Section 2.4.

(6) In addition to the data sources discussed in Chapter 6, what data sources should be used to develop emission rates for HC, CO, NO_x, PM and toxic emissions?

Besides the emissions data gaps identified in subsection 2.4.2, one area identified for improvement is the need for better activity data to match the increase sophistication of the MOVES emissions modeling approach as outlined in Section 2.5 and summarized in subsection 2.5.3.

(7) Are there publicly available test program data not included in the MOVES GHG plan that should be?

During discussions with EPA, all available data sources have been considered, but many have not been included yet because of proprietary sources or data quality concerns. This is an on-going area of concern within EPA's MOVES-development team. It is important to consider the data quality concerns when determining additional testing programs. Areas of future work are described in subsection 2.2.4. Additional testing should focus on light and heavy-duty trucks and on high emitters for regulated pollutants especially.

(8) Obviously, PEMS cannot address sec-by-sec data collection for air toxics and evaporation; what approach will make the most sense for filling in the bins for these emissions in the future? – the model structure needs to accommodate that future need.

The current development plan leaves considerations of evaporative emissions largely unidentified. For example, EPA has no plans to include evaporative emissions in MOVES GHG. Presentations by EPA in 2003 included no additional specifics for evaporative emissions beyond those associated with MOBILE6 estimates. Likewise, toxic emissions have not been characterized in the EPA Draft Design beyond lumping their estimates with other regulated pollutant hydrocarbons and particulate emissions. No specific plans for toxic emissions development has been outlined, so the current plan of applying speciation profiles to the regulated pollutants is expected.

Emission rate structure*:*

(9) Are the operating mode bins and source bins proposed for characterizing fuel consumption and CO_2, N_2O and CH_4 emissions appropriate for a wide variety of model years and technologies?

Section 2.2.3 identifies many vehicle source bins that could be defined and demonstrates that the data are not currently sufficient to address all these bins. EPA has responded that it realizes that the number of vehicle bins will be winnowed to only those necessary, and expects no more vehicle bins than are in MOBILE6. These are data gaps for light and heavy-duty trucks.

Section 2.5.2.2 discusses the issues with defining activity (operating mode) bins, and concludes that regressions can be used to better characterize emissions.

(10) Has the proposed approach (i.e., the VSP approach) been adequately justified based on the background material and analysis presented in the report?

Section 3 discusses light-duty emission and Section 2.3.3 discusses heavy-duty emissions. VSP well represents fuel consumption estimates, but other additional driving activity parameters will be necessary to model the regulated pollutants.

(11) Is it appropriate to rely on this approach in developing modeling emission rate structures to be used for modeling criteria pollutants?

Section 2.3 discusses this in great detail and suggests several additional considerations when addressing the modeling of regulated pollutants, especially for light-duty high emitters in subsection 2.2.6. The ENVIRON team identified several areas for further consideration; testing and treatment of light-duty high emitters (Sections 2.2.4 and 2.2.6), the dearth of data modeling of regulated pollutants (especially CO/PM) from heavy-duty vehicles (Sections 2.2.4 and 2.3.3), generation of sufficient activity, the use of VSP bins for emissions correlations (Section 2.5.2.2), and other concerns outlined throughout the report.

(12) Is the model structure flexible enough to handle cold-start, heavy-duty trucks as well as off-road?

Heavy-duty laboratory modal data are just becoming available and off-road data are not well developed at this point. EPA expects to use the same approach to cold start in MOVES as in MOBILE6, which is an increment of emissions for each start. This approach would work as well for heavy-duty as light-duty. So yes, the model will be flexible enough to address heavy-duty cold start.

We are very interested in the off-road emissions estimates having been heavily involved in analyzing some instrumented equipment activity data and emissions data in our "Shootout" and other work for EPA, but we did not propose to evaluate the off-road estimates at this time because EPA has not yet formulated a plan for off-road engines emissions estimates.

Approach for populating emission rates*:*

(13) Is the approach proposed for populating the MOVES GHG emission rate database using a hybrid of empirical analysis and physical model predictions appropriate?

Section 3 discusses the use of PERE. However, EPA reported in December that PERE was being used to inform the emissions empirical correlations rather than used directly in the modeling. PERE or a strictly empirical approach can be equally effective provide sufficient data is available. As discussed for light-duty in Section 3.4 and for heavy-duty Section 2.3.3, fuel consumption correlates well with the vehicle power demands over a wide range of operation.

(14) Has the proposed approach been adequately justified based on the background material and analyses presented in the report?

The EPA Draft Design report was not intended to justify the approach. The justification for the approach is the subject of the on-going analyses that EPA is performing.

(15) Does the contractor have a specific recommendation for when to apply either method?

While the PERE model is not necessary for accurately modeling emissions, it appears to work well in explaining fuel consumption. There were no specific reasons for it use however.

Physical model application*:*

(16) Is the PERE approach proposed for calibrating the physical model to empirical data appropriate?

Section 3.2.3 addresses this question directly. However, EPA reported in December that PERE was being used to inform the emissions empirical correlations rather than used directly in the modeling. PERE or a strictly empirical approach can be equally effective provide sufficient data is available.

(17) Is the application of the physical model appropriate to model those parameters or effects which have little or no supporting data, including future technologies and/or standards?

As discussed in Section 2.2.4, EPA does not, as of September 2003, have data beyond the 2001 model year. The latest December workshop did not reveal any additional considerations for future technologies.

(18) Has the proposed approach been adequately justified based on the background material and/or analysis presented in the report?

We are unsure about the specific report referenced in this question, but assume that it is the "Proof of Concept" PERE report. The justification for the proposed approach for MOVES in general and MOVES GHG specifically is an on-going concern. The report's conclusion have been shown through the data analysis to be consistent with the data available.

Emission adjustments*:*

(19) Are the adjustment factors proposed for inclusion in MOVES GHG appropriate?

Section 3.4 discusses correlating factors for MOVES GHG. The ENVIRON report suggests an additional term (d(VSP)/dt). EPA (December 2003 workshop) has chosen to include vehicle speed instead and argues that the ENVIRON term and vehicle speed correlate. As described in Section 3.2 and 3.4, the PERE adjustment for vehicle speed is justified on the basis of the engine speed term, though vehicle speed and engine speed do not necessarily correlate.

(20) Has the proposed approach been adequately justified based on the background material and/or analysis presented in the report?

We are unsure about the specific report referenced in this question, but we assumed that this was the Draft Modeling Plan, which was vague about adjustment factors. Section 2.4 addresses adjustment factors though primarily for regulated pollutants.

Uncertainty estimation*:*

(21) Is the propagation of error method proposed for quantifying uncertainty in MOVES GHG estimates appropriate? (22) Has the proposed approach been adequately justified based on the background material and/or analysis presented in the report?

Section 2.6 addresses this question. EPA's most recent work evaluating the propagation of errors approach considered only more simplified functional forms than used in MOVES, and did not use any actual emissions data for the evaluation. Once MOVES is better defined, more work is needed to determine whether the propagation or errors method is appropriate or not.

2. Issues general to the full implementation of MOVES and the Draft Design and Implementation Plan

The contractor is asked to provide input on key issues for the development of the full implementation of MOVES, in the form of responses to the following questions:

Data Availability:

(23) How many discrete emissions bins will be required under the current MOVES methodology?

The number of vehicle bins possible under the draft design document is quite large as discussed in Section 2.2.3, but EPA (December 2003) expects no more bins than were used in MOBILE6.

Section 2.5.2.2 discusses activity binning and concludes that regressions, at least for emissions as a function of VSP, better represent emissions rates than would a binning process especially for high VSP conditions.

(24) Is there an adequate breadth (varying in standard levels, vehicle types, etc.) or depth (adequate amount of data) of data on which to base the model design?

Shortfalls in data by vehicle category (based on the data available as of September 2003) are outlined in Section 2.2.4.

(25) Has EPA used an adequate sample of vehicles on which to base its model design?

Shortfalls in data by vehicle category (based on the data available as of September 2003) are outlined in Section 2.2.4. In addition, as outlined in Section 4.3, some activity levels (high VSP conditions) may be underreported depending upon the test cycles or instrumented vehicle data collected.

Emission rate structure*:*

(26) Are the operating mode bins and source bins proposed for characterizing fuel consumption and HC, CO, and NO_x emissions appropriate for a wide variety of model years and technologies?

The number of vehicle bins possible under the draft design document is quite large (discussed in Section 2.2.3), but EPA (December 2003) expects no more bins than were used in MOBILE6.

Section 2.5.2.2 discusses activity binning and concludes that regressions, at least for emissions as a function of VSP, better represent emissions rates than would a binning process, especially for high VSP conditions.

(27) Has the proposed approach (i.e., the VSP approach) been adequately justified based on the background material and analysis presented in the report for these criteria pollutants?

Section 2.2.6, Section 3.4 (for fuel consumption), and Section 4.2.2 and appendices (provides data plots) discuss the relationship of all emissions and VSP for light-duty vehicles and highlights areas where further development is warranted. Section 2.3.3 discusses these relationships for heavy-duty diesel vehicles types.

(28) How will MOVES handle the MOBILE6-related fuel factor effects on emissions (e.g., RVP effects on CO) when dealing with modern or future vehicle technologies?

It has been unclear exactly how these adjustments will be addressed. An overview of adjustment factors is provided in Section 2.4.

Vehicle Categories:

(29) Are the proposed vehicle categories (use type, truck weight splits, emission standard categories, engine and emission control technology categories) appropriate to characterize emissions for current vehicles?

In the Draft Design document, the number of vehicle types have been overestimated based on the definitions outlined (as discussed in Section 2.2.3). EPA does not expect the final categories to be more numerous than are found in MOBILE6 by combining many of the categorical definitions. Section 2.2 discusses the lack of correspondence between activity data available (especially for heavy-duty truck types) and the vehicle types defined in MOVES; however, this problem already exists with MOBILE6.

(30) For future vehicles?

As discussed in Section 2.2.4, EPA does not, as of September 2003, have data beyond the 2001 model year. The latest December workshop did not reveal any additional considerations for future technologies.

Methodologies for determining vehicle activity:

(31) Are the proposed methodologies to determine vehicle hours operated, source operating hours by roadway type, etc. adequately robust?

Section 2.5 discusses in detail the limitations of the available activity data. Section 4.3 discusses how EPA might assist local transportation planning agencies in gather necessary data especially by road type and congestion (time of day) level.

(32) On a macroscale level, will these types of estimations introduce an inappropriate amount of inaccuracy into inventory projections?

Section 2.5 outlines how activity data will be incorporated into the emission estimates. The accuracy of those estimates will depend more on using the proper activity data than on the model method itself. This will also be true for macroscale modeling where average conditions will be used to represent in-use activity.

VSP Bin Definitions:

(33) Are the proposed VSP bin definitions appropriate for all vehicle categories as defined above?

As described in Section 2.5.2.2, the ENVIRON team thinks regressions would be better than VSP binning. If VSP binning is pursued, EPA needs to determine if the current VSP bins result in a bias, and adjust the number and range of each bin accordingly.

VSP for heavy-duty trucks should be in terms of kW compared with kW/tonne for light-duty vehicles because the emissions standards for heavy-duty engines are in units of g/kW while light-duty vehicles standards are g/mile.

(34) Will the VSP approach be the ideal method to address future vehicles, specifically the various applications of hybrid technology?

Future vehicles have yet to be addressed, and no data have been developed through 2003. Throughout the ENVIRON report (such as Sections 2.2.6, 2.3.3, 3.4, 4.2.2, and 4.3), it is clear that VSP is a strong, but not the only correlating variable for all pollutants for the vehicles tested up to model years 2001. For hybrid vehicles the power demanded by the vehicle may not be associated at the same point in time when the engine generates that power. But no plans have been revealed to address that issue.

(35) Will hybrids and other technologies such as displacement on demand require a large proliferation of technologies that will need to be tracked separately?

The data have not as yet been generated to address that issue.

(36) Are the bin ranges appropriate for all criteria pollutants (HC, NO_x, CO, and PM)?

As described in Section 2.5.2.2, the ENVIRON team thinks regressions would be better than VSP binning. If VSP binning is pursued, EPA needs to determine if the current VSP bins result in a bias, and adjust the number and range of each bin accordingly.

Section 2.1.6 (and Appendices B-E) and 2.3.3 describe that EPA has not defined all variables necessary to model emissions. This is especially true with high emitter light-duty vehicles, and CO/PM emissions from heavy-duty diesel vehicles.

(37) Will the use of VSP bins require separate correction factors for each bin to address fuel type, RH, accessory load (i.e., air conditioning)?

Section 2.3 discusses that adjustments may not affect each activity region identically. Fuel and humidity are two areas where the effect should be further investigated. Accessory and air conditioning loads are incremental loads that will have a greater proportional effect at lower VSP or could be incorporated into the calculation of VSP.

Advanced Technology Vehicles:

(38) Does the MOVES design structure and implementation plan adequately account for/handle advanced and alternative technology vehicles? (39) … or for vehicles meeting future standards such as Tier 2?

The model plan has not considered and as of September 2003 had not emission tested such vehicles beyond the 2001 model year.

Model Validation:

(40) Does an appropriate plan exist to validate the model?

EPA's model plan has not yet addressed model validation.

(41) Is there assurance that this new modeling design paradigm will result in better information than previous models, especially at the macroscale inventory level?

EPA's model plan has not yet addressed model validation, and no such assurance can yet be made.

(42) Are there viable methods available to validate both the model output as well as the accuracy of changes in individual factors influencing emissions?

EPA's model plan has not yet addressed model validation. Field observations, including tunnel studies; remote-sensing measurements, and I/M program data can be used to evaluate model output and changes in factors affecting emissions.

On-Board Data (PEMS):

(43) Is on-road measurement methodology in and of itself adequate for proper model development?

The functional review in Section 4.4 indicates that the PEMS measure method has been generally verified by laboratory measurement. But the exhaust flow measurement method deserves additional work to verify the estimates of mass emissions levels under all conditions.

(44) Does the use of statistical approaches such as multivariate regression allow for sufficient differentiation of the most important variables that affect "central tendency" (i.e., fleet average) emission rates?

Section 3.4 discusses correlating factors for MOVES GHG. The ENVIRON report suggests an additional term (d(VSP)/dt). EPA (December 2003 workshop) has chosen to include vehicle speed instead and argues that the ENVIRON term and vehicle speed correlate. The regression approach is sound, if the important explanatory variables are included in the regression.

(45) If not, what data sources are required to supplement on-board data?

Under Section 4.1, we note various emission estimates that will not be gathered using the PEMS method. Under Section 4.3, we note that field measurement may not provide data gathering under sufficient vehicle behavior to provide complete estimates for the model.

(46) Have correlations between PEMS-based and dynamometer-based measurements of exhaust emissions been sufficiently demonstrated for all conditions envisaged by the MOVES model?

Under Section 4.2.1 of the report, we note that the cycle total estimates using the PEMS method can be considered equivalent to laboratory methods by using data that had been under gone QA/QC. Under Section 4.2.2, we note that modal data deserve additional evaluation especially with more recent versions of the PEMS instruments. This indicates that the data will be accurate on a macro-scale, but may need additional work to provide adequate micro-scale estimates.

(47) Can the current PEMS system be used on the old vehicles (those without computers or standardized computer read outs)?

EPA reports that it has taken delivery on a new PEMS instrument that does not rely on the vehicle's computers (see Section 4.6).

(48) If not, how will sec-by-sec data be collected and accounted for these vehicles?

Under Section 4.6, further review of these newer PEMS instruments is warranted especially with older and failing or mal-maintained vehicles.

(49) Is PEMS accuracy adequate and what confidence level is there in using PEMS data to populate different mobile source categories and constituents, (off-road, heavy-duty diesel vehicles, Tier 0 gasoline vehicles, recent model year light-duty gasoline vehicles, etc.)?

PEMS data available to date covers only functioning Tier 1 vehicles. We note in Section 4.3 that field data will be adequate to cover the estimates for the vehicle behavior driven.

(50) What are the size, scope and resource requirements necessary to ensure that the underlying database of real-world PEMS measurements is sufficiently robust to provide the capability to model these important individual effects, e.g., ambient temperature, I&M, fuel factors (particularly RVP), facility type, and fleet distribution?

This question cannot be answered until the set of bins is defined and the approaches to estimating the individual effects listed are also defined. The level of uncertainty that will be tolerated needs to be defined also in order to assess the resource requirements.

Operating Mode Generator:

(51) Is the model methodology to develop an operating mode generator (based on 12 default driving cycles) adequate to estimate the fraction of operation by VSP bin?

Section 2.4 discusses the incorporation of activity data especially the need for activity distributions (such as the distribution of VSP) by link and time of day (or congestion condition). The operating mode generators will then need to provide sufficient detail to estimate the distributions of all the important parameters (VSP, and speed, or change in VSP, and other variables) because the emissions likely respond to these variables nonlinearly. The ENVIRON team expects that EPA and State DOT's will need to begin additional activity data gathering efforts to provide reasonable activity distributions.

Vehicle Emission Standards:

(52) Does the model design accommodate the various vehicle emission standards (OBD, SFTP, varying durability levels, Cold CO, etc.)?

Section 2.1 outlines the considerations when defining vehicle bins. The model year vehicle definitions will need to consider the emission standard (OBD, SFTP, durability requirements, and cold CO levels). Both absolute emissions and the emission response will be different based on the emissions standards. Figure 2.1 showsthat the vehicle response to VSP is considerably different whether the vehicle meets its emission standard under lower VSP conditions but responds similarly at high VSP.

High emitter characterization*:*

(53) Do the options discussed in *the Draft Emission Analysis Plan for MOVES GHG* for quantifying fleet variability ensure that the full range of emitters can be accurately quantified, with regard to greenhouse gases and HC, CO, NO_x, and PM?

Section 2.1.5 and 2.1.6 describe in detail issues regarding high emitter light-duty vehicles.

(54) Does the contractor have a specific recommendation with regard to the proposed approaches?

Section 2.1.5 and 2.1.6 describe in detail issues regarding high emitter light-duty vehicles.

(55) Is IM240 test data adequate for this characterization?

Section 4.3 shows that IM-240 test data are limited to lower VSP levels. Therefore if IM-240 data are used exclusively, emissions under higher VSP conditions will not be measured.

(56) How should RSD be used or not used in this characterization?

Section 2.1.6 addresses this question.

Uncertainty characterization*:*

(57) Does the characterization of emission-based uncertainty and variability adequately address sources of uncertainty in the overall model estimates?

Section 2.6 addresses this question.

(58) What other sources of uncertainty and variability should be considered?

Section 2.6 addresses this question.

Appendix B

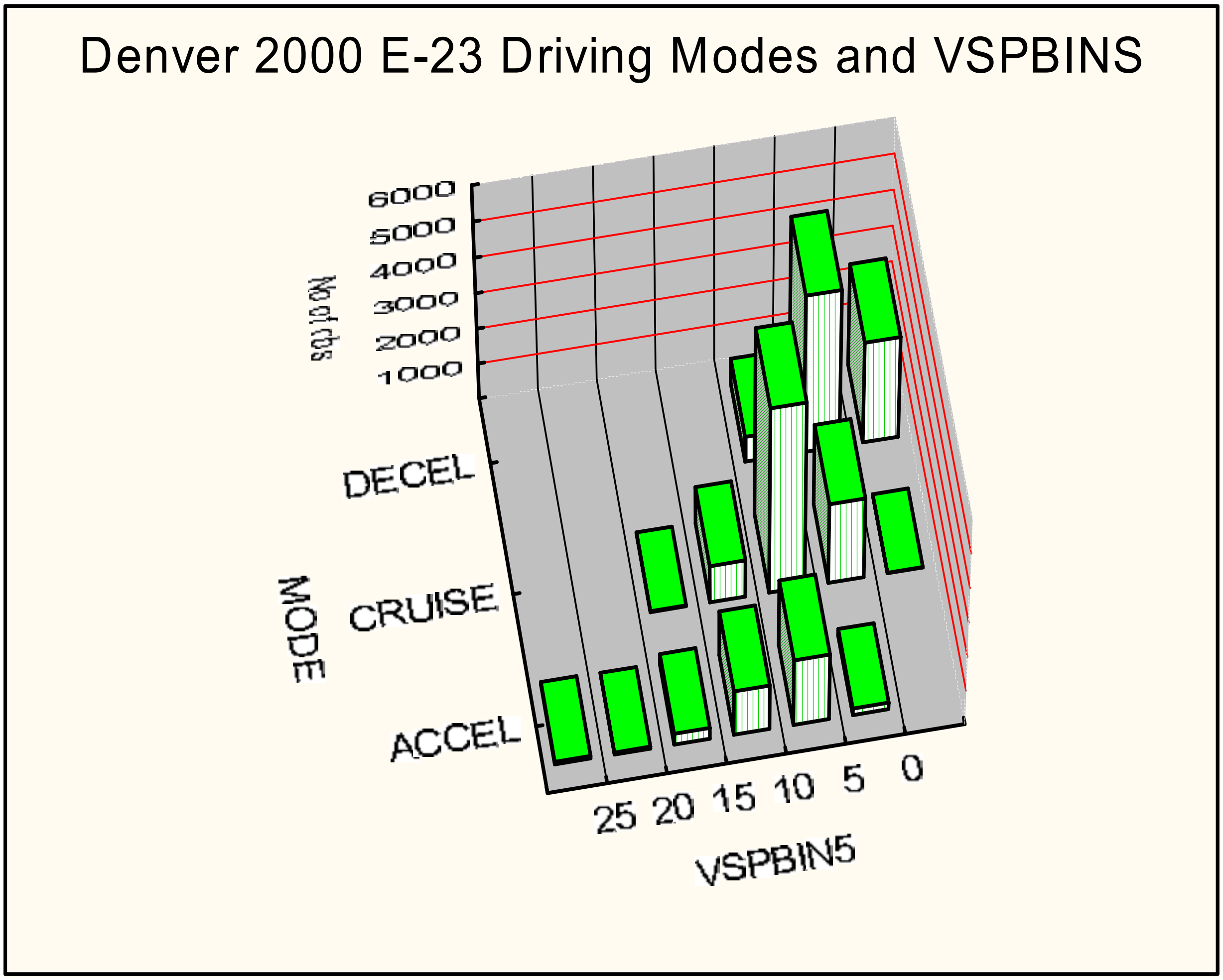
Summary of Light-Duty Vehicles

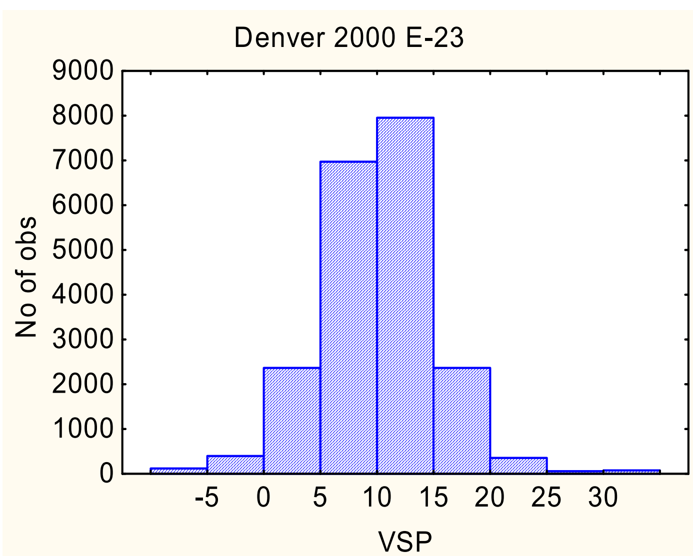
Emitter Type	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
Vehicle Number	117	229	242	250	270	284	293	334
Make	Honda	Honda	Saturn	Olds	Mercury	Honda	Plymouth	Mercury
Model	Accord	Civic LX	SL2	98	Tracer	Accord LX	Voyager	Cougar
Year	1992	1993	1994	1994	1991	1993	1994	1992
Engine Size (liters)	2.2	1.6	1.9	3.8	1.9	2.2	3	3.8
Number of Cylinders	4	4	4	6	4	4	6	6
List Weight (lbs)	3,250	2,625	2,625	3,875	2,750	3,500	5,200	3,875
Odometer (miles)	80,394	61,032	64,967	54,825	41,866	97,869	80,722	55,397
Rated Power (hp)	125	125	124	149.94	88	140	154.81	140
Catalyst								
Fuel System								
Vin Number	JHMCB767 3NC027802	JHMEG865 6PS032290	1G8ZK5577 PZ298535	1G3CX5 2L8R432 2050	3MAPM10J 1PR666392	1HGCB985 4PA007079	4TARN8JA 5RZ289086	1MEPM6041N H631291
License Number	2ZER662	3FDN303	3DWZ497	DEALER	3GKB956	N/A	3G30218	3PUG347
Vehicle Category	4	9	9	8	6	8	17	4
Tier Type	0	1	1	1	0	1	1	0
Vehicle Type	Car	car	car	car	car	car	truck	car
State	CA	CA	CA	CA	CA	CA	CA	CA
FTP Composite CO	1.37	1.28	1.66	1.24	1.07	2.70	1.28	1.16
FTP Composite HC	0.14	0.10	0.16	0.16	0.09	0.21	0.14	0.12
FTP Composite NOx	0.17	0.23	0.21	0.21	0.22	0.40	0.21	0.21
MEC 900 sec CO	10.37	12.21	11.46	12.88	30.17	17.90	31.63	13.23
MEC 900 sec HC	0.11	0.12	0.10	0.22	0.28	0.20	0.32	0.14
MEC 900 sec NOx	0.06	0.11	0.14	0.23	0.58	0.78	0.66	0.20
US06 CO	5.34	10.17	5.27	17.38	12.82	15.42	32.41	8.87
US06 HC	0.09	0.11	0.03	0.44	0.09	0.18	0.30	0.08
US06 NOx	0.09	0.11	0.13	0.27	1.16	0.91	0.74	0.08

Type	Rich	Rich	Rich	High	High	High	HIGH NO	High
Vehicle Number	113	125	136	97	205	277	298	300
Make	Nissan	Dodge	Nissan	Oldsmobile	Dodge	Volkswagen	Chevy	Chevy
Model	Sentra	Spirit	240SX	98	Caravan	Fox GL	AstroVan	Celebrity
Year	1990	1990	1993	1983	1985	1992	1990	1989
Engine Size (liters)	1.6	2.5	2.4	5	2.2	1.8	4.3	2.5
Number of Cylinders	4	4	4	8	4	4	6	4
List Weight (lbs)	2,625	3,125	3,125	4,250	2,750	2,500	3,000	3,000
Odometer (miles)	141,134	183,392	43,009	16,347	55,665	78,738	145,799	133,333
Rated Power (hp)	90	150	155	175.38	101	81	175	104.99
Catalyst								
Fuel System								
Vin Number	JNIGB22B2 LU533311	1B3XA46K9 LF809639	JNIMS36P6P W309936	1G3AN69Y6 DM812996	2BRFR21C6 FR302297	9BWGA2300 NP001155	1GNDM15Z 4LB178836	3G1AW51R XKS513810
License Number	2TLU970	2SQC440	3GYG074	989HYA (New Mex)	2PWE630	CYH813 (KY)	3GZ763	2MTD032
Vehicle Category	4	5	7	20	22	20	23	20
Tier Type	0	0	0	0	0	0	0	0
Vehicle Type	car	car	car	car	truck	car	truck	car
State	CA	CA	CA	49	49	49	CA	CA
FTP Composite CO	10.69	12.58	6.58	162.58	105.79	45.82	2.20	126.52
FTP Composite HC	0.43	0.50	0.26	7.79	8.37	2.80	0.79	7.88
FTP Composite NOx	0.22	0.46	0.29	0.23	0.44	1.08	6.37	0.50
MEC 900 sec CO	10.44	77.82	28.08	189.15	78.80	17.95	24.75	118.43
MEC 900 sec HC	0.34	1.79	0.32	3.60	4.82	0.93	0.58	10.13
MEC 900 sec NOx	0.50	0.86	0.16	0.23	0.58	1.12	3.40	0.84
US06 CO	15.70	203.83	30.58	N/A	102.77	18.80	28.49	124.10
US06 HC	0.69	3.65	0.23	N/A	5.25	1.49	0.48	6.58
US06 NOx	0.41	0.99	0.16	N/A	0.64	1.84	2.68	0.88

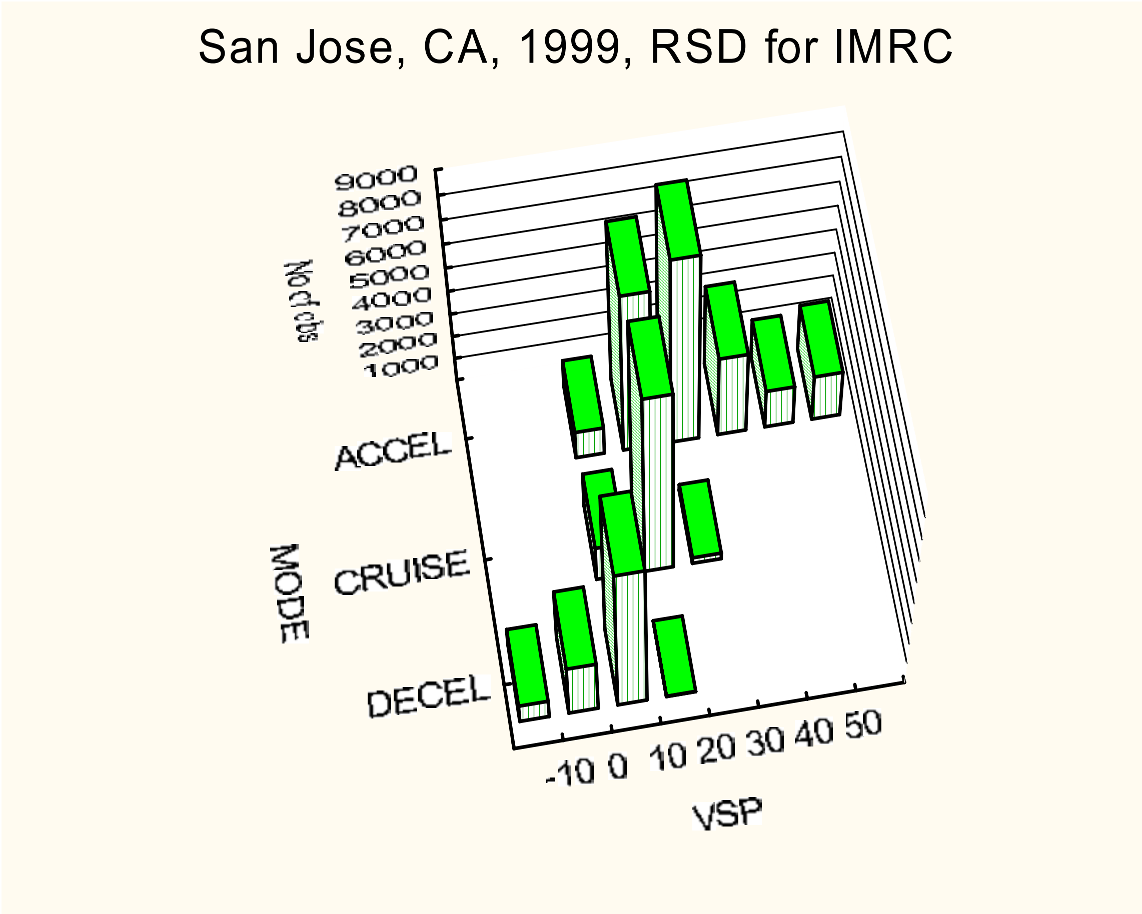
Appendix C

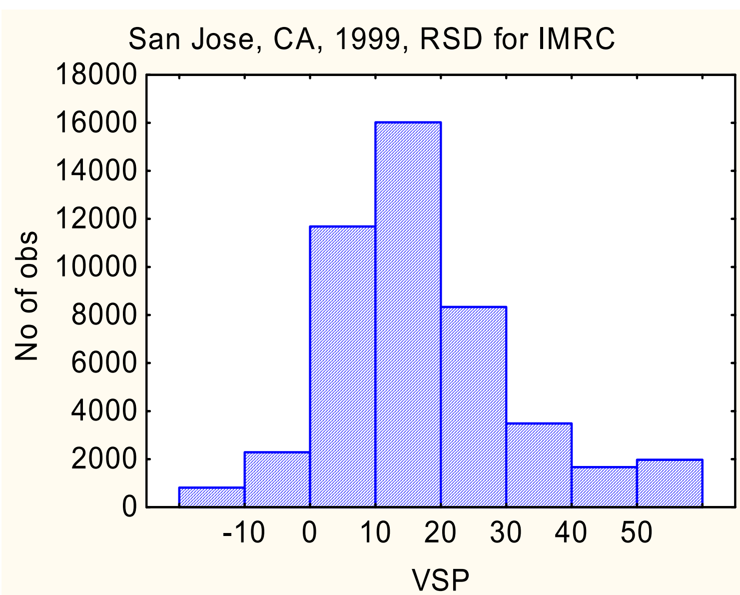
VSP and Driving Mode Distributions for Remote Sensing Sites





Remote Sensing VSP and Driving Mode Distribution at Denver 2000 E-23; an Ideal Remote Sensing Site

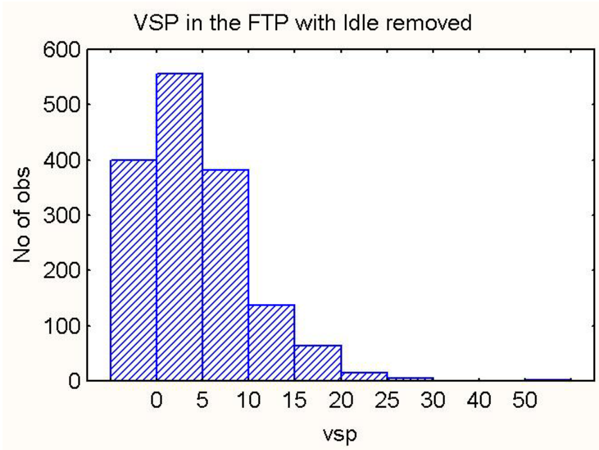


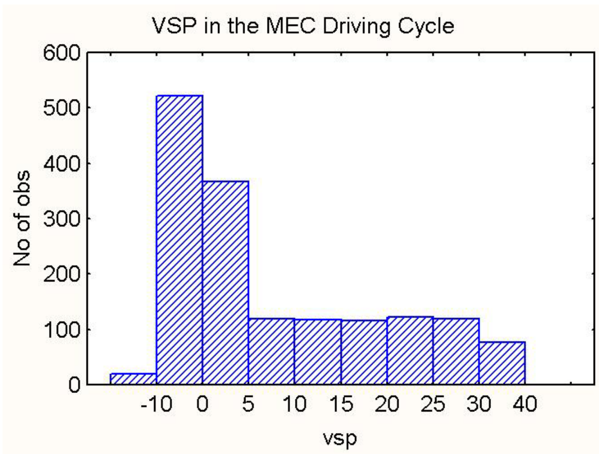


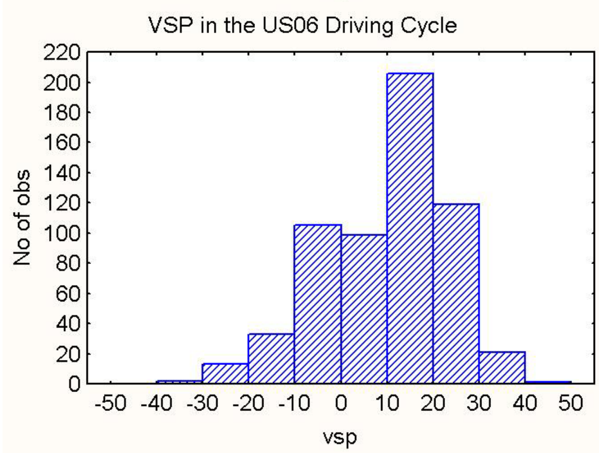
San Jose, CA, remote sensing for the Inspection Maintenance Review Committee in 1999; a high speed, high volume remote sensing site.

Appendix D

Histograms of VSP for Driving Cycles used in NCHRP 25-11


VSP in the FTP with Idle removed
No of obs
0
100
200
300
400
500
600
0 5 10 15 20 25 30 40 50
vsp

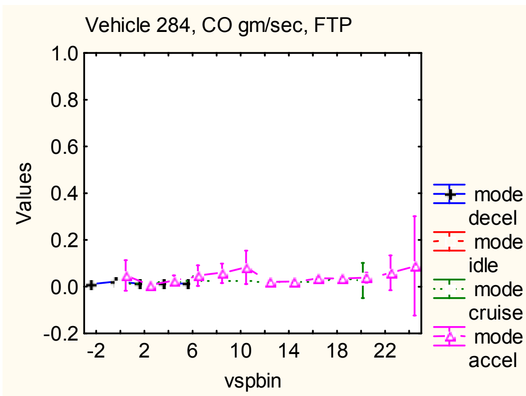

VSP in the MEC Driving Cycle
No of obs
0
100
200
300
400
500
600
-10 0 5 10 15 20 25 30 40
vsp

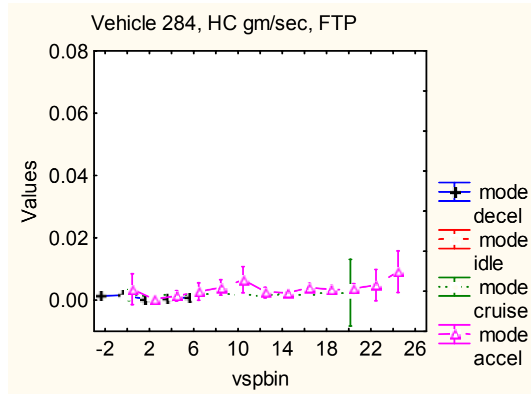

VSP in the US06 Driving Cycle
No of obs
0
20
40
60
80
100
120
140
160
180
200
220
-50 -40 -30 -20 -10 0 10 20 30 40 50
vsp

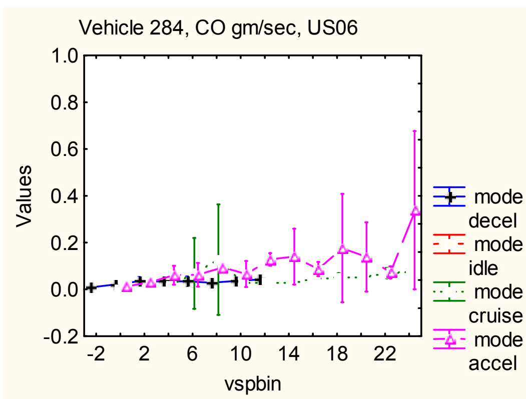
Appendix E

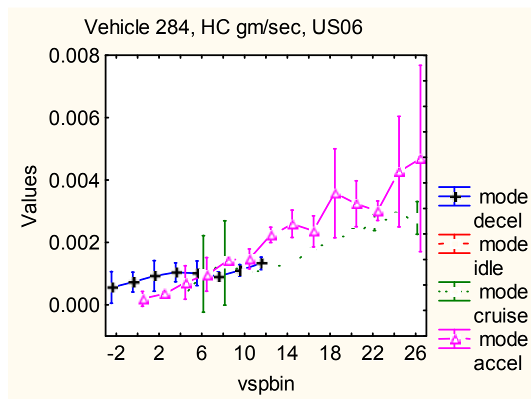
Gram/Mile Emissions for Selected Vehicles

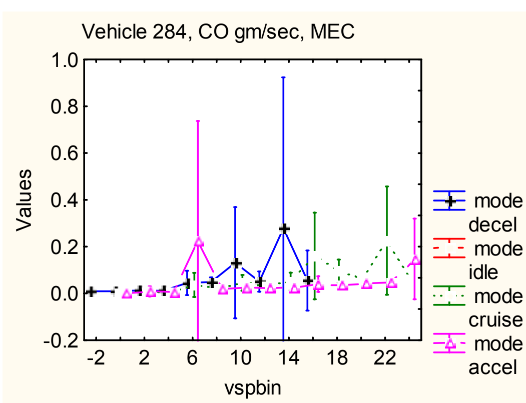
Vehicle 284 is a Tier 1 normal emitter. Although its CO emissions variability increased with more extreme driving, 95% of readings in any mode are < 1 gm/sec, in any VSPBIN less than 24 kW/t, in any of the cycles. Although HC emissions variability increased with more extreme driving, 95% of readings in any mode are < 8 mg/sec, in any VSPBIN < 24 kW/t, in any of the cycles.

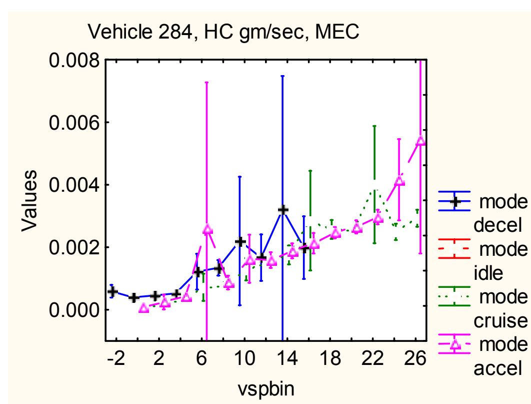




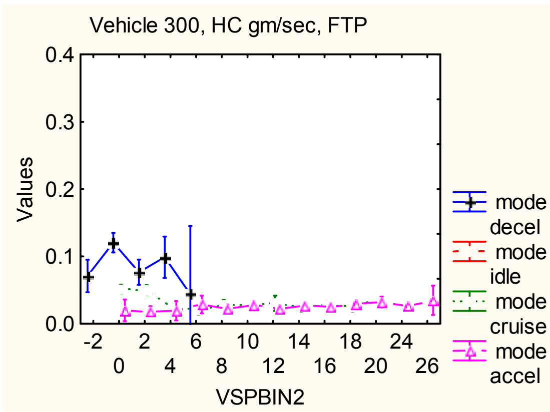


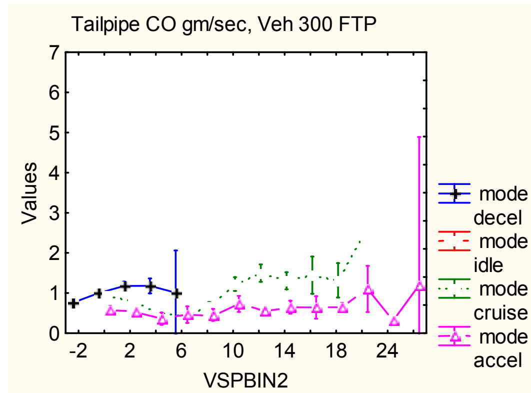


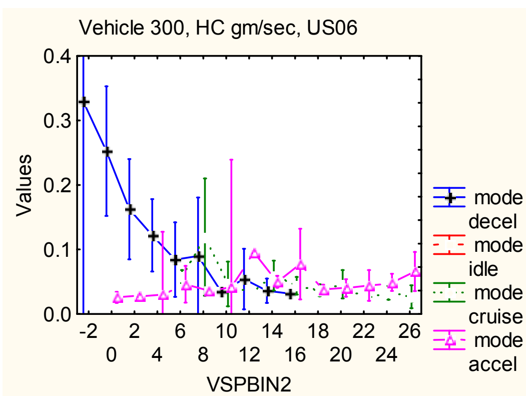


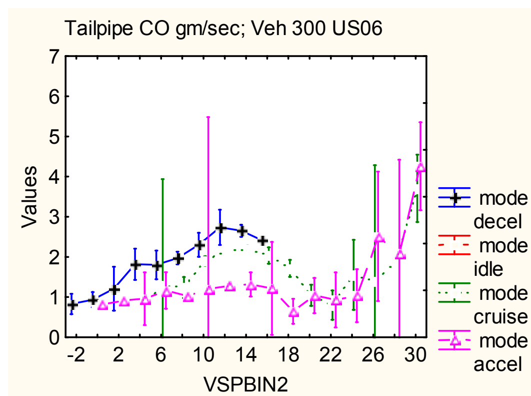


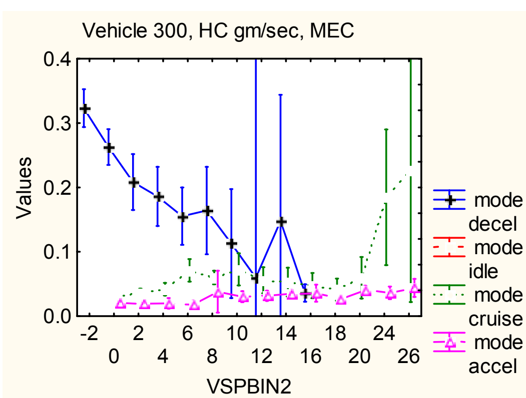
Vehicle 300 had very high CO and HC. It is a Tier 0 car. As the driving got more extreme, Vehicle 300 emits more HC during deceleration. CO emissions in the MEC and US06 cycles peak in the 10 to 16 VSP range during deceleration and cruise driving modes. One explanation for this behavior may be that vehicle 300 continued to inject fuel into the engine during deceleration and when insufficient air was available for oxidizing the fuel to CO, it was emitted as HC.

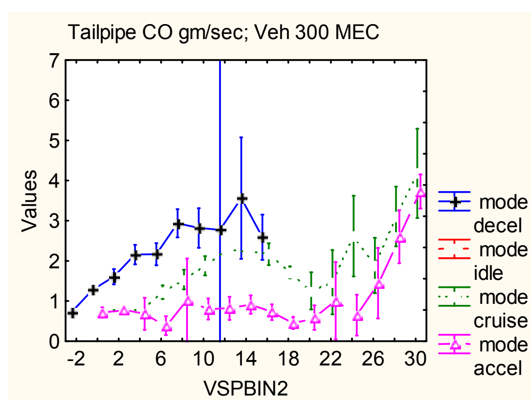




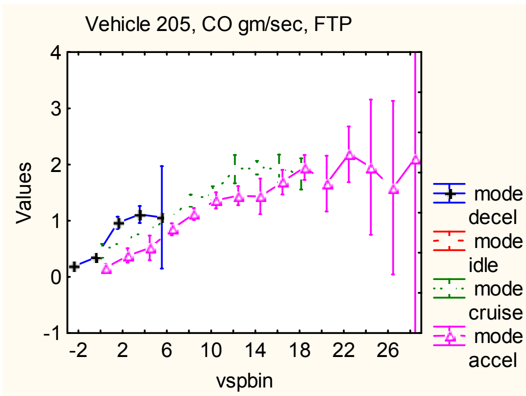


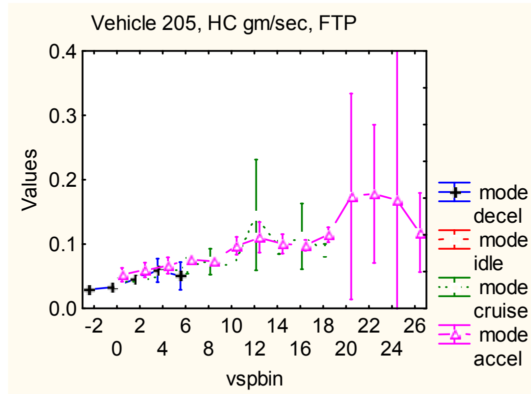


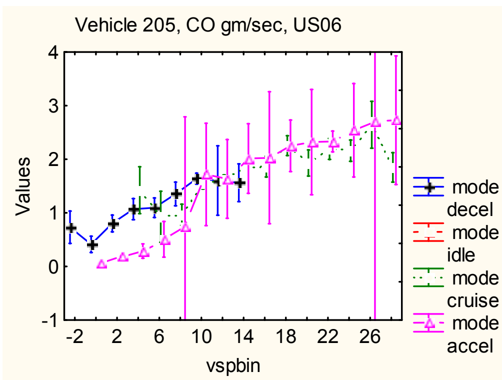


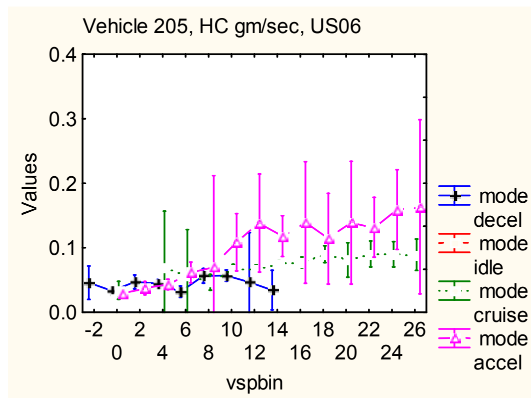


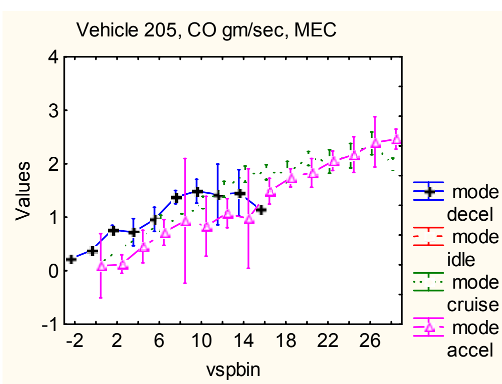
Vehicle 205 was a high CO and HC Tier 0 vehicle. The CO and HC gm/sec variation within a VSPBIN increased during acceleration especially in the more aggressive driving cycles.

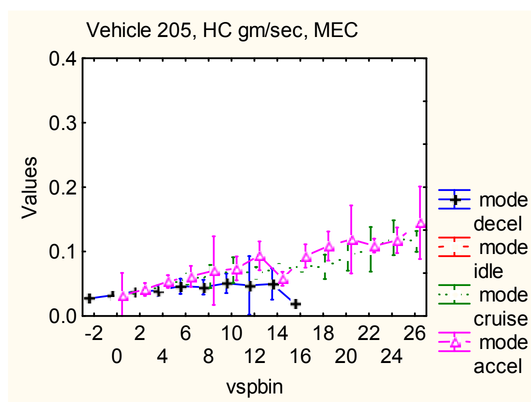




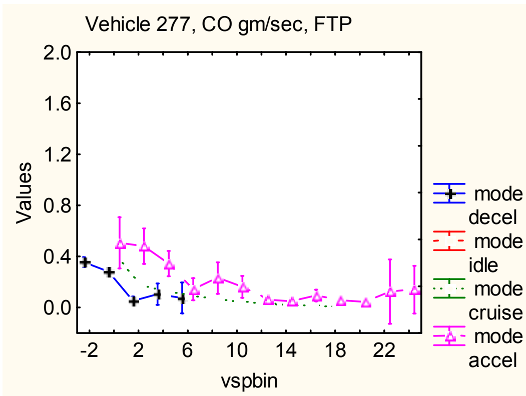


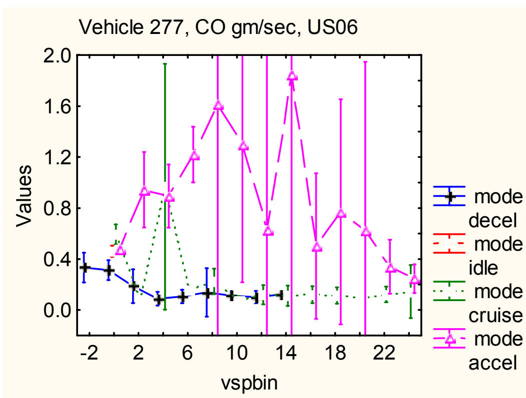


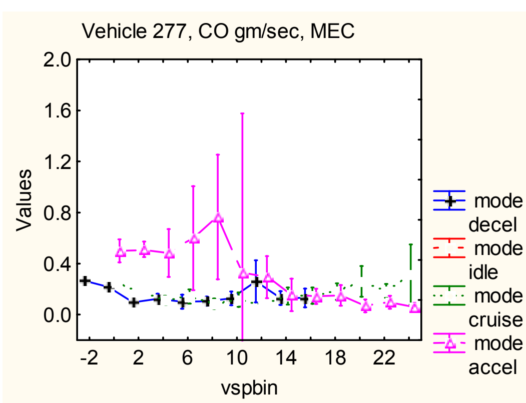




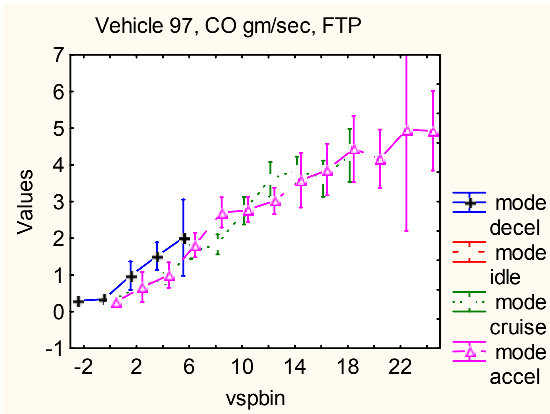
Vehicle 277 was a high CO, Tier 0 vehicle. Vehicle 277 emitted more CO during acceleration, and the amount, and the variability, increased markedly with the severity of the cycle.

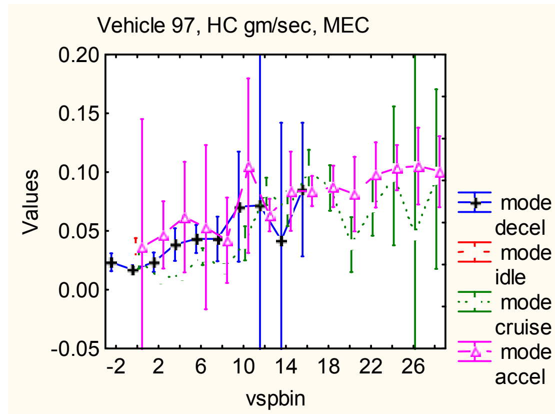


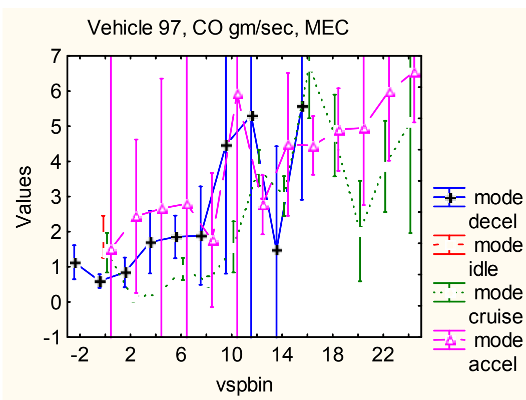


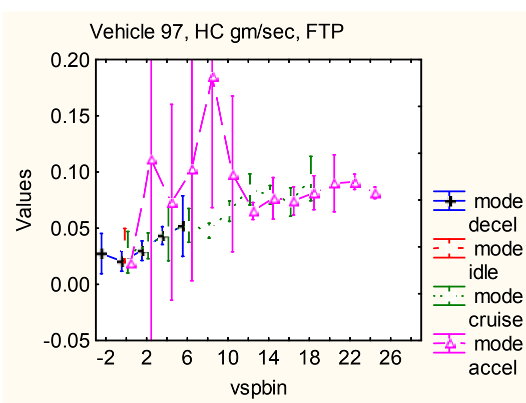


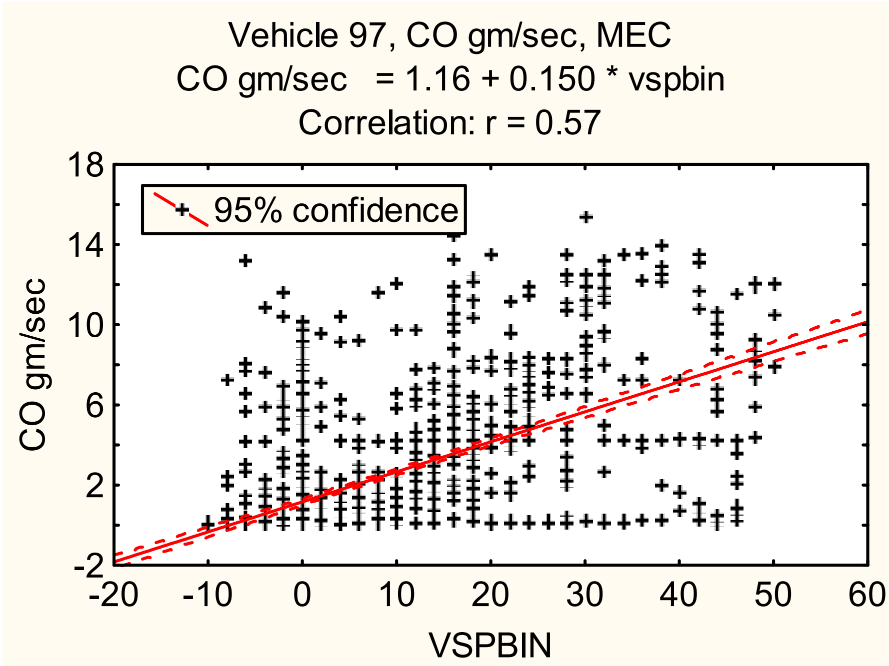
Vehicle 97 was a high CO, Tier 0 vehicle. Vehicle 97 was not run on the US06 cycle. Vehicle 97 CO became extremely variable in all modes in the MEC driving cycle. Vehicle 97 HC became extremely variable in all modes in both the FTP and MEC driving cycle. Use of a BINS based on VSP and “a”*d(VSP)/dt can reduce the amount of scatter in both CO and HC for Vehicle 97 in the MEC. “a” is best between 0.15-0.25.



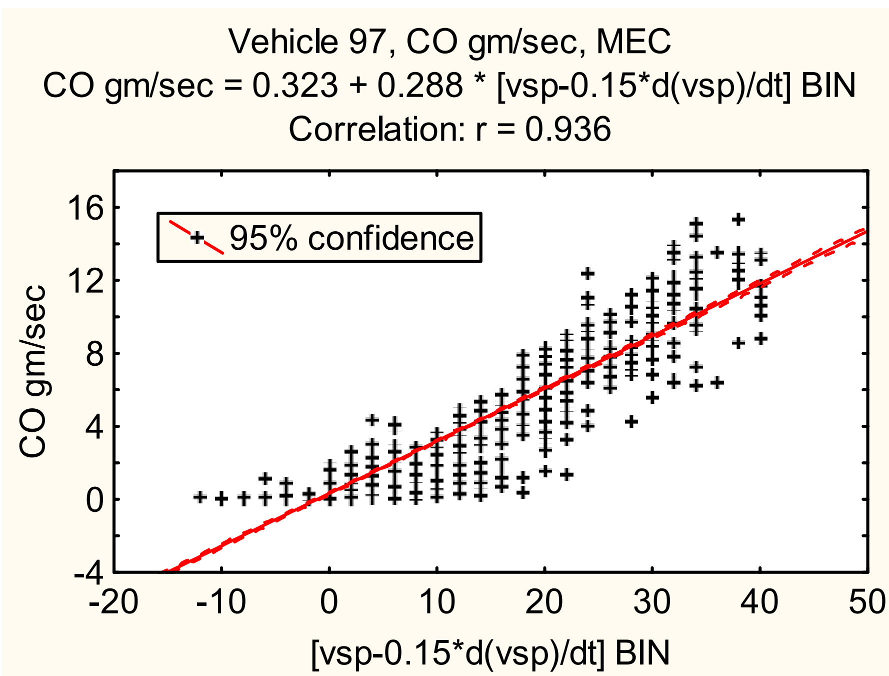




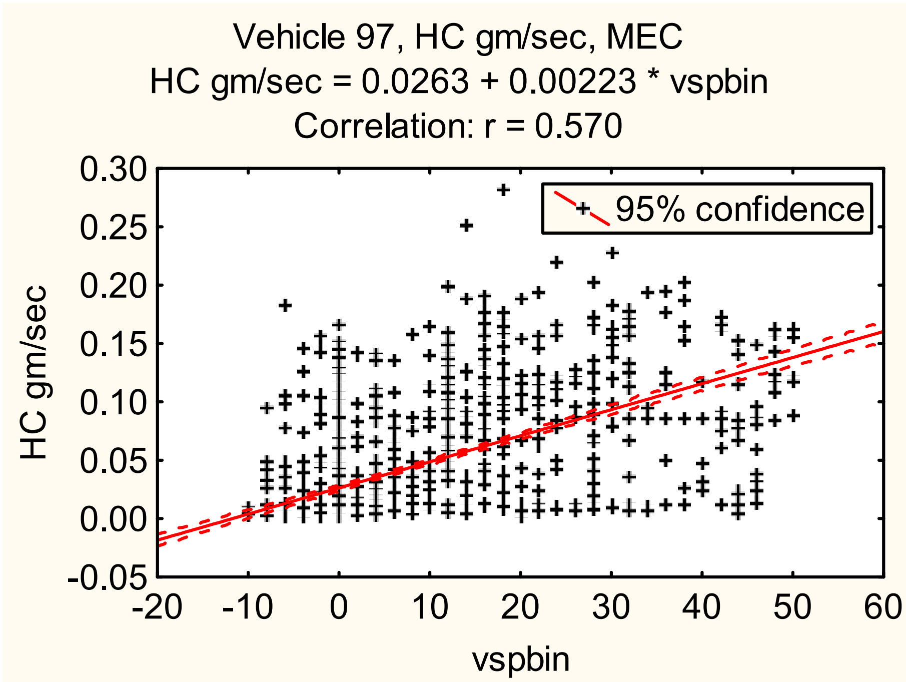


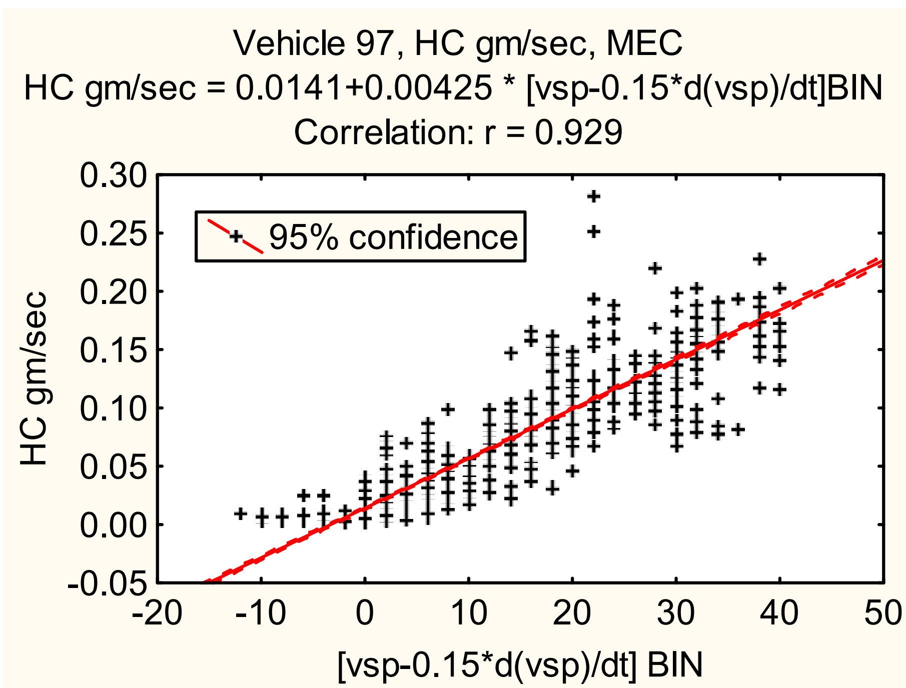


Vehicle 97, CO gm/sec, MEC
CO gm/sec = 1.16 + 0.150 * vspbin
Correlation: r = 0.57
95% confidence
CO gm/sec
VSPBIN
18
14
10
6
2
-2
-20
-10
0
10
20
30
40
50
60



Vehicle 97, CO gm/sec, MEC
CO gm/sec = 0.323 + 0.288 * [vsp-0.15*d(vsp)/dt] BIN
Correlation: r = 0.936
95% confidence
CO gm/sec
[vsp-0.15*d(vsp)/dt] BIN
16
12
8
4
0
-4
-20
-10
0
10
20
30
40
50


Vehicle 97, HC gm/sec, MEC
HC gm/sec = 0.0263 + 0.00223 * vspbin
Correlation: r = 0.570
95% confidence
HC gm/sec
vspbin
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-20
-10
0
10
20
30
40
50
60


Vehicle 97, HC gm/sec, MEC
HC gm/sec = 0.0141+0.00425 * [vsp-0.15*d(vsp)/dt]BIN
Correlation: r = 0.929
95% confidence
HC gm/sec
[vsp-0.15*d(vsp)/dt] BIN
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-20
-10
0
10
20
30
40
50

Appendix F

Analysis Plots for Vehicles 1, 2, and 16

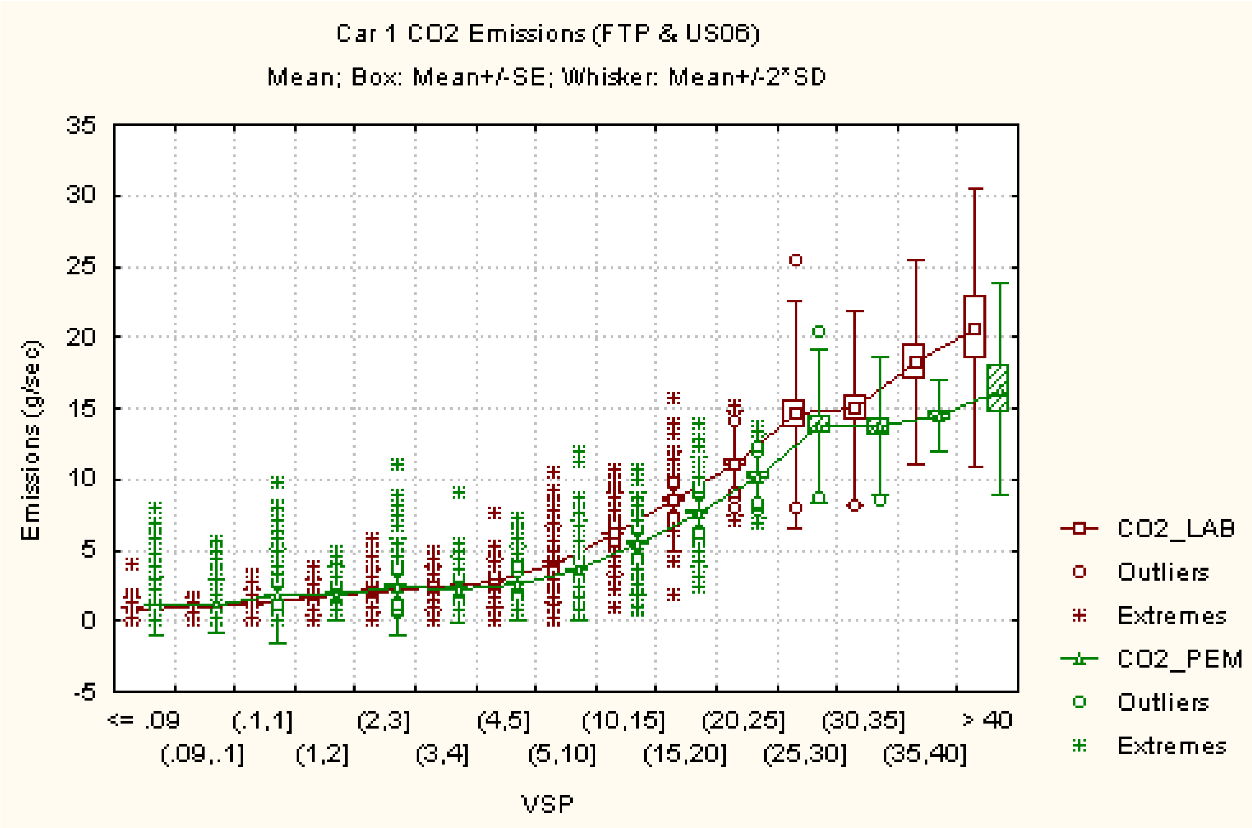


Figure F-1. Vehicle 1 CO2 emissions by VSP bin.

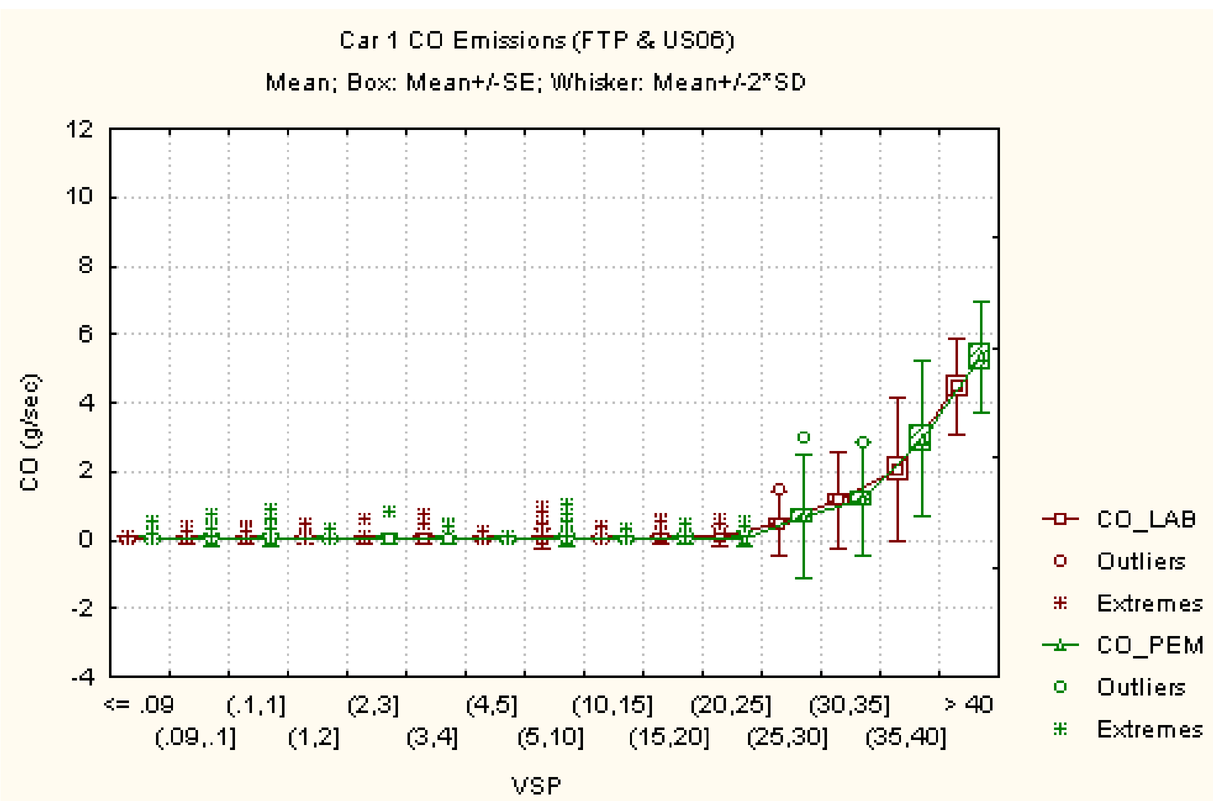


Figure F-2. Vehicle 1 CO emissions by VSP bin.

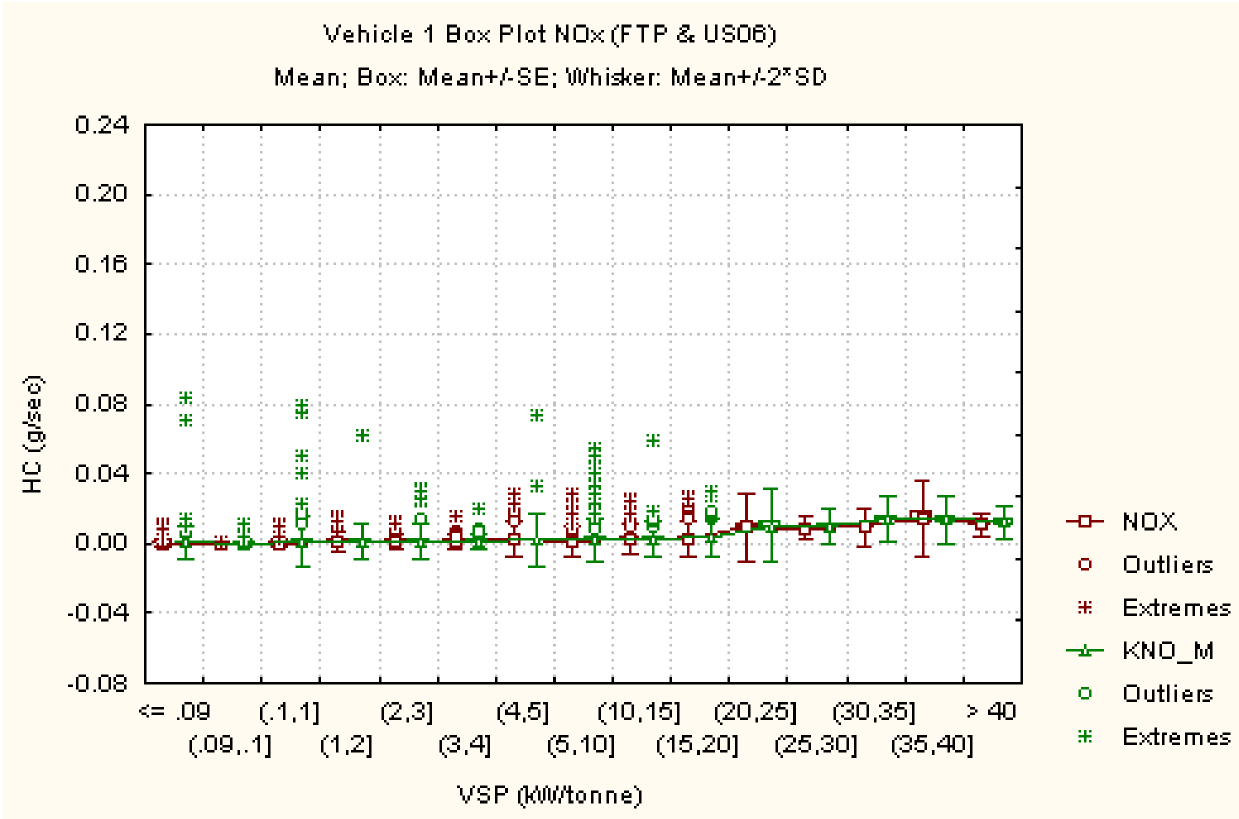


Figure F-3. Vehicle 1 NOx (NO) emissions by VSP bin.

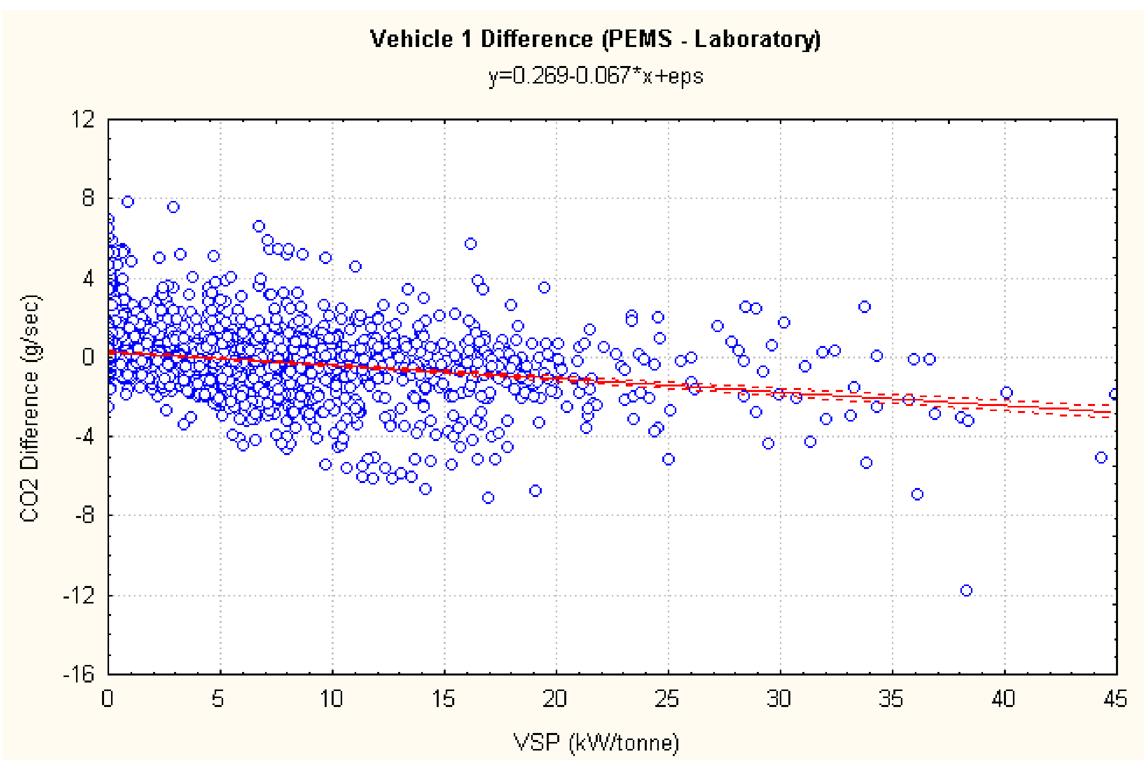


Figure F-4. Vehicle 1 CO2 emissions: PEMS – EPA modal.

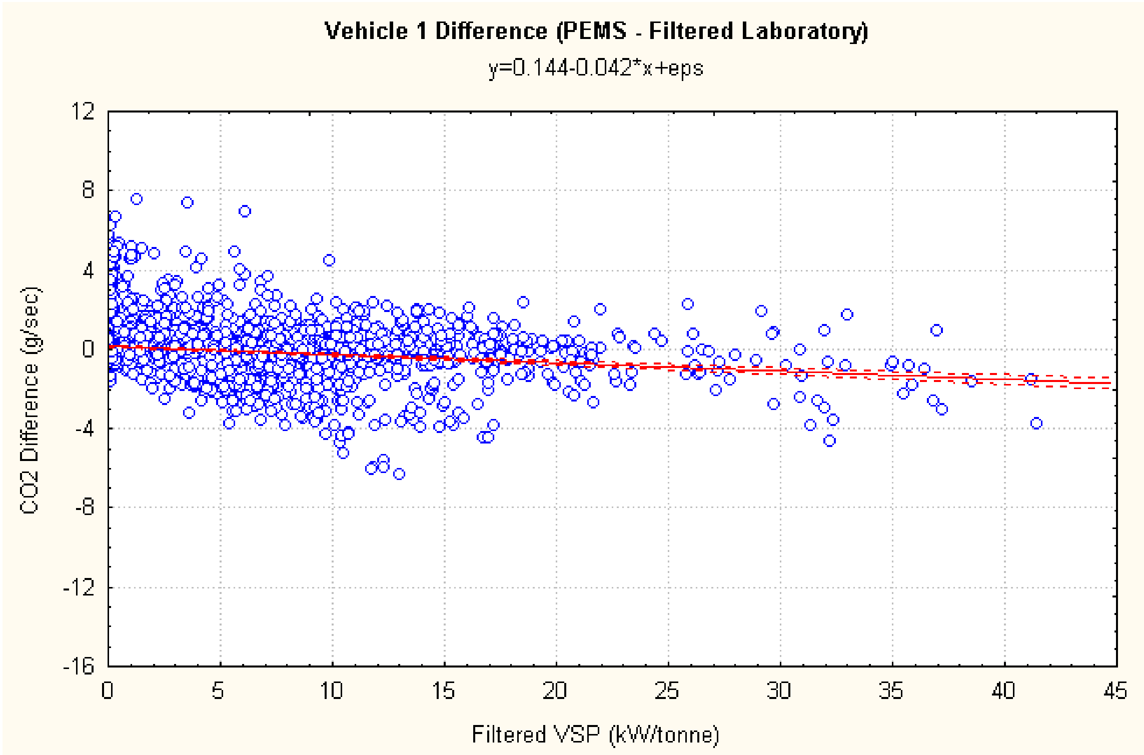


Figure F-5. Vehicle 1 CO2 emissions: PEMS (raw) – EPA modal (3 second rolling average).

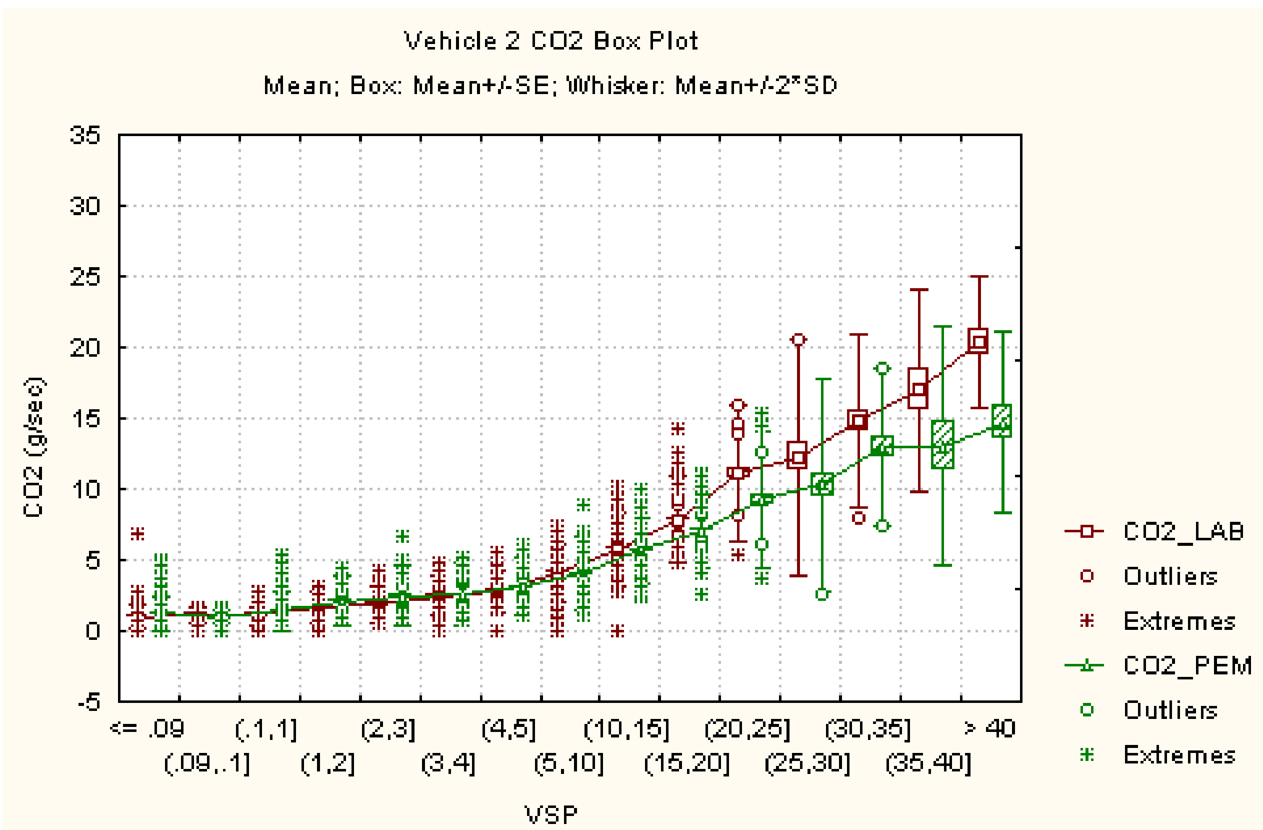


Figure F-6. Vehicle 2 CO2 emissions by VSP bin.

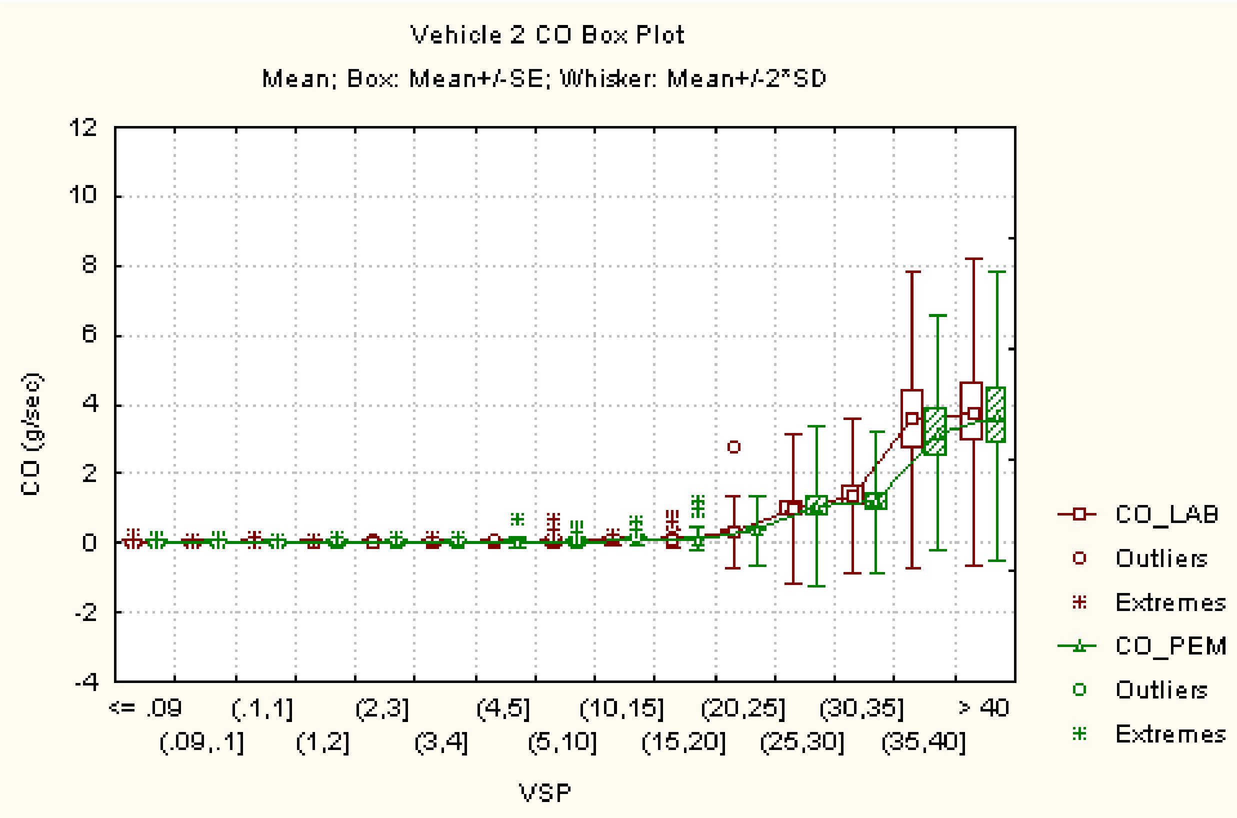


Figure F-7. Vehicle 2 CO emissions by VSP bin.

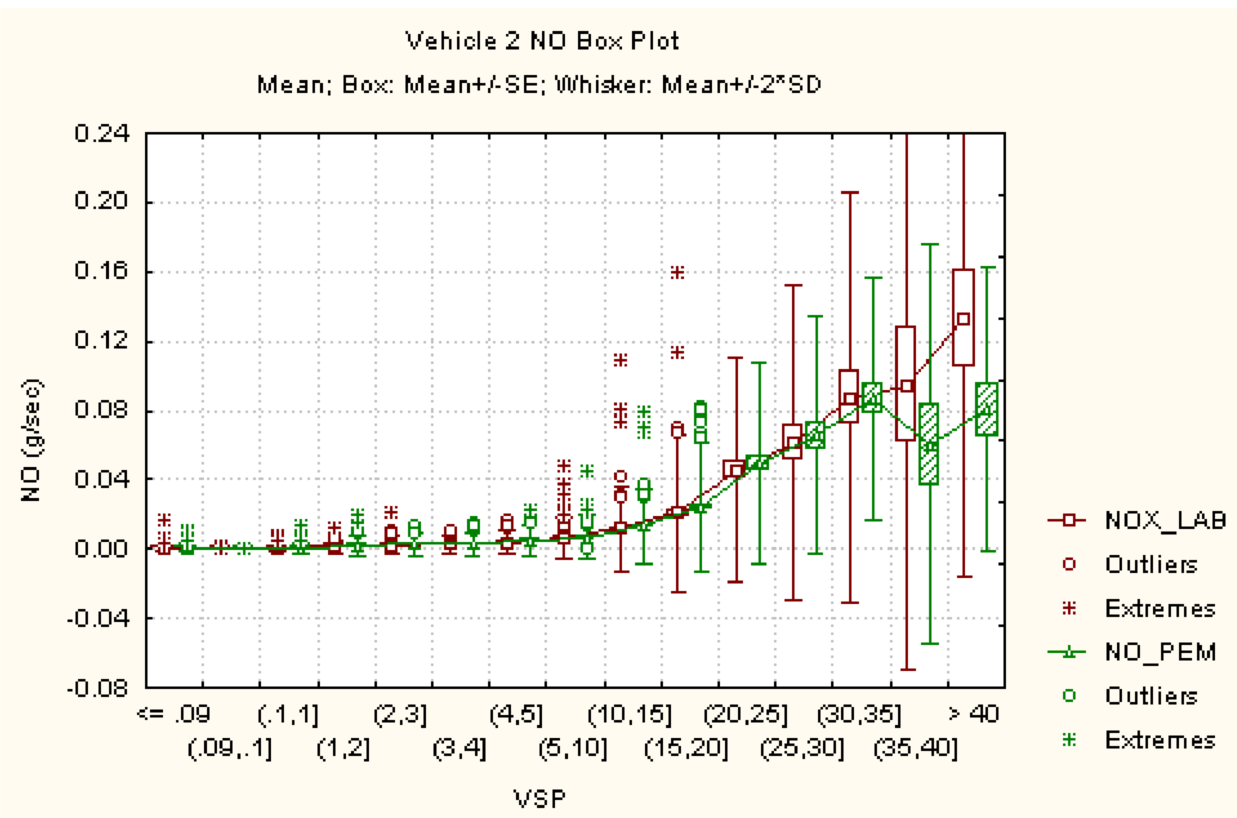


Figure F-8. Vehicle 2 NOx (NO) emissions by VSP bin.

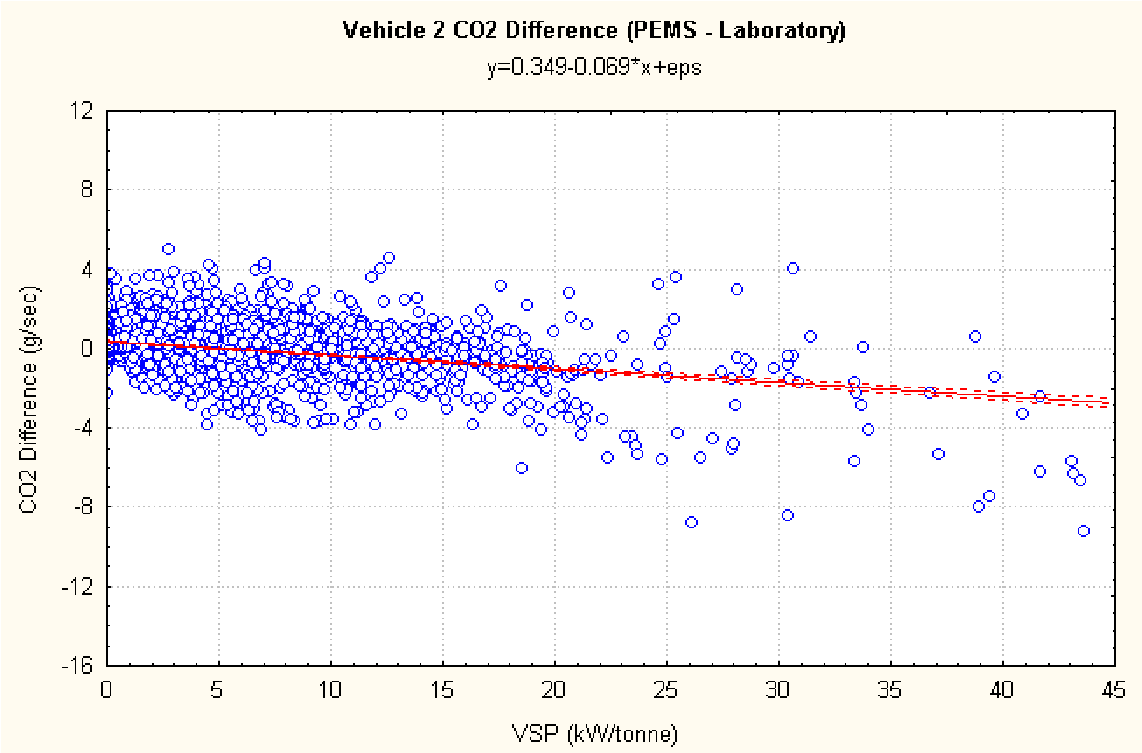


Figure F-9. Vehicle 2 CO2 emissions: PEMS – EPA modal.

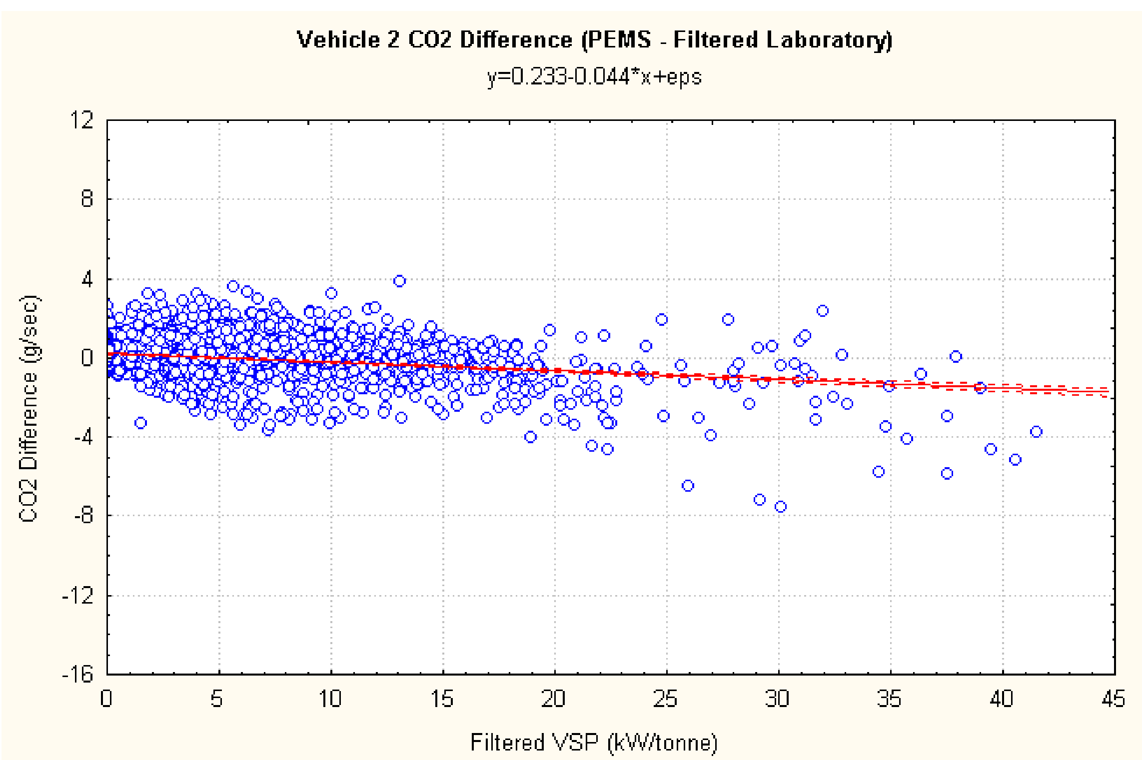


Figure F-10. Vehicle 2 CO2 emissions: PEMS (raw) – EPA modal (3 second rolling average).

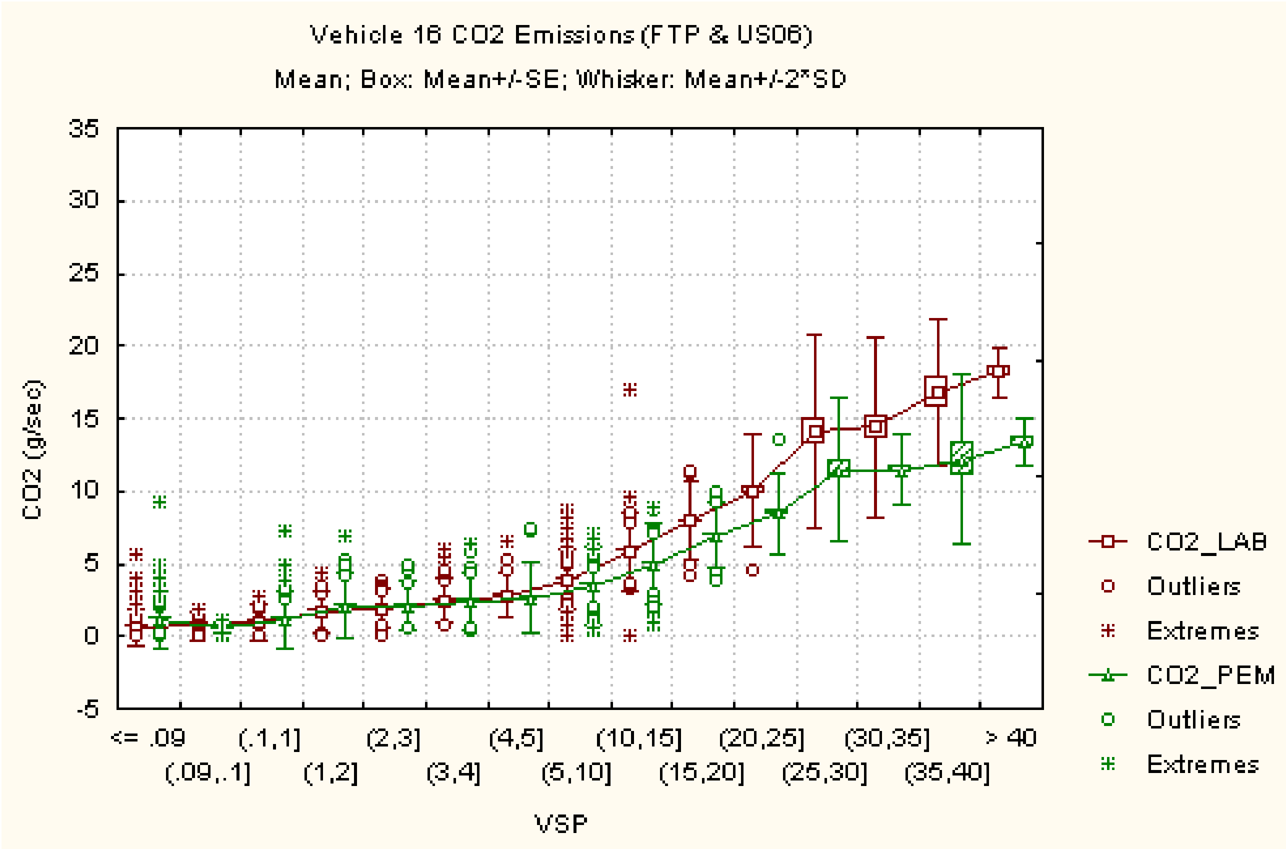


Figure F-11. Vehicle 16 CO2 emissions by VSP bin.

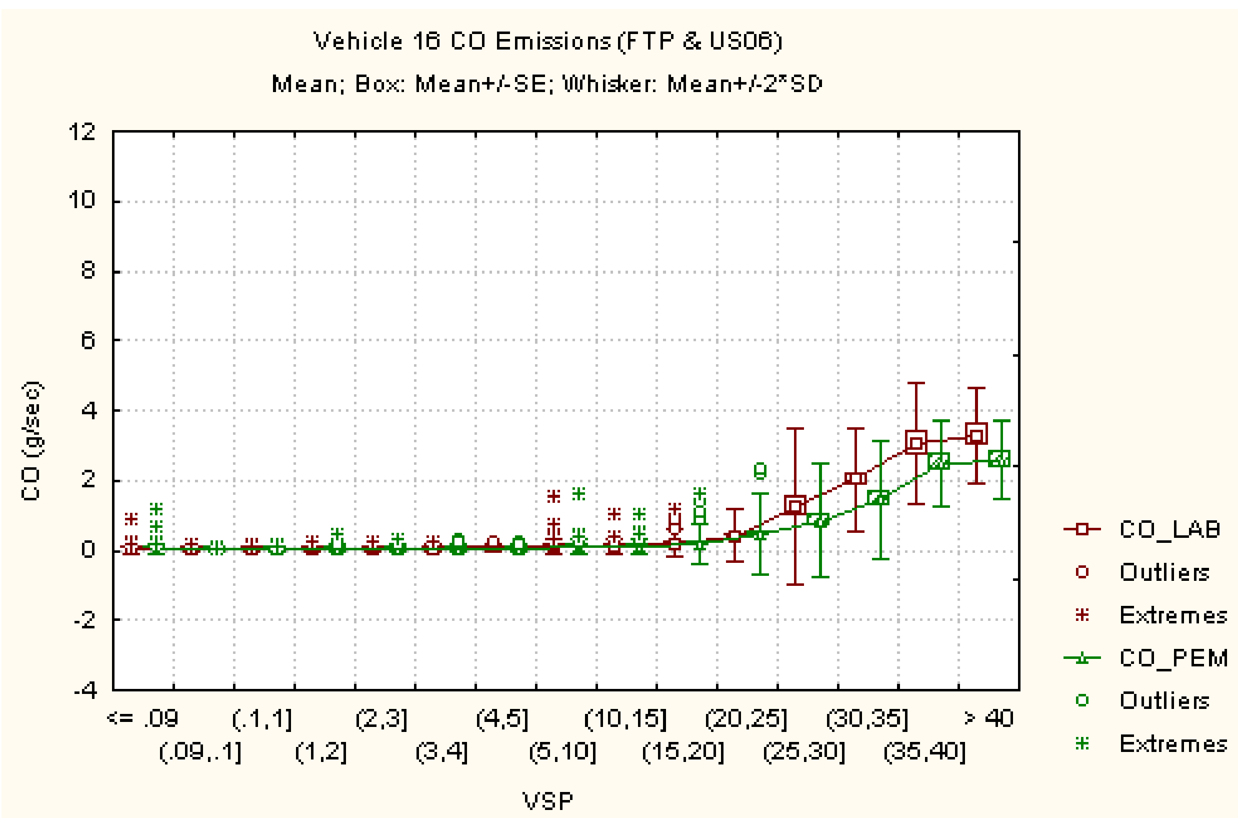


Figure F-12. Vehicle 16 CO emissions by VSP bin.

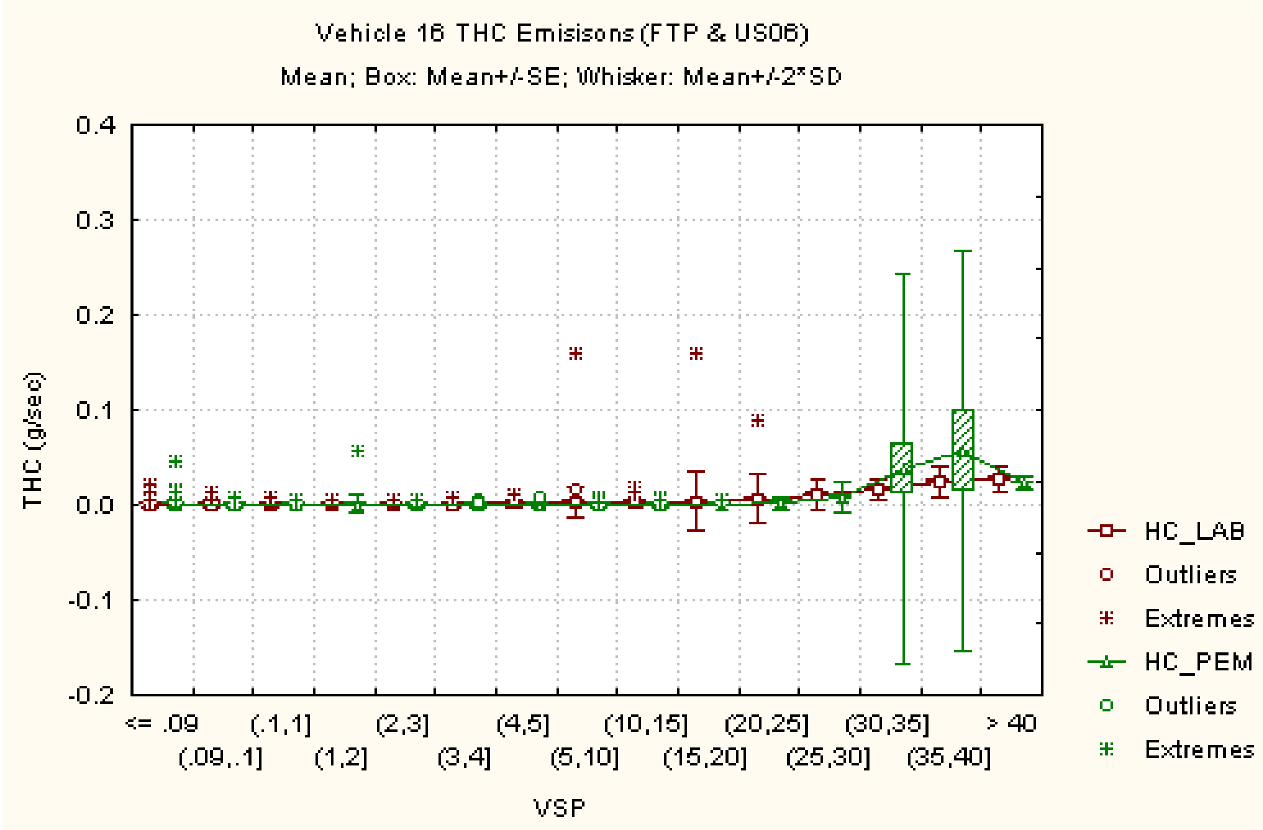


Figure F-13. Vehicle 16 THC emissions by VSP bin.

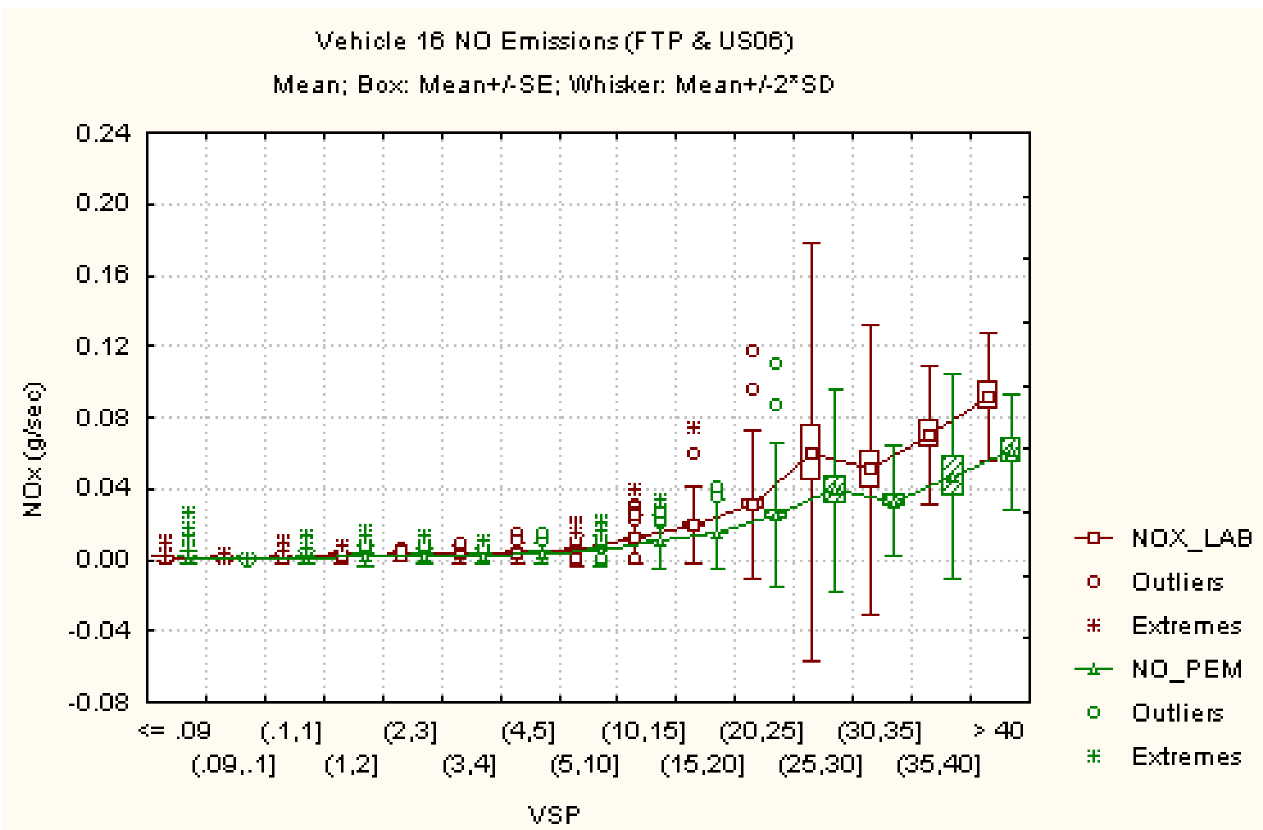


Figure F-14. Vehicle 16 NOx (NO) emissions by VSP bin.

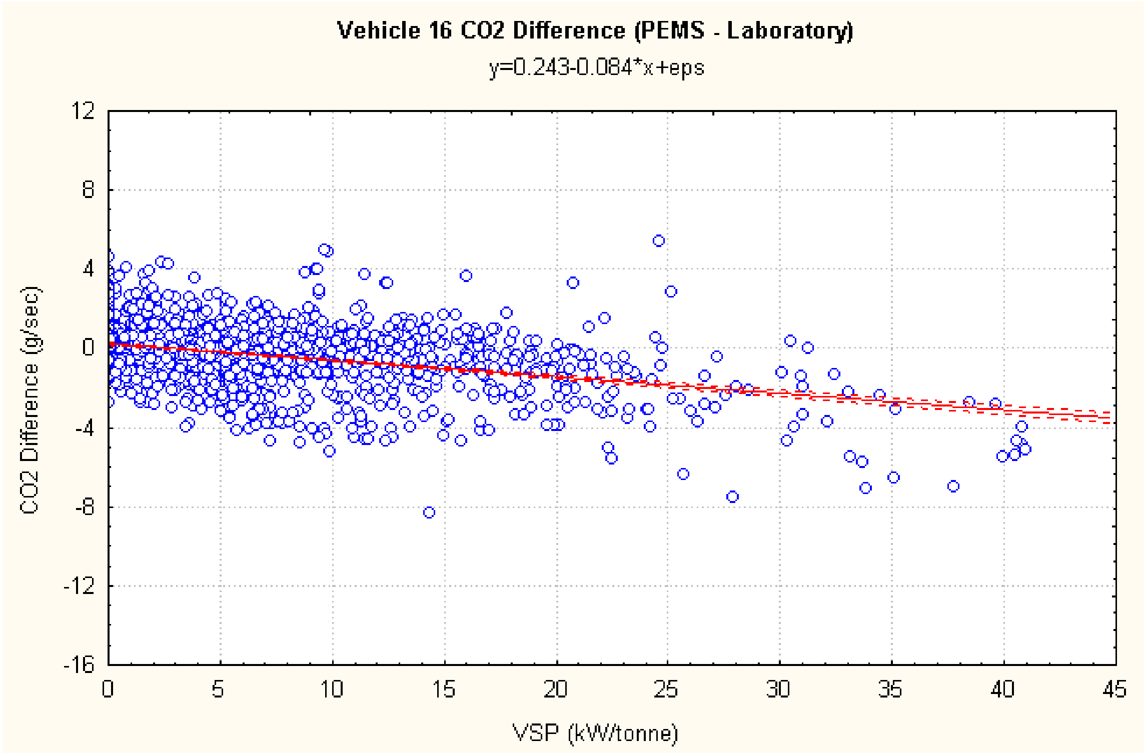


Figure F-15. Vehicle 16 CO2 emissions: PEMS – EPA modal.

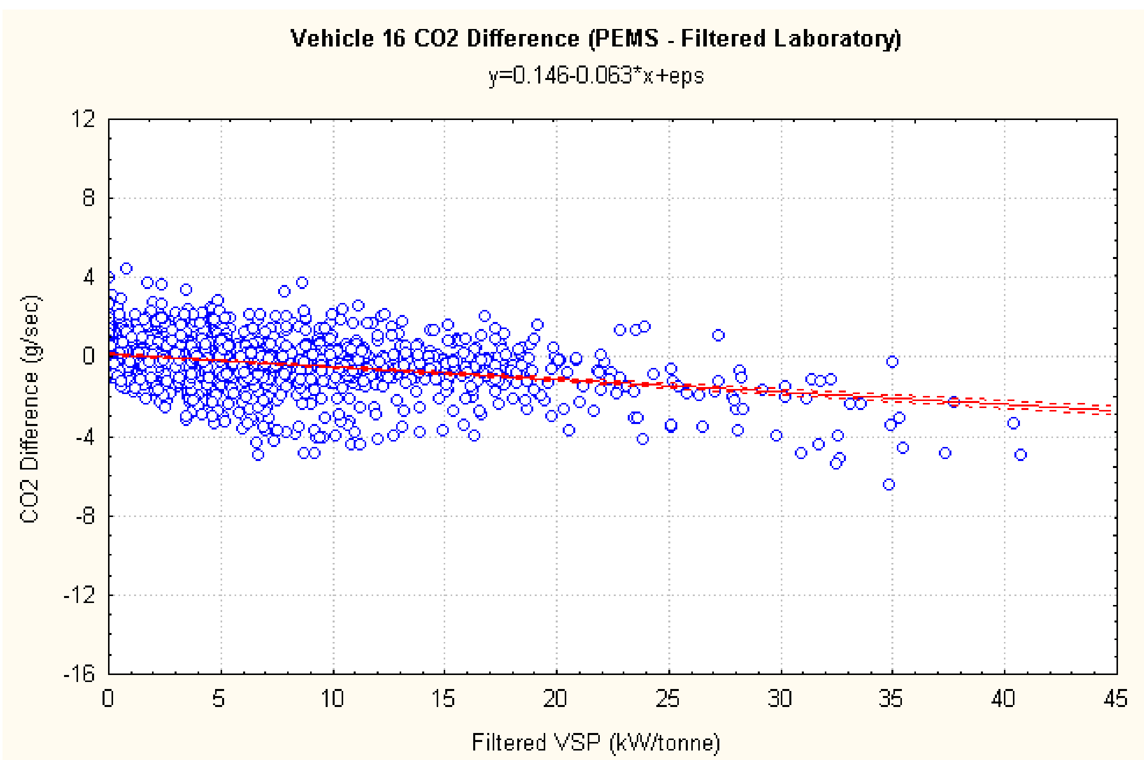


Figure F-16. Vehicle 16 CO2 emissions: PEMS (raw) – EPA modal (3 second rolling average).