ABSTRACT

ZHAI, HAIBO. Regional On-Road Mobile Source Emissions Characterization for Conventional and Alternative Vehicle Technologies. (Under the direction of Dr. H. Christopher Frey and Dr. Nagui M. Rouphail).

The development of alternative fuels and vehicle technologies could lead to reductions in emissions and reduced reliance on petroleum fuels. The objectives of this study are to evaluate the potential reductions in air pollutant emissions associated with real world operation of future vehicles that utilize advanced fuels or technologies in comparison to conventional vehicles. For light duty vehicles, the fuels or energy sources considered are gasoline, ethanol (E85), compressed natural gas, hydrogen, and electricity. The technologies considered are internal combustion engines, hybrids, fuel cell, and electric vehicles. For heavy duty vehicles, biodiesel is considered for trucks and compressed natural gas is considered for buses, in addition to conventional diesel fuels and technologies. For most of the vehicle fuel and technology combinations, modal fuel use and emissions models were developed based on available second-by-second portable emission measurement system (PEMS) or dynamometer tailpipe emissions data.

Link-based average emission rates were estimated for different link-based average speeds and roadway types based upon second-by-second speed profiles measured on the road as part as previous PEMS measurements, supplemented by data from the literature in some cases. The results enable comparison of different vehicle technologies and fuels for each of several link-based average speeds and roadway facility types.

The linked-based emissions factors are coupled with the outputs of a transportation demand model for emission inventory estimation and assessment of the potential changes in emissions that can accrue from technology and fuel use. The results will provide support for decision making regarding alternative fuels, adoption of new vehicle technologies, and air quality management.

Regional On-Road Mobile Source Emissions Characterization for Conventional and Alternative Vehicle Technologies

by

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DEDICATION

This dissertation is dedicated to my family for love and support.

BIOGRAPHY

Haibo Zhai was born in Lianshui, Jiangsu Province in the southeastern China. He obtained his Bachelor of Engineering in water and wastewater engineering from Xi'an University of Technology in 1999 and Master of Engineering in environmental engineering from Tongji University in 2002. After his graduation, he worked as an environmental engineer at an environmental science & technology consultant company in Shanghai, China for half a year. In November 2002, he went to the University of Hong Kong for graduate research study in coastal water quality data-driven modeling and forecasting. In August 2004, he joined in the Department of Civil, Construction and Environmental Engineering at North Carolina State University, Raleigh, North Carolina, pursuing his PhD degree, where his research mainly focused on vehicle fuel use, emission factor and emission inventory modeling to evaluate the effects of the changes of fuel, vehicle technology, and land use on regional mobile source emissions.

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PART I INTRODUCTION

1.1 Introduction

In 2006, national on-road vehicles emitted 54,100 thousand short tons carbon monoxide (CO), 6,600 thousand short tons nitrogen oxides (NO_x), and 3,850 thousand short tons volatile organic compounds (VOC) (EPA, 2007). Highway vehicles contributed about 54% of CO, 36% of NO_x and 22% of VOC emissions in the U.S. national emission inventory. Vehicles were the largest contributors for national CO and NO_x emissions and the second largest for VOC emissions (EPA, 2007). Motor vehicles, as a major source of air pollution, also contribute to adverse health effects. For example, CO decreases the delivery of oxygen; NO_x reduces the efficacy of lung function and respiratory system; and NO_x and VOC are the main precursors of ground-level ozone, which can decrease the ability of the lung to perform its normal functions (Schwela and Zali, 1999, Nicolopoulou-Stamati *et al*., 2005). As transportation-related mobile source emissions lead to adverse effects, it is important to accurately estimate on-road emissions and investigate the spatial characteristics and quantity of emissions for air quality modeling and exposure assessment.

Vehicles with alternative fuel and propulsion system may make up more than 27% of the total new light-duty vehicle sales in 2030. These include flex-fuel vehicles, hybrid electric vehicles, advanced diesel, electric and fuel cell vehicles (EIA, 2007). This next generation of vehicles can play an important role in reducing emissions. On a fuel life-cycle basis, ethanol dedicated vehicles, electric vehicles, and fuel-cell vehicles can reduce greenhouse gas (GHG) emissions by over 40% (Wang, 1999). Spark ignition engines and fuel-cell vehicles powered by cellulosic ethanol and solar hydrogen (for fuel-cell vehicles only) can reduce GHG emissions by over 80% (Wang, 1999). Compressed natural gas

(CNG) can offer offers carbon dioxide emission reductions of up to 30% (Lave *et al*., 2000). In the near future, hybrid gasoline-electric vehicles will likely become the dominant vehicle platform in the near future as hybrid electric vehicles can reduce gasoline consumption and GHG emissions by 30% to 50% (Romm, 2006).

Land development shapes travel behavior; thus, land use may affect the location, magnitude, temporal patterns, and speciation of emissions. An integrated land use and transportation study in the Sacramento estimated reductions in vehicle miles of travel (VMT) and emissions of CO, NO_x and particulate matter (PM) by 5% to 7%, compared to a future base scenario for a 20-year time horizon (Rodier *et al.*, 2002). Land use strategies therefore play an important part of a regional air quality management strategy. Smart growth is based on land use patterns that are compact, transit-oriented, walkable, bicycle-friendly, and include mixed-use development with a range of housing choices. Over a long-time horizon, smart growth strategies may significantly influence the quantity and location of emissions from on-road mobile sources, as a result of reduced demand for travel.

Vehicle emissions models are often coupled with transportation models for air quality management. Most macroscopic transportation demand and land use models such as TransCAD (TranCAD, 2005), TranPlan (TranPlan, 2005) or TRANUS (Modelistica, 2005) produce as output average link speed and link VMT by vehicle and road class. These values are subsequently entered into emissions models such as MOBILE6 (EPA, 2003) to produce link and network-wide emissions. Recent research using Portable Emission Monitoring Systems (PEMS) indicates that emissions are not directly proportional to VMT, but are episodic in nature, with high emissions events coinciding with periods of high acceleration and speed (Unal *et al.*, 2003, Frey *et al.*, 2001, Frey *et al.*, 2003). In essence, emissions during a trip depend on the instantaneous vehicle engine load, which is represented by the second-by-second speed profile. In order to integrate the outputs from transportation and emission models, it is useful to quantify the relationship between real world vehicle activities and the average speed on a roadway.

The highway emission factors model, MOBILE6, is currently used to address a wide variety of air pollution modeling needs such as development of emission inventories and assessment of emissions control strategies (EPA, 2003). Compared to previous versions, MOBILE6 is based on new and improved data and a better understanding of vehicle emission processes. However, its basic emission rates are derived from standard driving cycles. Some driving cycles on different facility types were developed to adjust the basic emission rates according to speed ranges. However, these driving cycles may not be sufficiently representative of real-world traffic conditions at a link level. Also, the effects of road grade on emissions are not reflected in these driving cycles. There is only one cycle each to represent driving on local roadways and freeway ramps. MOBILE6 does not distinguish between on-ramp versus off-ramp emissions. These can be significantly different due to their very different driving modes. In MOBILE6, CO_2 emission factors are estimated according to a mass balance on carbon in the fuel based on fuel economy performance estimates (EPA, 2003). It can not be adjusted by any other factor. However, vehicle fuel economy is allowed to vary with speed (Davis *et al*., 2007). Finally, MOBILE6 can not model emission factors for alternative fuels and advanced vehicle technologies, such as ethanol fueled flex-fuel vehicles, biodiesel fueled vehicles, and hybrid electric vehicles. There are needs for new emissions modeling approaches, and emissions data to deal with the limitations associated with current emission factor models.

1.2 Objective

The objectives of this study are to:

1) Characterize vehicle activities and emissions under real-world traffic conditions on a road link basis for both conventional and advanced technology vehicles;
2) Estimate and characterize regional on-road mobile sources emissions over a long term;
3) Quantify the impacts of alternative or advanced vehicle technology market penetration on regional mobile source emissions.

1.3 Overview of Research Scope

This section provides an overview of the research scope aimed to achieve the main objectives. In general, four principal components will be investigated:

(1) Link-based vehicle activities and emissions characterization under real-world traffic conditions

Speed profiles for light-duty and heavy-duty vehicles measured under real-world traffic conditions using PEMS are identified on a link-basis and stratified by facility and vehicle types, link mean speed. Modal emission models are used to develop link-based emission rates for a given speed range for the following vehicles: light-duty gasoline vehicles, diesel transit buses, heavy-duty diesel and biodiesel vehicles, light-duty diesel vehicles, ethanol- and CNG- fueled vehicles, and hybrid electric vehicles. Benchmark comparisons for link-based emission rates are carried out to evaluate the impacts of link mean speed on emission rates and obtain speed correction factors.

(2) Development of emission factors for conventional vehicles

MOBILE6 is used to estimate the basic emission rates. Speed correction factors are subsequently estimated based on PEMS data, and the resulting emission factors are the product of base basic emission rates and speed correction factors.

(3) Development of emission factors for alternative vehicle technologies

EPA's annual vehicle certification emission test results, which are based on Federal Test Procedures, are used to characterize basic emission rates for those vehicles. Similar to conventional vehicles, speed correction factors and emission factors are estimated. When no measurement data are available for some vehicle class, estimates from the technical literature are utilized instead.

(4) Regional on-road emission inventory estimation and characterization

Transportation demand models produce link-based vehicle activity data. On-road emission inventory can be estimated using a bottom-up approach. The patterns of emissions can be characterized by facility and vehicle classes. Multiple scenarios are developed to quantify the impacts of vehicle technologies on regional emissions over a long planning term.

1.4 Organization

This dissertation consists of nine parts, in which six journal manuscripts are included in the main body. Appendices are given at the end of the document. The seventh journal manuscript is included in the appendix. Each part of the dissertation contains a separate reference list.

Part I introduces the background information regarding regional on-road emission factors and emission inventories, research objectives and tasks, and dissertation organization.

Part II gives an overview of the methodology regarding emission factor and emission inventory estimates.

Part III develops the methodology to estimate speed- and facility- specific emission rates for light-duty gasoline vehicles and characterizes link-based vehicle activities and emissions.

Part IV develops the methodology to estimate speed- and facility-specific emission rates for diesel transit buses and characterizes link-based bus activities and emissions.

Part V models and compares fuel consumptions for diesel and hydrogen fuel cell transit buses, and further evaluates the effects of substitution of diesel transit bus with hydrogen transit bus on energy and emissions on a life-cycle basis.

Part VI estimates link-based emission rates for heavy-duty diesel vehicles based on real-world data, and evaluates the impacts of various factors on vehicle emissions.

Part VII quantifies the differences in fuel consumption and tailpipe emissions for ethanol-85 and gasoline fueled vehicles based on a theoretical analysis and empirical data. In addition to dynamometer tests and EPA's annul vehicle certification tests, fuel consumption and emissions of Ethanol-85 fueled vehicle are also compared with gasoline vehicles based on PEMS data measured under real-world traffic conditions.

Part VIII develops the methodology to estimate regional on-road mobile sources emission inventory and characterizes the spatial patterns of emissions. In addition, multiple scenarios are developed to evaluate the impact of advanced vehicle technologies on regional emissions over a long planning horizon.

Part IX summarizes findings, main conclusions and recommendations of this research.

Three appendices are provided. Appendix A gives supporting information for Part IV. Appendix B describes the development of the methodology for hybrid electric vehicles to identify internal combustion engine operation rules. Based on engine operation rules, a modal model is applied to estimate link average emission rates for hybrid electric vehicles. Appendix C gives the MATLAB source codes for estimating regional on-road emission inventory.

1.5 References

Davis, S.C. and S.W. Diegel (2007), "Transportation Energy Data Book: Edition 26," ORNAL-6978, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 2007. http://cta.ornl.gov/data/download26.shtml Accessed on September 2.

EIA (2007), "Annual Energy Outlook 2007 with Projections to 2030," DOE/EIA-0383, Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC, February.

EPA (2003), "User's Guide to MOBILE6.1 and MOBILE6.2: Mobile Source Emission Factor Model," EPA420-R-03-010, Environmental Protection Agency, August.

EPA (2007), "National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data: 1970 - 2006 Average Annual Emissions, All Criteria Pollutants," Environmental Protection Agency, July 2007. Http://www.epa.gov/ttn/chief/trends/index.html. Accessed on September 23.

Frey, H.C., N.M Rouphail, A. Unal and J.D. Colyar (2001), "Emissions Reduction Through Better Traffic Management: An Empirical Evaluation Based Upon On-Road Measurements," Prepared by North Carolina State University for North Carolina Department of Transportation, North Carolina State University, Raleigh, NC, December.

Frey, H.C., A. Unal, N.M. Rouphail and J.D. Colyar (2003), "On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument," *Journal of the Air and Waste Management Association*, 53(8):992-1002.

Lave, L. B., H. L. MacLean, C. Hendrickson and R. Lankey (2000), "Life-Cycle Analysis of Alternative Automobile Fuel/Propulsion Technologies," *Environmental Science & Technology*, 34(17): 3598-3605.

Nicolopoulou-Stamati, P., L. Hens and C.V. Howard (2005), "Environmental Health Impacts of Transport and Mobility," *Series: Environmental Science and Technology Library*, Vol.21, Springer Press, Printed in the Netherlands.

Rodier, C., R. A. Johnston and J. E. Abraham (2002), "Heuristic Policy Analysis of Regional Land Use, Transit, and Travel Pricing Scenarios Using Two Urban Models," *Transportation Research Part D: Transport and Environment*, 7(4): 243-254.

Romm, J. (2006), "The Car and Fuel of the Future," *Energy Policy*, 34(17): 2609-2614.

Schwela, D. and O. Zali (1999), Urban Traffic Pollution, Routledge, New York.

TranCAD Homepage, Caliper Corporation, Newton, MA. http://www.caliper.com/tcovu.htm, Accessed on July 13, 2005.

TranPlan Homepage, Citilabs. http://www.citilabs.com/tranplan/index.html, Accessed on July 13, 2005.

TRANUS Homepage. TRANUS: Integrated Land Use and Transport Model. http://www.modelistica.com/tranus_english.htm. Accessed on September 6, 2007.

Unal, A., N.M. Rouphail and H.C. Frey (2003), "Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions," *Transportation Research Record, Journal of the Transportation Research Board*, 1842: 47-56.

Wang, M.Q. (1999), "Fuel-Cycle Greenhouse Gas Emissions Impacts of Alternative Transportation Fuels and Advanced Vehicle Technologies," *Transportation Research Record, Journal of the Transportation Research Board*, 1664:9-17.

PART II OVERVIEW OF METHODOLOGY

This chapter gives an overview of emission factor (EF) and emission inventory (EI) estimation methodologies adopted in this study. Travel demand models are also briefly introduced in this chapter.

2.1 Emission Factor Estimation

An emission factor is defined as the average emission rate of a given pollutant for a given source, relative to units of activity. It is the fundamental tool in developing emissions inventories for air quality management decisions and in developing emissions control strategies. The U.S. Environmental Protection Agency (EPA)'s MOBILE6 predicts emission factors of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2) in gram per mile for gasoline- and diesel- fueled highway motor vehicles, under various conditions for any calendar year between 1952 and 2050 (EPA, 2003). MOBILE6 basic emission rates of HC, CO, and NO_x are derived from emissions tests conducted under standard driving cycles. However, CO_2 emission rates are estimated according to a mass balance on carbon in the fuel and fuel economy (FE) performance estimates.

Although MOBILE6 incorporated many new enhancements such as updated information on basic emission rates and more realistic driving patterns, there are some limitations: (1) limited ability to represent real-world cycles and microscale influences, such as acceleration and deceleration, road grade (EPA, 2001), especially on a roadway link level; (2) only one cycle each used to represent driving on local roadways and freeway ramps (EPA, 2001); (3) insensitivity to factors such as facility type and speed that affect variability in fuel use and CO_2 emission rates (EPA, 2002a, EPA, 2002b); and limited capability to model advanced vehicle technologies and alternative fuels.

In this study, MOBILE6 is applied for predicting the link-based emission factors. The basic emission rates from MOBILE6 are subsequently adjusted using speed correction factors that are estimated based on real-world link speed profiles, instead of MOBILE6 driving cycles. Factors considered in emissions model development include vehicle fuel and technology, facility type, meteorology, vehicle speed, vehicle class and age, vehicle fleet distribution, and emission control standard and program. Emission factors are characterized by vehicle fuel and technology, facility type, speed, and calendar year. In general, emission factors are estimated as follows:

$$EF_{Y,T,f,V} = BER_{Y,C,f,v} \times SCF_{T,f,V} \times TCF_{C,T} \tag{1}$$

Where:

C = conventional fuel and technology (gasoline or diesel);

f = facility type (freeway, arterial, local and collector, on- and off- ramp);

T = fuel and technology class (ethanol-85, hybrid-electric, etc.);

v = average speed used to estimate the basic emission rate;

V = average traffic speed (mph);

Y = calendar year;

BER = basic emission rate (gram/sec);

EF = emission factor (gram/sec);

SCF = speed correction factor;

TCF = technology correction factor (1.00 for conventional vehicles).

For HC, CO, and NO_x, basic emission rates (BERs) are derived from MOBILE6, whereas BERs for CO_2 are estimated based on fuel economy for specified driving cycles. As described above, speed correction factors are estimated based on real-world link speed profiles, which will be characterized by facility type, link mean speed, vehicle class and technology.

For light duty vehicles, the fuels considered are gasoline, ethanol (E85), compressed natural gas (CNG), hydrogen, and electricity. The technologies considered are internal combustion engines, hybrids, fuel cell, and electric. For heavy duty vehicles, biodiesel is considered for trucks and compressed natural gas is considered for buses, in addition to conventional diesel fuels and technologies. Technology correction factor accounts for the effects of advanced technologies on vehicle emissions.

2.1.1 Basic Emission Rates Estimates for HC, CO, and NO_x

For light-duty gasoline vehicles, heavy-duty trucks and buses, and light-duty diesel vehicles, basic emission rates are estimated based on MOBILE6 modeling for each pollutant. Basic emission rates are specified based on many factors including temperature, humidity and barometric pressure, vehicle class and age, calendar year, average cycle speed, emissions standard, vehicle inspection and maintenance (I/M) programs. BER may also vary with vehicle age. Therefore, the final basic emission rates are average values weighted by the fraction of vehicles by age for a given vehicle class and are estimated as:

$$BER(F,VC,v,T,H,P) = \sum_{i=0}^{24}\left(a_i \times BER_i(F,VC,v,T,H,P)\right) \quad (2)$$

Where:

a_i = fraction of vehicles by age for a given vehicle class;

BER = basic emission rate (gram/mile);

F = facility type;

H = relative humidity;

i = vehicle age index (0, 1, 2…, 24);

P = barometric pressure (inches of mercury);

T = temperature (^{o}F);

v = average cycle speed to estimate basic emission rates in MOBILE6 (mph);

VC = vehicle class.

2.1.2 Basic Emission Rates Estimates for CO_2

The basic emission rates for CO_2 in MOBILE6 are estimated based on fuel economy rather than emission tests. The method to estimate basic emission rates for CO_2 is therefore different from the approach for other pollutants. Emission factors of CO_2 in MOBILE6 are not affected by other factors such as facility type and speed. Fuel economy for conventional and advanced vehicle technologies are tested based on Federal Test Procedure (FTP) and highway fuel economy test (HFET) cycles. Average speed is 21.2 mph for FTP cycle and 48.3 mph for HFET cycle. Therefore, for a given type of fuel, basic emission rates on surface streets and freeways are estimated as Equations 3 and 4:

$$BER_{CO_2,\,City} = \frac{c\,\dfrac{gram\ C}{gallon\ Fuel} \times \dfrac{44\ gram\ CO_2}{12\ gram\ C} \times \alpha}{FE_{FTP}\ \dfrac{mile}{gallon\ Fuel}} \times 21.2\,\frac{mile}{hr} \times \frac{1\ hr}{3600\ \sec} \tag{3}$$

$$BER_{CO_2,\,Highway} = \frac{c\,\dfrac{gram\ C}{gallon\ Fuel} \times \dfrac{44\ gram\ CO_2}{12\ gram\ C} \times \alpha}{FE_{HFET}\ \dfrac{mile}{gallon\ Fuel}} \times 48.3\,\frac{mile}{hr} \times \frac{1\ hr}{3600\ \sec} \tag{4}$$

Where:

α = oxidation factor;

c = amount of carbon content in a given fuel;

$BER_{CO_2,\,City}$ = basic emission rate of CO_2 on surface streets in gram per sec;

$BER_{CO_2,\,Freeway}$ = basic emission rate of CO_2 on freeways in gram per sec;

FE_{FTP} = fuel economy for FTP cycle in mile per gallon;

FE_{HFET} = fuel economy for HFET cycle in mile per gallon.

Fuel economy guides provide fuel economy data for light-duty conventional and advanced vehicles (Fuel Economy Guide, 2007). For light-duty gasoline vehicles, EPA also provided fuel economy trends (EPA, 2006). Once speed correction factors for CO_2 BERs are characterized by facility type, speed, vehicle fuel and technology, CO_2 emission factors for a given fuel type may also be sensitive to facility type and speed variations as other pollutants.

2.1.3 Speed Correction Factors Estimates

Speed correction factor (SCF) is defined as the ratio of average emission rate for any speed of interest to link average emission rate at a base speed on a specified roadway type, for a given vehicle technology. SCFs for a given vehicle technology are estimated from speed- and facility- specific average link emission rates, which in turn are estimated based on measured link speed profiles. Speed profiles under real-world traffic conditions were collected by Portable Emissions Measurement Systems (PEMS) (Frey *et al.*, 2001, Frey *et al.*, 2006). Link speed profiles are classified by facility type and link mean speed. Link-based vehicle emission models for conventional and advanced technologies are developed based on modal fuel use and emissions models, stratified with respect to vehicle specific power (VSP) and applied to real world facility- and speed-specific driving cycles for link emission rate estimation. Therefore, speed correction factors are characterized by vehicle fuel and technology, facility type and link mean speed. Estimation of link average emission rates for conventional and advanced vehicle technologies is discussed in detail.

2.1.4 Technology Correction Factors

Technology correction factors (TCFs) account for emissions changes when replacing conventional vehicle technologies with new generation vehicles that have alternative fuel and/or propulsion systems.

There are no correction factors for conventional light-duty gasoline vehicles, diesel trucks and buses.

For advanced light-duty vehicles, U.S. EPA has built up annual certification test results database (EPA, 2007). The standard FTP cycle is used for emission certification testing, which has an averge cycle speed of 21.2 mph. For advanced light-duty vehicle technologies and altenative fuels including E85- and CNG- fueled cars, and hybrid electric vehicle, average cycle emission rates for vehicles from model years 2001 through 2007 are used. Electric and fuel cell vehicles are considered no tailpipe emissions. Based on FTP test results for advaned technologies, TCFs can be expressed as:

$$TCF = \frac{CER_{T,f,v}}{BER_{C,f,v}} \tag{5}$$

Where:

C = conventional vehicle fuel and technology (light-duty gasoline vehicles);

f = facility type index (arterial);

T = advanced vehicle technology (E85, HEV, and CNG cars);

v = average driving cycle speed for basic emission rates (21.2 mph);

BER = basic emission rate for gasoline cars from MOBILE6 (gram/mile);

CER = average cycle emission rate based on EPA's certification tests (gram/mile).

For advanced heavy-duty vehicles, TCFs are supplemented by data from the literatures about emission comparisons for biodiesel-20 versus diesel trucks, and CNG versus diesel buses, since no database is currently available for estimating fleet-based average emission rates.

2.2 Emission Inventory Estimation

In general, on-road emissions are typically estimated as the product of an emission factor and an activity indicator as follows:

$$EI = EF \times A \tag{6}$$

Where:

A = activity indictor;

EF = emission factor;

EI = emission inventory.

There are two typical methods to produce an emission inventory: a top-down approach and a bottom-up approach (Cook *et al.*, 2006). A top-down approach relies on more aggregated information and default modeling inputs. A typical top-down based model is EPA's National Mobile Inventory Model (NMIM). A bottom-up approach relies on combining motor vehicle emission factors and vehicle activity data from a travel demand model estimated at the road link level to generate hourly emissions data. The modeling system in this study follows the bottom-up approach for high resolution emission inventory. A conceptual flow chart for this modeling system is shown in Figure 1. Regional on-road mobile sources emission inventory for conventional versus advanced vehicle technologies are discussed in detail in Chapter VIII.

2.3 Travel Demand Model Introduction

Travel demand models (TDMs) are used to forecast traffic flows on regional transportation networks (Papacostas and Prevedouros, 2001). As shown in Figure 2, TDMs incorporate a traditional four-step demand forecasting process. An integrated land use and transport model, TRANUS, combines a state-of-the-art model of activity location and interaction, land use and the real estate market, with a comprehensive multimodal transport model (TRANUS, 2007). There are three main types of data that are typically available from transportation models that can be used for emission estimation: link characteristics; link traffic volumes; and vehicle origin and destination (O-D) trips by traffic analysis zone (TAZ). The TDM will generate link-based outputs such as: link ID, link origin and destination, facility type, link distance, operator (vehicle) class, free flow speed, congested speed, traffic volume, all of which are used as inputs to estimate a link-based mobile source emission inventory.

2.4 References

Cook, R., J.S. Touma, A. Beidler and M. Strum (2006), "Preparing highway emissions inventories for urban scale modeling: A case study in Philadelphia," *Transportation Research Part D: Transport and Environment*, 11(6): 396-407.

EPA (2001), "Final Facility Specific Speed Correction Factors," EPA420-R-01-060, M6.SPD.002, Environment Protection Agency, November.

EPA (2002a), "Updating Fuel Economy Estimates in MOBILE6.3," EPA420-P-02-005, Environment Protection Agency, August.

EPA (2002b), "Update Heavy Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-duty Engine Emission Conversion Factors," EPA420-R-02-005, Environment Protection Agency, February.

EPA (2003), "User's Guide to MOBILE6.1 and MOBILE6.2: Mobile Source Emission Factor Model," EPA420-R-03-010, Environment Protection Agency, August.

EPA (2005), "EPA's National Mobile Inventory Model (NMIM), A Consolidated Emissions Modeling System for MOBILE6 and NONROAD," EPA420-R-05-024, Environment Protection Agency, December.

EPA (2006), "Light-Duty Automotive Technology and Fuel Economy Trends: 1975 through

2006," EPA420-S-003, Environment Protection Agency, July.

EPA (2007), Annual Certification Test Results & Data. http://www.epa.gov/otaq/crttst.htm. Accessed on September 21.

Frey, H.C., N.M. Rouphail and H. Zhai (2006), "Speed- and Facility-Specific Emission Estimates for On-Road Light-Duty Vehicles on the Basis of Real-World Speed Profiles," *Transportation Research Record: Journal of the Transportation Research Board,* 1987: 128-137.

Fuel Economy Guide (2007), Website: http://www.fueleconomy.gov/feg/FEG2000.htm. Accessed on September 21, 2007.

Papacostas, C.S. and P.D. Prevedouros (2000), Transportation Engineering and Planning, Third Edition, Prentice Hall, ISBN-10: 0130814199.

TRANUS (2007), General Description of the TRANUS System, http://www.modelistica.com/. Accessed on September 21.

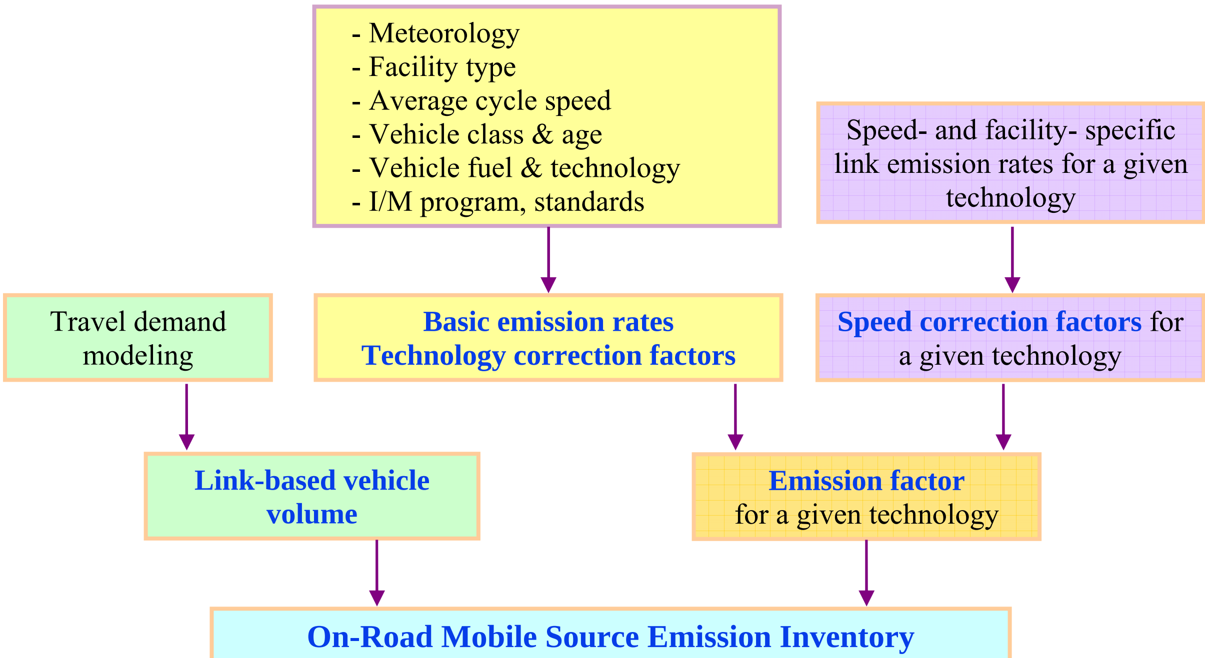

Figure 1. Conceptual Framework of Emission Factor and Inventory Estimation

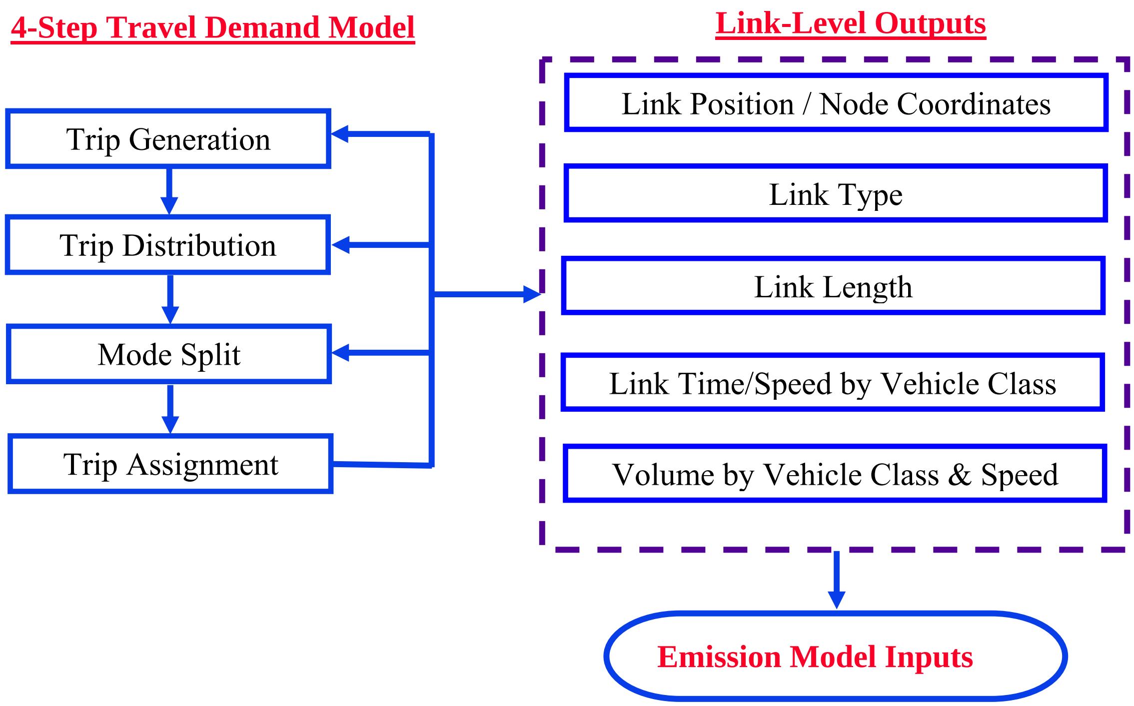

Figure 2. Conceptual Travel Demand Model Inputs to Emission Estimation

PART III SPEED- AND FACILITY-SPECIFIC EMISSION ESTIMATES FOR ON-ROAD LIGHT-DUTY VEHICLES ON THE BASIS OF REAL-WORLD SPEED PROFILES [*]

[*] This manuscript was published in *Transportation Research Record: Journal of the Transportation Research Board*, 2006, 1987:128-137.

Abstract

Estimating the emission consequences of surface transportation operations is a complex process. Decision makers need to quantify the air quality impacts of transportation improvements aimed at reducing congestion on the surface street network. This often requires the coupling of transportation and emission models in ways that are sometimes incompatible. For example, most macroscopic transportation demand and land use models such as TransCAD, TranPlan or TRANUS produce average link speed and link VMT (vehicle miles of travel) by vehicle and road class. These values are subsequently used to estimate link-based emissions using standard emission models such as EPA's MOBILE6 model. On the other hand, recent research using Portable Emission Monitoring Systems (PEMS) indicates that emissions are not directly proportional to VMT, but are episodic in nature, with high emissions events coinciding with periods of high acceleration and speed.

This research represents an attempt to bridge the gap in transportation and emission models, through the use of real-world distributions of Vehicle Specific Power (VSP) bins that are associated with average link speeds for various road classes. A successful effort in this direction would extend the use of transportation models to improve emissions estimation using the limited output produced by such models. In addition, the variability of emissions and emission rates over average speeds for a given facility type is explored and recommendations are made to extend the methodology to additional facility types.

Key Words: Emissions, Arterials, Portable Emissions Monitoring System, Vehicle Specific Power, Transportation Emissions

3.1 Introduction and Research Objectives

For the purpose of assessing and managing the role of highway vehicle emissions on air quality problems, vehicle emissions models are often coupled with transportation models. Most macroscopic transportation demand and land use models such as TransCAD (TranCAD, 2005), TranPlan (TranPlan, 2005) or TRANUS (TRANUS, 2005) produce as output the average link speed and link VMT (vehicle miles of travel) by vehicle and road class. These values are subsequently entered into standard emission estimation models such as the U.S. Environmental Protection Agency's (EPA's) MOBILE6 (EPA, 2003) to produce link and network-wide emissions. Recent research using Portable Emission Monitoring Systems (PEMS) indicates that emissions are not directly proportional to VMT, but are episodic in nature, with high emissions events coinciding with periods of high acceleration and speed (Unal *et al*., 2003, Frey *et al*., 2001, and Frey *et al*., 2003). In essence, emissions during a trip depend on the instantaneous vehicle engine load, which is represented by the second-by-second speed profile. In order to bridge the gap between transportation and emission models, it is important to quantify the relationship between real world speed profiles and the average speed on a roadway (class).

This research proposes a conceptual approach, based on Vehicle Specific Power (VSP) Binning, to integrate real-world speed profiles with link-based mean speed from Travel Demand Models (TDM). VSP, a proxy variable for engine load, can be estimated from a speed profile augmented by the knowledge of road grade associated with that profile. The approach is applied to the estimation of light-duty vehicle average emissions at various mean speeds for a specified roadway type. To gain some understanding of the accuracy of the (mean) emissions estimates, the method also characterizes the variability in emissions between vehicle runs on a single link.

Thus, the principal objectives of this research are to: (a) Assess key similarities and differences in speed and VSP profiles for a given roadway type and range of average speeds; (b) Assess variability of emissions across links for the same facility type and average speed; (c) Estimate light-duty vehicle average emission rates for various link-based mean speeds and various roadway types and quantify the variability in average facility-specific emissions; (d) Compare changes in average emissions due to speed variation between Mobile6 and the VSP binning approach; and (e) Gain insights onto the implications of the findings for transportation and emissions models. A summary of the state of the practice in emission modeling is first presented. This is followed by a description of the methodology and data sources used in this study. Detailed results are then provided for the case of an urban arterial. Summary results for freeway segments (basic and ramps) are given in the next section. Summary, conclusions and recommendations for further research are then provided.

3.2 State of Practice in Emission Modeling

MOBILE6 (EPA, 2003) is currently used to address a wide variety of air pollution modeling needs such as development of emission inventories and assessment of emissions control strategies. MOBILE6 is an emission factor model that estimates average emissions, in grams per mile, for Hydrocarbons (HC), Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Carbon Dioxide (CO_2), Particulate Matter (PM), and toxics from cars, trucks, and motorcycles under various operating (level of service) conditions. MOBILE6 calculates emission factors for vehicles produced in calendar years 1952-2050 for 28 individual vehicle types for four roadway classifications. The emission factor estimates depend on factors such as ambient temperatures, travel speeds, start modes, fuel volatility, and mileage accrual rates (EPA, 2003). Many of the variables affecting vehicle emissions can be specified by the user.

Even though MOBILE6 is based on new and improved data and a better understanding of vehicle emission processes, its basic emission rates are derived from standard driving cycles (EPA, 2003). Second-by-second data collected in the laboratory and on the road show that average emissions for a trip are often dominated by short-term events. Furthermore, the standard driving cycles may not be sufficiently representative of real-world conditions because of failure to represent the influence of real-world traffic flow and actual facilities situations (Unal *et al*., 2003, Frey *et al*., 2001, and Frey *et al*., 2003). In short, driving-cycle-based models lack the temporal and spatial resolution to properly account for the micro-scale nature of vehicle emissions.

Portable Emissions Monitoring Systems (PEMS) are gaining increased acceptance for quantifying emissions under real-world operational conditions (Unal *et al*., 2003, Frey *et al*., 2001, and Frey *et al*., 2003). PEMS produces second-by-second micro-scale data that can be aggregated as needed. PEMS data also enable the characterization of variability in emissions measurements for representative real-world trips. A PEMS typically consists of gas analyzers, an engine diagnostic scanner, and an onboard computer. The gas analyzer measures the volume percentage of NO, HC, CO, CO_2, and oxygen in the vehicle exhaust. Simultaneously, the engine scanner is connected to the On-board Diagnostics (OBD) link of the vehicle, from which engine and vehicle data may be downloaded during vehicle operation.

Based on the recommendations of the National Research Council (NRC, 2002), and to keep pace with new analysis needs, modeling approaches, and data, EPA is developing MOtor Vehicle Emission Simulator (MOVES) for the estimation of emissions produced by on-road and non-road sources (Koupal *et al*., 2004, EPA, 2004, Frey *et al*., 2002, Scora *et al*., 2002, and ENVIRON, 2002). An early version, MOVES2004, has been released that deals only with greenhouse gas emissions of on-road vehicles (EPA, 2004). Future versions will include estimation of emissions of HC, CO, NO_x, and PM for on-road vehicles (Koupal *et al*., 2004). As part of the development of the conceptual basis for MOVES, researchers at North Carolina State University (NCSU) developed a second-by-second database, including both PEMS and dynamometer data, of approximately 100 Tier 1 light duty gasoline vehicles (Frey *et al*., 2002). This database was used as the basis for statistical analysis with techniques including Hierarchical Tree-Based Regression (HTBR) in order to identify key explanatory variables with respect to emissions (Frey *et al*., 2002). VSP was consistently identified as the most important explanatory variable. Based on coefficient values for a generic light duty vehicle, VSP is given by:

$$VSP = v[1.1a + 9.81(\sin(\mathrm{atan}(grade))) + 0.132] + 0.000302v^3 \quad (1)$$

Where

VSP = vehicle specific power (m^2/s^3);

v = vehicle speed (m/s);

a = acceleration (m/s^2);

grade = road grade (decimal fraction).

The coefficients in the equation can be tailored to specific vehicles, but these generic values provide a useful basis for characterization of VSP for a typical light duty fleet. A methodology for estimation of vehicle emissions was developed based on 14 VSP bins (Frey *et al*., 2002). The 14 bins were defined such that the average emission rates are statistically different when comparing bins and each bin has a comparable contribution to total emissions. Bins 1 and 2 characterize emissions during negative values of VSP, such as during deceleration or travel on a downslope. Bin 3 includes emissions during idling. Bins 4 to 14 are for monotonically increasing VSP ranges. The average emission rate is smallest for Bin 3 and largest for Bin 14 for all pollutants considered. High VSP can be attained based on various combinations of high speed, high acceleration, and high positive road grade. In order to improve the modal definitions, parameters related to vehicle and status, such as engine displacement and odometer reading, were included. The emission rates used here are based upon the database described previously and details reported elsewhere (Frey *et al*., 2002).

3.3 Methodology

The methodology employed for estimating link-based facility-specific emissions is founded upon: (a) defining roadway links for various roadway types for compatibility with transportation model outputs, (b) using real-world activity data obtained in previous and ongoing research via PEMS; (c) developing a micro-scale VSP-based modeling approach to estimate emissions (as described above); (d) developing total emissions and emission rates by speed and facility type; and (e) comparing the method's sensitivity to average link speed to current estimation approaches (i.e. MOBILE6).

3.3.1 Defining Roadway Links

Most transportation models define a link as basically a uniform roadway segment between two endpoints. The endpoint typically is an intersection that has some type of traffic control (e.g. traffic signal, stop sign, or interchange) or a point where a change in segment geometry occurs. To some extent, the definition depends on the class of roadway. For example, the segment between two interchanges for a freeway is defined as one link; the segment between two signals having a fixed speed limit on a surface street is regarded as one link. On and off-ramps are defined separately as different links.

For purposes of identifying and analyzing real-world links, PEMS data collected in previous and ongoing projects at NCSU were used (Unal *et al*., 2003, Frey *et al*., 2001, and Frey *et al*., 2003, and Zhang *et al*., 2005). In one project, vehicle starting and end points on each trip, and positions of street intersections along an arterial in Raleigh, NC (Chapel Hill Road) were recorded. Cumulative driving distances relative to the starting point were calculated according to the measured speed at each second. Second-by-second speed profiles were synchronized to road grade measurements made every one-tenth mile along Chapel Hill Road. In addition, a second database has recently been developed for travel on three routes between NCSU and North Raleigh and three routes between North Raleigh and Research Triangle Park (RTP), involving over 200 hours of second-by-second data that includes repeated trips on each route and travel direction with selected vehicles. These data enable us to extend the analysis to other facility types such as freeway segments, ramps and local streets. In the latter database, second-by-second GPS coordinates of vehicles on the trip were available and were overlaid on a Wake County GIS map (Wake County, 2005). This capability enables the team to appropriately define links along the routes and to match road grade data to the vehicle positions during a trip (Zhang *et al*., 2005).

3.3.2 PEMS Data Collection

Field data collection on Chapel Hill Road was carried out to cover both peak and off-peak periods. Over one hundred runs were made to capture a variety of traffic conditions and also to characterize variability in emissions. In addition, vehicles traveled in both directions for each origin and destination pair associated with a run. For the recent project three primary vehicles (a Chevrolet Cavalier, Dodge Caravan, and Chevrolet Tahoe) were driven along six routes. The routes covered several facility types including freeways, arterials, local streets and collectors, and ramps in order to capture a large range of variability in real-world vehicle emissions. Each primary vehicle traveled approximately 65 hours and replicate runs were made to assess inter-run variability. Routes of interest are shown in Figure 1.

3.3.3 VSP Binning Approach

Using the second-by-second speed profiles, and instantaneous acceleration and grade, VSP was computed from Equation (1) for individually defined links. The values were then categorized into 14 VSP Bins. The driving pattern was modeled based on the distribution of time spent in each VSP bin. The speed profiles are categorized by average travel speed (e.g., 45 km/h) if they produce a mean speed within +/- 5 km/h (e.g., 40 to 50 km/h) of the desired value. Since the primary interest is in the activity patterns (i.e. the time distribution of VSP bins) candidate speed profiles from all vehicles and runs that occurred on the same link can be combined. However, before data from multiple runs were combined, the similarity in speed profiles, VSP distributions and variability in average emissions for multiple runs were assessed.

Emissions were estimated, using the VSP-based binning approach, based on multiple speed profiles. Emissions for one link were estimated as the product of the time spent in each bin multiplied by the corresponding bin emission rate. Subsequently, and for each run, the average link emission rate was calculated by dividing the total emissions by the link travel time. The inter-run variability in emissions was characterized using the coefficient of variation (CV), which is the standard deviation divided by the mean value. To estimate the average emissions on one trip for a given roadway type, the variability in average emissions between links was assessed before average emission rates across links for the same roadway type were aggregated. An average emission rate across links can be used if there are similarities among links after the assessment of variability in emissions. Based on a stratification by road class (i.e., freeway, arterial, local street and ramps) and average speed ranges (i.e. 10-20 km/h, 20-30 km/h, 30-40 km/h.), variability in average emissions are characterized with respect to roadway type as well as with respect to mean speed.

3.4 Results and Discussion

The mean speed for each run on every link along each type of roadway was first calculated. Nine speed bins were defined based upon link mean speeds: 10-20 km/h through 90-100 km/h. For each speed bin, the speed profiles, time distribution of VSP bins, average emission and variability in emissions estimates are assessed. To illustrate the methodology used, the results presented herein focus on the "major arterial" facility class. Vehicle activity profiles for other classes are briefly summarized.

3.4.1 Activities Analysis and Emissions Estimates for Light-Duty Vehicles on Major Arterials

Five separate links (labeled 1 through 5) were defined along Chapel Hill Road. These have lengths of 0.32 km, 0.40 km, 1.29 km, 2.01 km, and 0.16 km, respectively. The range in link mean speeds for these 5 links varied widely from 4 km/h to 75 km/h, providing a good range for the analysis. According to the distribution ranges of mean speeds, emissions estimates and related analyses were carried out for six speed bins ranging from 10-20 km/h to 60-70 km/h.

Speed profiles and Time Distribution of VSP Bins

Visual inspection of the speed profiles can assist in determining the degree of similarity across runs for the same speed bin. Examples of speed profiles for speed bin 30-40 km/h on Link 3 (9 runs) and Link 4 (5 runs) are depicted in Figure 2. Except for a shift in the position where the vehicle stops in two runs (coded 413N and 345N) the speed profile structures for inter-runs on Link 3 are surprisingly similar. A similar pattern emerges for link 4, with one run (416N) showing an earlier slowdown on the link than most other runs.

Emissions estimates based on the VSP-binning approach are determined by the fraction of link travel time spent in each VSP bin. Patterns of VSP bin time distributions should be similar across runs on the same link if the speed profiles are also similar. For example, the time distributions of VSP bins for multiple individual vehicle runs on Links 3 and 4 runs in both directions are depicted in Figure 3. There is surprising consistency in the inter-run comparison of these distributions, more so than for the speed profiles themselves. The most frequent activity is for Bin 3, which includes idle. The fraction of time generally decreases with an increase in VSP bin. An "average" VSP bin distribution was then calculated for each of the five links on Chapel Hill Rd. A comparison of the mean distributions, averaged over multiple vehicle runs, for each of five links for a speed range of 30-40 km/h is depicted in Table 1.

On average, about 25 percent of time is spent at low VSP including idle, almost 30 percent of time is spent at negative values of VSP (e.g., deceleration), 40 percent is spent at low to moderate VSP, and 5 percent is spent at high VSP. Although there are some quantitative differences in the average distributions among the links, the key question is whether there are significant differences in emissions.

Assessment of Variability in Emissions Rate Estimates

The mean emission rate on a mass per time basis, and the 95 percent confidence interval for the mean, was estimated for each link and each pollutant on the basis of the VSP binning approach described earlier (Frey *et al*., 2002), applied to a particular speed bin. In most cases, when comparing multiple links for a given pollutant, there is substantial overlap in the confidence intervals, implying statistical similarities in the mean emission rates. The emission rates for CO tend to have more inter-run variability on a given link, leading to wider confidence intervals. This is likely because CO emissions tend to be more sensitive to "enrichment," particularly at higher VSP, than the other pollutants. However, the similarity in mean emission rates for all pollutants implies that data from multiple links can be combined to create a larger database.

Once a combined database was developed that included multiple links, an assessment was made of the effect of mean link speed on the mean emission rate, where the mean emission rate was estimated based upon the VSP binning approach. An example of results is shown in Figure 4 for a primary arterial with three ranges of average speed. The mean emission rate for each pollutant increases monotonically as average speed increases. The ratio of the highest to the lowest mean value for a given pollutant is approximately a factor of 3, and the differences between these mean values are statistically significant. Thus, mean speed is a useful explanatory variable. However, mean speed alone does not capture the details of microscale events that affect emissions. For example, when comparing the highest to lowest emission rate among the 14 VSP bins, the variability is typically an order-of-magnitude. In addition, there is variability in the mean itself. For instance, for the average speed of 30-40 km/h on major arterials, the average emission rate of CO is 19.5 mg/s, but the mean value ranges from 11.7mg/s to 25.2 mg/s when comparing individual links of this category with each other. Thus, there is some loss of information associated with the use of highly aggregate measures of vehicle activity, such as mean link speed.

As mean speed increases, the travel time on a link decreases even though the emission rate tends to increase. The resulting estimates of total emissions for the example case study are shown in Figure 5. These results indicate that the total emissions tend to decrease as mean speed increases. Of course, an increase in mean speed is associated with a decrease in travel time. The speed profiles for higher average link speeds typically have more constant cruising speed, whereas the speed profiles for lower average link speeds may have more deceleration and acceleration events. The latter, in particular, can lead to higher total emissions. The total emissions on one trip depend on both on the travel time and the average emission rates, but are influenced by micro-scale events. For example, driving situations, whether caused by driver behavior or traffic flow problems that lead to increased frequency of acceleration events, can lead to higher average emission rates.

Contrasting Sensitivity of Emissions to Average Link Speed: VSP vs. MOBILE6

The relative differences in average emissions for different mean link speeds obtained from the VSP-based approach using real world speed profiles were compared to results from the MOBILE6 model for a range of average speeds. In MOBILE6, the input parameters were based on EPA national default data, 2000 calendar year, July daily minimum and maximum temperatures of 72.0^{o} F and 92.0^{o} F, and Fuel Reid Vapor Pressure (RVP) of 8.7 psi. The mass per mile emission rates from MOBILE6 were converted into a mass per second basis. The relative percentage changes in emissions rates were estimated with reference to an average speed of 15 km/h (for MOBILE6) and a speed bin of 10-20 km/h for the VSP-based approach. The results for NO, CO and HC are shown in Table 2.

Both NO and CO emission rates appear to be sensitive to changes in average speeds in both methods, and there is good agreement in both cases. For example, the increase in NO emissions when comparing 55 to 15 km/h is approximately 140 percent based on both estimation methods. For CO and the same speed comparison, both estimation methods produce a similar estimate of approximately a 170 percent increase. For HC, the VSP-based results are less sensitive to mean link speed than are the MOBILE6 results, with a maximum change of only 54 percent versus 114 percent. HC emissions tend to be more sensitive to vehicle technology, and it is possible that the MOBILE6 runs did not closely match the distribution of Tier 1 vehicles used in the VSP binning database. However, in general, both the VSP-based and MOBILE6-based estimates imply the following similar trends: (a) emission rates on a mass per time basis increase monotonically with mean link speed; (b) CO emissions tend to increase more than for the other pollutants; and (c) HC emissions tend to increase less than for the other pollutants. Thus, there is significant qualitative agreement in the results. This lends some assurance that the VSP-based approach, when aggregated to represent link-based vehicle activity, can produce reasonable results.

3.4.2 Extensions to Other Facility Classes

The methodology described here has also been extended to freeway segments, ramps, local streets and collectors to estimate facility-specific average emissions by speed range, but because of space limitations details are not presented here. Preliminary results regarding on-ramps and freeway segments are briefly summarized.

Vehicle activity analysis and emissions estimates for freeway on-ramps

Examples of speed profiles for an on-ramp link (Six Forks Rd. at Interstate-540, see Figure 1), based on multiple vehicle trips, and the corresponding time distribution of VSP bins are shown in Figure 6(a) and 6(b). These results are for a speed bin of 20-30 km/h at a single point interchange. The speed profiles here assume that the on-ramp influence area starts on the surface street segment which is typically controlled by a traffic signal. Thus the idle time represents delay at that signal prior to actually entering the on-ramp roadway proper. Other end-point definitions could have been used, such as when the vehicle exited the signalized intersection. Similarities appear in both the speed profiles, especially for the acceleration events, and in the time distribution of VSP across runs and vehicles (except for run *KsCv1R1am3r* in Figure 6(b). Before combining the results from multiple vehicles, variability in average emissions for individual vehicles was assessed. The results showed that average emissions estimates with 95 % confidence intervals for multiple vehicles typically overlapped each other and thus could be combined.

For the example on-ramp, there are three consecutive modal activities, as indicated in Figure 6(a): deceleration, idle and acceleration. The average proportion of time spent in each of the 3 modes is 14.3%, 41.1%, and 44.6%, respectively. However, emissions varied greatly between these modes. For example, the CO_2 emission rate during acceleration is about four times that of idle and three times that during deceleration. In general, accelerations dominated emissions for the on-ramp trip. Average emissions for on-ramps were therefore higher than those predicted on a major arterial, due to the larger fraction of time spent accelerating on the on-ramp (e.g., compare Figures 3 and 6(a) & 6(b)).

Vehicle activity analysis and emissions estimates for freeway segments

The same procedures were applied to freeway links on Interstate-440 in Raleigh that has a speed limit of 60 mph (96 km/h). Link speed profiles and time distributions of VSP bins for one link are shown in Figure 6(c) & 6(d). The speed profiles appear to be similar to each other. However, the VSP profiles appear to have more variability than was the case for lower speeds on arterials. The VSP distribution appears to be approximately symmetric, with the largest proportion of time spent in bins 4 through 9. These results may suggest that the use of average speed for emission estimation on un-congested freeway segments could produce less reliable results than for the arterial or on-ramp cases.

3.5 Conclusions

Transportation models typically provide link-based average speed. The approach demonstrated here enables conversion of detailed information regarding vehicle dynamics to an average speed. The case studies demonstrate that there are consistent trends in the speed profiles, distributions of time spent in various VSP-based modes, and average emissions using this approach. Thus, this approach enables incorporation of real-world emissions data into transportation models.

A comparison of real world speed profiles for specific links of different roadway facility types reveals that there are often significant similarities when such profiles are grouped with respect to average link speed. Furthermore, the second-by-second speed profiles can be used to estimate time-based distributions of VSP, which in turn can be used to explain a substantial portion of variability in second-by-second vehicle emissions. This methodology is a means to link the aggregate vehicle activity output of transportation models (e.g., mean speed) with micro-scale profiles that influence actual emissions.

Although there is inter-run variability in speed profiles on a given link, in many cases the mean emissions estimate for a given link is comparable to that for another link of the same roadway class and speed bin. This implies that there are opportunities to combine data from multiple links of a given roadway class in order to develop larger databases and to reduce statistical sampling error.

The average emission rates of Tier 1 vehicles were estimated to differ significantly as a function of mean link speed for arterials. The use of average speed to characterize vehicle activity may be a useful basis for estimating emissions for a given facility type; however, there is clearly a loss of information if only average speed is used in comparison to any individual speed profile. The VSP-based approach can explain more variability in emissions than can an average speed-based approach, but both approaches produce similar results when only average speed is used as the key measure of traffic dynamics. A comparison of a range of mean link speeds for arterials could explain approximately a factor of three variations in mean vehicle emissions rate, which is far less than the total variability in microscale emissions. Thus, while the use of mean link speed is a practical way to couple the output of transportation models with emissions models, more accurate and precise emissions estimates are likely to be obtained on the basis of better estimates of real world speed profiles.

A comparison of the VSP bin-based approach to the results of the driving cycle-based MOBILE6 indicated substantial concordance in results. For NO_x, CO, and HC, the average emission *rate* increased with average speed. Especially for NO_x and CO, the relative changes in emissions rates as a function of changes in average speed were very similar. Furthermore, the relative sensitivity of emissions rate to average speed was highest for CO and lowest for HC in both approaches. This comparison provides a degree of comfort that the VSP-based approach can be used to aggregate micro-scale data to produce driving cycle-based estimates.

Although the average emission rate increases with average speed for arterials, the total emissions for the links considered in this study tend to decrease. This result can be understood in terms of differences in micro-scale aspects of the speed profiles, such as changes in the frequency and duration of acceleration events that tend to contribute disproportionately to total emissions.

The methodology demonstrated here can be applied to other roadway facility types, such as freeway links and ramps. The specifics of the results may differ among roadway types and speed bins.

In summary, this paper has demonstrated a methodology for using PEMS data as a basis for linking the aggregate activity estimates of transportation models with emissions estimation approaches. Recommendations are to extend the application of the method to additional roadway types and speed bins, and to apply the method with a transportation model in order to demonstrate the implementation of the methodology for practical use.

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3.7 References

TranCAD (2005), Caliper Corporation, Newton, MA. http://www.caliper.com/tcovu.htm. Accessed July 13, 2005.

TranPlan Homepage (2005), Citilabs. http://www.citilabs.com/tranplan/index.html. Accessed on July 13, 2005.

Modelistica TRANUS Homepage (2005), Modelistica Company, http://www.modelistica.com/. Accessed on July 9, 2005.

EPA (2003), "User's Guide to MOBILE6.1 and MOBILE6.2: Mobile Source Emission Factor Model," EPA420-R-03-010, Environmental Protection Agency, August.

Unal, A., N.M. Rouphail and H.C. Frey (2003), "Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions," *Transportation Research Record: Journal of the Transportation Research Board*, 1842:47-56.

Frey, H.C., N.M Rouphail, A. Unal and J.D. Colyar (2001), "Emissions Reduction Through Better Traffic Management: An Empirical Evaluation Based Upon On-Road Measurements," Prepared by North Carolina State University for North Carolina Department of Transportation, North Carolina State University, Raleigh, NC. December.

Frey, H.C., A. Unal, N.M. Rouphail and J.D. Colyar (2003), "On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument," *J. Air & Waste Manage. Assoc.*, 53(8): 992-1002.

National Research Council (2002), Modeling Mobile Source Emissions, National Academy Press, Washington, DC.

Koupal, J., E. Nam, B. Giannelli and C. Bailey (2004), "The MOVES Approach to Modal Emission Modeling," Presented at CRC On-Road Vehicle Emissions Workshop, March. http://www.epa.gov/otaq/models/ngm/may04/crc0304a.pdf. Accessed in March, 2006.

EPA (2005), "A Roadmap to MOVES2004," EPA420-S-05-002, U.S. Environmental Protection Agency, Ann Arbor, MI, March.

Frey, H.C., A. Unal, J. Chen, S. Li and C. Xuan (2002), "Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle & Equipment Emission System," EPA420-R-02-027, Prepared by North Carolina State University for U.S. Environmental Protection Agency, Ann Arbor, MI. August.

Scora, G., C. Malcolm, T. Younglove and M.J. Barth (2002), "Mobile Source Emissions New Generation Model: Using a Hybrid Database Prediction Technique," EPA68-C-01-169, Prepared by University of California at Riverside: College of Engineering-Center for Environmental Research and Technology University for U.S. Environmental Protection Agency, Ann Arbor, MI. February.

ENVIRON International Corporation (2002), "Onboard Emission Data Analysis and Collection for the New Generation Model," PR-CI-01-12239, Prepared for U.S. Environmental Protection Agency, Ann Arbor, MI. February.

Zhang, K and H.C. Frey (2005), "Road Grade Estimation for On-Road Vehicle Emissions Modeling Using LIDAR Data," 2005-A-1137-AWMA, Proceedings of the Annual Meeting of the Air & Waste Management Association, Minneapolis, MN, June.

Wake County GIS Services Homepage (2005), Wake County Government, North Carolina. http://www.wakegov.com/county/propertyandmapping/gis.htm. Accessed on July 9, 2005.

Table1. Mean VSP Bin Time Distribution (%) for Chapel Hill Rd. Links; Speed Bin 30-40 km/h

VSP BIN	Link # *				
	1	2	3	4	5
1	19.08	17.92	13.63	19.74	21.59
2	6.62	10.77	3.58	11.93	22.48
3	5.00	19.46	39.16	29.09	12.70
4	21.15	11.85	8.21	19.00	6.11
5	22.64	10.70	7.22	6.41	11.07
6	7.20	11.86	7.94	4.57	10.01
7	6.94	5.69	6.96	3.76	4.34
8	5.20	1.91	5.39	2.11	4.36
9	1.53	3.18	2.37	0.95	1.87
10	1.00	2.21	1.97	1.06	2.50
11	2.07	1.97	1.65	0.73	1.66
12	0.51	0.92	0.96	0.41	0.66
13	1.06	0.79	0.39	0.12	0.00
14	0.00	0.78	0.56	0.13	0.66

* Links are numbered in increasing order upstream to downstream.

Table 2. Percentage Increase in Average Emissions on A Mass per Second Basis Compared to Benchmark

Pollutant	Average Speed (km/h)	Percentage (%) Mobile6 Estimates	Speed Bin (km/h)	Percentage (%) VSP Binning Estimates
NO	15	Benchmark	10-20	Benchmark
	25	37	20-30	44
	35	72	30-40	75
	45	107	40-50	106
	55	142	>50	134
CO	15	Benchmark	10-20	Benchmark
	25	37	20-30	76
	35	73	30-40	126
	45	117	40-50	132
	55	168	>50	169
HC	15	Benchmark	10-20	Benchmark
	25	27	20-30	20
	35	55	30-40	35
	45	85	40-50	41
	55	114	>50	54

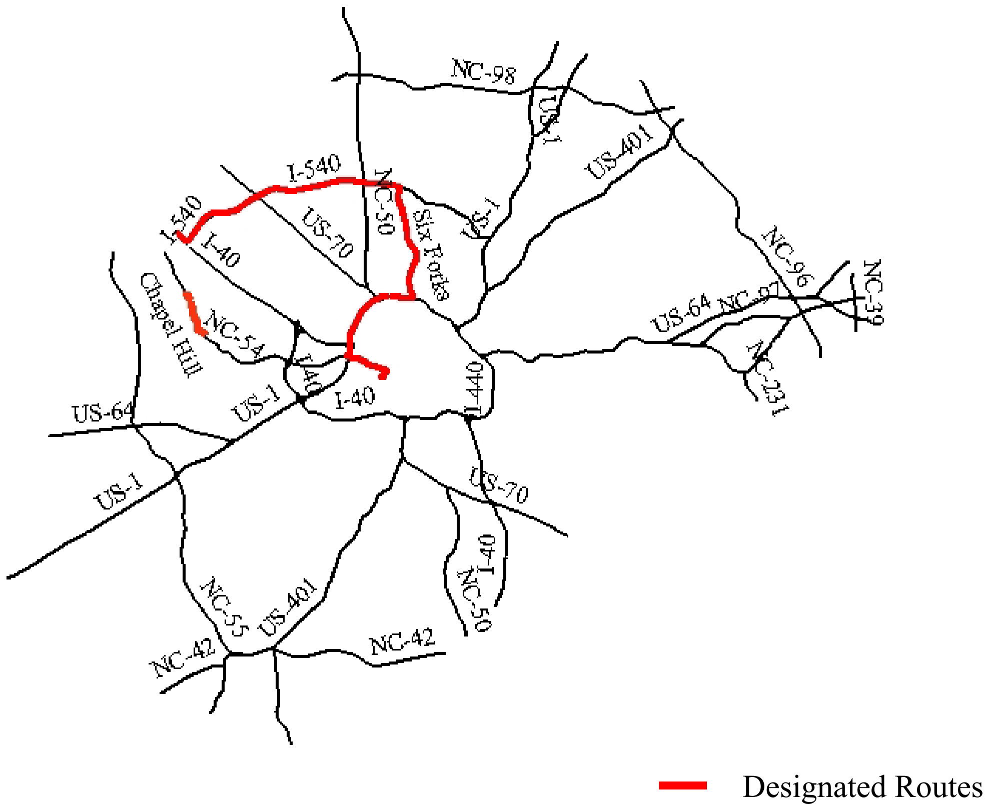
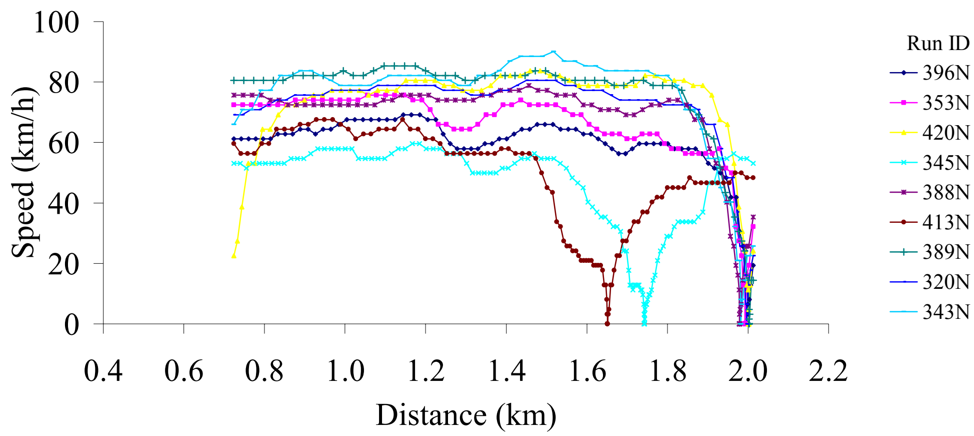
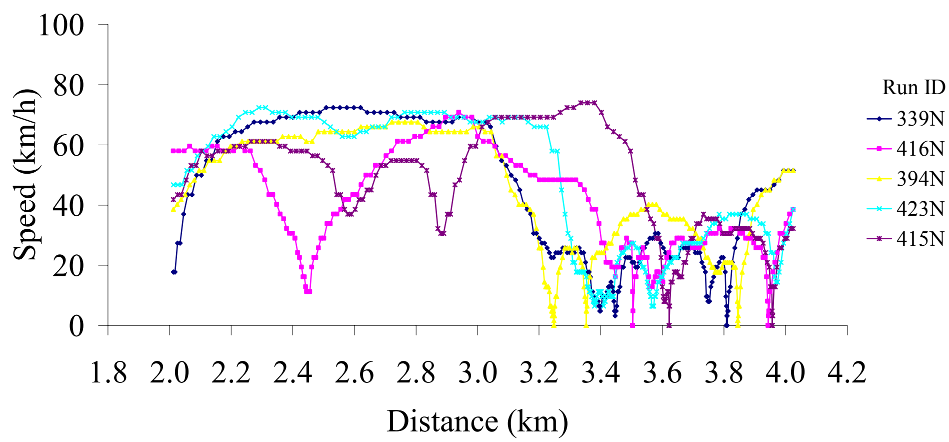


Figure 1. Travel Routes for PEMS Data Collection

* I- Interstate facilities; Six Forks and Chapel Hill Roads- Major Arterials

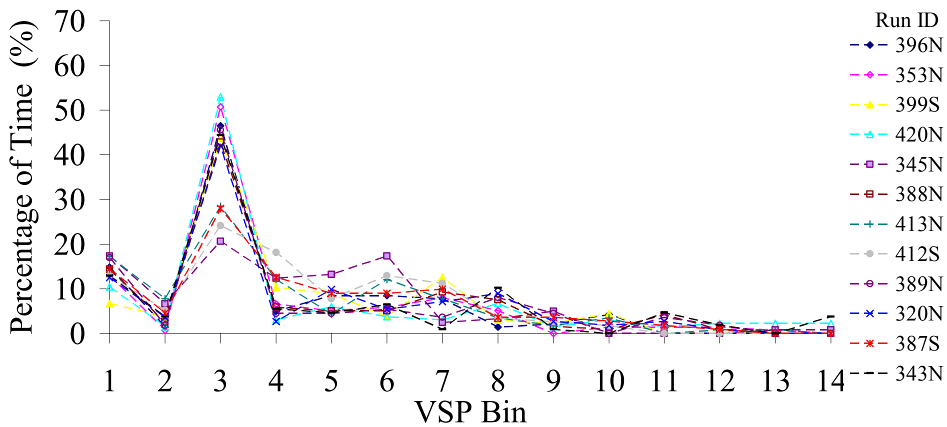


(2a) Link 3

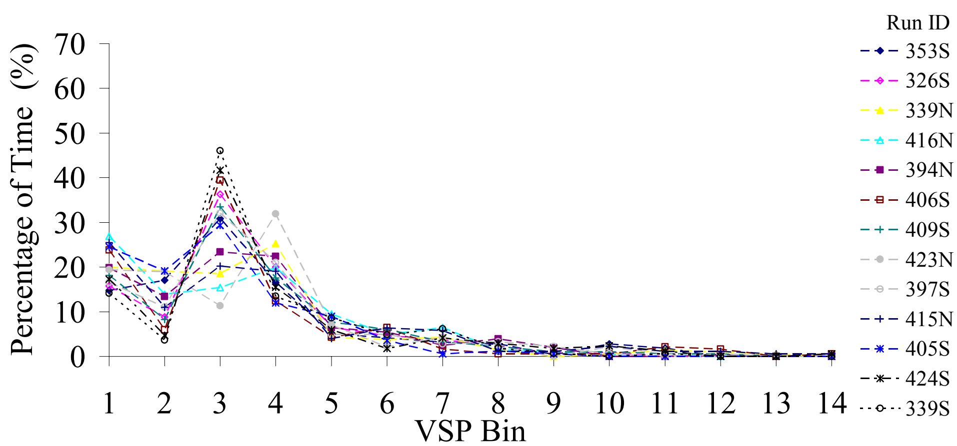


(2b) Link 4

Figure 2. Examples Speed Profiles from Multiple Vehicle Runs on Links 3 and 4, Chapel Hill Road; Average Speed: 30-40 km/h



(3a) Link 3



(3b) Link 4

Figure 3. VSP Bin Distributions for Links 3 and 4 on Chapel Hill Rd.; Average Speed= 30-40 km/h

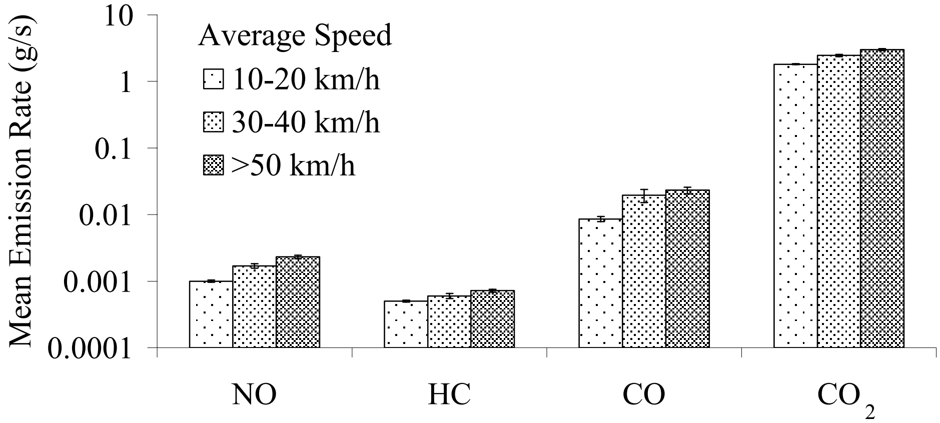


Figure 4. Mean and Stand Errors for Emission Rates for Three Speed Ranges, Using Combined Data from Five Links on Chapel Hill Rd.

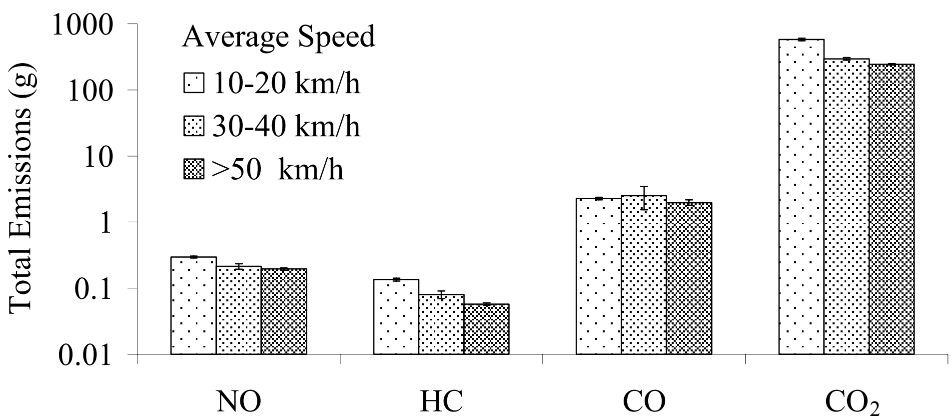
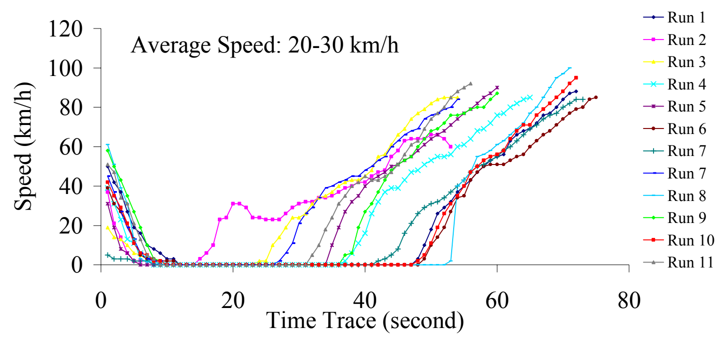
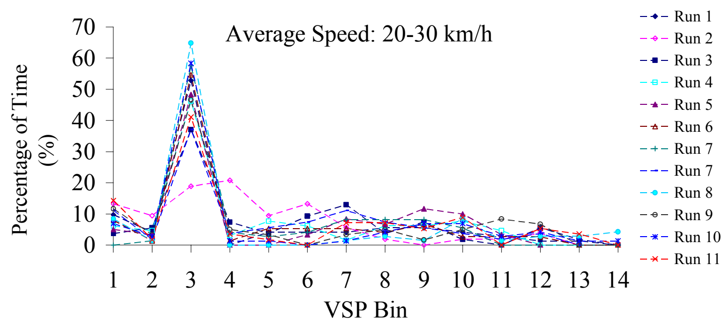


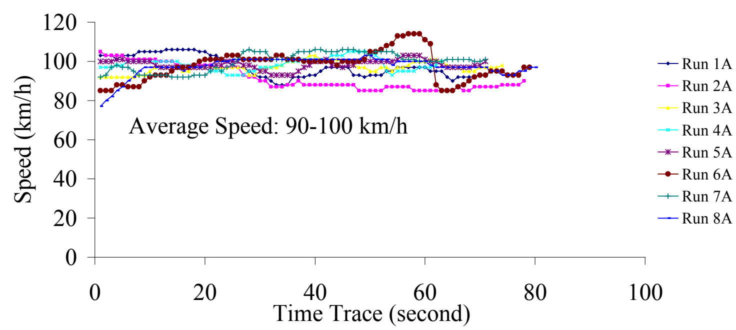
Figure 5. Total Link Emissions for Three Speed Ranges, Applied to Link 3 on Chapel Hill Rd.



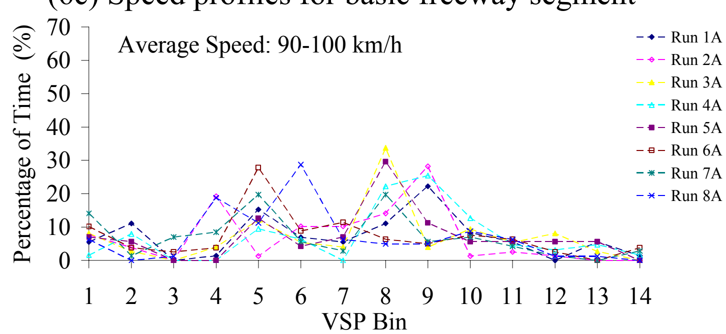
(6a) Speed profiles for on-ramp influence distance



(6b) Time distribution of VSP bins for on-ramp influence distance



(6c) Speed profiles for basic freeway segment



(6d) Time distribution of VSP bins for freeway segment

Figure 6. Example of Speed Profiles and Time Distributions of VSP Bins for Multiple Vehicle Runs on Basic Freeway and On-Ramp Segments

PART IV A VEHICLE SPECIFIC POWER APPROACH TO SPEED- AND FACILITY- SPECIFIC EMISSIONS ESTIMATES FOR DIESEL TRANSIT BUSES [†]

[†] This manuscript is in preparation for submission to *Environmental Science & Technology*.

Abstract

Vehicle emissions models can be coupled with transportation models to estimate regional mobile sources emissions. Most macroscopic travel demand models predict link average speed and vehicle miles traveled, by vehicle and road classes. However, emissions during a trip often depend on transient vehicle dynamics that influence the instantaneous engine load. Vehicle specific power (VSP) is a proxy variable for engine load that has been shown to be highly correlated with emissions. This study estimates roadway link average emission rates for diesel-fueled transit buses based on link mean speeds, using newly defined VSP modes from data gathered by a Portable Emissions Monitoring System. Speed profiles were categorized by facility type and mean travel speed, and stratified into discrete VSP modes. VSP modal average emission rates and the time spent in the corresponding VSP modes were then used to make aggregate estimates of total and average emission rates for a road link. The results showed that the average emission rates were sensitive to link mean speed, but not to facility type. A recommendation is made regarding the application of link average emission rates along with transportation models for the purpose of regional emissions estimates for diesel transit buses.

Key Words: Vehicle specific power, Emissions, Speed profile, Link, Diesel buses

4.1 Introduction and Objective

Vehicle emissions models can be coupled with transportation models to estimate regional mobile sources emissions. Compatibility between vehicle activity indicators predicted from transportation model that are required inputs into emissions models is necessary for the development of accurate estimates of emission inventories (1-2), and the assessing of emission consequences of alternative fuels and propulsion systems. Currently, emission factors from heavy-duty vehicles are based primarily upon engine dynamometer tests (3-4). As such, these methods offer little or no linkage between the emission estimates and the real-world duty cycles that these vehicles experience on the road.

Emissions measurements for diesel transit buses have been made using chassis dynamometers, remote sensing, and tunnel studies (5-7). However, remote sensing and tunnel studies measure emissions at only pre-determined fixed locations, not continuously along a route. Portable Emissions Monitoring Systems (PEMS) represent an acceptable alternative for measuring emissions under real-world operating conditions (8-9). PEMS produce micro-scale level data and enable the characterization of variability in emissions measurements under representative real-world vehicle activities and traffic conditions (8-10).

Research on light-duty vehicles has shown that emissions are not directly proportional to vehicle miles traveled (VMT), but are episodic in nature (10). Differences in vehicle size and weight, engine technology, operating mode, vehicle speed, vehicle acceleration and ambient conditions all have effects on instantaneous vehicle emissions (4, 11-12). Activity-based models were developed to estimate emissions for heavy-duty vehicles based on speed and acceleration modes (13-15). In addition to speed, acceleration, and cycle load, other factors such as aerodynamic and rolling resistances may affect emissions (16-18). A road-load-based model estimates transit bus emissions as a function of the power demand for given transit bus activities and environmental conditions. Basic emissions rates in grams per brake-horsepower hour are obtained from engine dynamometer or chassis dynamometer test results (19).

Prompted by recommendations from a National Research Council study (20), the U.S. Environmental Protection Agency (EPA) is in the process of developing the MOVES model for estimation of emissions generated from on-road and non-road sources (21). In developing the conceptual basis for MOVES, vehicle specific power (VSP) was consistently identified as a strong explanatory variable that was highly correlated with emissions (22). While the VSP modeling approach was used to estimate emissions from light-duty vehicles (7, 23-24), less attention has been devoted to its application to transit buses.

The objectives of this research are to: (a) develop VSP modal average emission rates for diesel-fueled transit buses using PEMS data; (b) estimate link average emission rates for a given link mean speed that are applicable to diesel-fueled transit buses on a given facility type; (c) assess the variability in link-based emissions and their sensitivity to speed and facility type; and (d) gain insights into the implications of the findings for future integration of transportation and emissions models and in the development of diesel transit bus emission inventories.

4.2 Methodology

This section describes the database used in the analysis, presents an exploratory analysis for key variables in the database, and applies the VSP modal emission approach to estimate emission rates for diesel fueled transit buses.

4.2.1 PEMS Database

On-board data for diesel transit buses were provided by the U.S. EPA (25). The fleet consisted of 12 diesel transit buses. Four of these vehicles were model year 1995 and the rest were 1996 models. All buses are New Flyer models with Detroit Diesel Series 50 engines. These buses weigh 12 tons and have 8.5 liter engines. The PEMS recorded vehicle positions using global positioning system (GPS), ambient conditions, vehicle speed, carbon dioxide (CO_2), hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) emission rates on a second-by-second basis along the pre-determined bus routes. Since each bus made only one trip along its route, the fleet dataset consisted of 12 bus trips with a total of 21.7 hours of records.

The fleet data was subsequently divided into a calibration dataset and a validation dataset. The calibration dataset was used to develop the VSP-based model and the validation dataset was used to assess the predictive ability of the model. Portions of continuous second-by-second data selected from each bus route (ten minutes for each bus), were combined to produce a 7,200-second validation dataset; the remaining 71,000 seconds were retained for model calibration. The two datasets were compared with respect to their cumulative distribution functions (CDFs) for speed and acceleration. This was done to ensure that the model would be validated against data that was representative of the vehicle activities.

4.2.2 Link Definition

A link was defined as the segment of road between two consecutive bus stops. Second-by-second GPS coordinates of the vehicles as well as the location of transit stops were overlaid using ArcGIS (26). This capability enabled the identification of transit bus links along the routes. The defined links were then categorized by facility type. The coded facility types included principal and minor arterials, local and collector streets.

4.2.3 Exploratory Analysis

Spearman's rank correlations were computed to assess whether an association exists between pairwise combinations of selected variables based on individual bus PEMS data. Second-by-second ambient conditions, roadway grade, vehicle speed, acceleration, and emission rates were included in the correlation analysis. Key variables affecting vehicle emissions were identified and utilized to develop vehicle emissions models. In addition, autocorrelation in second-by-second emission rates are investigated.

4.2.4 Vehicle Specific Power and VSP Modes

VSP is defined as the engine power output per unit mass of vehicle and is expressed as a function of vehicle speed, road grade and acceleration (23). VSP takes into account aerodynamic drag, tire rolling resistance and road grade. VSP for transit buses was estimated using typical coefficient values (17, 27) and expressed as:

$$VSP = \mathrm{v} \times (a + g \times \sin(\varphi) + \psi) + \zeta \times \mathrm{v}^3 \tag{1}$$

Where:

VSP = vehicle specific power (m^2/s^3);

v = vehicle speed (m/s);

a = vehicle acceleration (m/s^2);

φ = road grade (dimensionless);

ψ = rolling resistance term coefficient (0.092 m/s^2);

ζ = drag term coefficient (0.00021 m^{-1}).

Based on second-by-second data, VSP values were estimated and then grouped into discrete modes. Modal average emission rates were estimated for each VSP mode. Total trip-based emissions are estimated as the product of the VSP modal average emission rate and the time spent in the VSP mode, summed over all modes:

$$TE = \sum_{i}^{I} TVSP_i \times ER_i \tag{2}$$

Where:

i = VSP mode index;

I = the number of VSP modes;

ER_i = VSP modal average emission rate for Mode i (g/s);

$TVSP_i$ = time spent in VSP Mode i on a trip (s);

TE = total emissions for a trip (g).

Using the validation dataset, total emissions estimates were compared with the corresponding measured emissions for model evaluation.

4.2.5 Mean Link Speed Approach to Average Emission Rates Estimates

Link speed profiles were categorized by facility type and mean link speed, and further stratified by the discrete VSP modes. Thus, time distributions of VSP modes were obtained at the link level. For a given link mean speed on a specified facility type, the link average emission rate is estimated as the product of the fraction of link travel time spent in each VSP mode multiplied by the corresponding modal emission rate:

$$E_{j,k_f} = \sum_{i=1}^{I} \left\{ \left(\frac{t_{i,j,k_f}}{T_{j,k_f}} \right) \times ER_i \right\} \tag{3}$$

$$\overline{E}_{k_f} = \frac{1}{J} \sum_{j=1}^{J} E_{j,k_f} \tag{4}$$

Where:

E_{j,k_f}	= average emission rate on link j for speed mode k on the facility f (g/s);
$\overline{E}_{k_f}$	= link average emission rate for speed mode k on the facility f (g/s);
ER_i	= VSP modal average emission rate for Mode i (g/s);
f	= facility type index (principal arterials, minor arterials, local and collectors);
k	= speed mode index;
K	= the number of speed ranges;
k_f	= the combination of facility type and speed mode;
i	= VSP mode index;
I	= the number of VSP modes;
j	= link index;
J	= the number of links;
t_{i,j,k_f}	= time spent in VSP mode i on link j for speed mode k on the facility f (s);
T_{j,k_f}	= total travel time on link j for speed mode k on the facility f (s).

The observed speed profiles were classified into average speed ranges, in increments of 5 mph, ranging from 5 to 30 mph. Thus, there are five speed modes (K=5). Links with the same speed mode and facility type were grouped together. Inter-link variability in average emissions was computed using the coefficient of variation (CV), prior to aggregating average emission rates across links. Variability in link average emission rates were characterized with respect to facility type as well as mean link speed.

Given a mean link speed and facility type, total emissions for the link are estimated as the product of link average emission rate and link travel time:

$$TE_{k_f} = \overline{E}_{k_f} \times T_{k_f} \tag{5}$$

Where:

$\overline{E}_{k_f}$ = link average emission rate for speed mode k on the facility f (g/s);

T_{k_f} = link travel time for speed mode k on the facility f (s);

TE_{k_f} = total emissions for the link with speed mode k on the facility f (g).

Total emissions for a trip are estimated by summing emissions estimates from all links along the trip.

Speed profiles along bus routes by seven different vehicles were selected to form the model database in order to estimate speed- and facility- specific average emission rates. Since no or incomplete bus stop GPS coordinates were available for the other five bus routes, bus links along these those routes could not be identified.

4.3 Results and Discussion

The exploratory analysis was carried out to investigate the influence of factors that potentially affect transit bus emissions. A VSP-based approach to modeling pollutant emissions for diesel transit buses was also developed, validated and applied. Finally, speed- and facility- specific average emission rates estimates were estimated. VSP modal and link average speed-specific average emission rates were applied for comparison of their estimation capacities.

4.3.1 Exploratory Data Analysis

Spearman rank correlation coefficients between emissions and selected variables based upon individual buses data are shown in Table 1. The results indicate that percent throttle, fuel consumption, torque, oil pressure, VSP and acceleration are correlated with pollutant emissions from diesel transit buses. Corresponding p-values were less than .05 for these parameters. However, many of these variables such as percent throttle and torque can not be predicted in practice without having access to engine data, and therefore can not be integrated with outputs from transportation models. As a result, VSP was chosen as the most appropriate explanatory variable to use in developing emissions models for diesel transit buses. In addition, there are autocorrelation in second-by-second emission rates.

4.3.2 Vehicle Specific Power Modes and Modal Average Emission Rates

The relationship between VSP and emissions is investigated, modeled and validated in this section.

VSP Mode Definition and Modal Average Emission Rate Estimates

The relationship between VSP and emissions was initially explored through the use of plots of average emission rates for each strata of VSP in increments of 1 m^2/s^3 as illustrated for the CO_2 pollutant in Figure 1. Generally, there is a monotonic increase in emissions with positive VSP for all pollutants, with the possible exception of CO emission rates which tended to decrease when VSP values exceeded 10 m^2/s^3.

Two considerations were taken into account when determining the number of VSP modes: (a) modes should have significantly different average emission rates from each other; and (b) no single mode should dominate the estimate of total emissions. From these considerations, VSP values were categorized into eight modes as shown in Table 2. VSP Mode 1 includes idling. Modal average emission rates were initially estimated separately for each of twelve buses in order to investigate the inter-vehicle variability in emissions. For a given VSP Mode *i*, the ratio of the highest versus lowest modal average emission rates among 12 vehicles is calculated for each pollutant. The average inter-vehicle ratio among each of the 8 modes was 12.1, 6.3, 2.6 and 1.6 for HC, CO, NO_x and CO_2, respectively, indicating a large inter-vehicle variability in HC and CO emissions. In general, Buses 6, 9 and 10 had the lowest modal HC emission rates whereas Buses 11, 14 and 15 had the lowest modal CO emission rates. Fleet average modal emission rates were estimated as the averages from all 12 vehicles by VSP mode as shown in Figure 2.

CO emissions were found to be sensitive to bus acceleration. During heavy accelerations, more fuel is injected, which can lead to increased incomplete combustion that results, in turn, in high CO emissions (28). For all buses except for Buses 9, 10, 14 and 15, the average emission rates of CO for Mode 8 were lower than those of some other modes. This can be explained by low percentage of heavy acceleration events associated with VSP Mode 8 for those buses. As an example, based on data for Bus 1, only 3% of VSP Mode 8 data were for acceleration exceeding 3 mph/s. By contrast, for VSP Modes 6 and 7, there were 16% and 11% of data with accelerations exceeding 3 mph/s, respectively.

The data show a clear gradual increase in average emission rates with increasing VSP for CO_2 and NO_x. For HC, the average emission rate did not significantly increase with the VSP. The ratio of the highest to lowest modal average emission rates was calculated to evaluate variability in emissions accounted for by VSP modes. The ratio was 12.3, 7.2, 10.5 and 1.7 for CO_2, NO_x, CO and HC, respectively, which indicates that there is large inter-modal variability in CO_2, NO_x and CO emissions but smaller variability in HC emissions. High HC emission rates (g/bhp-hr) occurred at highly fuel lean equivalence ratios of less than 0.40 and more than 1.30 (25). However, equivalence ratio and VSP are weakly related. Thus, the VSP modal approach does not explain a large portion of the variability in HC emission rates. On the other hand, HC emission rates and total emissions from on-road diesel engines are small relative to gasoline engines.

Validation of VSP Modeling Approach

Total emissions estimates based upon validation data for each vehicle individually and all vehicles collectively were compared with the corresponding measured total emissions, and errors of estimates were calculated. Based upon the fleet validation dataset, the VSP modeling approach produced reasonable estimates for total pollutant emissions, with estimation errors of only 2.6% to 5.9% depending on the pollutant. The errors for individual vehicles ranged from -15.5% to 24.2%, -31.4% to 115.4%, -28.8% to 103.5%, and -55.5% to 839.6% for CO_2, CO, NO_x and HC, respectively. Thus, there is more variability in the error rates for individual vehicle than for a fleet average.

To evaluate the effect of autocorrelation on modal emissions models, a comparison was made based on using alternative consecutive averages. Since the average duration per modal event for each mode ranged from 1.2 seconds to 5.0 seconds for link speed profiles, the data were grouped into segments of consecutive two second averages, three second averages, as well as five second averages. The autocorrelation for each of the two, three and five second average data were estimated. For example, for NO_x, the autocorrelation coefficients at the second lag for Bus 1 data were 0.51, 0.39, 0.29 and 0.13 for 1, 2, 3 and 5 second averages, respectively. The average difference in modal emission rates among each mode for each pollutant was less than 5% when comparing second-by-second and consecutive averages. The average difference of estimation errors in total emissions estimated for 12 trip speed profiles is less than 1.3 % for CO_2, HC and NO_x, and less than 4.1% for CO when comparing the 2 or 3 or 5 second consecutive average-based models to the original modal model based on second-by-second data. Therefore, autocorrelation has no significant effect on predictions from the VSP modal emissions model. This is because the modal model "averages out" a large portion of the second-by-second autocorrelation.

4.3.3 Speed- and Facility- Specific Link Average Emission Rates Estimates

Time distributions of VSP modes of speed profiles were calculated for selected mean link speeds. Link average emission rates were estimated and evaluated.

Time Distributions of VSP Modes

Patterns of the VSP mode time distributions were compared and tested for similarity across links before data from numerous links having the same speed mode and facility type were combined. The coefficient of variation (CV) of the percent of time for each VSP mode was calculated to quantify the variability in time distributions of VSP modes for numerous link speed profiles. For example, the time distributions of VSP modes for link speed profiles on principal arterials were calculated for mean link speed ranging from 25 mph to 30 mph. For this interval, about 37 % of the time was spent in VSP Mode 1, and less than 12 % was spent in any other mode. The CV is 0.25 for VSP Mode 1 and ranges from 0.41 to 0.72 for other modes. CV's are typically larger when mean values are smaller.

Assessment of Inter-link Variability in Estimated Emission Rates

The time distribution of VSP modes was very similar among numerous links with the same mean speed mode and facility type. Subsequently, data from numerous links with the same attributes were combined to further estimate link average emission rates and their 95% confidence intervals. Table 3 shows that almost all the CVs of link average emission rates for numerous links in a given speed and facility bin and for all pollutants were less than 0.20, indicating a small variation in emission rates among multiple links for a given speed mode on a given facility type.

Given the similarities in the average emission rates for links in the same speed mode and facility type, these data were aggregated across links. Table 3 indicates that for a given facility type, the average emission rates of pollutants except for HC were found to be sensitive to variations in average link speed and could be expressed as a function of average link speed. For a principal arterial example, a speed range of 25 to 30 mph produces average time-based emission rates for CO_2, CO, NO and HC that are 44%, 43%, 39%, and 11% higher than the 10 to 15 mph range. As detailed in the supplemental information, ANOVA tests on the effects of facility type and mean speed on average emission rates showed that facility type is not a significant explanatory variable. Thus, data across facility type could be combined to reduce the statistical sampling error.

Time distributions of VSP modes and average emission rates from the combined dataset are shown in Figures 3 and 4, respectively. VSP Mode 1 dominated the link travel time for all speed bins. With an increase in link mean speed, the percent of time spent in Mode 1 decreased whereas the time spent in higher VSP modes increased. Link average emission rates were sensitive to the link mean speed, although HC mean emission rates showed less sensitivity than do emission rates for other pollutants. The ratio of the highest to the lowest link-based average emissions was about a factor of 2.0, 1.8, 1.7 and 1.2 respectively for CO_2, CO, NO_x and HC. Compared with the ratios of the VSP modal average emission rates, the variability of link-based average emissions explained solely by link mean speed was significantly lower, implying some loss of information associated with the use of a highly aggregate measure of vehicle activity such as mean speed. This result is consistent with findings from a study of gasoline light-duty vehicle emissions estimates (23).

4.3.4 Comparing VSP and Mean Link Speed Approaches in Predicting Trip-based Emissions

Total emissions for bus trips can be estimated based on either the VSP modal approach or mean link speed approach. Given second-by-second speed profiles, the VSP modal approach is applied to estimate total emissions using Equation (2) whereas the mean link speed approach has to be applied using Equation (5) if only mean link speeds are provided by a travel demand model outputs.

A comparison of both approaches was conducted to test their ability in predicting total trip emissions based on individual bus trip data, and fleet emissions for seven selected buses. Emissions estimation errors for both approaches are given in Table 4 at the individual bus and fleet level. For the fleet emissions estimates, errors were within $\pm 2\%$ for CO_2 and CO emissions, and about 18% for NO emissions and 35% for HC emissions. The relatively larger estimation error for HC emissions is related to the low proportion of variability explained by the VSP modes.

For individual vehicle trip emissions estimates, there was substantial inter-vehicle variability in the errors. For CO_2, errors for both methods were within $\pm$ 20% for each vehicle. For CO emissions, the estimation error ranged from -33% to 51%, except for Bus 14 which had an error of 120%. For NO emissions estimates, errors were within $\pm$ 30%, except for Buses 9 and 10, which had errors of 44% and 76%, respectively. For HC emissions, the errors ranged from -32% to 9% for most of the buses. The HC errors for Buses 6, 9, and 10 ranged from 150% to 215%. The low variability in HC modal emission rates resulted in large estimation error for trip emissions for some individual buses.

Because of high inter-vehicle variability in VSP modal average emission rates for HC, using the fleet average emission rates to predict individual vehicle total emissions can result in large estimate residuals. This implies that fleet average models are not appropriate for estimating emissions of individual vehicles. In general, although there was some loss of information associated with the use of highly aggregate measures of vehicle activity, both approaches produced reasonable and similar estimates of trip-based emissions at the fleet level.

4.4 Implications and Recommendations

Since most transportation demand models provide link-level statistics of vehicle activities, there is a need for an associated aggregated link emissions estimation method. The methodology described here enables the incorporation of real-world emissions and vehicle activity for diesel transit buses. VSP is a useful explanatory variable for variability in diesel bus emissions, especially for CO_2, NO_x and CO. Aggregated average emission rates based on the VSP approach are estimated in the link level, which are compatible with link vehicle activity outputs from TDMs. The comparison of VSP modal and link mean speed approaches to emissions estimation indicated that the use of highly aggregated measures of vehicle activity provided from TDMs such as link mean speed, can achieve reasonable emissions estimation at the fleet level. These types of link-based emission estimates from real-world activity and emissions data should be coupled with TDMs to improve the accuracy of emissions estimates. The methodology should be applied to additional speed ranges, faculty types, and vehicles based on additional data collection in the real world to confirm the trends uncovered in the transit bus sample used in this study.

4.5 Acknowledgements

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4.6 Supporting Information Available

Text, tables, and figures pertaining to typical speed profiles, comparisons of the cumulative distribution functions of speed and accelerations for calibration and validation datasets, relationship between VSP and emission rates, the effects of autocorrelation on modal emissions model, inter-vehicle variability in modal emission rates, the effects of acceleration on CO modal emission rates, validation of the VSP modal model, time distribution of the VSP modes for link speed profiles, and ANOVA application to test the effects of speed and facility type on link emission rates.

4.7 References

(1) Washington, S.; Guensler, R. *Modeling Air Quality for Conformity, Current Deficiencies, and New Directions*, Proceeding of the Transportation Research Committee Summer Conference, Porland, OR, **1994**:281-287.

(2) Niemeier, D.A.; Zheng, Y; Kear, T. UCDrive: A new gridded mobile source emission inventory model, *Atmos. Environ.* **2004**, 38 (2):305-319.

(3) Shorter, J.H.; Herndon, S.; Zahniser, M.S.; Nelson, D.D.; Wormhoudt, J.; Demerjian, K.L.; Kolb, C.E. Real-time Measurements of Nitrogen Oxide Emissions from In-use New York City Transit Buses Using a Chase Vehicle. *Environ. Sci. Technol.* **2005**, 39 (20):7991-8000.

(4) Shah, S.D.; Johnson, K.C.; Miller, J.W; Cocker III, D.R. Emission Rates of Regulated Pollutants from On-road Heavy-duty Diesel Vehicles, *Atmos. Environ.* **2006**, 40 (1):147-153.

(5) Prucz, J.C.; Clark, N.N.; Gautam, M.; Lyons, D.W. Exhaust Emissions from Engines of the Detroit Diesel Corporation in Transit Buses: A Decade of Trends, *Environ. Sci. Technol.* **2001**, 35 (9):1755-1764.

(6) Yanwitz, J.; Mccormick, R.L.; Graboski, M.S. In-use Emissions from Heavy-Duty Diesel Vehicles, *Environ. Sci. Technol.* **2000**, 34 (5):729-740.

(7) Kado, N.Y.; Okamoto, R.A.; Kuzmicky, P.A.; Kobayashi, R.; Alyala, A.; Gebel, M.E.; Rieger, P.L.; Maddox, C.; Zafonte, L. Emissions of Toxic Pollutants from Compressed Natural Gas and Low Sulfur Diesel-Fueled Heavy-Duty Transit Buses

Tested over Multiple Driving Cycles, *Environ. Sci. Technol.* **2005**, 39 (19):7638-7649.

(8) Frey, H.C.; Unal, A.; Chen, J.; Li, S.; Xuan, C. Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle & Equipment Emission System; EPA420-R-02-027, Prepared by North Carolina State University for U.S. Environmental Protection Agency, Ann Arbor, MI. August **2002**.

(9) Frey, H.C.; Unal, A.; Rouphail, N.M.; Colyar, J. On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument, *J. Air Waste Manage. Assoc.* **2003**, 53 (8):992-1002.

(10) Unal, A.; Rouphail, N.M.; Frey, H.C. Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions, *Transp. Res. Rec.* **2003**, 1842:47-56.

(11) Clark, Nigel N.; Kern, Justin M.; Atkinson, Christopher M.; Nine, Ralph D. Factors affecting heavy-duty diesel vehicle emissions, *J. Air Waste Manage. Assoc.* **2002**, 52 (1):84-94.

(12) Kean, Andrew J.; Harley, Robert A.; Kendall, Gary R. Effects of vehicle speed and engine load on motor vehicle emissions, *Environ. Sci. Technol.* **2003**, 37 (17):3739-3746.

(13) Clark, N. et al, A Predictive Tool for Emissions from Heavy-Duty Diesel Vehicles, *Environ. Sci. Technol.* **2003**, 37 (1):7-15.

(14) Weinblatt, Herbert; Dulla, Robert G.; Clark, Nigel N. Vehicle activity-based procedure for estimating emissions of heavy-duty vehicles, *Transp. Res. Rec.* **2003**, 1842:64-72.

(15) Grant, Christopher D.; Guensler, Randall; Meyer, Michael D. *Variability of heavy duty vehicle operating mode frequencies for prediction of mobile emissions*, Proceedings of the Air & Waste Management Association's Annual Meeting & Exhibition, 96-RA108A.05, **1996**.

(16) Barth, M ; An, F ; Norbeck, J ; Ross, M. Modal Emissions Modeling: A Physical Approach, *Transp. Res. Rec.* **1996**, 1520:81-88.

(17) Andrei, Paul. *Real World Heavy-duty Vehicle Emissions Modeling*, Master Thesis, West Virginia University, **2001**.

(18) Zhang, K; Frey, H.C. *Road Grade Estimation For On-Road Vehicle Emissions Modeling Using LIDAR Data*, *J. Air Waste Manage. Assoc.* **2006**, 56 (6):777-788.

(19) Yoon, Seungju ; Li, Hainan ; Jun, Jungwook ; Ogle, Jennifer H; Guensler, Randall L; Rodgers, Michael O. Methodology for Developing Transit Bus Speed–Acceleration Matrices for Load-Based Mobile Source Emissions Models. *Transp. Res. Rec.* **2005,** 1941:26-33.

(20) National Research Council, Modeling Mobile Source Emissions, National Academy Press, **2002**.

(21) Koupal, J.; Nam, E.; Giannelli, B.; Bailey, C. *The MOVES Approach to Modal Emission Modeling*, Presented at CRC On-Road Vehicle Emissions Workshop, March 29, **2004**.

(22) Jimenez-Palacios, J. Understanding and Quantifying Motor Vehicle Emissions and Vehicle Specific Power with TILDAS Remote Sensing, Doctoral Thesis to the

Department of Mechanical Engineering at Massachusetts Institute of Technology, **1999**.

(23) Frey, H.C.; Rouphail, N.M.; Zhai, H. Speed- and Facility-Specific Emission Estimates for On-Road Light-Duty Vehicles based on Real-World Speed Profiles, *Transp. Res. Rec.*. **2006**, 1987:128-137.

(24) Huai, Tao; Durmode, Thomas D.; Miller, J. Wayne; Pisano, John T.; Sauer, Claudia G.; Rhee, Sam H.; Norbeck, Joseph M. Investigation of NH_3 Emissions from New Technology Vehicles as a Function of Vehicle Operating Conditions, *Environ. Sci. Technol.* **2003**, 37 (21):4841-4847.

(25) Frey, H.C.; Unal, A.; Chen, J. *Recommended Strategy for On-board Emission Data Analysis and Collection for The New Generation Model*, Prepared by North Carolina State University for U.S. Environmental Protection Agency, Ann Arbor, MI. February, **2002**.

(26) City of Ann Arbor, Ann Arbor Geographic Information System, website: http://www.ci.ann-arbor.mi.us/GISOnline/index.html, Accessed on April 11, **2006**.

(27) U.S. Environmental Protection Agency, *EPA's Onboard Analysis Shootout: Overview and Results*, EPA420-R-02-026, October **2002**.

(28) Wang, W.G.; Lyons, D.W.; Clark, N.N.; Gautam, M. Emissions from Nine Heavy Trucks Fueled by Diesel and Biodiesel Blend without Engine Modification, *Environ. Sci. Technol.* **2000**, 34 (6):933-939.

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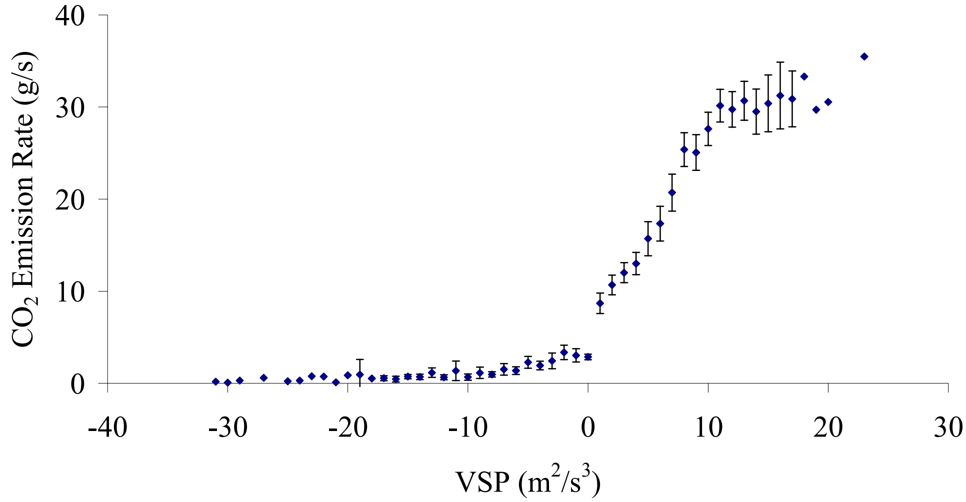

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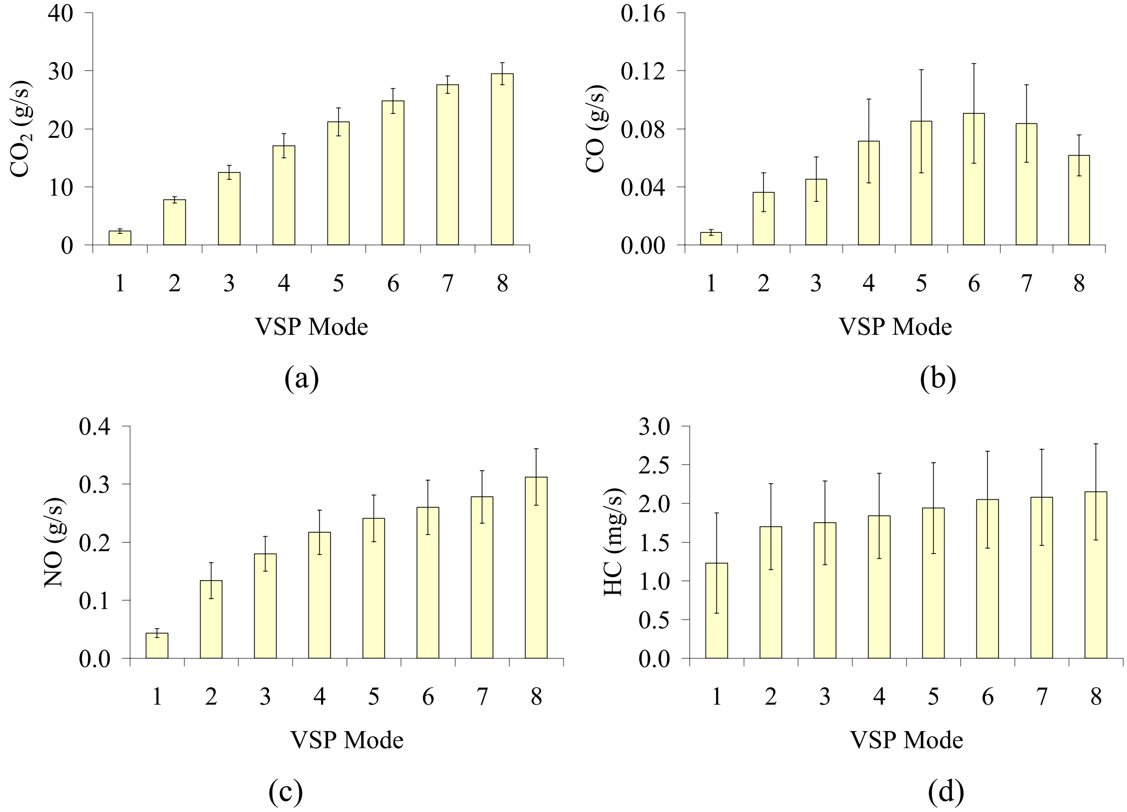

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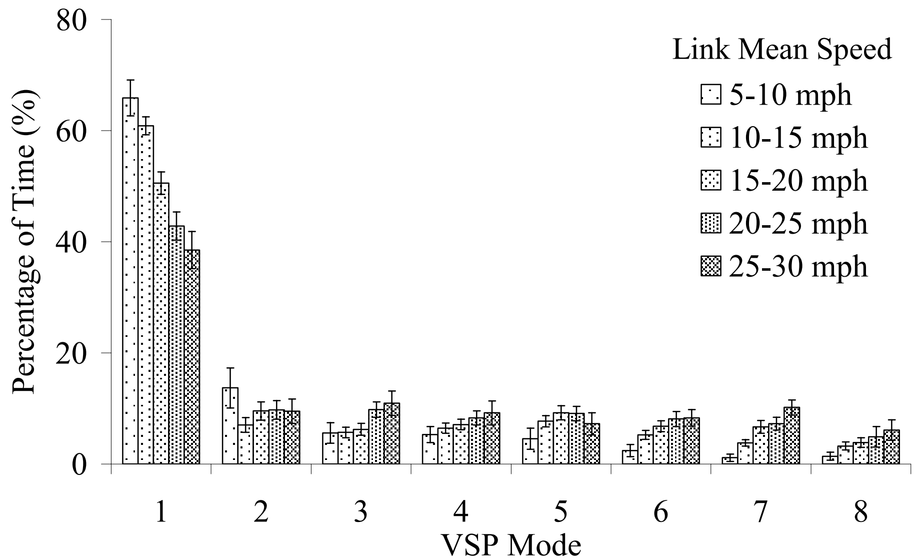

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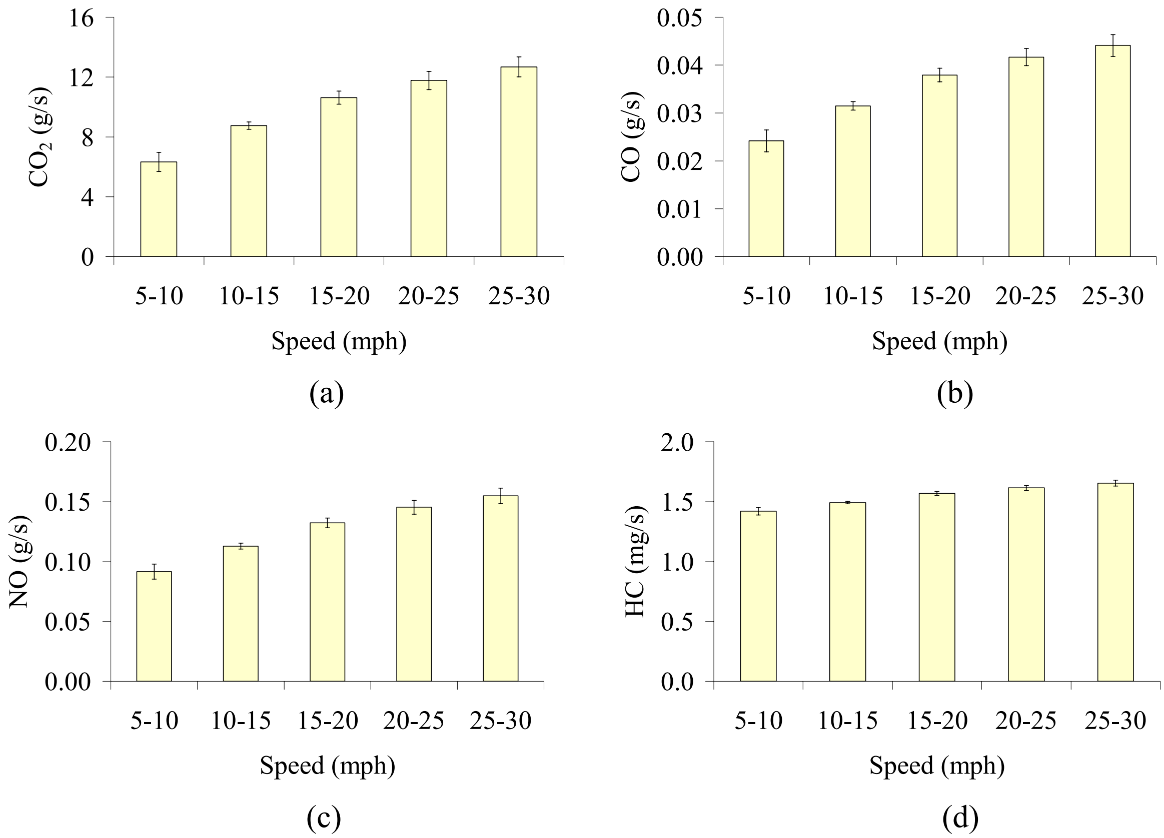

Figure 4. Link Mean Speed Specific Average Emission Rates with 95% Confidence Intervals on Mean based upon Data for 7 Buses for Which GPS Data Were Available

Table 1. Spearman Rank Correlation Coefficients of Pollutant Emission Rates versus Potential Explanatory Variable based upon Data for 12 Buses [a]

Potential Explanatory Variable	Pollutant			
	CO_2 (g/s)	CO (g/s)	NO (g/s)	HC (g/s)
Ambient temperature (˚C)	-0.08 (-0.18 [c], 0.05 [d])	0.08 (-0.04, 0.26)	-0.07 (-0.19, 0.07)	0.03 (-0.20, 0.39)
Ambient humidity (grains/lb)	-0.06 (-0.2, 0.02)	0.03 (-0.12, 0.22)	-0.07 (-0.19, 0.04)	-0.01 (-0.21, 0.26)
Road grade (%)	0.14 (0.06, 0.22)	0.02 (-0.04, 0.08)	0.15 (0.07, 0.24)	-0.03 (-0.18, 0.03)
Vehicle speed (mph)	0.44 (0.30, 0.57)	0.37 (0.05, 0.70)	0.35 (0.17, 0.53)	0.36 (-0.15, 0.69)
Vehicle acceleration (mph/s)	0.72 (0.59, 0.82)	0.55 (0.40, 0.70)	0.65 (0.54, 0.77)	0.34 (-0.19, 0.55)
Vehicle specific power[b] (m^2/s^3)	0.78 (0.73, 0.85)	0.53 (0.38, 0.65)	0.74 (0.64, 0.82)	0.33 (-0.18, 0.52)
Oil temperature (˚F)	0.04 (-0.06, 0.22)	-0.01 (-0.16, 0.1)	0.04 (-0.07, 0.19)	-0.06 (-0.34, 0.22)
Oil pressure (psi)	0.67 (0.33, 0.83)	0.65 (0.28, 0.8)	0.5 (0.25, 0.65)	0.56 (0.15, 0.79)
Coolant temperature (˚F)	0.07 (-0.11, 0.24)	-0.06 (-0.21, 0.07)	0.07 (-0.04, 0.23)	-0.09 (-0.44, 0.20)
Fuel flow rate (g/s)	0.93 (0.83, 0.99)	0.66 (0.46, 0.82)	0.90 (0.80, 0.95)	0.49 (-0.08, 0.79)
Percent throttle (%)	0.90 (0.84, 0.96)	0.72 (0.51, 0.84)	0.85 (0.76, 0.92)	0.54 (0.07, 0.79)
Torque (lbf-ft)	0.91 (0.81, 0.97)	0.61 (0.40, 0.79)	0.90 (0.78, 0.95)	0.44 (-0.10, 0.67)
RPM	0.72 (0.53, 0.85)	0.66 (0.42, 0.78)	0.55 (0.45, 0.66)	0.55 (0.09, 0.77)
Engine Output (bhp)	0.92 (0.82, 0.99)	0.64 (0.49, 0.80)	0.90 (0.81, 0.95)	0.47 (-0.08, 0.69)

[a] Average correlation coefficients based on second-by-second data of all vehicles.
[b] VSP is calculated from Equation (1).
[c] The minimum of correlation coefficients based on each vehicle.
[d] The maximum of correlation coefficients based on each vehicle.

Table 2. Definition of VSP Modes for Transit Buses

VSP Mode	VSP Range (m^2/s^3)
1	VSP $\leq$ 0
2	0<VSP<2
3	2 $\leq$ VSP<4
4	4 $\leq$ VSP<6
5	6 $\leq$ VSP<8
6	8 $\leq$ VSP<10
7	10 $\leq$ VSP<13
8	VS $\geq$ 13

Table 3. Speed- and Facility- Specific Link Average Emission Rates and Their Variability

Pollutant	Speed Range (mph)	Facility Type [a]								
		Principal Arterial			Minor Arterial			Collector and Local		
		Mean (g/s)	No. of Links	CV[b]	Mean (g/s)	No. of Links	CV[b]	Mean (g/s)	No. of Links	CV[b]
CO_2	5-10	-	-	-	-	-	-	6.3	15	0.18
	10-15	8.7	38	0.15	8.9	17	0.12	8.7	18	0.10
	15-20	10.7	39	0.17	10.4	12	0.16	10.6	13	0.16
	20-25	11.9	45	0.21	10.9	6	0.16	11.5	10	0.17
	25-30	12.5	20	0.14	13.1	7	0.11	-	-	-
CO	5-10	-	-	-	-	-	-	0.024	15	0.17
	10-15	0.031	38	0.14	0.032	17	0.13	0.032	18	0.11
	15-20	0.038	39	0.16	0.037	12	0.13	0.039	13	0.14
	20-25	0.042	45	0.17	0.037	6	0.15	0.042	10	0.17
	25-30	0.044	20	0.14	0.044	7	0.10	-	-	-
NO	5-10	-	-	-	-	-	-	0.092	15	0.12
	10-15	0.111	38	0.12	0.114	17	0.10	0.115	18	0.07
	15-20	0.132	39	0.13	0.131	12	0.12	0.135	13	0.12
	20-25	0.147	45	0.16	0.136	6	0.12	0.145	10	0.14
	25-30	0.154	20	0.12	0.156	7	0.08	-	-	-
HC	5-10	-	-	-	-	-	-	0.0014	15	0.04
	10-15	0.0015	38	0.04	0.0015	17	0.03	0.0015	18	0.02
	15-20	0.0016	39	0.04	0.0016	12	0.03	0.0016	13	0.04
	20-25	0.0016	45	0.05	0.0016	6	0.05	0.0016	10	0.05
	25-30	0.0017	20	0.04	0.0017	7	0.03	-	-	-

[a] "-" indicates that data were not available for this combination of average link speed and facility type.
[b] CV represents coefficient of variation of link emission rates across links.

Table 4. Estimated Errors in Predicted Total Emissions based on VSP and Mean Speed Approaches [a]

Bus Code	Total Measured Emissions for Vehicle (g)				Estimation Error (%)							
					VSP Approach [b]				Mean Speed Approach [c]			
	CO_2	CO	NO	HC	CO_2	CO	NO	HC	CO_2	CO	NO	HC
1	33900	164	544	4	1	-26	-22	9	-6	-31	-27	1
4	74500	450	1140	13	13	-33	-5	-1	18	-30	-3	0
6	66400	250	750	4	1	-7	16	149	6	1	20	152
8	78700	220	796	12	-14	12	7	-11	-16	8	7	-11
9	76800	225	607	5	-13	9	44	156	-14	7	43	156
10	64100	177	504	4	1	38	76	210	15	51	88	214
14	43800	69	466	9	5	121	23	-32	9	140	26	-30
Fleet	438200	1560	4810	51	-2	-1	16	35	1	2	18	35

[a] These predictions are based on bus trip data including both calibration and validation datasets.
[b] Estimation is based on Equation (2).
[c] Estimation is based on Equation (5).

PART V COMPARING REAL-WORLD FUEL CONSUMPTION FOR DIESEL- AND HYDROGEN-FUELED TRANSIT BUSES AND IMPLICATION FOR EMISSIONS ‡

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Abstract

This research explores the influence of key factors such as speed, acceleration, and road grade on fuel consumption for diesel and hydrogen fuel cell buses under real-world operating conditions. The effect of on-board passenger load on diesel bus fuel consumption is also assessed. A Vehicle Specific Power (VSP) based approach is used for modeling fuel consumption for both types of buses. In order to evaluate the robustness of the modeling approach, VSP-based modal average fuel consumption rates are compared for diesel buses in the United States and Portugal, and for the Portuguese diesel and hydrogen fuel cell buses that operate on the same route. For diesel buses in both countries, there is similar intra-vehicle variability in fuel consumption using VSP modes. For the fuel cell bus, the hydrogen fuel consumption rate was found to be less sensitive to VSP variations and had smaller variability compared to diesel buses. Relative errors between trip fuel consumption estimates and actual fuel use, based upon predictions for a portion of real-world activity data that were not used to calibrate the models, were generally under 10% for all observations. The VSP-based modeling approach is recommended for further applications as additional data become available. Emission changes based upon substituting hydrogen versus diesel buses are also evaluated.

Key Words: Fuel consumption, Emissions, Diesel bus, Hydrogen fuel cell bus, Comparison, Modeling, Vehicle specific power, Passenger load.

5.1 Introduction and Background

There is growing interest in the use of alternative fuels and propulsion systems for highway vehicles. Among highway vehicles, transit buses have been a focal point for development of zero- and near-zero-emissions fuel cell technology (Eudy *et al.*, 2001). Thus, there is a need to characterize baseline fuel use of conventional diesel transit buses and to develop a consistent methodology that can be used to compare buses of various fuel types and propulsion systems.

Bus fuel consumption and efficiency are highly dependent on vehicle and engine attributes. Passenger load, travel speed, the number of stops, road grade and the frequency of traffic interruptions affect fuel consumption (Ang *et al.*, 1989). Quantitative exploration of the effects of these factors on fuel consumption is needed in order to develop methods and strategies for fuel consumption prediction and fuel economy improvement.

Two general approaches are usually considered in modeling fuel consumption and emissions: physically-based analytical models and empirically-based models. Examples of physically-based modeling approaches applicable to transit buses include EcoGest and the Physical Emissions Rate Estimator (PERE). The main inputs of EcoGest include vehicle characteristics, number of passengers, roadway characteristics and a synthetic speed profile. EcoGest is capable of estimating instantaneous as well as trip average fuel consumption and emissions (Silva *et al.*, 2006). PERE uses vehicle parameters and second-by-second driving traces as input, and estimates second-by-second fuel consumption rates (Nam *et al.*, 2005). PERE is based upon the assumption that fuel consumption rates for diesel and gasoline vehicles, such as passenger cars and diesel buses, are determined by Vehicle Specific Power (VSP), engine speed, engine displacement volume, vehicle mass, and other factors.

The empirically-based modal approach is exemplified by the MOVES2004 model released by the U.S Environmental Protection Agency (EPA). MOVES2004 can estimate energy consumption for transit buses (EPA, 2005). Power demand is a key variable that explains fuel consumption and emission rates (Jimenez-Palacios, 1999). VSP, a surrogate for power demand, has been used for emissions estimation for light-duty gasoline vehicles and diesel transit buses (Frey *et al.*, 2002 and Zhai *et al.*, 2006). MOVES2004 and PERE are complementary models. Where possible, MOVES2004 is based on second-by-second measurements of vehicle fuel use and emissions obtained either using dynamometers in a laboratory or from real-world measurements from Portable Emissions Measurement Systems (PEMS). Where such data are not available, PERE may be used to fill data gaps in MOVES2004 energy consumption rates.

An example of the use of PEMS data was a study conducted by EPA, where city transit buses operated by the Ann Arbor Transit Authority (AATA) were monitored. Both fuel consumption and emission measurements were taken while buses were driven on their established routes (EPA, 2002).

Hydrogen fuel cell buses have been proposed as an environmentally-friendly alternative to conventional buses, since they have the potential for eliminating tailpipe emissions (Vandenborre *et al.*, 1996). The Clean Urban Transport for Europe (CUTE) project encompassed the implementation and evaluation of both a hydrogen fuel infrastructure and fuel cell vehicles in nine participating European cities (Haraldsson *et al.*, 2005). While life cycle-based evaluation models of hydrogen-fueled vehicles, such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, have been reported (Wang, 2001), few studies regarding fuel consumption and emissions reductions under real-world traffic conditions have been carried out.

5.2 Research Objectives

The principal objectives of this research are to: (a) evaluate factors that significantly affect transit bus fuel consumption under real-world operating conditions; (b) propose a conceptual approach for modeling vehicle specific fuel consumption at a micro-scale taking into account key operational factors; (c) assess differences in fuel consumption for diesel buses in the United States and Portugal in order to evaluate the transferability of the modeling approach; (d) compare fuel consumption for diesel and hydrogen fuel cell buses that operate on identical routes; and (e) estimate emission changes from substitution of hydrogen-fueled buses for diesel buses.

5.3 Database and Description

The bus databases used in this study came from two sources: (1) data provided to the research team by EPA that were collected in cooperation with the Ann Arbor Transportation Authority (AATA) for 12 diesel transit buses; and (2) data collected in the city of Porto, Portugal as part of the CUTE project and provided by the Instituto Superior Técnico (IST) of Lisbon, Portugal, for both diesel and hydrogen fuel cell buses.

5.3.1 AATA Database

On-board data for diesel transit buses in Ann Arbor were gathered using PEMS installed on 12 diesel transit buses, while they traveled on their regular routes (EPA, 2002). The routes differed by vehicle, since a particular vehicle typically had a unique route assignment. The tested buses included New Flyer models with Detroit Diesel Series 50 engines. All buses weigh 12 tons and have 8.5 liter engines. Four of these vehicles are 1995 model year and the others are 1996 model year. The PEMS used was a SEMTECH-D manufactured by Sensors, Inc. The PEMS includes (a) an engine scanner for recording data from the vehicle's electronic control module (ECM); (b) a GPS unit for recording vehicle position and altitude; (c) gas analyzers for measuring pollutant concentrations in the exhaust; (d) exhaust probe and sample hose; (e) weather probe; and (f) a computer for combining these data streams into one file and estimating emission rates on a mass per time basis. The ECM provided real-time volumetric fuel consumption rate data that were converted to a mass flowrate. From the exhaust concentration data, fuel-based pollutant emission rates can be estimated (i.e. in terms of mass of pollutant per mass of fuel consumed). The latter two quantities are multiplied to arrive at mass per time emission rates. The data for the AATA buses are reported on a second-by-second basis. There are 2520 to 8640 seconds of observations for each of the twelve buses.

5.3.2 Porto Database

For both diesel and fuel cell buses, the tested bus routes in Porto have substantial road grades (up to 10%) and low average speed. The route length is 7.8 km and is entirely urban.

Data were collected on one line of the Sociedade de Transportes Colectivos do Porto (STCP) network. This route is circular without a terminal stop and has constant circulation. Data were collected for both vehicles on one day from approximately 6:30 AM to 6:00 PM, which covered a variety of traffic conditions. One hydrogen fuel cell bus and one diesel bus traveled on this route, in the same direction, during the same time period and from the same starting point under similar ambient conditions.

The Porto diesel bus tested in 2004 is a 2002 Mercedes Citaro with a 12 liter engine. The bus weight was 11.5 tons. There were 14 measured trips for the diesel bus. The bus was equipped with a second-by-second data collection measurement system that consisted of a fuel flowmeter, a command/display unit, a data acquisition board and a laptop computer. Vehicle dynamics were recorded, including vehicle speed and fuel consumption rate. A global positioning system (GPS) unit with a barometric altimeter was used to track the route and its topography. The monitoring system allowed the bus to run its regular route, with minimal interference to its normal duty cycle. Passenger counts were manually recorded.

The tested fuel cell bus was a small series production Mercedes Citaro that weighs approximately 14 tons. Two fuel cell stacks were fed from 350 bar compressed hydrogen storage that had a combined power of 300 kW. Electric current was sent to a 200 kW electric engine that drove a conventional gearbox. The bus was not a hybrid. The minimum power output of the fuel cell was approximately 25 kW. During idling and low loads, some power was dumped into a cooling system. This arrangement is clearly not the most efficient, but was adopted in order to simplify the vehicle design and ensure the reliability needed for regular operation for purposes of a demonstration vehicle. There were 11 measured trips.

For each trip, vehicle speed, fuel consumption rate and controller area network (CAN) motor RPM were recorded twice per second.

Each of the AATA diesel buses, Porto diesel bus, and Porto hydrogen fuel cell bus databases were divided into a calibration and validation dataset. The calibration data sets were used to develop VSP-based modal fuel consumption models. The models were applied to the activity data of the validation datasets to predict fuel consumption, and the predicted and actual fuel consumption were compared in order to quantify the error in the model estimates. Overall, about 60 to 70% of data for each type of vehicle were used for model calibration. For the AATA diesel database, eight buses were selected for the calibration dataset and four buses were selected for the validation dataset. These data sets have similar distributions of vehicle speed, acceleration and road grade. For the Porto diesel bus, nine trips were selected for the calibration dataset and five trips were selected for the validation dataset. For the Porto fuel cell bus, eight trips were selected for calibration and three trips were selected for validation. For the Porto buses, each of the calibration and validation datasets for both vehicles included trips that occurred in the morning and the afternoon. Therefore, these latter datasets incorporate a similar range of traffic and environmental conditions.

5.4 Methodology

The methodology consisted of: (a) conducting an exploratory analysis to assess the relationships between fuel consumption and factors that significantly affect it; (b) developing a VSP-based approach for estimating fuel consumption at a micro-scale level; (c) comparing fuel consumption between different vehicles for a given fuel (i.e. diesel); (d) comparing fuel consumption between buses with differing fuel types; and (e) developing fuel-based emission factors to evaluate tailpipe emission reductions for hydrogen-fueled buses.

5.4.1 Exploratory Analysis

Various trip-based factors affect the amount of fuel that is consumed during a vehicle's real-world duty cycle. These include speed, acceleration and road grade. In addition, passenger load on transit vehicles could impact fuel consumption. Spearman's rank correlation is used to assess whether a statistically significant monotonic relationship exists between fuel consumption and each of these factors. In addition, fuel consumption rates for diesel buses are stratified into categories according to speeds and on-board passenger load to compare fuel consumption for different passenger loads at a given range of speed. The key variables affecting vehicle fuel consumption identified in the exploratory analysis constituted the basis for the development of a modeling approach.

5.4.2 Vehicle Specific Power-based Approach

VSP takes into account aerodynamic drag, tire rolling resistance and road grade. VSP is generally defined as power per unit mass of the vehicle and is a function of vehicle speed, acceleration, and road grade. VSP for transit buses were estimated based on typical coefficient values that are representative of the types of buses that are analyzed here (Andrei, 2001 and Zhai *et al.*, 2006):

$$VSP = v \times (a + g \times \sin(\varphi) + 0.092) + 0.00021 \times v^3 \tag{1}$$

Where: *VSP* is vehicle specific power (m^2/s^3); v is the instantaneous speed at which the vehicle is traveling (m/s); a is the instantaneous acceleration of the vehicle (m/s^2); and φ is instantaneous road grade (decimal fraction); 0.092 is the rolling resistance term coefficient; and 0.00021 is the drag term coefficient. VSP was estimated for each second of measured in-use data.

The in-use data were stratified based on ranges of VSP in order to define VSP-based modes. Average fuel consumption rates were calculated for each mode. Two considerations were taken into account when determining the number of discrete VSP modes: (a) each mode should produce an average fuel consumption rate that is statistically different from any other mode; and (b) no single mode should dominate the estimate of total fuel consumption. These criteria yielded a total of eight VSP modes. The definition of each mode is given in Table 1 (Zhai *et al.*, 2006). Although the modal definitions were developed based on data from the AATA buses, the same mode definitions were used for all buses (including those from Porto) in order to facilitate comparisons. The same approach was adopted for all calibrations.

The calibration data were utilized to estimate VSP-based modal average fuel consumption rates, and trip-based fuel consumption. The later was estimated as:

$$E = \sum_{j=1}^{J} FR_j \times TVSP_j \qquad (2)$$

Where: E is total trip fuel consumption (in liters for diesel buses; in grams for hydrogen buses); j is VSP mode index, J= the number of VSP modes (J= 8 for diesel buses and 6 for hydrogen buses as explained later); FR_j is fuel consumption rate for VSP mode *j* (l/s for diesel bus; g/s for hydrogen bus); and $TVSP_j$ is the bus trip time spent in VSP mode *j*.

For purposes of model validation, the total trip fuel consumption was estimated based upon the validation datasets for AATA buses, and Porto diesel and hydrogen buses. Trip-based fuel consumption estimation errors were quantified through comparisons with measurements of total fuel consumed.

The magnitude and variability in average fuel consumption between AATA and Porto diesel buses, and between the Porto diesel and hydrogen fuel cell bus are compared. In order to compare fuel consumption for diesel and hydrogen fuels, the fuel consumption for diesel was converted to an equivalent hydrogen-basis. The conversion was done based on lower heating values of 120 MJ (MegaJoule) per kilogram for hydrogen and 35.7 MJ per liter for diesel (Chandler, *et al.*, 2006).

5.4.3 Implication for Emissions

The effect of substituting diesel buses with hydrogen-fueled buses on air quality was evaluated based upon the estimation of fuel cycle and tailpipe emissions. Fuel cycle refers to the "well-to-pump" stage commonly referred in fuel life cycle analysis. Currently, the most likely fuel pathway for producing hydrogen is steam reforming of natural gas. The GREET model was used to estimate fuel cycle energy consumption in units of Btu per MMBtu of hydrogen or diesel and emissions of volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2) in units of gram per MMBtu for both hydrogen and diesel fuels (Wang, 2001). The diesel fuel cycle emissions rates were converted to an equivalent hydrogen-basis for emission comparisons.

In a previous study, tailpipe average emission rates in grams per second were estimated for hydrocarbons (HC), CO, NO_x, and CO_2 using a VSP binning approach based upon the AATA database (Zhai *et al.*, 2006). VSP modal average fuel consumption rates in liters per second were also estimated. Fuel-based average emission rates were developed using time-based emission rates divided by corresponding fuel consumption rates. Fuel-based average emission rates for diesel buses were further converted to an equivalent hydrogen-basis to evaluate emission tailpipe reductions by substituting hydrogen-fueled for diesel buses.

Only one real-world driving cycle in the hydrogen-fueled bus database was used to evaluate differences in energy consumption and differences in emissions based on substitution of a hydrogen for diesel bus.

5.5 Results and Discussion

The methodology was applied to the diesel and fuel cell bus data.

5.5.1 Exploratory Analysis Results

The exploratory analysis was applied to the combined dataset. Table 2 shows Spearman correlation coefficients for fuel consumption rate and selected explanatory factors for all tested vehicles. All p values are less than 0.05, indicating that all correlation coefficients are statistically significant. Speed and acceleration are highly correlated with fuel consumption for both diesel and hydrogen fuel cell buses. The correlation coefficients for speed and fuel consumption rates are higher for diesel than for hydrogen buses, indicating a stronger effect for the former. Road grade is weakly correlated with fuel consumption for both types of buses.

The effect of on-board passenger load was explored for one diesel bus because such data were only available in Porto. Five speed bins (including idle) and three levels of on-board passenger load defined speed and passenger load categories. As shown in Figure 1, passenger load has a significant effect on fuel consumption, particularly at the middle and high speed ranges. However, as expected, passenger load has almost no effect on fuel consumption during idling, or under very low speeds (≤ 10 km/h).

5.5.2 Fuel Consumption Modeling Results Using VSP Approach

Real world speed profiles, from which vehicle acceleration can be estimated, were combined with road grade data from the vehicle routes in order to estimate second-by-second VSP using Equation (1). Dynamic fuel consumption rates were grouped into micro-VSP bins of size 1 m^2/s^3 to ascertain their relationship to VSP for both diesel and hydrogen fuel cell buses. As shown in Figures 2a and 3a, average fuel consumption rates are similar when VSP values are less than zero; however, an approximately monotonic increase in fuel consumption rate is noted for both diesel and fuel cell buses, as VSP increases up to a critical value of about 10 m^2/s^3. Beyond that point, changes in average fuel consumption rate dampen considerably while the variability significantly increases. The vertical lines in Figures 2 and 3 represent 95% confidence intervals (CI) on the mean. The widest fuel consumption rate confidence intervals are associated with high VSP values because few such samples are available in the calibration dataset.

VSP-based modal model

Using the 8 VSP modes in Table 1, a driving pattern was modeled according to the distribution of time spent in each VSP mode. Average fuel consumption rates corresponding to each of the VSP modes were estimated for the diesel and fuel cell buses based upon the individual calibration datasets. These estimates are depicted in Figures 2b and 3b. In general, average modal fuel consumption estimates increase monotonically with VSP, although there is an exception for Mode 8 for the Porto diesel bus. For the hydrogen fuel cell bus, VSP modal average fuel consumption rates are statistically indistinguishable for Modes 6 and higher. The ratio of the highest to lowest mean value among the modes is 10.8, 10.3 and 4.4, respectively, for AATA diesel buses, the Porto diesel bus, and the Porto fuel cell bus. A large ratio indicates larger inter-modal variability in fuel consumption over the course of the trip.

Trip-based fuel consumption was estimated based upon calibration datasets. The R^2 values for the VSP-based models for the calibration data are 0.70 for AATA diesel buses, 0.90 for the Porto diesel bus, and 0.61 for the Porto hydrogen fuel cell bus. Thus, the VSP-based approach is able to explain a substantial portion of the short-term variability in fuel consumption.

VSP-based model validation

The ability of the VSP modal method to predict total fuel consumption for a trip was evaluated. The calibration dataset was used to estimate mode-specific fuel consumption rates and the validation dataset is used to evaluate the predictive ability of the VSP model. For the fuel cell bus, modes 6 through 8 were combined into one mode with VSP $\geq$ 8 m^2/s^3 because of similarity in average fuel consumption. Based on the time spent in each of the VSP modes in a given trip, total trip fuel consumption was estimated using Equation (2). The prediction errors between measured and predicted total trip fuel consumption are summarized in Table 3. For AATA diesel buses, the errors range from -9.5% to 10.6%. For the Porto diesel bus, the errors range from -8.7% to 9.0%, whereas for the hydrogen fuel cell bus, the errors range from -0.8% to 2.6%. These errors are considered to be reasonable and indicate that the VSP approach is capable of providing good predictions of trip-based fuel consumption for transit buses that span various engine technologies.

VSP and passenger load

The calibration data from the Porto bus for which passenger counts were available were used to develop a VSP-based model that is further stratified by ranges of passenger load. As shown in Figure 4, with the exception of Modes 1 and 2, higher passenger loads result in higher fuel consumption, especially at the higher VSP modes. Total trip fuel consumption was estimated based on both the fraction of time spent in each VSP and associated passenger load mode. As shown in Table 3, the trip prediction errors range from

-6.4% to 4.4%, which are reasonable and consistently lower than the range of errors obtained by the VSP-only approach (-7.3% to 9%).

Fuel consumption based upon VSP modeling

Modal fuel consumption rates were compared among the diesel buses. Figure 2b shows that both the AATA diesel buses and the Porto diesel bus exhibit similar trends. For example, modal average emission rates increase with increasing VSP mode. For 3 of the 8 modes, the average fuel consumption rates are not statistically significantly different. For 6 of the 8 modes, the difference in average fuel consumption rate between the AATA and Porto buses is less than 15 percent. Thus, for most modes, the differences are not substantial even if they are statistically significant. Therefore, the fuel consumption rates for the AATA and Porto buses appear to be similar.

A comparison of modal fuel consumption rates between the Porto diesel and fuel cell buses is shown in Figure 3b. Overall, the hydrogen bus fuel consumption rates are less sensitive to high values of VSP. However, they are larger than the diesel fuel consumption rates at low VSP values but lower at high VSP values. The fuel cell bus weighs approximately two tons more than the diesel bus, and dumps power at low loads in order to maintain a minimum fuel cell power output. This accounts for the higher fuel consumption in lower VSP modes. The fuel cell bus tested here was designed to demonstrate the reliability of system components but was not optimized for efficiency. However, when operating at higher VSP values, the fuel cell bus appears to have higher efficiency. For this particular application, VSP Mode 1 plays an important role because it includes idling and coasting - two important driving modes in urban buses. Therefore, small differences in Mode 1 can have direct impacts on the overall performance of a given transit bus on an urban route.

5.5.3 Emissions Evaluation

Fuel cycle and vehicle energy use and emissions, and their differences, for both hydrogen and diesel fueled buses are given in Table 4. Since hydrogen is a carbon-free fuel, hydrogen fuel cell vehicles produce only pure water as exhaust (Colella *et al.*, 2005). Modal tailpipe emissions of the AATA buses are quantified elsewhere (Zhai, *et al.*, 2006). Tailpipe emissions reductions achieved by replacing conventional diesel buses with hydrogen-fueled buses are quantified, as are differences in fuel cycle emissions. The estimated change in energy consumption is also given. The results indicate that substituting hydrogen produced from steam reforming of methane versus diesel as the basis for transit bus service may result in an increase in energy consumption and CO_2 emissions but substantial decreases in HC, CO, and NO_x emissions as well as particles (although not addressed within the present study). The fuel cycle emissions for hydrogen (H_2) product might be reduced in the future pending alternative technologies, with a possible cost trade-off.

5.6 Conclusions

The VSP approach, which integrates the effects of speed, acceleration, and road grade, into a single parameter, is able to explain a substantial portion of variability in fuel consumption. Relative variations in the VSP-based modal average fuel consumption for AATA buses in the US and the Porto diesel buses in Portugal were found to be similar. VSP-based modal average fuel consumption for the hydrogen fuel cell bus had smaller relative variability when compared to diesel buses. However, the fuel cell bus was not optimized for fuel economy, and thus additional work is needed to characterize fuel cell buses as the technology improves.

The VSP modal approach was shown to produce trip fuel consumption estimates that are accurate to within plus or minus 10%. The modal approach can be improved by further stratification based on passenger load, where such data are available.

The VSP-based modal approach is useful for characterizing bus trips and their fuel consumption. This approach should be further evaluated by application to a larger number of vehicles, as well as to a variety of fuel and propulsion systems. Furthermore, the VSP-based approach is a practical means via which to evaluate the effect of driving patterns on total fuel consumption and thus could be used to support policy analyses aimed at improving real-world fuel economy and air quality. Since the results here are based on a very small number of buses, data for more buses are needed.

Overall fuel cycle and vehicle energy consumption may increase if diesel fuel is replaced with hydrogen obtained from steam reforming of methane. Although CO_2 emissions may increase, substitution of hydrogen versus diesel buses may significantly decrease emissions of CO, NO_x and HC. The comparison among the various buses analyzed here is based on only one driving cycle. Empirical data and analytical comparisons are needed for additional driving situations.

5.7 Acknowledgements

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5.8. References

Andrei, P. (2001), "Real World Heavy-Duty Vehicle Emissions Modeling," Master's thesis, West Virginia University, Morgantown, WV.

Ang, B.W. and T.F. Fwa (1989), "Study on the fuel-consumption characteristics of public buses," *Energy (Oxford)*, 14(12):797-803.

Chandler, K. and L. Eudy (2006), "Santa Clara Valley Transportation Authority and San Mateo County Transit District," Report NREL/TP-540-39365, National Renewable Energy Laboratory, March.

Colella, W.G., M.Z. Jacobson and D.M. Golden (2005), "Switching to A U.S. Hydrogen Fuel Cell Vehicle Fleet: The Resultant Change in Emissions, Energy Use, and Greenhouse Gases," *Journal of Power Sources*, 150(1-2):150-181.

EPA (2002), "On-Road Emissions Testing of 18 Tier 1 Passenger Cars and 17 Diesel Powered Public Transportation Buses," EPA420-R-02-030, Environmental Protection Agency, Ann Arbor, MI, October.

EPA (2005), "A Roadmap to MOVES2004," EPA420-S-05-002, Environmental Protection Agency, Ann Arbor, MI, March.

Eudy, L. and R. Parish (2001), "Hydrogen Fuel Cell Bus Evaluation," *Proceedings of the 2001 DOE Hydrogen Program Review*, NREL/CP-570-30535, April.

Frey, H.C., A., Unal, J. Chen, S. Li and C. Xuan (2002), "Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission System," EPA420-R-02-027, Prepared by North Carolina State University for U.S. Environmental Protection Agency, Ann Arbor, MI, August.

Haraldsson, K., A Folkesson and P. Alvfors (2005), "Fuel Cell Buses in the Stockholm CUTE Project - First Experiences from A Climate Perspective," *Journal of Power Sources*, 145(2):620-631.

Jimenez-Palacios, J. (1999), "Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing," PhD Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Nam, E.K. and R.A. Giannelli (2005), "Fuel Consumption Modeling of Conventional and Advanced Technology Vehicles in the Physical Emission Rate Estimator (PERE)," EPA420-P-05-001, Environmental Protection Agency, Ann Arbor, MI, February.

Silva, C.M., T.L. Farias, H.C. Frey and N.M. Rouphail (2006), "Evaluation of Numerical Models for Simulation of Real-World Hot-Stabilized Fuel Consumption and Emissions of Gasoline Light-Duty Vehicles," *Transportation Research Part D: Transport and Environment*, 11(5):377-385.

Vandenborre, H. and R. G. Sierens (1996), "A Hydrogen Fuelled City Bus," *International Journal of Hydrogen Energy*, 21(6):521-524.

Wang, M.Q. (2001), "Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies," ANL/ESD/TM-163, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Argonne, IL, June.

Zhai, H., H.C. Frey and N.M. Rouphail (2006), "Speed and Facility-Specific Emissions Estimates for Transit Buses based on Measured Speed Profiles," *Proceedings, Annual Meeting of the Air & Waste Management Association*, New Orleans, LA, June 20-23.

Table 1. Definition of Vehicle Specific Power (VSP) Modes

VSP Mode	VSP Range(m^2/s^3)	VSP Mode	VSP Range(m^2/s^3)
1	$VSP \leq 0$	5	$6 \leq VSP<8$
2	$0<VSP<2$	6	$8 \leq VSP<10$
3	$2 \leq VSP<4$	7	$10 \leq VSP<13$
4	$4 \leq VSP<6$	8	$VSP \geq 13$

Source: Reference (Zhai *et al*., 2006).

Table 2. Spearman Rank Correlation for Fuel Consumption Rates versus Selected Factors based upon the Combined Trip Database

Data Source	Fuel Type	Speed	Acceleration	Road Grade
AATA	Diesel	0.59	0.66	0.11
Porto	Diesel	0.79	0.32	0.10
	Hydrogen	0.49	0.40	0.21

Table 3. Summary of Trip Fuel Consumption Prediction Errors for the Validation Datasets

Data Source	Fuel Type (units)	Trip Code	Measured Trip Fuel Consumption	Fuel Consumption Prediction Error	
				VSP Approach	VSP and Passenger Load Approach
AATA	Diesel (l)	1	13.09	0.8%	N/A
		5	26.05	10.6%	N/A
		8	31.19	-9.5%	N/A
		14	19.37	3.4%	N/A
Porto	Diesel (l)	3	3.96	9.0%	0.6%
		6	5.45	-7.3%	0.3%
		9	5.82	-8.7%	-6.4%
		12	5.85	-2.3%	4.4%
		14	4.67	2.2%	0.04%
	Hydrogen (kg)	3	1.89	-0.8%	N/A
		6	1.66	2.6%	N/A
		9	1.86	-0.8%	N/A

Note: "-" represents underestimate; and "N/A" represents no data available.

Table 4. Comparison of Energy and Emissions based on Fuel Cycle and Tailpipe Emissions: Hydrogen versus Diesel Bus

Energy or Pollutant	Stage	Energy or Average Emission[c]		Overall Change (%)
		Hydrogen	Diesel	
Energy (MMBtu/cycle)	Fuel cycle	0.136	0.033	+51.4%
	Driving cycle	0.185	0.179	
	Fuel Cycle + Driving Cycle	0.321	0.212	
CO_2 (g/g H_2-eq[a])	Fuel cycle	12.5	1.6	+11.6%
	Tailpipe	0.0	9.6	
	Fuel cycle + Tailpipe	12.5	11.2	
CO (10^{-2} g/g H_2-eq)	Fuel cycle	0.33	0.13	-91.6%
	Tailpipe	0.00	3.80	
	Fuel cycle + Tailpipe	0.33	3.93	
NO_x (10^{-1} g/g H_2-eq)	Fuel cycle	0.07	0.04	-95.5%
	Tailpipe	0.00	1.50	
	Fuel cycle + Tailpipe	0.07	1.54	
HC[b] (10^{-3} g/g H_2-eq)	Fuel cycle	1.4	0.9	-65.0%
	Tailpipe	0.0	3.1	
	Fuel cycle + Tailpipe	1.4	4.0	

[a] g H_2-eq refers to the energy-equivalent mass of hydrogen in grams, when comparing diesel and hydrogen fuels.

[b] HC average emission in fuel cycle only refers to volatile organic compounds.

[c] Estimates of energy consumption and emissions of the fuel cycle for hydrogen derived from steam reforming of natural gas and for diesel fuel are based upon the GREET model (Wang, 2001). In-use vehicle energy consumption is estimated based on the modal fuel use models of this paper, applied to a typical driving cycle in Porto, Portugal. The tailpipe emissions for the diesel buses are estimated from the modal emissions model of Zhai, *et al.* (2006).

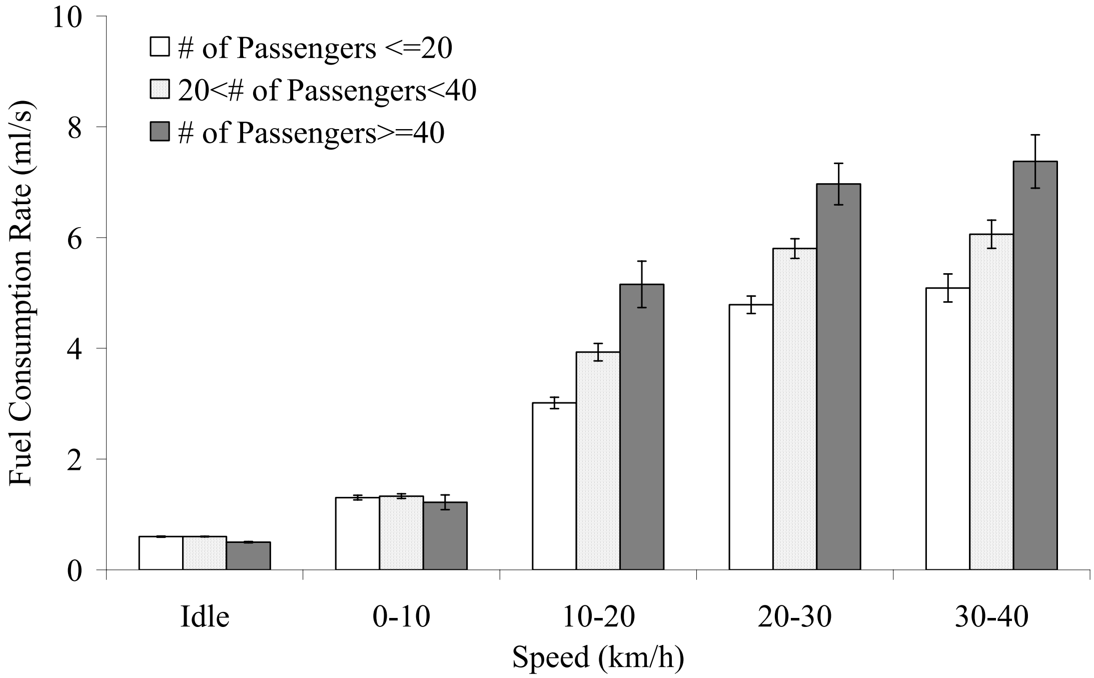
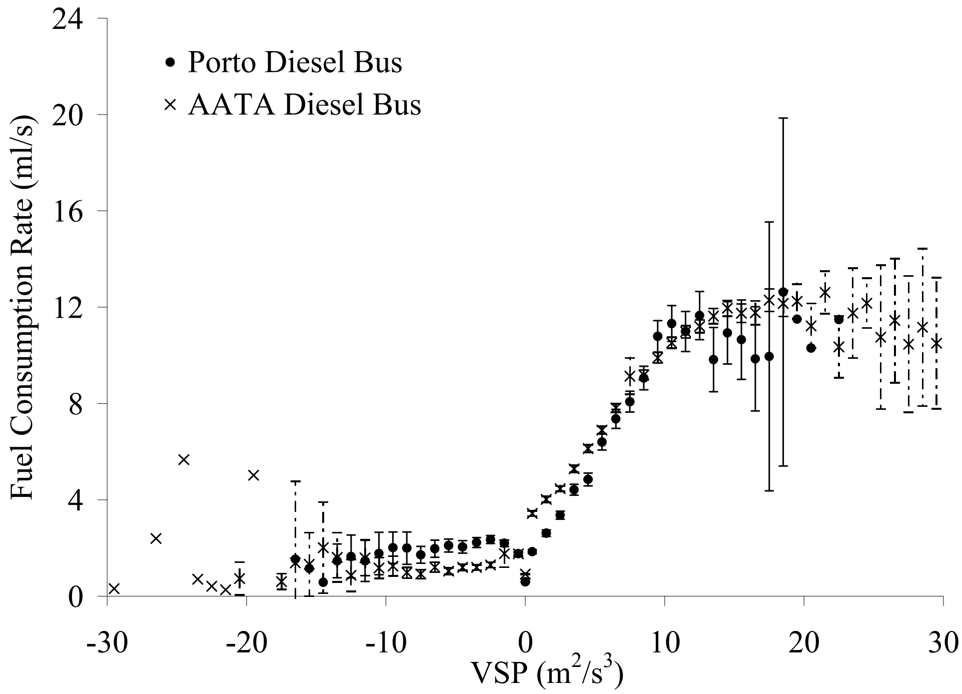
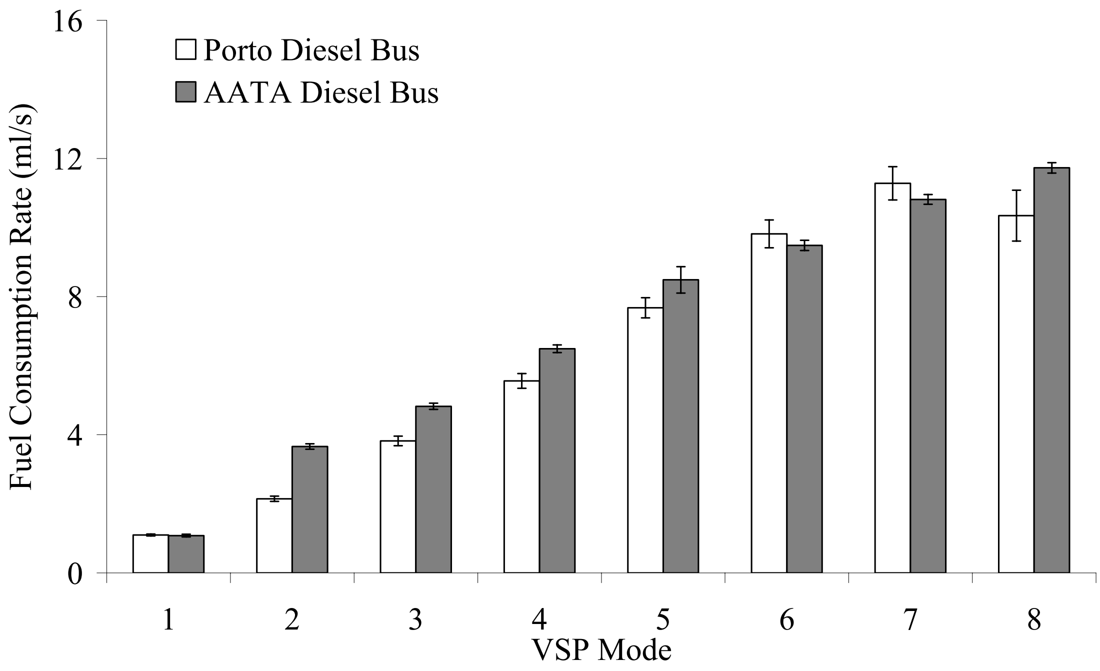


Figure 1. Effect of On-Board Passenger Load on Mean Fuel Consumption Rate, with 95% Confidence Intervals for Porto Diesel Bus

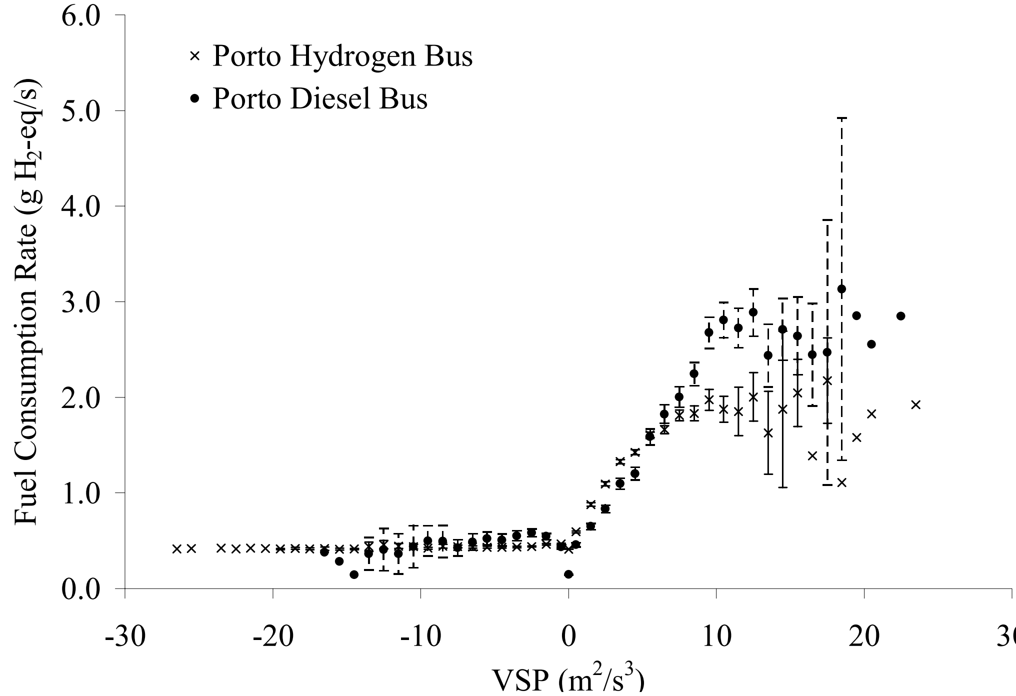


(2a) Diesel buses VSP and average fuel consumption, with 95% confidence intervals

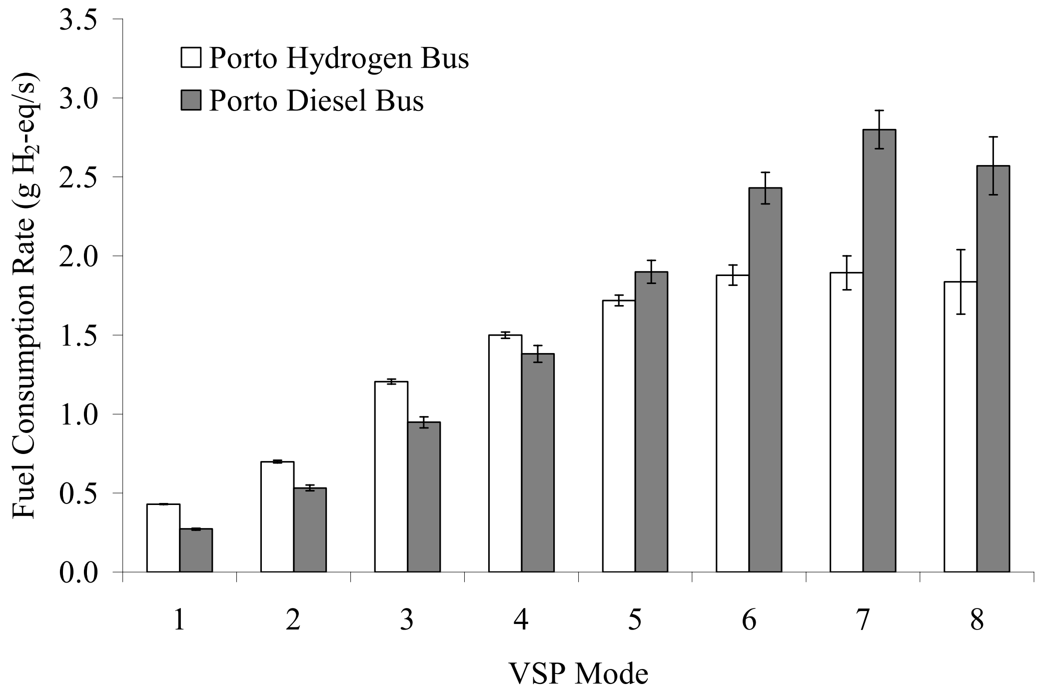


(2b) VSP mode average fuel consumption rate, with 95% confidence intervals, for diesel buses

Figure 2. Fuel Consumption Rate by VSP Mode for Ann Arbor and Porto Diesel Buses



(3a) VSP and average fuel consumption, with 95% confidence intervals



(3b) VSP mode average fuel consumption rate, with 95% confidence intervals, for Porto buses

Figure 3. Fuel Consumption Rate by VSP Mode for Porto Diesel and Hydrogen Fuel Cell Buses

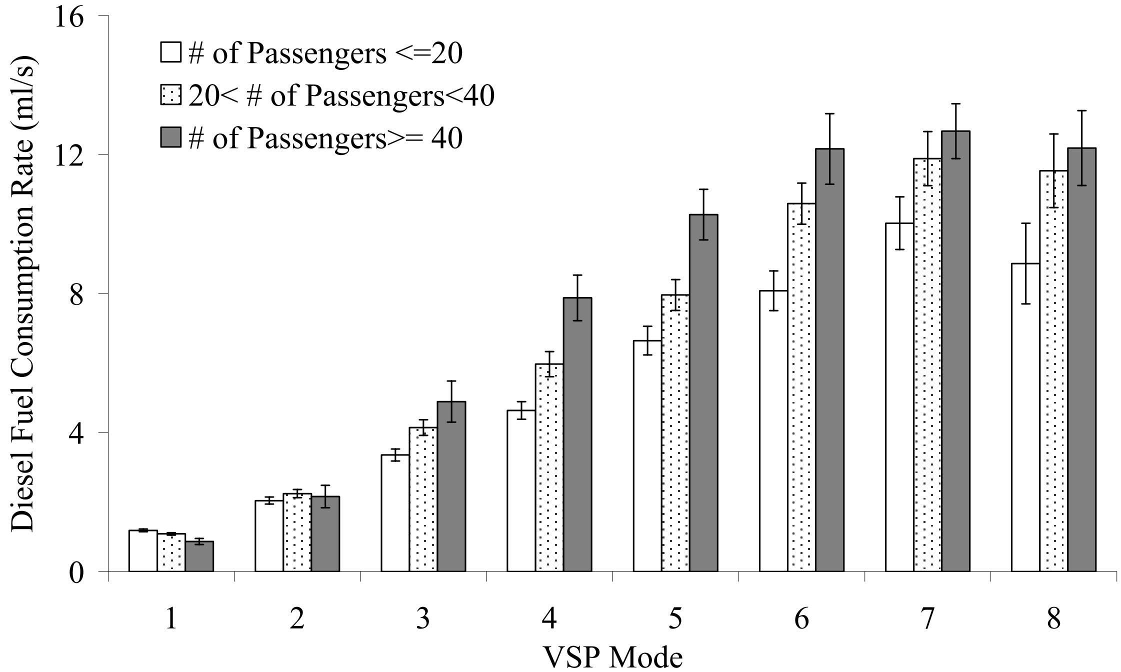


Figure 4. VSP and Passenger Load Modal Average Fuel Consumption with 95 % Confidence Intervals for the Porto Diesel Bus

Part VI LINK-BASED EMISSION FACTORS FOR HEAVY-DUTY DIESEL TRUCKS BASED ON REAL-WORLD DATA [§]

[§] This manuscript was recommended by the Transportation Research Board's Transportation and Air Quality Committee for publication in *Transportation Research Record: Journal of the Transportation Research Board*, 2008.

Abstract

Heavy-duty diesel vehicles contribute a substantial fraction of nitrogen oxides and particulate matter to the on-road vehicle emission inventory. The objectives of this study are to estimate roadway link-based emission rates for heavy-duty trucks for use in emission inventory estimation, and to quantify the impact of factors affecting truck emissions. A speed-acceleration modal emissions approach is developed from a database gathered via a portable emissions measurement system for single rear axle and tandem dump trucks. Second-by-second real-world truck speed profiles on links are analyzed based on observed patterns of time distributions of speed-acceleration modes. Link-based emission rates are estimated as the product of the fraction of time spent in each mode and the corresponding modal average emission rate. The sensitivity of link-based emission rates to key factors including chassis type, vehicle load and fuel type is presented. Single rear axle trucks have lower emission rates than tandems for CO_2, PM, NO and HC, but higher CO emission rates. Loaded trucks have higher fuel use and emissions than unloaded trucks. Replacing diesel fuel with biodiesel fuel for heavy-duty trucks may reduce tailpipe NO exhaust emissions and will reduce emissions of PM, CO and HC. However, both fuels generate similar CO_2 emissions. Benchmark comparisons for link-based emission rates show that NO emission rates increase with mean speed. However, link-based CO and HC emission rates were not as sensitive to speed variation as NO emissions. The link-based emission rates approach is recommended to couple heavy-duty vehicle emission inventory estimation with transportation demand models.

Key Words: Heavy-Duty Diesel Trucks, Portable Emissions Monitoring System, Real World Speed, Acceleration, Link Emission Rates.

6.1 Introduction

Heavy-duty diesel vehicles (HDDVs) contribute a substantial fraction of nitrogen oxides (NO_x), and particulate matter (PM) released to the atmosphere (Gajendran *et al.,* 2003). In 2002, heavy-duty diesel vehicles accounted for approximately 46% of NO_x and 54% of PM_{10} of the nationwide on-road vehicle emission inventory (EPA, 2007). Therefore, close attention should be paid to HDDV emissions characteristics and mitigation as they relate to vehicle duty cycles.

Emission measurement methods for HDDVs typically include engine and chassis dynamometer tests, tunnel studies, and remote sensing (Yanowitz *et al.*, 1999, Yanowitz *et al.*, 2000, Chellam *et al.*, 2005, Burgard *et al.*, 2006). Many engine dynamometer test cycles are based upon steady-state modal profiles that are not likely to be representative of real world vehicle activity patterns. Chassis dynamometer tests are expensive and there are few such dynamometers. Tunnel studies are limited in their ability to discriminate among specific vehicle types. With remote sensing, each measurement is only a snap shot of the vehicle activity at a single location, and thus does not characterize the entire duty cycle (Frey and Kim, 2005). The U.S. Environmental Protection Agency (EPA) has developed an on-road transportable diesel emissions characterization facility for measuring real-world emissions of heavy-duty combination trucks (Brown *et al.*, 2002). Portable emissions measurement system (PEMS) and transportable HDDV emissions testing laboratories have been developed to allow a better quantification of transportation activity and operational effects on vehicle emissions, especially under real-world traffic conditions (Vojtisek-Lom *et al.*, 2001, Frey *et al.*, 2003, Cocker *et al.*, 2004).

HDDVs are greater than 8,500 pounds in gross vehicle weight (EPA, 2002a). Emissions from HDDVs are affected by various factors including vehicle class and weight, driving cycle, and fuel type *(*Clark *et al.*, 2002, Brodrick *et al.*, 2004*)*. On-road measurement of fine particle in a tunnel study showed that HDDVs emit 15-20 times the number of particles per unit mass of fuel burned compared to light-duty vehicles (Kirchstetter *et al.*, 1999). The emission rates of volatile organic compounds and carbon monoxide (CO) from gasoline-fueled single-unit trucks can be 2.5 to 5 times higher than those of heavy-duty diesel trailer trucks. Emission rates of NO_x from diesel-fueled tractor-trailer trucks can be five times higher than those of gasoline-fueled single-unit trucks (Miller *et al.*, 2003). Increases in gross vehicle weight may also result in increases in NO_x emission rates during accelerations and higher-speed steady-state operations (Brodrick *et al.*, 2004). CO and PM emission rates were found to be insensitive to the vehicle weight during nearly steady-state operation, but increased with weight when vehicles were tested on transient driving cycles (Gajendran *et al.*, 2003). NO_x emission rates from HDDVs driving at low speeds, in simulated congested traffic, can be much higher than while cruising on the freeway *(*Shah *et al.*, 2006*)*. In addition, biodiesel fuel is gaining increasing interest as an alternative fuel for HDDVs. An evaluation of biodiesel impacts on exhaust emissions by the U.S. EPA showed that compared to petroleum diesel, B20 biodiesel (20% blend stock and 80% petroleum diesel) reduced about 10% of CO and PM emissions, and 20% of total hydrocarbon emissions, but increased NO_x emissions by 2 percent (EPA, 2002b). There are few studies about how emissions from biodiesel fueled heavy-duty are affected by real-world vehicle operation patterns and loads.

The emission factor model, MOBILE6 utilizes diesel engine emissions certification data as well as a series of conversion factors to convert certification data derived from engine testing to in-use grams per mile emission factors (EPA, 2002a). In addition, the off Federal test procedure cycle was developed to estimate excess NO_x emissions produced by HDDVs that are not explicitly covered by a certification test (EPA, 2002c). However, basic emission rates are estimated from stationary dynamometer tests. Furthermore, the emission factor model does not account for the effects of truck operating weight on emissions. Emission rates for HDDVs were found to be highly dependent on vehicle operating mode (Shah *et al.*, 2006). A vehicle activity-based study estimated emissions of HDDVs *(*Clark *et al.*, 2003, Weinblatt *et al.*, 2003*)*. In that case study, NO_x emissions from transit buses were found to be sensitive to acceleration, but not as much to vehicle speed, for a given acceleration range. However, the effect of vehicle load on link-level emissions could not be effectively evaluated for HDDVs under real-world driving cycles.

Compatibility between vehicle activity indictors from transportation and emissions models outputs is a pre-requisite to the development of accurate estimates of regional emission inventories. Transportation models produce link-level activity data. Therefore, there is a need for link-based emission factors for HDDVs in emission inventory estimation.

6.2 Objectives

The goal of this study is to develop a methodology for estimating roadway link-level emission rates, and to evaluate the effects of vehicle activity and operation on those emissions. The methodology is illustrated based on heavy-duty vehicles operating using diesel and biodiesel fuels under real-world driving cycles and under different loads. In addition, emission rate differences for different chassis types are quantified.

The principal objectives of this research are to: (a) estimate link-level emission rates for heavy-duty trucks; (b) quantify the effects of vehicle activity and load on truck emissions; (c) compare emissions for different chassis types; and (d) compare emissions for diesel versus biodiesel fueled trucks.

6.3 Database Description

6.3.1 Emissions Data

An OEM-2100 “Montana” PEMS was used for data collection. This OEM-2100 components, data collection capabilities, and data quality assurance protocols, as well as the study design for field data collection and basic results, are detailed in a previous TRB paper (Frey *et al.*, 2006). Frey and Kim (2006) tested two categories of dump trucks including four single rear axle trucks and four tandem trucks with engines subject to Tier 1 emission regulations. The engine displacement was 7.2 liters for single rear axle dump trucks and 10.2 liters for tandem trucks. The average weight of a typical load was approximately 7.0 tons for the single rear-axle trucks and 14.5 tons for the tandems. The load weight was comparable to the unloaded weight of the vehicle. Each vehicle was tested for one day using B20 biodiesel and one day using petroleum diesel. Measured pollutants included CO, hydrocarbons (HC), NO, opacity, and carbon dioxide (CO_2). The field study was designed to test the effect of vehicle type, fuels, loading configuration and operating mode.

6.3.2 Activity Data

Vehicle activities under real world traffic conditions were investigated at the roadway link level. A link is defined as a roadway segment between two junctions. Thus, the segment between two interchanges is defined as a freeway link, and the segment between two traffic signals on a surface street is regarded as a surface street link. Second-by-second GPS coordinates of each vehicle during its trip were recorded by the PEMS and overlaid on a transportation network GIS map. HDDV speed profiles on freeways collected by Battelle in California were also used (Battle, 1999). Measured link speed profiles for single rear axle and tandem dump trucks on arterials were gathered by Frey and Kim (2005).

6.4 Methodology

The methodology employed for estimating link-based emission rates consists of: (1) developing a speed-acceleration modal approach based on PEMS data, and estimating modal emission rates; (2) estimating facility-specific real-world truck activity data at the link level; (3) estimating speed- and facility- specific average emission rates for heavy-duty trucks; and (4) quantifying the impacts of selected vehicle activity and fuel factors on truck emissions.

6.4.1 Speed-Acceleration Modal Analysis

For heavy-duty vehicles, the chassis type, load and fuel type are all factors that may affect exhaust emissions. The emission database was classified by chassis type (single versus tandem axles), load status (empty versus loaded) and fuel type (diesel versus biodiesel). For a given data subset, emissions data in each second were stratified into discrete predetermined modes according to instantaneous speed and acceleration measurements. Five acceleration ranges (high-deceleration, low deceleration, cruise, low acceleration, and high acceleration), and thirteen speed ranges (from 0 to 65 mph in 5 mph increments) were constructed from the database. Idling was categorized as a separate mode. Modal average emission rates were then estimated using second-by-second PEMS measurements.

6.4.2 Link-based Average Emission Rates Estimation

Speed profiles were categorized by facility type and link mean speed. The recorded speed profiles were classified into average link speed ranges, in increments of 5 mph, ranging from 25 to 45 mph for arterials and from 45 to 60 mph for freeways. Second-by-second speed profiles for links were subsequently stratified into discrete speed-acceleration modes. Such stratification enables the use of modal average emission rates to obtain aggregate estimates of emission rates on a link. Link emission rates are estimated as:

$$E_{j,k} = \sum_{i=1} \left\{ \left(\frac{t_{i,j,k}}{T_{j,k}} \right) \times ER_i \right\} \tag{1}$$

Where i is the speed-acceleration mode index; j is the link index; k is the speed profile run index; $t_{i,j,k}$ is time spent in speed-acceleration mode i on link j for run k (sec); $T_{j,k}$ is the total travel time spent on link j for run k (sec); ER_i is the modal average emission rate for speed-acceleration mode i; and $E_{j,k}$ is the link average emission rate for run k on link j. Link-based average emission rates are then obtained by averaging emission rates for all links on the same roadway type and across all speed profiles within a pre-specified link mean speed range.

Link average emission rates were characterized by chassis type, load and fuel. The comparison of CO_2 emissions between diesel and biodiesel fuels is assessed with respect to a benchmark based upon theoretical fuel combustion emission factors. In addition, sensitivity of emissions to link mean speed is evaluated based on benchmarking with MOBILE6 estimates.

6.5 Results and Discussion

Modal average emission rates estimates are presented. Link-based emission rates are estimated and specified by key factors affecting emissions. The impacts of these factors on emissions are quantified and evaluated.

6.5.1 Modal Average Emission Rates Estimates

Table 1 shows an example of speed-acceleration modal average emission rates for loaded single rear axle trucks powered by diesel fuel. In general, modal emission rates at high speed and high acceleration are significantly larger than those at low speed and during deceleration. The lowest emission rates occurred during idling. Table 1 also indicates that emission rates are significantly sensitive to vehicle acceleration for all pollutants at each speed level. For example, when comparing high acceleration versus high deceleration for average speeds between 35 and 40 mph, the modal average emissions rates are approximately a factor of 2 to 11 greater, depending on the pollutant. For any given acceleration range, modal emission rates for CO_2 tend to increase with speed. However, modal emission rates for PM, CO, NO_x and HC do not consistently show such a trend. For example, NO_x and CO modal emission rates do not consistently increase with speed for the low acceleration modes. Ratios of maximum to minimum modal emission rates are 29.5, 18.4, 15.7, 11.0 and 5.5 for CO_2, PM, NO_x, CO and HC respectively, which indicates that a significant amount of variability in emissions is being captured by these modes.

In addition, modal emission rates of NO_x shown in Table 1 under the cruise mode at high speeds are lower than those under the high acceleration mode at low speeds. This implies that, compared to cruising on freeways, HDDVs driving at low speeds and frequent acceleration in congested traffic conditions may result in higher NO_x emissions, which is similar to the result by other researchers (Shah *et al.*, 2006).

6.5.2 Link-based Speed- and Facility- Specific Average Emission Rates

Speed profiles and modal time distribution

Four speed ranges were considered on arterials and freeways based on the availability of multiple link speed profiles. However, there were few speed profiles available representing the relatively low speed range for freeway segments. Table 2 summarizes the number of speed profiles analyzed by speed level and roadway type.

Time traces of speed profiles were plotted to visualize the driving patterns. Figure 1a shows multiple runs on several arterial links with a mean speed range of 35-40 mph for single rear axle trucks. In some runs, trucks accelerate from relatively low speeds at the start, cruise for a while, and then decelerate; in others, trucks cruise at relatively high speeds then decelerate. The average percentage of time spent in each speed-acceleration mode for all speed profiles for single rear axle trucks is estimated from the data. Figure 1b illustrates the results for the profiles shown in Figure 1a links. On average, single real axle heavy-duty trucks spent 45% of their travel time in cruise mode (zero or low acceleration), 17% of their travel time in low deceleration and 17% of their travel time in low acceleration modes.

Since emission rates were found to be sensitive to variation in acceleration, the variation of in the travel time spent in various driving modes is investigated as a function of link mean speed. Table 3 shows that single rear axle trucks spent the largest portion of time in cruise mode, followed by low deceleration and low acceleration modes for all reported link mean speeds. Furthermore, the fraction of time spent in cruise mode increased, but time spent in high acceleration decreased, as link mean speed increased.

Speed profiles from tandem trucks were analyzed and compared with those from single rear axle trucks in order to investigate similarity and variability in activity patterns for both chassis types. Twenty speed profiles for tandem trucks on arterials were also studied for mean speed ranges from 35 mph to 40 mph. The average percentage of time spent in each driving mode is 12.6% for high deceleration, 17.7% for low deceleration, 34.6% for cruise, 24.1% for low acceleration, 10.2% for high acceleration and 0.5% for idling. Compared to the data shown in Table 3 for single real axle trucks for the same range of mean speeds, the difference of time spent in modes for both types of dump trucks is less than 1 percentage point for deceleration and high acceleration modes, 9 percentage points for cruise mode and 7 percentage points for low acceleration. Link-based emission factors are estimated based on speed profiles from both types of trucks.

Link average emission rates

Using Equation (1), link-based average emission rates were estimated for arterials and freeways. These were also specified by chassis type, fuel type and load, yielding sixteen categories of link-based average emission rates. Figure 2 shows the rates for loaded diesel-fueled trucks and the 95th percentile confidence intervals on the mean.

Single rear axle trucks have lower emission rates of CO_2, NO_x, PM and HC, compared to tandem trucks, but have higher CO emission rates for a given speed level. Link-based emission rates for CO_2 for both axle configurations and NO_x for tandem trucks show an increasing trend with link mean speed. Link average PM emission rates tend to increase with average speed on freeways. On the other hand, link-based emission rates for CO and NO_x for single rear axle trucks, and PM for both axle configurations on arterials do not significantly increase with speed. HC link-based emission rates for single rear axle trucks also indicate an increasing trend with link mean speed. However, for tandem trucks, HC link-based emission rates do not significantly vary across mean speeds. The ratios of maximum to minimum link-based emission rates are given in Table 4 in order to highlight the variability in link-based emissions that can be explained by link mean speed. The values in Table 4 are much lower than the ratios of maximum to minimum speed-acceleration modal average emission rates, implying information loss due to aggregation from the modal to the mean speed approach.

In addition, link-based emission rates for the speed range of 40-45 mph were not significantly different from each other for arterials and freeways, which indicated that facility type may have an insignificant effect on emissions, when controlling for speed. However, there were only two of speed profiles available for this speed range for freeways, and thus there is a need for more activity data to further explore this hypothesis.

6.5.3 Impact of Selected Key Factors on Truck Emissions

To evaluate the impact of other explanatory factors on truck emissions, ratios of emission rates for loaded versus unloaded cycles were calculated, controlling for chassis type, fuel type, facility type and link mean speed range. Table 5 summarizes those ratios for various speed ranges on arterials. The ratios all exceed one. These ratios may be affected by sample sizes of speed-acceleration modes, especially when there are few samples available for some modes and high variability in sample emissions. For example, for loaded diesel-fueled tandem trucks, there are only six samples available individually for both modes: speed from 45 mph to 50 mph and acceleration less than -2 mph per second, and speed from 50 mph to 55 mph and acceleration less than -2 mph per second. However, the ratio of modal average emission rates for loaded versus unloaded is more than 7.0 for both speed-acceleration modes, which may result in high ratios of estimates for loaded versus unloaded duty, especially at high link mean speeds. Overall, loaded operation increases truck emissions for both types of fuels and vehicle types. The average percentage increase for all pollutants is approximately 34% for diesel and 36% for biodiesel.

Table 6 shows ratios of link-based exhaust rates of tandem versus single rear axle trucks on arterials. The ratios for CO_2, NO_x and HC are all above 1, but for CO the ratios are less than one, for both types of fuels and loads. On average, the difference for tandem trucks versus single rear axle is 41% for CO_2, 60% for NO_x, 76% for PM, 113% for HC and -20% for CO. Thus, the data suggest that single rear axle trucks have lower CO_2, NO_x, PM and HC emission rates, but higher CO emission rates.

Table 7 shows emission ratios for biodiesel versus diesel fueled trucks. The ratios for the NO_x estimates have been corrected for ambient temperature and humidity effects (EPA, 2004). The mean ratios are all less than 1, implying that replacing diesel fuel with biodiesel fuel may decrease emissions of these three pollutants. The net differences in emission rates for biodiesel versus petroleum diesel differ somewhat from those reported by Frey and Kim (2006). Frey and Kim (2006) estimated the average percentage differences in emissions between the two fuels for an entire duty cycle, whereas here emissions rates are estimated for individual links that are only small components of an overall duty cycle.

A comparison of expected difference in CO_2 emissions between the two fuels was carried out using theoretical fuel combustion emission factors. The fuel lower heating value is 18,730 BTU/lb for diesel fuel and 18,100 BTU/lb for B20 biodiesel fuel. The percentage of carbon in weight is 86.4% for diesel fuel and 84.5% for biodiesel fuel (Frey and Kim, 2005). Thus, the fuel combustion emission factor for CO_2 is:

$$\frac{\frac{0.864\ lb\,C}{lb\,Fuel}\times\frac{44\ lb\,CO_2}{12\ lb\,C}}{18730\,\frac{BTU}{lb\,Fuel}}\times\frac{10^6\ BTU}{MBTU}=169.1\ \frac{lb\,CO_2}{MBTU}\quad \text{for diesel fuel;}$$

$$\frac{\frac{0.845\ lb\ C}{lb\ Fuel}\times\frac{44\ lb\ CO_2}{12\ lb\ C}}{18100\,\frac{BTU}{lb\ Fuel}}\times\frac{10^6\ BTU}{MBTU}=171.2\ \frac{lb\ CO_2}{MBTU}\quad \text{for biodiesel fuel.}$$

Thus, the theoretical ratio of CO_2 emissions for biodiesel versus diesel fuels is 1.01, an indication that both fuels should generate very similar CO_2 emissions. For the single rear axle trucks, the observed ratio of CO_2 emissions for biodiesel versus petroleum diesel was 1.04 on arterials and 0.93 for freeways when data for one truck that towed a trailer was excluded. For the tandems, the observed average ratios are 0.95 for arterials and 0.96 for freeways. Overall, the observed ratios are quite comparable to the theoretical ratios within the precision of the measurements.

6.5.4 Sensitivity of Emissions to Link Mean Speed: Modal Approach vs. MOBILE6

The relative differences in link-based average emission rates at different mean link speeds were compared to results from the MOBILE6 model for a range of average speeds on each roadway type. The MOBILE6 input parameter values are 2000 calendar year, July daily minimum and maximum temperatures of 72.0 ^{o}F and 92.0 ^{o}F, and Fuel Reid Vapor Pressure (RVP) of 8.7 psi., while other parameters are based on EPA national default data including vehicle miles traveled by model year, vehicle class, vehicle age distribution. The mass per mile emission rates from MOBILE6 were converted into a mass per second basis. For MOBILE6, the relative percentage changes in emissions rates were estimated with reference to an average speed of 17.5 mph on arterials and 42.5 mph on freeways. For the modal approach, the corresponding speed ranges were 15-20 mph on arterials and 40-45 mph on freeways. Comparative results for NO, CO and HC are shown in Table 8.

The results indicate that NO emission rates appear to increase with link mean speeds in both methods. However, the link-based estimates are, relatively speaking, less sensitive to mean link speed than are MOBILE6 results, for both roadway types. HC emission rates appear to not be sensitive to changes in average speeds in both methods, and there is good agreement in both cases. CO emission rates based on MOBILE6 for arterials are not sensitive to speed variation whereas sensitivity increases with average speeds on freeways. In contrast, CO emission rates estimated by the modal-based approach using PEMS database are not sensitive to mean speeds regardless of roadway type. Both methods have a significant qualitative agreement in the results.

6.6 Conclusions

Modal emission rates for HDDVs were found to be consistently sensitive to acceleration variation, but not as much to speeds, especially for CO and HC. Link-based emission rates of CO_2 for single rear and tandem axle trucks, and NO for tandem trucks increased with link mean speed. However, link-based emission rates for CO and HC were not significantly different from each other for various link mean speeds, especially on arterials. Link-based PM emission rates for both chassis types on arterials are also not sensitive to differences in link mean speed. However, they tend to increase with mean speed on freeways. Single rear axle trucks generated lower emission rates of CO_2, NO and HC, but higher CO emission rates than tandem trucks. Vehicle load resulted in increases of approximately 34% for diesel and 36% for biodiesel in emissions, compared to the unloaded condition. Link-based emission rates of PM, NO, CO and HC for B20 biodiesel fuel were found to be lower than those for diesel fuel. However, both types of fuels generated similar CO_2 emissions. Similar to the results reported by previous researchers, increases in gross vehicle weight and loaded duty for heavy-duty trucks result in increases in NO_x emission rates; the substitution of biodiesel for diesel reduces PM, CO and HC emission rates. However, NO_x emission rates were also reduced.

The reported link-based emission rates may be coupled with transportation model outputs such as traffic volume and travel time on roadway links for the purpose of estimating HDDV emission inventories on a regional scale. However, there is a need for data on additional driving cycles at various facility types (or at least for a wider range of link speeds) and for the inclusion of other types of heavy-duty vehicles in order to develop more comprehensive fleet-based estimates. The use of emission ratios for loaded versus unloaded cycles is recommended to adjust emission factors to account for various duty cycles. Finally, comparisons of emission rates between biodiesel and diesel fuels indicate that the substitution of biodiesel for diesel may bring about environmental benefits in tailpipe emissions reductions. However, when substituting one fuel for another, there is a need for a life cycle inventory comparison of the entire fuel cycle.

6.7 Acknowledgments

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6.8 References

Battelle (1999), "Heavy-Duty Truck Activity Data," Prepared by Battelle for Office of Highway Information Management and Office of Technology Applications, Federal Highway Administration, Washington D.C. April.

Brodrick, C.J, E. A. Laca, A. F. Burke, M. Farshchi, L. Li and M. Deaton (2004), "Effect of Vehicle Operation, Weight, and Accessory Use on Emissions from a Modern Heavy-Duty Diesel Truck," *Transportation Research Record*, 1880:119-125.

Brown, J. E., F.G. King, Jr., W.A. Mitchell, W.C. Squier, D.B. Harris and J. S. Kinsey (2002), "On-Road Facility to Measure and Characterize Emissions from Heavy-Duty Diesel Vehicles," *Journal of the Air & Waste Management Association*, 52(4):388-395.

Burgard, D., G. A. Bishop and D.H. Stedman (2006), "Remote Sensing of In-Use Heavy-Duty Diesel Trucks," *Environmental Science & Technology*, 40(22):6938-6942.

Clark, N.N., J. M. Kern, C. M. Atkinson and R. D. Nine (2002), "Factors Affecting Heavy-Duty Diesel Vehicle Emissions," *Journal of the Air and Waste Management Association*, 52(1):84-94.

Clark, Nigel N., P. Gajendran and J. M. Kern (2003), "A Predictive Tool for Emissions from Heavy-Duty Diesel Vehicles," *Environmental Science & Technology*, 37(1):7-15.

Chellam, S., P. Kulkarni and M. P. Fraser (2005), "Emissions of Organic Compounds and Trace Metals in Fine Particulate Matter from Motor Vehicles: A Tunnel Study in Houston, Texas," *Journal of the Air and Waste Management Association*, 55(1):60-72.

Cocker III, D. R., S. D. Shah, K. Johnson, J. W. Miller and J. M. Norbeck (2004), "Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines 1. Regulated Gaseous Emissions," *Environmental Science & Technology*, 38(7):2182-2189.

EPA (2002a), "Update Heavy Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-duty Engine Emission Conversion Factors," EPA420-R-02-005, Environmental Protection Agency, Ann Arbor, MI, February.

EPA (2002b), "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions," EPA-420-P-02-001, Environmental Protection Agency, Ann Arbor, MI, October.

EPA (2002c), "Development of Heavy-Duty NO_x Off-Cycle Emissions Effects for MOBILE6," EPA420-R-02-004, Environmental Protection Agency, Ann Arbor, MI, January.

EPA (2003), "40 CFR Chapter I Section 86.1342-90. Humidity Correction Factor," Environmental Protection Agency, Ann Arbor, MI, July.

EPA (2005), "National Emissions Inventory Air Pollutant Emissions Trends Data," Environmental Protection Agency, Posted in August 2005. http://www.epa.gov/ttn/chief/trends/. Accessed on June 29, 2007.

Frey, H.C., A. Unal, N.M. Rouphail and J.D. Colyar (2003), "On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument," *Journal of the Air and Waste Management Association*, 53(8):992-1002.

Frey, H.C. and K. Kim (2005), "Operational Evaluation of Emissions and Fuel Use of B20 Versus Diesel Fueled Dump Trucks," FHWY/NC/2005-07, Prepared by North Carolina State University for North Carolina Department of Transportation, Raleigh, NC, September.

Frey, H.C. and K. Kim (2006), "Comparison of Real-World Fuel Use and Emissions for Dump Trucks Fueled with B20 Biodiesel versus Petroleum Diesel," *Transportation Research Record,* 1987:110-117.

Gajendran, P. and N.N. Clark (2003), "Effect of Truck Operating Weight on Heavy-Duty Diesel Emissions," *Environmental Science & Technology*, 37(18):4309 -4317.

Kirchstetter, T.W., R. A. Harley, N. M. Kreisberg, M. R. Stolzenburg and S.V. Hering (1999), "On-road Measurement of Fine Particle and Nitrogen Oxide Emissions from Light- and Heavy-duty Motor Vehicles," *Atmospheric Environment*, 33 (18):2955-2968.

Miller, T. L., W. T. Davis, G.D. Reed, P. Doraiswamy and J. S. Fu (2003), "Characteristics and Emissions of Heavy-Duty Vehicles in Tennessee under the MOBILE6 Model," *Transportation Research Record*, 1842: 99-108.

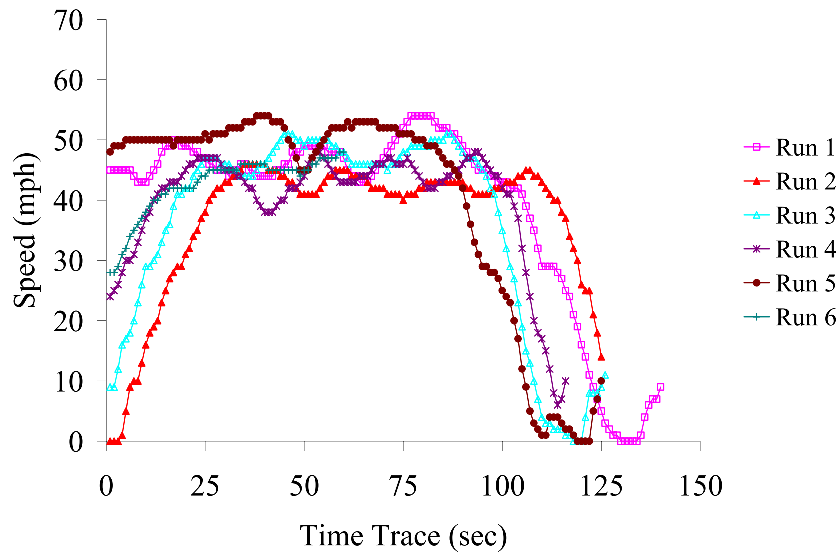
Shah, S. D., K. C. Johnson, J. W. Miller and D. R. Cocker III (2006), "Emission Rates of Regulated Pollutants from On-Road Heavy-Duty Diesel Vehicles," *Atmospheric Environment*, 40(1):147-153.

Vojtisek-Lom, M. and J.E. Allsop (2001), "Development of Heavy-Duty Diesel Portable, On-Board Mass Exhaust Emissions Monitoring System with NO_x, CO_2 and Qualitative PM Capabilities," Society of Automotive Engineers, 2001-01-3641.

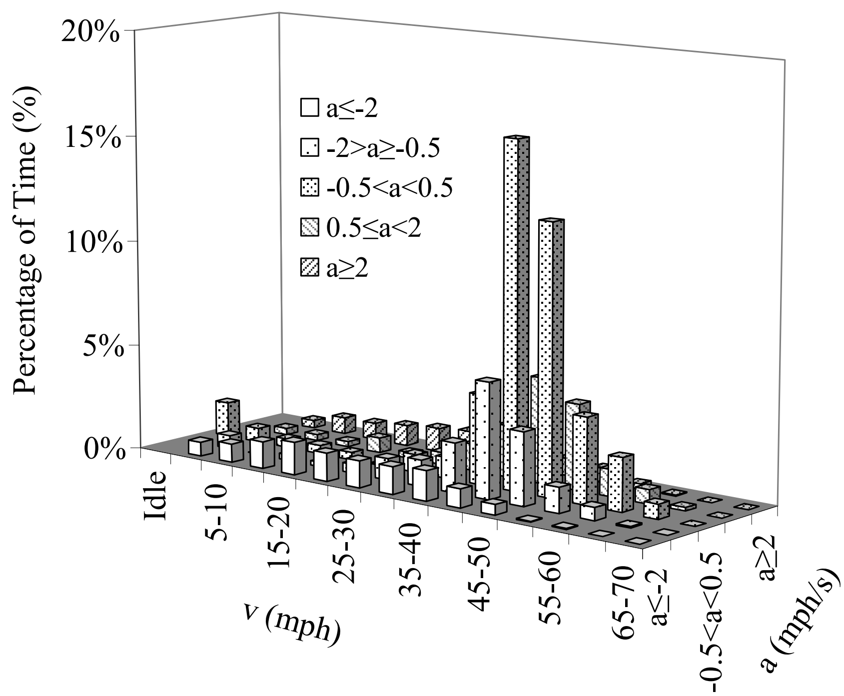
Weinblatt, H., R.G. Dulla and N.N. Clark (2003), "Vehicle Activity-Based Procedure for Estimating Emissions for Heavy-Duty Vehicles," *Transportation Research Record*, 1842:64-72.

Yanowitz, J., M. S. Graboski, L. B. A. Ryan, T. L. Alleman and R. L. Mccormick (1999), "Chassis Dynamometer Study of Emissions from 21 In-Use Heavy-Duty Diesel Vehicles," *Environmental Science & Technology*, 33(2):209-216.

Yanowitz, J., R. L. Mccormick and M. S. Graboski (2000), "In-Use Emissions from Heavy-Duty Diesel Vehicles," *Environmental Science & Technology*, 34(5):729-740.



(a) Representative speed profiles



(b) Percentage of time spent in each speed-acceleration mode

Figure 1. Sample Link Speed Profiles and Average Time Distribution of Speed/Acceleration Mode for Link Mean Speed Range of 35-40 mph on Arterials

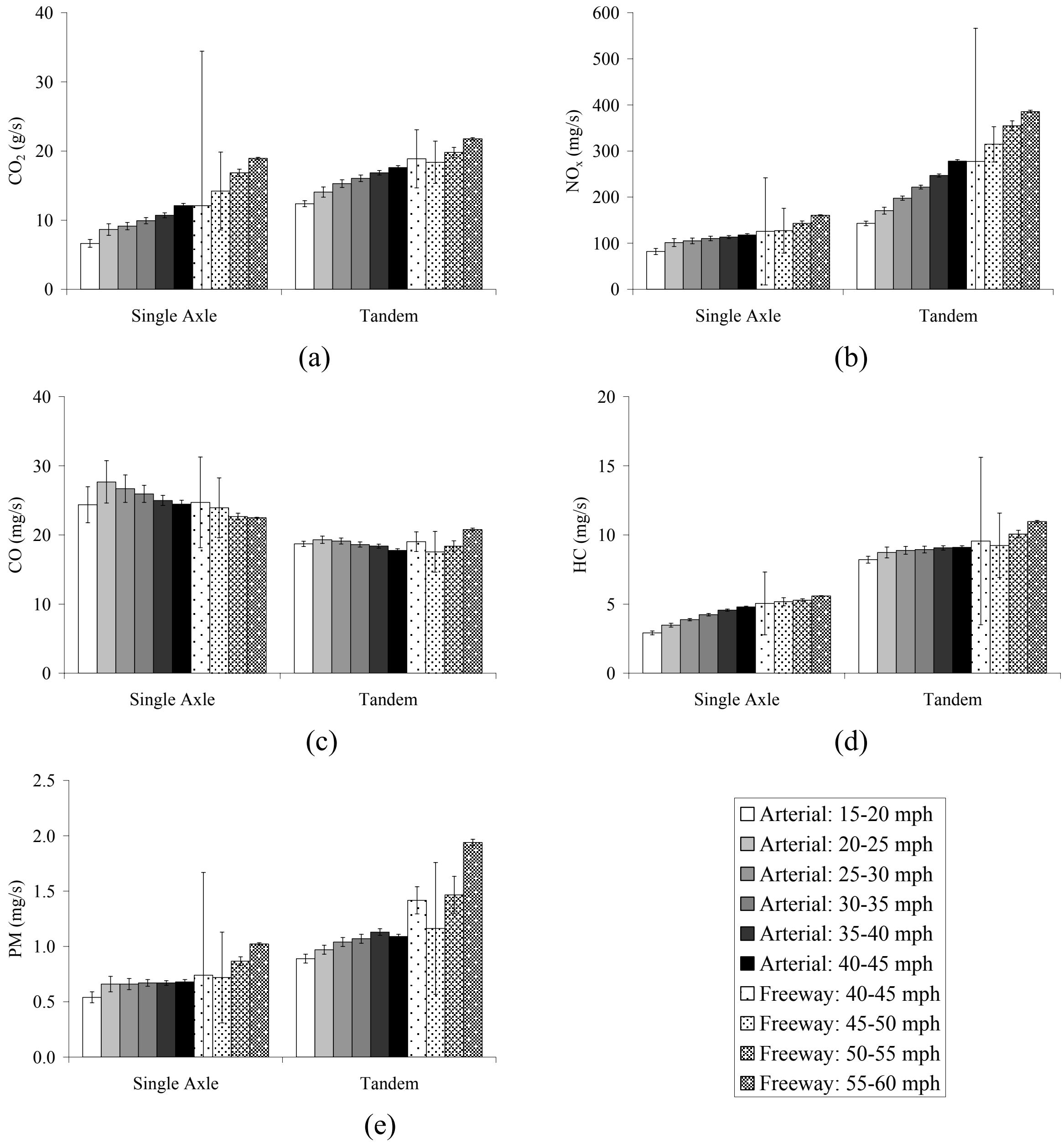


Figure 2. Link-based Average Emission Rates for Loaded Diesel-Fueled Single Rear and Tandem Axle Trucks by Speed Range and Facility Type

Table 1. Speed-Acceleration Modal Average Emission Rates for Loaded Diesel-Fueled Single Rear Axle Trucks (g/s)[a]

Speed (mph)	Pollutant	Acceleration (mph/s)					Pollutant	Acceleration (mph/s)				
		a ≤ -2	-2 < a ≤ -.5	-.5<a<.5	.5 ≤ a<2	a ≥ 2		a ≤ -2	-2 < a ≤ -.5	-.5<a<.5	.5 ≤ a<2	a ≥ 2
Idle	CO_2			0.88			NO_x			0.019		
0-5		1.16	1.62	2.34	2.94	3.93		0.023	0.033	0.044	0.048	0.056
5-10		1.26	2.22	4.30	6.09	8.40		0.020	0.042	0.062	0.083	0.116
10-15		1.17	2.23	3.80	7.47	12.5		0.020	0.036	0.053	0.090	0.146
15-20		1.34	3.95	5.35	11.6	15.1		0.026	0.059	0.063	0.129	0.181
20-25		2.01	6.44	7.75	14.2	17.6		0.028	0.090	0.083	0.169	0.195
25-30		2.71	6.83	8.20	14.4	19.4		0.038	0.086	0.097	0.178	0.196
30-35		2.96	4.57	8.85	15.2	18.4		0.046	0.066	0.115	0.162	0.183
35-40		1.98	4.38	8.11	15.7	23.4		0.043	0.076	0.121	0.177	0.207
40-45		2.10	5.78	10.5	15.1	20.5		0.034	0.076	0.118	0.143	0.193
45-50		3.85	7.46	12.6	16.9	21.5		0.054	0.074	0.112	0.136	0.175
50-55		2.94	8.25	15.8	18.2	23.3		0.054	0.074	0.130	0.160	0.186
55-60		4.66	16.0	19.8	17.1	25.9		0.064	0.133	0.168	0.130	0.291
60-65		n/a	15.6	13.9	17.2	n/a		n/a	0.144	0.131	0.148	n/a
Idle	CO			0.0053			HC			0.0011		
0-5		0.0070	0.0090	0.0094	0.0083	0.0132		0.0024	0.0026	0.0015	0.0012	0.0013
5-10		0.0064	0.0145	0.0193	0.0269	0.0391		0.0025	0.0033	0.0026	0.0019	0.0026
10-15		0.0066	0.0155	0.0218	0.0380	0.0583		0.0028	0.0028	0.0021	0.0022	0.0031
15-20		0.0080	0.0257	0.0289	0.0474	0.0560		0.0026	0.0035	0.0029	0.0029	0.0041
20-25		0.0082	0.0312	0.0371	0.0448	0.0516		0.0022	0.0041	0.0028	0.0033	0.0043
25-30		0.0137	0.0232	0.0264	0.0367	0.0584		0.0028	0.0045	0.0042	0.0040	0.0058
30-35		0.0143	0.0204	0.0292	0.0359	0.0398		0.0034	0.0044	0.0050	0.0039	0.0046
35-40		0.0120	0.0190	0.0269	0.0335	0.0423		0.0029	0.0050	0.0060	0.0041	0.0061
40-45		0.0110	0.0162	0.0229	0.0243	0.0408		0.0027	0.0044	0.0056	0.0042	0.0054
45-50		0.0139	0.0178	0.0232	0.0230	0.0357		0.0032	0.0043	0.0055	0.0051	0.0050
50-55		0.0153	0.0172	0.0236	0.0290	0.0357		0.0036	0.0041	0.0051	0.0049	0.0059
55-60		0.0170	0.0193	0.0222	0.0270	0.0365		0.0045	0.0053	0.0058	0.0052	0.0017
60-65		n/a	0.0180	0.0220	0.0254	n/a		n/a	0.0050	0.0053	0.0053	n/a

Table 1. Speed-Acceleration Modal Average Emission Rates for Loaded Diesel-Fueled Single Rear Axle Trucks (mg/s) (continued)

Speed (mph)	Pollutant	Acceleration (mph/s)				
		a ≤ -2	-2 < a ≤ -.5	-.5<a<.5	.5 ≤ a<2	a ≥ 2
Idle	PM			0.09		
0-5		0.13	0.16	0.20	0.28	0.37
5-10		0.15	0.26	0.37	0.58	0.77
10-15		0.15	0.29	0.37	0.69	1.11
15-20		0.17	0.33	0.45	0.92	1.28
20-25		0.16	0.65	0.63	1.12	1.38
25-30		0.23	0.59	0.72	1.11	1.35
30-35		0.33	0.43	0.75	0.99	1.20
35-40		0.23	0.43	0.65	0.97	1.33
40-45		0.19	0.41	0.66	0.81	1.21
45-50		0.25	0.38	0.58	0.81	1.18
50-55		0.29	0.46	0.72	0.96	1.20
55-60		0.46	0.89	1.06	0.94	1.59
60-65		n/a	1.03	1.04	1.05	n/a

[a] Data aggregated across all facility types.

Table 2. Number of Speed and Facility-Specific Speed Profiles

Speed Range (mph)		15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60
Facility Type	Arterial [a]	18	23	49	69	83	91	n/a	n/a	n/a
	Freeway [b]	n/a	n/a	n/a	n/a	n/a	2	3	15	73

[a] Source of data: Frey et al., 2005 for single rear axle dump trucks and tandem dump trucks;
[b] Source of data: Battelle, 1999.

Table 3. Average Percentage of Trip Time Spent in Each Acceleration Mode on Arterials (%) for Single Rear Axle Trucks

Acceleration (mph/s)	Driving Mode	Mean Speed (mph)			
		25-30	30-35	35-40	40-45
$a \leq -2$	High Deceleration	12.4	11.2	11.6	9.2
$-2 < a \leq -.5$	Low Deceleration	17.5	16.4	16.7	14.3
$-.5 < a < .5$	Cruise	25.9	33.4	43.6	46.0
$.5 \leq a < 2$	Low Acceleration	21.6	21.3	16.9	21.8
$a \geq 2$	High Acceleration	19.2	12.7	9.4	8.5
0	Idle	2.7	4.6	1.6	0.2

Table 4. Ratios of Maximum to Minimum Link Emission Rates for Loaded Diesel-Fueled Trucks[a]

Facility Type	Chassis Type	Pollutant				
		NO_x	HC	CO	CO_2	PM
Arterial	Single Rear Axle[b]	1.4	1.6	1.1	1.8	1.3
	Tandem[c]	1.9	1.1	1.1	1.4	1.3
Freeway	Single Rear Axle[b]	1.3	1.1	1.1	1.6	1.4
	Tandem[c]	1.4	1.2	1.2	1.2	1.7

[a] Link-based emission rates upon which these ratios are computed are those in Figure 2.
[b] The four tested single rear axle dump trucks have 7.2 liter engine and gross vehicle weight of 33,000 lb.
[c] The four tested tandem dump trucks have 10.2 liter engine and gross vehicle weight of 50,000 lb.

Table 5. Ratio of Link Average Emission Rate for Loaded versus Unloaded Trucks on Arterials

Fuel Type	Pollutant	Speed Range (mph) 15-20		20-25		25-30		30-35		35-40		40-45		Overall Ratio	
		Single	Tandem	Single	Tandem	Single	Tandem	Single	Tandem	Single	Tandem	Single	Tandem	Single	Tandem
Diesel	NO_x	1.36	1.65	1.35	1.64	1.30	1.74	1.29	1.81	1.26	1.90	1.22	1.94	1.30	1.78
	HC	1.33	1.39	1.37	1.34	1.33	1.31	1.28	1.27	1.24	1.25	1.14	1.24	1.28	1.30
	CO	1.29	1.35	1.20	1.27	1.18	1.25	1.14	1.18	1.13	1.15	1.10	1.09	1.17	1.22
	CO_2	1.47	1.41	1.48	1.38	1.40	1.44	1.37	1.46	1.34	1.48	1.31	1.46	1.39	1.44
	PM	1.38	1.33	1.35	1.29	1.27	1.27	1.22	1.22	1.18	1.19	1.10	1.06	1.25	1.23
B20	NO_x	1.43	1.49	1.52	1.44	1.61	1.45	1.66	1.43	1.67	1.40	1.66	1.41	1.59	1.44
	HC	1.50	1.35	1.44	1.29	1.44	1.29	1.41	1.27	1.38	1.25	1.39	1.27	1.43	1.29
	CO	1.05	1.25	1.09	1.20	1.11	1.20	1.19	1.17	1.22	1.18	1.24	1.22	1.15	1.20
	CO_2	1.34	1.43	1.40	1.37	1.44	1.36	1.45	1.32	1.43	1.30	1.39	1.30	1.41	1.35
	PM	1.28	1.44	1.27	1.41	1.29	1.42	1.29	1.40	1.29	1.42	1.28	1.49	1.28	1.43

Table 6. Ratio of Link Average Emission Rate for Tandem versus Single Rear Axle Trucks on Arterials

Fuel Type	Pollutant	Speed Range (mph) 15-20		20-25		25-30		30-35		35-40		40-45		Overall Ratio	
		Unloaded	Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded	Loaded
Diesel	NO_x	1.44	1.74	1.39	1.68	1.41	1.88	1.43	2.01	1.45	2.18	1.49	2.36	1.43	1.98
	HC	2.69	2.82	2.58	2.52	2.32	2.29	2.13	2.11	1.97	1.99	1.74	1.90	2.24	2.27
	CO	0.73	0.77	0.66	0.70	0.68	0.72	0.69	0.72	0.72	0.74	0.73	0.73	0.70	0.73
	CO_2	1.94	1.86	1.75	1.63	1.63	1.67	1.52	1.62	1.42	1.57	1.30	1.46	1.59	1.64
	PM	1.72	1.65	1.53	1.47	1.58	1.58	1.60	1.60	1.67	1.69	1.66	1.60	1.63	1.60
B20	NO_x	1.44	1.50	1.48	1.40	1.56	1.40	1.60	1.37	1.64	1.37	1.71	1.45	1.57	1.42
	HC	2.26	2.04	2.26	2.03	2.17	1.95	2.08	1.88	1.97	1.80	1.83	1.68	2.10	1.90
	CO	0.79	0.94	0.79	0.87	0.83	0.90	0.90	0.89	0.93	0.90	0.91	0.90	0.86	0.90
	CO_2 [a]	1.31	1.40	1.31	1.29	1.27	1.20	1.22	1.12	1.16	1.06	1.09	1.02	1.23	1.18
	PM	1.88	2.12	1.94	2.15	1.88	2.06	1.82	1.98	1.69	1.87	1.60	1.86	1.80	2.01

[a] One of four single rear axle trucks (vehicle Number 4743) towed a trailer when it tested on biodiesel, which consumed more fuels and generated more CO_2 emissions. When excluding that unusual vehicle, the average ratio for tandem trucks versus single rear axle trucks is 1.36 for unloaded duty and 1.28 for loaded duty based on single rear axle truck speed profiles.

Table 7. Ratio of Link Average Emission Rates for Biodiesel versus Diesel Fueled Trucks

Chassis Type	Duty	Pollutant	Speed (mph)										Mean Ratio
			Arterial						Freeway				
			15-20	20-25	25-30	30-35	35-40	40-45		45-50	50-55	55-60	
Single Axle	Unloaded	NO_x[a]	0.81	0.75	0.72	0.71	0.71	0.69	0.63	0.67	0.67	0.65	0.70
		HC	0.83	0.80	0.73	0.68	0.65	0.61	0.66	0.58	0.78	1.00	0.73
		CO	0.99	0.88	0.82	0.76	0.73	0.75	0.73	0.86	0.99	1.05	0.86
		PM	1.03	0.98	0.92	0.89	0.86	0.81	0.69	0.69	0.66	0.66	0.82
	Loaded	NO_x[a]	0.84	0.83	0.87	0.90	0.91	0.92	0.93	0.93	0.96	0.96	0.91
		HC	0.94	0.84	0.79	0.75	0.72	0.75	0.73	0.78	0.97	1.04	0.83
		CO	0.80	0.80	0.78	0.79	0.79	0.84	0.77	0.90	1.00	1.07	0.85
		PM	0.94	0.92	0.94	0.94	0.94	0.94	0.90	0.89	0.84	0.86	0.91
Tandem	Unloaded	NO_x[a]	0.87	0.86	0.86	0.86	0.86	0.85	0.87	0.88	0.94	1.01	0.89
		HC	0.70	0.70	0.68	0.67	0.65	0.65	0.61	0.63	0.64	0.65	0.66
		CO	1.07	1.06	1.01	0.99	0.95	0.93	0.89	0.88	0.89	0.91	0.96
		PM	1.12	1.24	1.10	1.01	0.87	0.78	0.63	0.49	0.51	0.52	0.83
	Loaded	NO_x[a]	0.82	0.78	0.74	0.70	0.66	0.64	0.66	0.68	0.74	0.74	0.72
		HC	0.68	0.68	0.67	0.67	0.65	0.66	0.64	0.66	0.68	0.66	0.67
		CO	0.99	1.00	0.97	0.98	0.97	1.04	0.92	1.09	1.00	0.88	0.98
		PM	1.21	1.35	1.23	1.17	1.04	1.09	0.73	0.87	0.69	0.52	0.99

[a] NO_x humidity correction factor applied for diesel engines based on U.S. EPA 40 CFR Section 86.1342-90, 2003 (EPA, 2003).

Table 8. Relative Change in Average Emissions on A Mass per Second Basis Compared to Benchmark for Loaded Diesel-Fueled Trucks (%)

Facility Type	Pollutant	Average Speed (mph)	Percentage Difference of Emission Factors versus Baseline for MOBILE6[b]	Speed Range (mph)	Percentage Difference of Emission Factors versus Baseline for Link-based Estimates		
					Single Rear	Tandem	Mean
Arterial	NO[a]	17.5	Benchmark	15-20	Benchmark	Benchmark	Benchmark
		22.5	19	20-25	23	19	21
		27.5	39	25-30	28	38	33
		32.5	62	30-35	34	55	45
		37.5	88	35-40	38	73	55
		42.5	120	40-45	44	94	69
	CO	17.5	Benchmark	15-20	Benchmark	Benchmark	Benchmark
		22.5	0	20-25	14	3	8
		27.5	-1	25-30	10	2	6
		32.5	-1	30-35	6	0	3
		37.5	1	35-40	3	-2	0
		42.5	6	40-45	0	-5	-2
	HC	17.5	Benchmark	15-20	Benchmark	Benchmark	Benchmark
		22.5	7	20-25	19	6	13
		27.5	11	25-30	33	8	21
		32.5	14	30-35	45	9	27
		37.5	17	35-40	57	10	34
		42.5	20	40-45	65	11	38
Freeway	NO[a]	42.5	Benchmark	40-45	Benchmark	Benchmark	Benchmark
		47.5	18	45-50	1	13	7
		52.5	43	50-55	14	28	21
		57.5	80	55-60	28	39	33
	CO	42.5	Benchmark	40-45	Benchmark	Benchmark	Benchmark
		47.5	9	45-50	-3	-8	-6
		52.5	25	50-55	-8	-3	-6
		57.5	52	55-60	-9	9	0
	HC	42.5	Benchmark	40-45	Benchmark	Benchmark	Benchmark
		47.5	4	45-50	2	-3	-1
		52.5	9	50-55	5	5	5
		57.5	17	55-60	10	15	13

[a] Relative changes for link-based method were estimated based on link-based emission rates for NO without correcting for temperature and humidity.

[b] Percentages in MOBILE6 are estimated based on composite emission factors for all types (#16~#23) of heavy-duty diesel vehicles.

PART VII FUEL CONSUMPTION AND TAILPIPE EMISSIONS COMPARISONS BETWEEN ETHANOL 85 AND GASOLINE FUELS FOR FLEXIBLE FUEL VEHICLES [5]

[5] This manuscript is in preparation for submission to *Journal of the Air & Waste Management Association*.

Abstract

Ethanol-based fuels may reduce dependence on imported petroleum and offer environmental benefits. The objective of this research is to evaluate differences in fuel consumption and tailpipe emissions of flexible fueled vehicles (FFVs) operated on ethanol 85 (E85) versus gasoline. Theoretical ratios of fuel consumption and CO_2 emissions for both fuels are estimated based on the same amount of energy released. Second-by-second fuel consumption and emissions from one FFV Ford Focus fueled with E85 and gasoline were measured under real-world traffic conditions in Lisbon, Portugal using a portable emissions measurement system (PEMS). Cycle average dynamometer fuel consumption and emission test results for FFVs are available from the U.S. Department of Energy, and emissions certification test results for ethanol-fueled vehicles are available from the U.S. Environmental Protection Agency. Based on the PEMS data, vehicle specific power (VSP)-based modal average fuel and emission rates for both fuels are estimated. Empirical ratios of fuel consumption and CO_2 emissions for the two fuels agree within a margin of error to the theoretical expectations. CO emissions were found to be typically lower. From the PEMS data, NO emissions associated with some higher VSP modes are higher for E85 when compared to gasoline. From the dynamometer and certification data, average HC and NO_x emissions were either higher or lower. The differences of average E85 versus gasoline emissions for all vehicle models are -22% for CO, 12% for HC and -8% for NO_x emissions, which imply that replacing gasoline with E85 reduces CO emissions, but may not significantly change NO_x tailpipe emissions, and may increase HC tailpipe emissions. On a fuel life cycle basis for corn-based ethanol versus gasoline, CO emissions decrease by 18%.

Emission reductions are 25% for total CO_2 and 50% for fossil CO_2. However, HC and NO_x emissions increase by 18% and 82% respectively.

7.1 Introduction

Ethanol-based fuels may offer an advantage of reduced national dependence on imported petroleum. Ethanol use is expected to increase from 4 billion gallons in 2005 to 14.6 billion gallons in 2030 (EIA, 2007a). Ethanol can be blended with gasoline to create E85, a blend of 85% ethanol and 15% gasoline by volume.

Ethanol can be produced from different types of biomass, such as corn or cellulosic biomass. Cellulosic biomass is composed mainly of cellulose and hemicellulose, as well as lignin, which can be found in herbaceous and woody plants (Spatari *et al*., 2005). Corn stover, an agricultural residue left in the field after corn is harvested, and switchgrass are some of the more popular cellulosic materials for ethanol production (Lavigne *et al*., 2007). Thus, ethanol is considered a renewable fuel.

A fuel life-cycle analysis is useful to evaluate the environmental benefits for an alternative fuel, which takes into account emissions at the stages of feedstock farming and transportation, ethanol production, transportation, blending and distribution, and vehicle operation. When made from corn, E85 is estimated to reduce total fuel cycle and vehicle greenhouse gas (GHG) emissions by 15 to 20 percent, compared to gasoline (EPA, 2006). For switchgrass, the estimated reduction in total GHG emissions is 57%, and it is 65% for corn stover-based feedstock. Corn stover ethanol GHG emissions are estimated to be slightly lower than those for switchgrass because of shared emissions with grain production (Spatari *et al.*, 2005). Cellulosic ethanol has larger estimated GHG emissions reductions than corn-based ethanol because less energy is needed to produce the cellulosic feedstock (Wang, 2005). Although cellulosic ethanol may achieve larger GHG emissions reductions, there are key barriers to more widespread commercialization including how to accelerate the hydrolysis reaction that breaks down cellulose fibers and what to do with the lignin byproduct (EIA, 2006).

The type of ethanol production plant affects life-cycle GHG emissions (Wang *et al.*, 2007). The percent reduction in total GHG emissions for corn ethanol versus gasoline can range from a 54% decrease for a biomass-fired dry mill plant to a 4 % increase for a coal-fired wet mill plant (EPA, 2007a).

Fuel life cycle carbon monoxide (CO) emissions are estimated to increase by 17%, and nitrogen oxide (NO_x) emissions increase by a factor of 9, for corn stover-based ethanol compared to gasoline (Sheehan *et al.*, 2004); For E85 derived from switchgrass, the total life cycle NO_x emissions are estimated to increase by 36 to 107 percent depending on the design of the fuel production facility (Wu *et al.*, 2006). In order to assess the emissions and air quality impacts of replacing gasoline with ethanol, an accurate estimate of the difference in emissions is needed (Jacobson, 2007).

More than 5 million flexible fuel vehicles (FFVs) were produced for the U.S. vehicle market from 1992 through 2005 (EIA, 2007b). FFVs are designed to run on gasoline or any ethanol blend up to 85 percent ethanol. The major difference in an FFV compared to a conventional gasoline vehicle is that the FFV has a fuel sensor that automatically detects the ethanol versus gasoline ratio. The computer adjusts the vehicle's fuel injection and ignition timing to compensate for the different fuel mixtures (DOE, 2007, NEVC, 2007). However, FFVs are not optimized for ethanol use. For example, because ethanol has a higher octane rating than gasoline, an ethanol dedicated engine could be designed with a higher compression ratio and, hence, higher efficiency.

Since ethanol is an oxygenated fuel, the use of ethanol may reduce emissions of products of incomplete combustion including CO (Reuter, *et al*., 1992, Guerrieri *et al.*, 1995, Poulopoulos *et al*., 2003). Durbin *et al.* (2006) observed that based on the Federal Test Procedure (FTP), CO emissions decreased, and non-methane hydrocarbons (NMHC) emissions increased with increasing ethanol content for some gasoline fuels, but were unaffected by ethanol content for other gasoline fuels, depending on fuel volatility.

There is concern that E85 is associated with higher emissions of some hydrocarbon species, such as aldehydes (Kelly *et al.*, 1999). Winebrake *et al.* (2001) estimated that fuel life cycle acetaldehyde emissions increased by a factor of 14 for corn-based E85 relative to gasoline. Guerrieri *et al.* (1995) reported that acetaldehyde emissions increased by over 200% as the ethanol content increased up to 40%. Durbin *et al.* (2006) reported that aldehyde emissions increased by 73% when the ethanol content was increased from zero to 10%. Replacing gasoline with E85 is reported to increase methane emissions from 43% to 340% (Lipman *et al.*, 2002, de Serves, 2005, GMC, 2007).

Guerrieri *et al.* (1995) found that NO_x exhaust emissions increased by 60% as the ethanol content in gasoline increased up to 40%. Durbin *et al.* (2006) found that NO_x emissions increased when ethanol content increased for some gasoline fuels, but were unaffected by ethanol content for other gasoline fuels, depending on fuel volatility. de

Serves (2005) reported that NO_x exhaust emissions decreased as the ethanol content in gasoline increased. For E85 versus gasoline, some studies find that NO_x emissions may increase (NREL, 1999a, GMC, 2007), whereas some other studies report that NO_x emissions may decrease (Black *et al.*, 1998, Kelly *et al.*, 1999, NREL, 1999b, MacDonald, 2005), or both increase or decrease for individual vehicles (NREL, 1998).

Fuel permeation is a factor associated with evaporative emissions of volatile organic compounds (VOC). For one FFV fuel system, Haskew *et al.* (2006) found that the diurnal average permeation rate increased by 79% for E10, and 38% for E20, but decreased by 51% for E85. A current project is investigating the impact of varying ethanol-gasoline blends on evaporative emissions based on a small fleet of latest model California certified FFVs (Haskew, 2007). Black *et al.* (1998) found that compared to reformulated gasoline, E85 decreased evaporative non-methane organic gases (NMOG) emissions by 30% based on a sealed housing for evaporative determination (SHED) test. In addition, in other fuel systems, including two California Enhanced Evaporative vehicles, a California Low Emission Vehicle II, and a California Zero Evaporative Emission Vehicle, the low ethanol blends from 6% to 20% increased permeation, compared to gasoline (Haskew *et al.* 2006).

With respect to agricultural environmental impact, corn production uses more insecticides, herbicides, and nitrogen fertilizers than crops such as herbaceous and woody biomass (Pimentel, 2003, MacLean *et al.*, 2000). For example, the quantity for herbicides is 6.2 kg for corn production per hectare, whereas it is 3.0 kg for switchgrass production per hectare (Pimentel, *et al.*, 2005). For water use, the quantity is 158 gallon per gallon of corn-based ethanol (Pimentel, 2003) and 125 gallon per gallon of switchgrass-based ethanol

(Pimentel, *et al*., 2005). Furthermore, the amount of land suitable for corn is much smaller than the amount of land suitable for grasses or woody biomass crops such as hybrid poplar trees that may be used as the feedstock for ethanol production (MacLean *et al*., 2000).

The U.S. Environmental Protection Agency (EPA) is developing a new generation modeling system, MOVES, to replace the MOBILE6 and NONROAD models. MOVES will estimate emissions for on-road and non-road mobile sources (Koupal *et al.*, 2004, EPA, 2005). In the development of the conceptual basis for MOVES, vehicle specific power (VSP) was identified a key explanatory variable with respect to emissions (Frey *et al.*, 2002, Scora *et al.*, 2002, ENVIRON, 2002). The VSP-based approach has been used in emissions modeling for conventional light-duty vehicles and heavy-duty vehicles (Frey *et al.*, 2002, ENVIRON, 2002, Huai *et al.*, 2005, Frey *et al.*, 2006, Zhai *et al.*, 2006). However, less attention has been devoted to FFVs, because of lack of second-by-second data.

Portable Emissions Monitoring Systems (PEMS) are gaining increased acceptance for quantifying emissions under real-world operational conditions (Frey *et al.*, 2003). PEMS data enable the characterization of variability in emissions measurements for representative trips in real-world traffic conditions.

7.2 Objective

The objective of this study is to evaluate differences in fuel consumption and tailpipe emissions of FFVs operated on E85 versus gasoline fueled vehicles based upon theoretical and empirical analyses. Where second-by-second PEMS data are available, the VSP-based modal modeling approach is used to estimate fuel consumption and emissions for E85 and gasoline. In addition, fuel consumption and tailpipe emissions are compared between E85 and gasoline based on available dynamometer and vehicle certification tests.

7.3 Data Source

Empirical analyses were carried out based upon available dynamometer test results and PEMS data.

Dynamometer tests results for FFVs conducted through the National Renewable Energy Laboratory are available from the Alternative Fuel Data Center (AFDC) of the U.S. Department of Energy (DOE) (AFDC, 2006). Tested vehicles were Ford Taurus and Chevrolet Lumina FFVs, and corresponding conventional gasoline Taurus and Lumina vehicles (Kelly *et al.*, 1999). E85 was tested in the FFVs, whereas gasoline was tested in the FFVs and the corresponding conventional gasoline vehicles. For Ford Taurus, there were 23 FFVs and 24 conventional gasoline vehicles; and for Chevrolet Lumina, there were 20 FFVs and 15 conventional gasoline vehicles. For each vehicle model, some vehicles were tested in more than one group of accumulated miles. CO_2, CO, NO_x, and THC emissions were measured in these dynamometer tests.

Annual vehicle emission certification test results and data are available from the U.S. Environmental Protection Agency (EPA, 2007b). Sixty-one pairs of comparable certified vehicles fueled by E85 and gasoline were available for model years from 1999 to 2008 for emission comparisons between E85 and gasoline.

In addition, second-by-second fuel consumption and emissions from a single FFV fueled with E85 and gasoline were measured under real-world traffic conditions in Lisbon, Portugal using PEMS. The PEMS was composed of several devices including a gas analyser, on-board diagnostic engine scanner, global positioning system, and fuel flow meter, which were connected to a laptop computer (Gonçalves *et al.*, 2005). The tested vehicle was a European 2006 Ford Focus with 1.8 liter engine certified to the EURO IV emissions standard. Data measured on the same route for both fuels were used to develop fuel consumption and emissions models and evaluate the differences between the two fuels. There were two trips per fuel and about 1.3-hours of second-by-second data per fuel. Vehicle speed, engine RPM, manifold absolute pressure (MAP), road altitude, fuel consumption rate, and emission rates of CO_2, CO and nitric oxide (NO) were recorded.

Supplementing the data above were a series of speed profiles that were collected under real-world traffic conditions on arterials, freeways, ramps, local and collector roads in previous work (Frey *et al.*, 2001, Frey *et al*., 2006). These speed profiles are classified into ranges of average speeds (in 10 km/h increments). Those data were used to evaluate the sensitivity of the link-based fuel consumption and emission rates to facility type and average speed.

7.4 Methodology

Fuel consumption and emissions are compared for E85 versus gasoline fuels based on theoretical and empirical analyses. The empirical analyses were carried out using dynamometer and certification test results, and PEMS data. Fuel cycle and vehicle tailpipe emissions differences between gasoline and E85 are also evaluated using a fuel life-cycle model.

7.4.1 Theoretical Analysis of Fuel Consumption and CO_2 Emissions: E85 versus Gasoline

Theoretical ratios of fuel consumption and CO_2 emissions for E85 versus gasoline assume that the same amount of energy is required (i.e. identical engine efficiency was assumed). The stoichiometric complete combustion reactions for gasoline and ethanol based on the equivalent molecular formula for both fuels are, respectively:

$$CH_{1.875} + 1.469(O_2 + 3.76N_2) \rightarrow CO_2 + 0.938H_2O + 5.523N_2 \quad (1)$$

$$CH_3O_{0.5} + 1.5(O_2 + 3.76N_2) \rightarrow CO_2 + 1.5H_20 + 5.64N_2 \quad (2)$$

Based on fuel chemical properties summarized in Table 1, the volume-based ratio of the lower heating value (LHV) for one gallon of gasoline versus E85 is 1.41. The LHV is used because H_2O in the exhaust will exit as water vapor. Using Equations (1) and (2) along with the lower heating values of both fuels, theoretical emission factors of CO_2 of fuel combustion in units of pounds per MBtu were calculated for both fuels. From this, the ratio of CO_2 emissions between the two fuels was estimated on an equivalent energy basis.

7.4.2 Analysis of Dynamometer and Certification Test Data

The DOE data for the Ford Taurus and Chevrolet Lumina vehicles include cycle average fuel consumption and emission rates based on the FTP-75 test procedure (AFDC, 2006). Average fuel consumption and emission rates were categorized by vehicle model and odometer reading (mileage accumulation). For a given vehicle model, average cycle fuel consumption and emission rates for both fuels were estimated including all vehicles within the same group of accumulated miles. For each vehicle model, the ratios of average fuel consumption and emission rates for E85 FFVs versus gasoline conventional vehicles were calculated for each range of accumulated miles. An equally weighted average ratio was estimated based upon all ranges of mileage accumulation for each vehicle model.

In addition, for DOE data, both fuels were tested on the same FFV. Therefore, ratios of fuel consumption and emission rates for E85-fueled FFVs versus gasoline-fueled FFVs were calculated for individual FFVs. Overall average ratios for all FFVs are estimated for each vehicle model.

The EPA's emission certification tests were used to compare the two fuels. Measured pollutants included CO, NO_x and non-methane organic gases (NMOG). Each pair of emission comparisons involved the same model year, vehicle model and engine size. All vehicles certified based on ethanol fuel are FFVs. For vehicles labeled with "FFV" in the database, the gasoline tests are based on FFVs. However, it is unclear from the database as to if the reported data on gasoline tests on vehicles without the "FFV" label are for non-FFV conventional gasoline vehicles. This is assumed as the most likely situation.

7.4.3 VSP-based Modal Model Development

Fuel consumption and emissions models were developed based on the PEMS data for the Ford Focus and were applied to real-world link speed profiles for both fuels for link-level fuel consumption and emission rates estimates.

Vehicle specific power (VSP) takes into account aerodynamic drag, tire rolling resistance and road grade (Jiménez-Palacios, 1999). By applying coefficient values for a generic light duty vehicle, VSP is calculated (Frey *et al.*, 2006):

$$VSP = \mathrm{v} \times [1.1 \times a + 9.81 \times (\sin(\mathrm{atan}(\varphi))) + \psi] + \zeta \times \mathrm{v}^3 \tag{3}$$

Where:

VSP	= vehicle specific power (m^2/s^3);
v	= vehicle speed (m/s);
a	= acceleration (m/s^2);
φ	= road grade;
ψ	= rolling resistance term coefficient (0.132 m/s^2);
ζ	= drag term coefficient (0.000302 m^{-1}).

As given in Table 2, fourteen VSP discrete modes were defined for light-duty vehicles in a previous study, taking into account that (a) VSP modes should have a statistically significantly different average emission rate from each other; and (b) no single mode should dominate the estimate of total emissions (Frey *et al*., 2002). These VSP modes were applied to the Ford Focus for both types of fuels. Using second-by-second speed profile, and acceleration and road grade, VSP was computed from Equation (3) and then categorized into the VSP modes. Modal average fuel consumption and emission rates for both types of fuels were estimated based on the PEMS database. Using the distribution of the amount of time spent in each mode based on the FTP cycle, the ratios of cycle average fuel consumption and emissions for E85 versus gasoline were calculated.

Speed profiles measured on actual roadway links were classified by link mean speed and facility type. Link average fuel consumption and emission rate were estimated as:

$$E_k = \sum_{i=1}^{I} \left\{ \frac{t_{i,k}}{T_k} \times ER_i \right\} \tag{4}$$

$$\overline{E} = \frac{1}{K}\sum_{k=1}^{K} E_k \tag{5}$$

Where:

i = mode index;

I = the number of VSP modes (14);

k = run index;

K = the number of runs on the link;

E_k = link average fuel consumption or emission rate estimate for run *k* (g/s);

$\overline{E}$ = average fuel consumption or emission rate for multiple runs K on a link (g/s);

ER_i = VSP modal average fuel consumption or emission rate (g/s) for Mode i;

$t_{i,k}$ = time spent in VSP mode *i* in run *k*;

T_k = total link travel time in run *k* (sec).

Link average fuel consumption and emission rates estimates are compared between gasoline and E85 fuels for various ranges of link average speed and by facility type.

7.5 Results and Discussion

Theoretical ratios of fuel consumption and CO_2 emissions for E85 versus gasoline are estimated. Average fuel consumption and emissions data of numerous dynamometer test cycles for both fuels are compared. Emission certification test results are presented. The VSP-based modal approach is applied to model fuel consumption and emissions for both fuels.

7.5.1 Theoretical Ratios of Fuel Consumption and CO_2 Emissions: E85 versus Gasoline

The theoretical ratio of fuel consumption for an equivalent amount of energy is 1.49 on a mass basis for E85 versus gasoline.

The CO_2 emission factor for gasoline is:

$$\frac{1\ gallon \times \dfrac{3.785\times10^{-3}\ m^3}{gallon} \times \dfrac{737\ kg}{m^3} \times \dfrac{2.20\ lb}{kg} \times \dfrac{0.865\ lb\ C}{lb\ Fuel} \times \dfrac{44\ lb\ CO_2}{12\ lb\ C}}{1\ gallon \times \dfrac{115500\ Btu}{gallon\ Fuel} \times \dfrac{10^{-6}\ MBtu}{Btu}} = 169 \frac{lb\ CO_2}{MBtu} \tag{6}$$

The CO_2 emission factor for E85 is:

$$\frac{1\ gallon \times \dfrac{3.785\times10^{-3}\ m^3}{gallon} \times \dfrac{782\ kg}{m^3} \times \dfrac{2.20\ lb}{kg} \times \dfrac{0.570\ lb\ C}{lb\ Fuel} \times \dfrac{44\ lb\ CO_2}{12\ lb\ C}}{1\ gallon \times \dfrac{81925\ Btu}{gallon\ Fuel} \times \dfrac{10^{-6}\ MBtu}{Btu}} = 166 \frac{lb\ CO_2}{MBtu} \tag{7}$$

The theoretical ratio of the CO_2 emission factor for E85 versus gasoline is therefore estimated at 0.98.

7.5.2 DOE Dynamometer Data

Dynamometer test results based on the DOE data are given in Table 3. The comparisons for E85 FFVs versus gasoline conventional vehicles are based upon fuel consumption rates in gallons per mile and emission rates in grams per mile. The average ratios of fuel consumption for E85 versus gasoline are 1.31 for the Taurus and 1.38 for the Lumina, close to the expected theoretical volume-based ratio of 1.41. CO_2 emission rates were similar for both fuels, which is also consistent with the theoretical expectation. For the

Taurus, CO and NO_x emission rates from the E85-fueled vehicles were slightly lower than those from the gasoline-fueled vehicles but not significantly different. THC emission rates from the E85-fueled vehicle were higher than from the gasoline-fueled vehicle. However, for the Lumina, CO, NO_x and THC emission rates from the E85-fueled vehicle were all significantly lower than those from the gasoline-fueled vehicle. The mass ratios of fuel consumption and emission rates for E85 FFVs versus conventional gasoline vehicles are shown in Figure 1(a).

Mileage accumulation did not have a significant effect on fuel economy and the ratio of fuel consumption for E85 versus gasoline, but appeared to have more effect on emission rates and the ratio of emission rates for E85 versus gasoline. For example, emission rates of NO_x and THC increased with mileage accumulation for the E85-fueled Taurus. However, these trends were not consistently observed for the gasoline-fueled vehicle tests for the Taurus or for the Lumina on either fuel. For the Taurus, the ratios of THC emission rates for E85 versus gasoline were 1.04, 1.16, and 1.59 for ranges of 0 to 5, 5 to 10 and 10 to 15 thousand accumulated miles, respectively, whereas for Lumina, such ratios for THC were around 0.50 at different ranges of accumulated miles.

Average ratios and their range on ratio of fuel consumption and emission rates for E85 fueled FFVs versus gasoline fueled FFVs are shown in Figure 1(b). These ranges are larger for CO, NO_x and THC than those for fuel consumption and CO_2. Coefficients of variation (CV) of the ratios for individual FFVs are calculated to quantify intervehicle variablity. For both vehicle models, CV values of the ratios are 0.01 for fuel consumption and CO_2, and approximately 0.25 for NO_x and THC. However, the corresponding CV for

CO is 0.14 for the Taurus, but 0.35 for the Lumina. These imply that compared to fuel consumption and CO_2, CO, NO_x and THC have relatively larger intervehicle variability in the ratios for E85 versus gasoline.

For both vehicle models, the average ratios of fuel consumption and CO_2 for E85 FFVs versus conventional gasoline vehicles are similar to those for E85 FFVs versus gasoline FFVs. However, compared to average ratios of CO, NO_x and THC for E85 FFVs versus conventional gasoline vehicles, ratios for E85 FFVs versus gasoline FFVs are similar for the Taurus, but larger for the Lumina. For the Lumina, average emission rates for conventional gasoline vehicles were larger than those given in Table 3 for the corresponding gasoline-fueled FFVs.

The results indicate a substantial amount of inter-vehicle variability even for a particular vehicle make and model. For example, for the Taurus, 5 out of 23 FFVs had lower CO emission rates on E85 versus gasoline. Similarly, 15 FFVs had lower NO_x emission rates and 4 FFVs had lower THC emission rates. A larger proportion of the Lumina FFVs had lower emission rates on E85 than gasoline compared to the Taurus. However, for both vehicle models and these pollutants, there was at least one and usually more vehicles with higher emission rates on E85.

7.5.3 Emission Certification Test Results

Differences in emissions for gasoline versus FFVs with E85 are given in Table 4 for 61 vehicles of model years from 1999 to 2008. For CO, NO_x and NMOG, there are higher emissions for E85 than for gasoline for 25%, 30% and 61% of the 61 vehicles, respectively.

The overall average emission rates among all certification vehicles were estimated for E85 and gasoline. The differences in the overall average emission rates for E85 versus gasoline are -20%, 23% and 5% for CO, NMOG and NO_x, respectively.

For CO and NO_x, there are no statistically significant trends for emission rate differences for E85 versus gasoline with respect to vehicle model year and engine size. For NMOG, p-values for slopes with respect to engine size and model year are less than 0.05. The percentage difference decreases on average as engine size increases and for newer model years. For example, for a 2.2 liter engine, the average high difference in emissions for E85 versus gasoline is 220 percent, whereas for a 4.0 liter engine, the average high difference is 35 percent. For 2000 model year, the average high difference is 76 percent, whereas the average high difference for several 2007 model year vehicles is 6 percent.

7.5.4 VSP-based Modeling of Fuel Consumption and Emissions

VSP modal average fuel consumption and emission rates were estimated for the PEMS data and are shown in Figure 2. Link-level fuel consumption and emissions were estimated for seven levels of speed ranges on four facility types for both fuels.

In general, there is an approximately monotonic increase in fuel consumption and emission rates with respect to VSP modes for both fuels, except for CO and NO for VSP Modes 13 and 14. There are wider confidence intervals on the mean values for higher VSP modes since few samples are available in that range. For a given VSP mode, the E85-fueled vehicle consumes more mass of fuel than the gasoline-fueled vehicle. Compared with gasoline, the E85-based emissions are similar for CO_2 and much lower for CO. There are no significant differences for modal average NO emission rates except for VSP Modes 10, 11 and 13. Modal average emission rates of NO for E85 are much larger for these high VSP modes. For both fuels, THC emissions were below the detection limits of the analyzer used.

Average cycle fuel consumption and emission rates for the FTP cycle were estimated using the VSP modal approach as well. The ratios of average cycle fuel consumption and emission rates for E85 versus gasoline for the selected vehicle were 1.54 for fuel, 1.02 for CO_2, 0.26 for CO and 0.99 for NO.

The ratio of the highest to lowest VSP modal average fuel consumption and emission rates were estimated for each fuel based on the PEMS data in order to assess inter-modal variability. The inter-modal ratio of fuel consumption and CO_2 modal emission rates is 10 for gasoline and 8 for E85. For CO, the ratio is 25 for gasoline and 20 for E85. The ratios for NO are 10 for gasoline and 39 for E85. These ratios imply that an amount of variability in fuel consumption and emission rates is accounted for by VSP modal approach. For E85, the R^2 value of the modal average fuel and emission rates is 0.73 for fuel and CO_2. For gasoline, these R^2 values are 0.78. However, the R^2 values are 0.14 for CO and 0.09 for NO based on E85 because of high variability in second-by-second emission rates for a given VSP mode and small sample sizes available for higher VSP modes. For E85, the coefficients of variation for a given VSP mode range from 1.0 to 3.6 for CO and from 1.6 to 4.1 for NO, which reflects high variability in emission rates. For E85, there are only 12 second-by-second data for VSP Mode 13 and 4 second-by-second data for VSP Mode 14. These smaller sample sizes result in larger confidence intervals on modal average emission rates for high VSP modes. For gasoline, the R^2 values for fuel use and emission rates are similar to the corresponding values for E85. The low R^2 values for NO and CO are because the effects of other variables are not captured by VSP alone. For example, high NO emission rates for some data samples are associated with instantaneous increases in MAP to high values. However, MAP is not observable from outside the vehicle and thus is not practical as an explanatory variable in many cases.

Link average fuel consumption and emission rates for gasoline and E85 fuels were estimated from the PEMS data by link average speed level on arterials, as shown in Figure 3. Link average fuel consumption and emission rates for all pollutants increase with mean speed. For a given mean speed, compared to gasoline, when fueled by E85 the FFV consumes 50 to 57 percent more fuel, has similar CO_2 emissions and has 72 to 74 percent lower average CO emission rates. The difference in average NO emission rates for E85 versus gasoline increases from 12% to 27% with link mean speed, since more time is spent in high VSP modes where modal emission rates are much larger for E85 than those for gasoline.

Data for additional facility types and average speed ranges are shown in Table 5, based on the availability of real-world speed profiles from related work (Frey *et al.*, 2006). For these speed profiles, the mass rate of fuel consumption increases by 44 to 57 percent when comparing E85 to gasoline for a given speed range and facility type. The CO_2 emission rates are approximately similar, differing by only a few percent. Likewise, the CO emission rate decreases by 76 to 69 percent, and the NO emission rate increases by 12 to 73 percent, except for a small increase at off-ramps. For freeways and on-ramps, NO emission rate differences increase up to 76%, since more time was spent in the higher VSP modes where modal NO emission rates for E85 are much larger than those for gasoline. For off-ramps, more time was spent in the lower VSP modes where modal NO emission rates for E85 are similar or lower than gasoline. Similar to dynamometer tests results, empirical ratios of fuel consumption and CO_2 emissions for E85 versus gasoline based upon PEMS data are relatively close to the theoretical ratios.

7.5.5 Overall Estimate of Differences in Tailpipe Emissions for E85 versus Gasoline

Differences in tailpipe emissions for E85 versus gasoline are summarized based on the DOE dynamometer tests, EPA certification tests and PEMS data. Average differences in emissions for each source of data are summarized in Table 6. Most of the data imply that replacing gasoline with E85 will reduce CO emission rates. However, HC emission rates may either increase or decrease, depending on the vehicle. For E85 versus gasoline, DOE dynamometer tests results indicated reductions for NO_x emissions; however, these data are only for two vehicle models. Overall, there were minor average differences in NO_x emissions based on certification tests. There were similar CO_2 emissions for both fuels based on available data.

The difference of average E85 emissions versus gasoline emissions for 64 vehicle makes and models is -22% for CO emissions, 12% for HC emissions and -8% for NO_x emissions. For fuel consumption and CO_2 emissions, the equally weighted average differences for 1 European vehicle model and 2 DOE test vehicle models are 46% and -2% on a mass basis.

7.5.6 Fuel Life-Cycle Emissions Differences for E85 versus Gasoline

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET1.8) life cycle model was used to compare fuel life cycle emissions of E85 versus gasoline (Wang, 2001). The model stages include farming and harvesting, feedstock transportation, fuel production, fuel product transportation, distribution, and storage, and vehicle operation. For E85, estimates were made assuming corn-based feedstock. E85 vehicle emission factors were estimated based on gasoline vehicle emission factors from GREET and average tailpipe emission rates differences for E85 versus gasoline from this study. All other parameters were kept at their default values for a simulation year of 2005. The results are given in Table 7. The use of corn-based ethanol is estimated to lead to a substantial increase in life cycle NO_x emissions, a moderate increase in life cycle VOC emissions, and reductions in total life cycle CO emissions. The total CO_2 emissions reduce 25%, which is more than total GHG reductions (15 to 20 percent) previously reported by EPA (EPA, 2006). In addition, based on the fraction of fossil fuel consumption in total energy use at each stage of the life cycle basis for both fuels, the substitution of gasoline with corn-based E85 reduces fossil CO_2 emissions by 50% as more fraction of non-fossil energy consumption are related to ethanol production, distribution and use, compared to gasoline .

7.6 Conclusions

Vehicles operating on E85 consume more mass fuel than those operating on gasoline. However, the two fuels produce similar CO_2 tailpipe emissions. On a fleet basis, replacing gasoline with E85 will reduce CO tailpipe emissions, will not significantly change NO_x tailpipe emissions, and will increase HC tailpipe emissions.

On the other hand, life cycle NO_x and HC emissions are estimated to increase. Reductions in life cycle CO and total CO_2 emissions are estimated. Increases in NO_x and HC emissions for substitution of gasoline with E85 bring the adverse effect on the ozone pollution control.

The substitution of gasoline with E85 has mixed effects on air quality, depending on pollutants. Quantification of differences in tailpipe emissions for E85 versus gasoline can be used in emission inventory estimation for evaluation of the impacts of E85 fuel on urban air quality. In addition, there are needs for cold start and evaporative VOC emissions comparisons for both fuels when investigating environmental impacts for substitution of gasoline with E85. When considering human health impacts, toxic emissions comparison for both fuels is needed.

Statistical trends of emission differences for E85 versus gasoline with respect to engine size and model year were observed for NMOG, but not for CO and NO_x. This finding implies the potential effects of vehicle model and technologies on emission differences over time. Tailpipe emission rates differences for both fuels are quantified based on the existing FFV technologies. Improvements in vehicle technologies and emission control systems may alter such differences, when considered over a long time horizon.

Where second-by-second data are available, the VSP modal approach can account for some variability in fuel consumption and emission rates for both fuels. This approach links the aggregate vehicle activity with micro-scale profiles that influence actual emissions to explain variability in link average emission rates for various speed ranges. Since travel demand models (TDMs) produce link-level vehicle activity outputs, link-based emission rates are recommended to couple with TDMs for high-resolution emission inventory estimation. However, there are needs of more PEMS data to further quantify the differences for the modal emission rates associated with high VSP modes. Link-based emission rates should be developed on the fleet basis.

Ethanol produced from agricultural crops is regarded as being renewable energy and reduces life-cycle GHG. Ethanol use reduces dependence on imported petroleum and thus promotes energy security. However, there are some tradeoffs associated with the use of corn-based ethanol with aspect to agricultural environmental impact and air quality such as groundwater pollution and river eutrophication (by the use of nitrogen fertilizer), and ozone precursor emissions. There are needs for improvements in technologies and practices for sustainable agriculture and ethanol production.

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7.8 References

Alternative Fuel Data Center of the U.S. Department of Energy Home Page (2006), Available at fttp://www1.eere.energy.gov/vehiclesandfuels/avta/light_duty/afv/emissions_data.html (accessed on December 10, 2006).

Black, F., S. Tejada and M. Gurevich (1998), "Alternative Fuel Motor Vehicle Tailpipe and Evaporative Emissions Composition and Ozone Potential," *Journal of the Air and Waste Management Association*, 48(7):578-591.

Durbin, T.D., J.W. Miller, T. Younglove, T. Huai and K. Cocker (2006), "Effects of Ethanol and Volatility Parameters on Exhaust Emissions," CRC Project No. E-67, Prepared by University of California-Riverside for Coordinating Research Council, Alpharetta, GA, January.

DOE (2007), "Flexible Fuel Vehicles: Powered by a Renewable American Fuel," U.S. Department of Energy, Washington DC, Washington, DC, May. Http://www.eere.energy.gov/afdc/pdfs/41597.pdf. (accessed on November 11, 2007).

EIA (2006), "Annual Energy Outlook 2006 with Projections to 2030," DOE/EIA-0383, Energy Information Administration, U.S. Department of Energy, Washington, DC, February.

EIA (2007a), "Annual Energy Outlook 2007 with Projections to 2030," DOE/EIA-0383, Energy Information Administration, U.S. Department of Energy, Washington, DC, February.

EIA (2007b), "Biofuels in the U.S. Transportation Sector," Energy Information Administration, U.S. Department of Energy, Washington, DC. http://www.eia.doe.gov/oiaf/analysispaper/biomass.html (accessed on November 18, 2007).

ENVIRON (2002), "Onboard Emission Data Analysis and Collection for the New Generation Model," PR-CI-01-12239, Prepared by ENVIRON International Corporation for U.S. Environmental Protection Agency, Ann Arbor, MI. February.

EPA (2005), "A Roadmap to MOVES2004," EPA420-S-05-002, U.S. Environmental Protection Agency, Ann Arbor, MI, March.

EPA (2006), "Alternative Fuel: E85 and Flex Fuel Vehicles," EPA 420-F-06-047, U.S. Environmental Protection Agency, Ann Arbor, MI, October.

EPA (2007a), "Emission Facts: Greenhouse Gas Impacts of Expanded Renewable and Alternative Fuels Use," EPA420-F-07-035, Environmental Protection Agency, Ann Arbor, MI, April.

EPA (2007b), Environmental Protection Agency: Annual Certification Test Results & Data, http://www.epa.gov/otaq/crttst.htm (accessed on June 20, 2007).

Frey, H.C., N.M. Rouphail, A. Unal and J. Colyar (2001), "Emissions Reduction through Better Traffic Management: An Empirical Evaluation Based Upon On-Road Measurements," FHWY/NC/2002-001, Prepared by North Carolina State University for North Carolina Department of Transportation, December.

Frey, H.C., A. Unal, J. Chen, S. Li and C. Xuan (2002), "Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle & Equipment Emission System," EPA420-R-02-027, Prepared by North Carolina State University for U.S. Environmental Protection Agency, Ann Arbor, MI. August.

Frey, H.C., A. Unal, N.M. Rouphail and J.D. Colyar (2003), "On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument," *Journal of the Air and Waste Management Association*, 53(8):992-1002.

Frey, H.C., N.M. Rouphail and H. Zhai (2006), "Speed- and Facility-Specific Emission Estimates for On-Road Light-Duty Vehicles on the Basis of Real-World Speed Profiles," *Transportation Research Record: Journal of the Transportation Research Board*, 1987:128-137.

GMC (2007), "2007 Model Year E85 and Gasoline Flex-Fuel Vehicle Certification Data Summary," General Motors Corporation, Detroit, MI.

Gonçalves, G. A. and T. L. Farias (2005), "On-Road Measurements of Emissions and Fuel Consumption of Gasoline Fuelled Light Duty Vehicles," Proceedings of the 8th International Conference on Energy for a Clean Environment - Clean Air 2005, Calouste Gulbenkian Foundation, Lisbon, Portugal, June 27-30.

Guerrieri, D.A., P.J. Caffrey and V. Rao (1995), "Investigation into the Vehicle Exhaust Emissions of High Percentage Ethanol Blends," *SAE Special Publications, Gasoline: Additives, Emissions, and Performance*, 1095:85-95.

Haskew, H.M., T.F. Liberty and D. McClement (2006), "Fuel Permeation from Automotive Systems: E0, E6, E10, E20 and E85," CRC Report No. E-65-3, Prepared by Harold Haskew

& Associates, Inc. and Automotive Testing Laboratories, Inc. for Coordinating Research Council, Alpharetta, GA, December.

Haskew, H.M. (2007), "Exhaust and Evaporative Emissions Testing of Flexible Fuel Vehicles," Proceedings of the 17th Coordinating Research Council On-Road Vehicle Emissions Workshop, San Diego, CA, March 26-28.

Huai, T., S.T. Durbin, T. Younglove, G. Scora, M. Barth, and J.M. Norbeck (2005), "Vehicle Specific Power Approach to Estimating On-Road NH_3 emissions from Light-Duty Vehicles," *Environmental Science and Technology*, 39(24):9595-9600.

Jacobson, M. (2007), "Effects of Ethanol (E85) versus Gasoline Vehicles on Cancer and Mortality in the United States," *Environmental Science and Technology,* 41(11):4150-4157.

Jiménez-Palacios, J. (1999), "Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing," PhD Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Kelly, K., L. Eudy and T. Cobum (1999), "Light-Duty Alternative Fuel Vehicles: Federal Test Procedure Emissions Results," NREL/TP-540-25818, National Renewable Energy Laboratory, September.

Koupal, J., E. Nam, B. Giannelli and C. Bailey (2004), "The MOVES Approach to Modal Emission Modeling," Presented at Coordinating Research Council On-Road Vehicle Emissions Workshop, March 29.

Lavigne, A. and S.E. Powers (2007), "Evaluating Fuel Ethanol Feedstocks from Energy Policy Perspectives: A Comparative Energy Assessment of Corn and Corn Stover," *Energy Policy*, 35(11):5918-5930.

Lipman, T. E. and M. A. Delucchi (2002), "Emissions of Nitrous Oxide and Methane from Conventional and Alternative Fuel Motor Vehicles," *Climatic Change*, 53(4):477-516.

MacDonald, T. (2005), "Alcohol Fuel Flexibility-Progress and Prospects," Presented at Fifteenth International Symposium on Alcohol Fuels, San Diego, CA, September 26-28.

MacLean, H.L., L.B. Lave, R.L. Lankey and S.A. Joshi (2000), "A Life-Cycle Comparison of Alternative Automobile Fuels," *Journal of the Air & Waste Management Association*, 50(10):1769–1779.

NEVC (2007), National Ethanol Vehicle Coalition Frequently Asked Questions, http://www.e85fuel.com/e85101/questions.php (accessed on November 11, 2007).

NREL. (1998), "Ohio's First Ethanol-Fueled Light-Duty Fleet: Final Study Results," National Renewable Energy Laboratory, October, Available at http://www.nrel.gov/vehiclesandfuels/fleettest/publications_light.html (accessed on December 13, 2007).

NREL. (1999a), "Fact Sheet: Dodge Caravan Ethanol-Fueled Minivan," National Renewable Energy Laboratory, May, Available at http://www.nrel.gov/vehiclesandfuels/fleettest/publications_light.html (accessed on December 13, 2007).

NREL. (1999b), "Fact Sheet: Ford Taurus Ethanol-Fueled Sedan," National Renewable Energy Laboratory, June, Available at http://www.nrel.gov/vehiclesandfuels/fleettest/publications_light.html (accessed on December 13, 2007).

Pimentel, D.(2003), "Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts Are Negative," *Natural Resources Research*, 12(2):127-134.

Pimentel, D. and T. Patzek (2005), "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower," *Natural Resources Research*, 14(1):65-76.

Poulopoulos, S.G. and C.J. Philippopoulos (2003), "The Effect of Adding Oxygenated Compounds to Gasoline on Automotive Exhaust Emissions," *Journal of Engineering for Gas Turbines and Power*, 125(1):344-350.

Reuter, R.M., J.D. Benson, V.R. Burns, R.A. Jr. Gorse, A. M. Hochhauser, W.J. Koehl, L. J. Painter, B.H. Rippon and J.A. Rutherford (1992), "Effects of Oxygenated Fuels and RVP on Automotive Emissions- Auto/Oil Air Quality Improvement Program," SAE Technical Paper Series No. 920326, Society of Automobile Engineers International Congress and Exposition, Detroit, MI, February 24-28.

Scora, G., C. Malcolm, T. Younglove and M.J. Barth (2002), "Mobile Source Emissions New Generation Model: Using a Hybrid Database Prediction Technique," EPA68-C-01-169, Prepared by University of California at Riverside for U.S. Environmental Protection Agency, Ann Arbor, MI. February.

de Serves, C. (2005), "Emissions from Flexible Fuel Vehicles with Different Ethanol Blends," Report No. AVL MTC 5509, Swedish Road Administration, Haninge, Sweden.

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh and R. Nelson (2004), "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol," *Journal of Industrial Ecology*, 7(3-4):117-146.

Spatari, S., Y. Zhang and H.L. Maclean (2005), "Life Cycle Assessment of Switchgrass- and Corn Stover-Derived Ethanol-Fueled Automobiles," *Environmental Science and Technology*, 39(24):9750-9758.

Wang, M. (1999), "GREET 1.5- Transportation Fuel-Cycle Model Volume 1: Methodology, Development, Use, and Results," ANL/ESD-39, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, August.

Wang, M. (2001), "Development and the Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies," ANL/ESD/TM-163, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, June.

Wang, M. (2005), "Updated Energy and Greenhouse Gas Emissions Results of Fuel Ethanol," The 15th International Symposium on Alcohol Fuels, San Diego, CA, September 26-28, Available at http://www.transportation.anl.gov/pdfs/TA/354.pdf (accessed on December 13, 2007).

Wang, M., M. Wu and H. Huo (2007), "Life-Cycle Energy and Greenhouse Gas Emission Impacts of Different Corn Ethanol Plant Types," *Environmental Research Letters*, 2, doi:10.1088/1748-9326/2/2/024001.

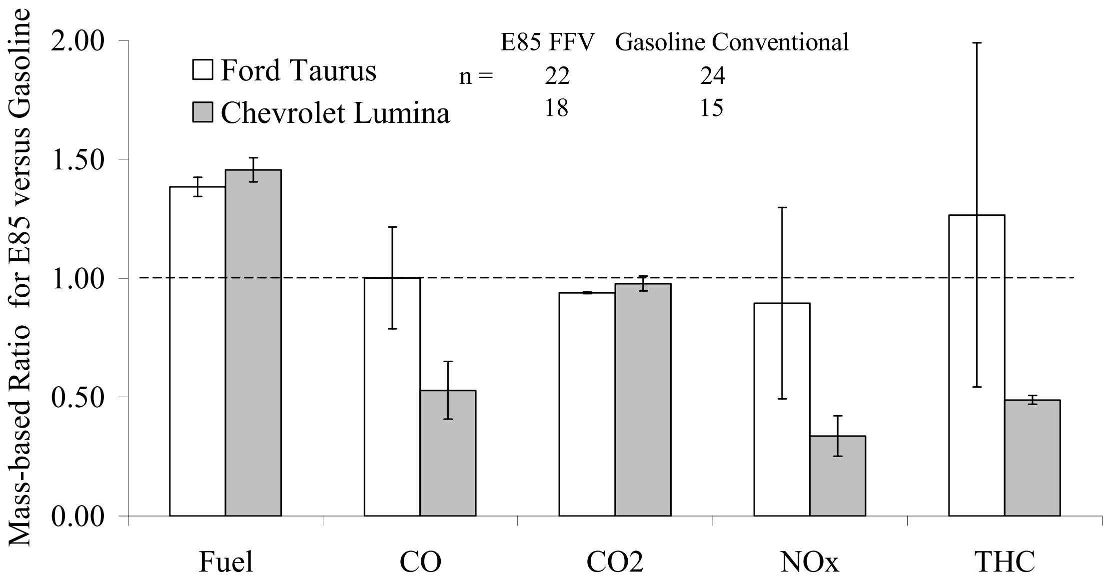
Wikipedia (2007), Lower Heating Value, Available at http://en.wikipedia.org/wiki/Lower_heating_value (accessed on December 10, 2007).

Winebrake, J.J., M.Q. Wang and D. He (2001), "Toxic Emissions from Mobile Sources: A Total Fuel-Cycle Analysis for Conventional and Alternative Fuel Vehicles," *Journal of the Air and Waste Management Association*, 51(7):1073-1086.

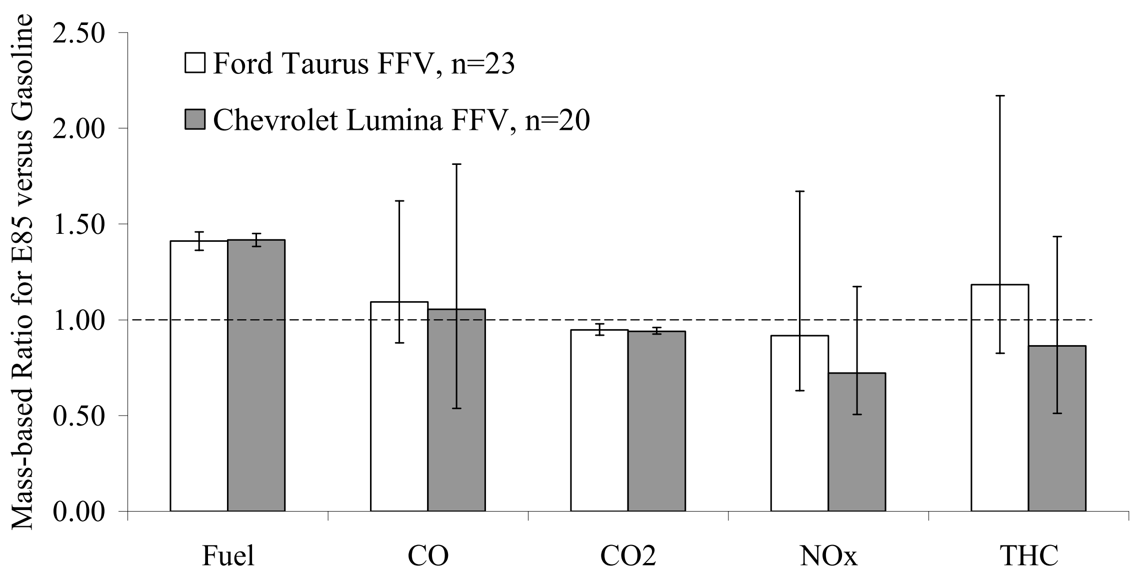
Wu M., Y. Wu and M. Wang (2006), "Energy and Emission Benefits of Alternative Transportation Liquid Fuels Derived from Switchgrass: A Fuel Life Cycle Assessment," *Biotechnology Progress*, 22(4):1012-1024.

Zhai, H., H.C. Frey and N.M. Rouphail (2006), "Speed- and Facility-Specific Emissions Estimates for Transit Buses based on Real-World Speed Profiles," Paper 06-A-195, Proceedings of the 99th Annual Meeting of the Air & Waste Management Association, New Orleans, June 20-23.

List of Figures and Tables



(a) Mean ratio and 95 percent confidence interval of the mean for E85 flexible fuel vehicles versus gasoline conventional vehicles[a,b]



(b) Mean ratio and maximum to minimum ranges of ratios for E85 FFVs versus gasoline FFVs

Figure 1 Ratios of Average Fuel Consumption and Emission Rates for E85 versus Gasoline based on DOE Dynamometer Tests on The FTP Cycle

[a] "n" represents number of vehicles. There are 22 Taurus FFVs for three ranges of accumulted miles from 0 to 15 thousand miles, 18 Lumina FFVs for four ranges of accumulated miles from 10 to 30 thousand miles.

[b] Based on average fuel consumption and emission rates for vehicles within the same range of accumulated miles for each vehicle model, ratios of fuel consumption and emission rates for E85 versus gasoline were calculated. An equally weighted average ratio estimated based upon all ranges of mileage accumulation for each vehicle model is shown in this figure.

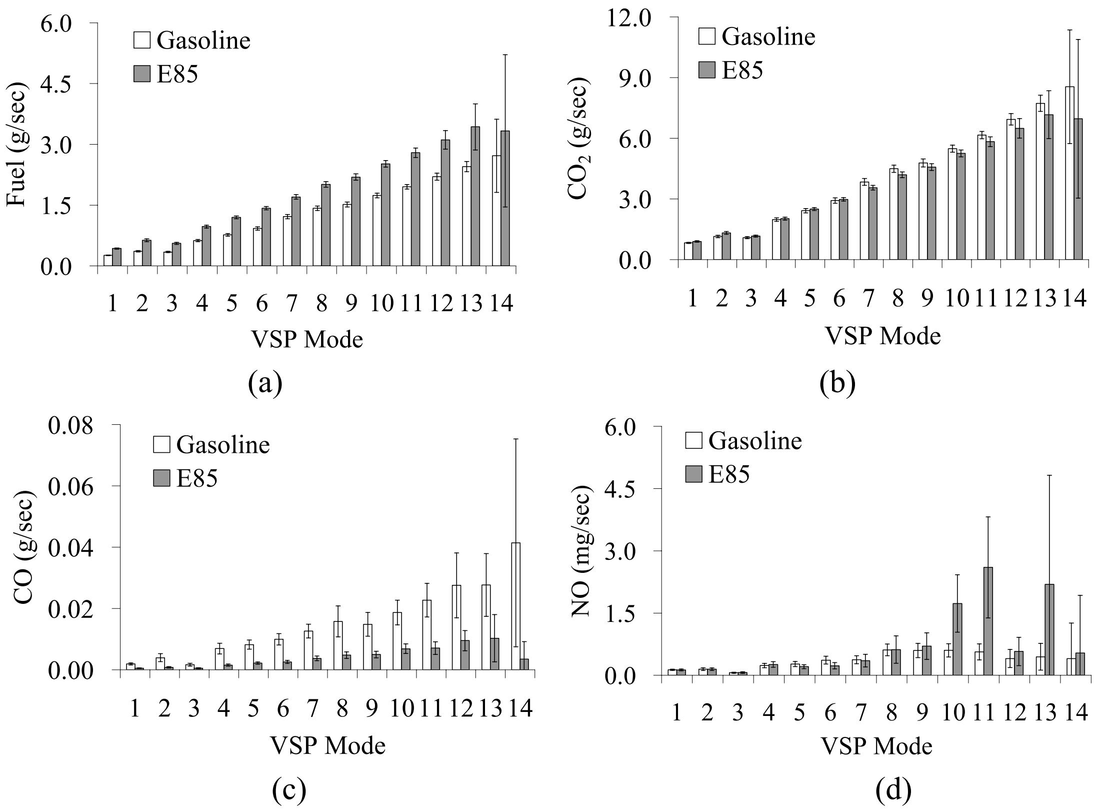


Figure 2. Modal Average Fuel Consumption and Emission Rates for a European 2006 Ford Focus based upon Portable Emissions Monitoring Systems Data [a]

[a] There are 1.3-hour second-by-second samples per fuel.

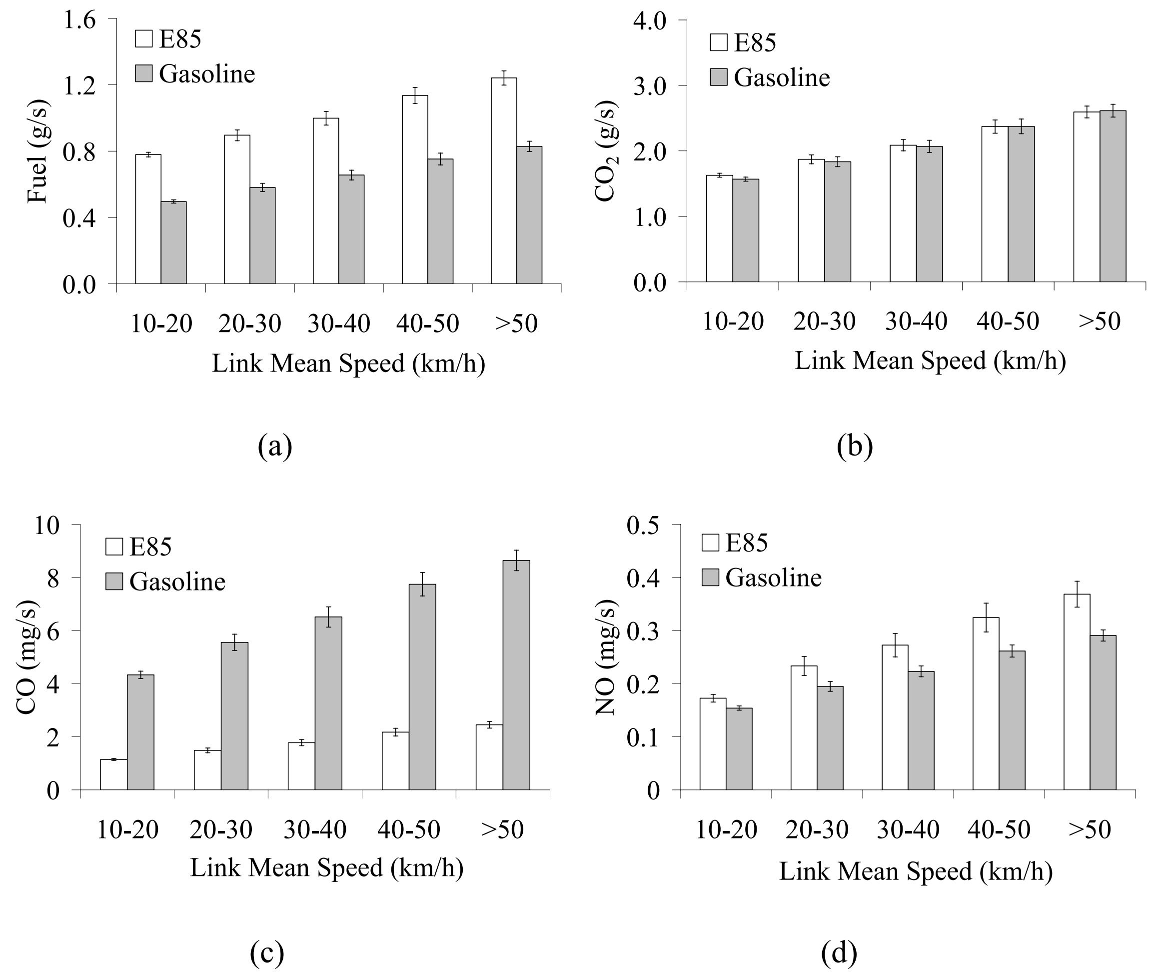


Figure 3. Mean Emissions Estimates and 95% Confidence Intervals for a 2006 Ford Focus based upon Real-World Link Speed Profiles on The Arterial Roadways [a]

[a] The number of speed profiles is 112, 54, 55, 98 and 202 for the five speed ranges indicated, respectively (Frey *et al.*, 2001).

Table 1. Physical and Chemical Properties of Selected fuels[a]

Fuel	Equivalent Molecular Formula	Equivalent Molecular Weight (g/gmole-C)	Weight Percent of Carbon (%)	Density (kg/m^3)	Lower Heating Value[c] (Btu/gallon)
Gasoline	$CH_{1.875}$	13.875	86.5	740	115,500
Ethanol	$CH_3O_{0.5}$	23	52.2	789	76,000
E85[b]	$CH_{2.758}O_{0.392}$	21.035	57.0	782	81,925

[a] Source: Wang, 1999.
[b] Calculated based on 15 volume percent gasoline and 85 volume percent ethanol.
[c] The lower heating value is defined as the amount of heat released by combusting a specified quantity of a fuel (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 150 °C (Wikipedia, 2007).

Table 2. Definition of The VSP Modes[a]

VSP Mode	VSP Range (m^2/s^3)	VSP Mode	VSP Range (m^2/s^3)
1	VSP < -2	8	13 ≤ VSP < 16
2	-2 ≤ VSP < 0	9	16 ≤ VSP < 19
3	0 ≤ VSP < 1	10	19 ≤ VSP < 23
4	1 ≤ VSP < 4	11	23 ≤ VSP < 28
5	4 ≤ VSP < 7	12	28 ≤ VSP < 33
6	7 ≤ VSP < 10	13	33 ≤ VSP < 39
7	10 ≤ VSP < 13	14	39 ≤ VSP

[a] Source: Frey *et al*., 2002.

Table 3. Average Fuel Consumption and Emission Rates for E85-Fueled Flexible Fuel Vehicles (FFVs) and Gasoline Fueled Conventional Vehicles based upon FTP75 Dynamometer Tests [a,b]

Vehicle Model	Fuel Type	Number of Vehicles[e]	Number of Tests	Mileage Accumulation (10^3 miles)	Fuel Economy (mpg)	Fuel Consumption (gallon/mile)	Average Emission Rates (g/mile)[f]			
							CO	CO_2	NO_x	THC
Taurus [c]	FFV E85	12	12	0-5	15.4	0.065	1.13	405	0.100	0.107
		11	11	5-10	15.4	0.065	1.35	402	0.117	0.135
		5	5	10-15	15.4	0.065	1.28	397	0.119	0.153
	Conventional Gasoline	15	15	0-5	20.0	0.050	1.15	431	0.100	0.103
		10	10	5-10	20.0	0.050	1.46	429	0.120	0.116
		12	12	10-15	20.4	0.049	1.17	423	0.168	0.096
	FFV Gasoline	12	12	0-5	20.3	0.049	1.08	428	0.132	0.104
		11	13	5-10	20.6	0.049	1.14	422	0.139	0.105
		5	6	10-15	20.7	0.048	1.29	418	0.122	0.128
Lumina [d]	FFV E85	15	15	10-15	13.9	0.072	2.46	448	0.184	0.125
		5	6	15-20	14.1	0.071	2.50	438	0.254	0.132
		5	5	20-25	13.9	0.072	3.27	443	0.192	0.135
		4	4	25-30	14.3	0.070	2.88	429	0.212	0.142
	Conventional Gasoline	11	12	10-15	19.6	0.051	4.26	447	0.645	0.258
		8	8	15-20	19.6	0.051	4.72	445	0.635	0.263
		4	4	20-25	18.9	0.053	5.58	461	0.641	0.285
		2	2	25-30	19.2	0.052	6.86	446	0.590	0.288
	FFV Gasoline	15	16	10-15	18.5	0.054	2.53	476	0.263	0.148
		5	6	15-20	18.9	0.053	2.54	465	0.358	0.155
		5	5	20-25	18.3	0.055	2.88	479	0.336	0.145
		4	5	25-30	19.2	0.052	2.16	457	0.327	0.130

[a] Different vehicles were tested for each fuel for a given vehicle model, fuel type, and mileage accumulation. The E85 tests were with Flexible Fuel Vehicles (FFVs) and the gasoline tests were with FFVs and corresponding conventional vehicles.
[b] Source of data: Alternative Fuel Data Center of the U.S. Department of Energy (AFDC, 2006).
[c] Model years are 1994-1995. For Taurus, there were 22 FFVs and 24 conventional gasoline vehicles for three ranges of accumulated miles.
[d] Model years are 1992 and 1993. For Lumina, there were 18 FFVs and 15 conventional gasoline vehicles for four ranges of accumulated miles.
[e] For each vehicle model fueled by E85 and gasoline, some vehicles were tested in more than one group of accumulated miles.
[f] For each fuel operated on each vehicle model, average emission rates were estimated for all vehicles within the same group of accumulated miles.

Table 4. Comparison of Emission Rates for Flexible Fuel Vehicles (FFVs) for E85 versus Gasoline based on EPA Vehicle Certification FTP Tests[a,b,c,d]

No.	Certification Year	Make	Model	Engine Size (liter)	Percent Difference (%)		
					CO	NMOG	NO_x
1	1999	Ford	Ranger FFV - 4WD	3	-39		
2	1999	Mazda	B3000 FFV - 4WD	3	-41		
3	2000	Chevrolet	S10 Pickup 2WD	2.2	6	324	-50
4	2000	Ford	Ranger FFV - 4WD	3	-27	3	
5	2000	Ford	Taurus FFV	3	-29	41	-67
6	2000	Ford	Taurus Wagon- FFV	3	28	42	-50
7	2000	Mazda	B3000 FFV - 2WD	3	-34	-31	
8	2001	Chevrolet	S10 Pickup 2WD	2.2	-17	168	0
9	2001	Ford	Ranger FFV - ETH 2WD	3	20	0	17
10	2001	Ford	Explorer FFV 4WD	4	-8	16	-67
11	2001	Ford	Taurus Wagon- FFV	3	-24	-18	-53
12	2002	Mazda	B3000 2WD FFV	3	24	400	-50
13	2002	Chevrolet	K1500 SUB'N 4WD	5.3	-6		100
14	2002	GMC	K1500 Sierra 4WD	5.3	-13		140
15	2002	Mercury	Mountaineer 4WD FFV	4	-14	-28	-50
16	2002	Chevrolet	S10 Pickup 2WD	2.2	-17	168	0
17	2002	Ford	Taurus Wagon- FFV	3	0	-2	0
18	2003	Chevrolet	K1500SLVRADO4WD	5.3	10		0
19	2003	Chevrolet	K1500 SUB'N 4WD	5.3	10		0
20	2003	Chrysler	Sebring Convertible	2.7	-		100
21	2003	Ford	Taurus Wagon- FFV	3	-18	-8	
22	2003	Mercury	Mountaineer 4WD FFV	4.0	-73	-1	-15
23	2004	Chevrolet	K1500 Silverado 4WD	5.3	21	74	0
24	2004	Dodge	RAM 1500 Pickup 4WD	4.7	20		0
25	2004	Ford	Sport Trac 4WD FFV	4.0	-5	92	29
26	2004	Ford	Taurus Wagon - FFV	3.0	44	127	-32
27	2004	Mercedes-Benz	C-Class Wagon	2.6	-34	55	-81
28	2004	Mercury	Mountaineer 4WD FFV	4.0	-28	18	-9
29	2005	Chevrolet	K1500 SUB'N 4WD	5.3	60	116	0
30	2005	Chrysler	Town & Country 2WD	3.3	33	35	-75
31	2005	Dodge	RAM 1500 Pickup 4WD	4.7	-83	-2	0
32	2005	Ford	Sport Trac 4WD FFV	4.0	54	105	71
33	2005	Ford	Taurus Wagon - FFV	3.0	-33	-3	127
34	2005	Mercedes-Benz	C240 FFV	2.6	-34	55	-81

(continued)

Table 4. Continued

No.	Certification Year	Make	Model	Engine Size (liter)	Percent Difference (%)		
					CO	NMOG	NO_x
35	2005	Mercury	Mountaineer 4WD FFV	4.0	-23	41	27
36	2006	Dodge	Stratus 4-DR	2.7	-14	39	0
37	2006	Ford	Taurus Wagon - FFV	3.0	-33	-4	127
38	2006	Chrysler	Town & Country 2WD	3.3	-27	22	-75
39	2006	Lincoln-Mercury	Town Car	4.6	-56	-41	20
40	2006	Chevrolet	K1500 SUB'N 4WD	5.3	-17	54	-25
41	2006	Nissan	Titan 4WD	5.6	-31	57	-38
42	2006	Nissan	Titan 2WD	5.6	-41	64	0
43	2007	Dodge	Caravan 2WD	3.3	-9	-4	-43
44	2007	Dodge	RAM 1500 Pickup 4WD	4.7	-46	-5	-36
45	2007	Nissan	Armada 4WD	5.6	-67	-59	0
46	2007	Jeep	Commander 2WD	4.7	14	13	-50
47	2007	Chevrolet	H15 Van Convawd	5.3	-59	-15	0
48	2007	Chevrolet	Impala	3.5	-25	72	300
49	2007	Chevrolet	K1500 AVAL 4WD	5.3	-33	12	-25
50	2007	Chevrolet	Uplander FWD	3.9	-35	75	33
51	2007	Lincoln-Mercury	Town Car	4.6	-60	-33	50
52	2008	Mercedes-Benz	C300	3.0	-6	58	5
53	2008	Ford	F150 FFV 4WD	5.4	9	-28	-50
54	2008	Chevrolet	H15 Van Convawd	5.3	-13	21	0
55	2008	Chevrolet	Impala	3.9	-53	29	-50
56	2008	Dodge	RAM 1500 PICKUP 4WD	4.7	-11	-47	-58
57	2008	Chrysler	Sebring	2.7	20	-12	-75
58	2008	Nissan	Titan 4WD	5.6	-67	-44	100
59	2008	Chrysler	Town & Country 2WD	3.3	0	21	
60	2008	Lincoln-Mercury	Town Car	4.6	-10	-4	0
61	2008	Chevrolet	Uplander FWD	3.9	-32	81	100
Difference of Average Emission Rates for Certification Vehicles above					-20	23	5

[a] Source of data: EPA Annual Certification Test Results & Data, http://www.epa.gov/otaq/crttst.htm.
[b] Percent differences are calculated based on projected emission levels at the end of the useful life 50,000 miles.
[c] Comparable certified vehicles fueled by E85 and gasoline were available for model years from 1999 to 2008.
[d] All vehicles certified based on ethanol fuel are FFVs. For vehicles labeled with the "FFV" in the database, the gasoline tests are based on FFVs. However, it is unclear from the database as to if the reported data on gasoline tests on vehicles without the "FFV" label are for non-FFV conventional gasoline vehicles.

Table 5. Percentage Differences in Average Fuel Consumption and Emission Rates from Substituting Gasoline with E85 Fuel based on Real-World Portable Emissions Monitoring Systems (PEMS) Data for a European Ford Focus[a]

Facility	Item	Speed (km/h)						
		10-20	20-30	30-40	40-50	50-60	60-70	90-100
Freeway	Fuel Rate		N/A[b]			48.1		45.3
	NO					42.8		72.4
	CO					-70.9		-68.9
	CO_2					-2.0		-3.8
Arterial	Fuel Rate	57.1	55.3	52.3	50.8	49.8		
	NO	12.0	18.4	22.2	24.1	26.8		
	CO	-73.6	-73.0	-72.7	-71.9	-71.7		
	CO_2	3.9	2.8	0.8	-0.1	-0.8		
Local and Collector	Fuel Rate		53.4	50.3	51.9			
	NO		14.8	17.5	26.3			
	CO		-72.2	-72.6	-71.5			
	CO_2		1.5	-0.5	0.5			
On-Ramp	Fuel Rate						44.3	
	NO						72.8	
	CO						-68.5	
	CO_2		N/A[b]				-4.5	
Off-Ramp	Fuel Rate						57.4	
	NO						-9.5	
	CO						-75.7	
	CO_2						4.2	

[a] Sources of speed profiles: Frey *et al.*, 2001 and Frey *et al.*, 2006.
[b] No measured speed profiles are available for these speed ranges.

Table 6. Summary of Average Differences in Emissions between E85 and Gasoline for Each Source of Data

Data Source	Comparison Category	Average Difference in Fuel Consumption and Emissions (%)				
		Fuel	CO_2	CO	NMOG or HC	NO_x
Dynamometer tests	E85 FFVs vs. Gasoline FFVs	42 (36, 46) [d]	-6 (-8, -2) [d]	8 (-46, 81) [d]	2 (-49, 117) [d]	-18 (-50, 67) [d]
	E85 FFVs vs. Gasoline Conventional Vehicles	42 (38, 47) [e]	-4 (-6, -2) [e]	-27 (-3, -51) [e]	-12 (-59, 24) [e]	-42 (-72, -13) [e]
	Average for DOE Data [a]	42	-5	-10	-5	-28
Certification tests	E85 FFVs vs. Gasoline FFVs and Conventional Vehicles	N/A [c]	N/A [c]	-20 (-83, 60) [d]	23 (-59, 400) [d]	5 (-81, 300) [d]
PEMS [b]	E85 FFVs vs. Gasoline FFVs	54	2	-74	N/A [c]	-1
Difference of average E85 emissions versus gasoline emissions for all vehicle models and makes		46	-2	-22	12	-8

[a] The differences are the average values of four pair comparisons for E85 FFVs versus gasoline FFVs, and E85 FFVs versus gasoline conventional vehicles for both models.

[b] Differences are estimated based on average emission rates estimates for the FTP cycle using VSP modal approach for E85 and gasoline.

[c] No measurement data were available.

[d] Minimum and maximum differences among individual vehicles.

[e] 95% confidence intervals on mean.

Table 7. Emissions for E85 and Gasoline on the Basis of a Fuel Life Cycle

Fuel Type	Pollutant	Emission Rates (gram/mile)				Percentage Change in Total Emission Rates Relative to Gasoline
		Feedstock[a,b]	Fuel[c]	Vehicle Operation[d,e]	Total	
Conventional Gasoline	CO_2	15	79	410	504	0
	Fossil CO_2	14	74	404	492	0
	VOC	0.019	0.126	0.227	0.371	0
	CO	0.047	0.054	5.210	5.311	0
	NO_x	0.147	0.154	0.300	0.601	0
Corn-based E85	CO_2	-228	203	402	377	-25%
	Fossil CO_2	44	95	106	246	-50%
	VOC	-0.047	0.249	0.235	0.437	18%
	CO	0.173	0.139	4.064	4.376	-18%
	NO_x	0.446	0.373	0.276	1.095	82%

[a] The feedstock stage includes recovering, transporting, and storing energy feedstocks, such as crude oil, corn or grass. For ethanol, the amount of CO_2 contained in the ethanol that is from the atmosphere is treated as a credit during plant growth.

[b] In dry milling, ethanol is produced from corn starch, and other constituents of the corn kernel are used to produce distillers' dried grains and solubles (DDGS). DDGS can be used for animal feeds. Wet milling plants co-produce corn gluten feed, corn gluten meal, and corn oil. GREET allocates emissions and energy use charge between ethanol and its co-products by using a displacement method or a market value-based method. The default method is the product displacement method.

[c] The fuel stage includes producing, transporting, storing, and distributing product fuels.

[d] The vehicle operation stage includes vehicle fuel consumption and evaporation emissions.

[e] In GREET, CO_2 emissions for all vehicle types are calculated by using a carbon balance approach; emissions of VOC, CO, and NO_x for conventional gasoline vehicles are calculated with EPA's MOBILE5b (Wang, 1999); and vehicle emissions of CO_2, VOC, CO, and NO_x from spark-ignition E85 vehicles are calculated using emission change rates results in our study. Reduction rate for evaporative VOC emissions is 15% (Wang, 1999).

PART VIII REGIONAL ON-ROAD MOBILE SOURCE EMISSIONS CHARACTERIZATION FOR CONVENTIONAL AND ALTERNATIVE VEHICLE TECHNOLOGIES [††]

[††] This manuscript is in preparation for submission to an environmental journal.

Abstract

Motor vehicles are a major source of air pollution. The development of alternative fuels and alternate vehicle propulsion technologies could lead to meaningful reductions in emissions and the reliance on imported petroleum fuels. The objectives of this study are to characterize regional on-road mobile source emissions and evaluate the reductions in air pollutant emissions associated with real world operation of vehicles that utilize alternative fuels or propulsion technologies in comparison to conventional vehicles. For light duty vehicles, the fuels considered are gasoline, ethanol, compressed natural gas, hydrogen, and electric charges. Engine technologies considered are internal combustion engines, hybrids, fuel cell, and electric. For heavy duty vehicles, biodiesel is considered for trucks and compressed natural gas is considered for buses, in addition to conventional diesel fuels and technologies. Vehicle emission models at the roadway link level were developed and stratified with respect to vehicle specific power and applied to real world facility- and speed-specific driving cycles. The results from this modeling approach are coupled with estimates of roadway link-level vehicle activity derived from the Triangle Regional Model to estimate the regional emission inventory a high level of resolution. During the morning peak hours, the largest fraction of emissions (39% to 48%) for hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NO_x) occurred on freeways, followed by arterials. This was consistent with the level of vehicle activities on these facilities, which comprised 37% and 34% of total regional vehicle kilometers traveled. Passenger cars were found to be major emission sources for CO and HC whereas trucks were major emission sources for NO_x and CO_2. In the short-term, HC and CO emissions have larger reduction potentials than NO_x and

CO_2. Opportunities for significant reductions in NO_x emissions may be feasible in the long-term. A sensitivity analysis on the effect of market penetration for advanced vehicle technologies shows that emissions for all pollutants consistently decrease with an increase in their market penetration. To reflect more realistic changes in emissions for long-term planning, future land use and associated transportation demand scenarios are recommended to be coupled with emissions modeling in order to investigate the integrated effects of land use and advanced technologies on regional emissions.

Keywords: Emission Factor, Emission Inventory, Vehicle Technology, Conventional Technology, Advanced Technology, Alternative Vehicle Technology.

8.1 Introduction

Highway vehicles contributed about 54% total carbon monoxide (CO), 36% nitrogen oxides (NO_x) and 22% volatile organic compounds (VOC) emissions to the 2006 U.S. national emission inventory. These were the largest contributors to the national CO and NO_x emissions and the second largest for VOC emissions (EPA, 2007). In general, there are two methods to estimate on-road mobile source emission inventory: a bottom-up approach and a top-down approach (Cook *et al.*, 2006). The bottom-up approach combines vehicle emission factors and vehicle activity data from a travel demand model estimated at a road link level to estimate emissions in various time periods (peak, off-peak, etc.). The top-down approach relies on more aggregated information and default modeling inputs. In contrast to the top-down approach, the bottom-up approach uses local inputs to estimate more accurate emission factors and vehicle activity data, and provides more detailed information on the spatial distribution of on-road motor vehicle emissions.

The U.S. Environmental Protection Agency (EPA)' emission factors model, MOBILE, has been used to address a wide variety of air pollution modeling needs including emission inventory estimation (EPA, 2004). MOBILE calculates average in-use fleet emission factors for hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and carbon dioxide (CO_2) for 28 individual vehicle types for calendar years 1952 through 2050. The MOBILE model uses emissions data from dynamometer tests over standard driving cycles, as well as local characteristics (Miller *et al.*, 2006). The current version of MOBILE6 incorporates updated information such as basic emission rates and driving patterns, and includes impacts of new regulations. In contrast to prior versions, multiple facility-specific driving cycles have been incorporated in MOBILE6 to address the impacts of different level of services on emissions (EPA, 2001). However, standard driving cycles may not be sufficiently representative of real-world conditions because of their inability to represent the influence of real-world traffic flow and actual facilities conditions, especially for links operating at different level of services (Unal *et al.*, 2003; Frey *et al.*, 2001; Frey *et al.*, 2003; Frey *et al.*, 2006). MOBILE6, for example, does not distinguish between emission rates for vehicles entering or exiting at freeway ramps (EPA, 2004). However, on-ramp and off-ramp emission rates can be significantly different due to their obviously different driving patterns (Frey *et al*, 2006). In addition, emission factors for CO_2 are estimated based on fuel economy instead of emission tests, and these are not adjusted to account for speed and facility type.

Travel demand models (TDM's) normally produce link-based vehicle activity data, such as mean speed, traffic volume, and vehicle type (Caliper, 2000; TRANUS, 2007), whereas emission factors models are often trip based. Therefore, there needs to be consistency between their modeling interfaces for the purpose of emission inventory estimation. A comparative study showed that using trip-based versus link-based traffic data for regional mobile source emissions may result in different estimates up to around 10% for CO and NO_x (Bai *et al*., 2007). Thus, link-based emissions models are needed in order to integrate with link-based vehicle activity data from TDM's. The development and application of new and existing measurement and analysis technologies enable models to more closely approximate actual emissions in time and space (Miller *et al*., 2006). Portable Emissions Monitoring Systems (PEMS) are gaining increased acceptance as a means for quantifying vehicle activities and emissions on a micro-scale level under real-world operational conditions (Frey *et al*., 2003; Younglove *et al*., 2005; and Rykowski *et al*., 2005). PEMS have enabled the characterization of variability in emissions measurements and vehicle activities for representative real-world driving conditions on a road link level for light-duty and heavy-duty vehicles (Frey *et al*., 2006 and Frey *et al*., 2008). Such characterizations for vehicle activities and emissions under real-world operations can be incorporated in the development of link-based emissions models.

Vehicle emissions reductions can be achieved using alternative vehicle propulsion technologies and fuels. On a life-cycle basis, ethanol dedicated vehicles, electric vehicles, and fuel-cell vehicles can reduce greenhouse gas (GHG) emissions by over 40% (Wang, 1999). Compressed natural gas (CNG) can reduce carbon dioxide emission by 30% (Lave *et* *al*., 2000). In the near future, hybrid gasoline-electric vehicles will likely become dominant, because they can reduce gasoline consumption and GHG emissions 30 to 50% (Romm, 2006). Advanced technology vehicles including include flex-fuel vehicles, hybrid electric vehicles, advanced diesel, electric and fuel cell vehicles, may make up more than 27% of total new light-duty vehicle sales by 2030 (EIA, 2007). Therefore, it is important to investigate the influence of an increase in market penetration for such vehicles on regional on-road emissions over a long horizon.

8.2 Research Objectives

To address the issue of the modeling interface of emissions and transportation models, emissions models are developed from real-world vehicle operational measurements at various link levels of service using PEMS. PEMS data can characterize vehicle activities and emissions for conventional and advanced vehicle technologies, which enable the evaluation of the effect of vehicle technologies on regional emissions. For light duty vehicles, the fuels considered are gasoline, ethanol, compressed natural gas, hydrogen, and electricity. The technologies considered are internal combustion engines, hybrids, fuel cell, and electric. For heavy duty vehicles, biodiesel is considered for trucks and compressed natural gas is considered for buses, in addition to conventional diesel fuels and technologies.

Thus, the overall objectives of this study are to estimate and characterize regional on-road mobile sources emissions, and to quantify the impacts of market penetration for advanced vehicle technologies on regional mobile source emissions over a long term.

Scenarios with different market penetrations of alternative vehicle technologies are applied to the current and future vehicle fleets in order to: (1) evaluate the effects of alternative vehicle technologies on current regional emissions for old or more recent model years; and (2) quantify emissions changes with and without alternative/advanced vehicle technologies over a long planning horizon. Additional scenarios are simulated to evaluate the potentials for the substitution of conventional vehicles with advanced technology vehicles in altering current regional emissions, assuming that the current vehicle fleet completely consists of new or old model year conventional vehicles.

8.3 Methodology

The methodology employed for characterizing regional on-road mobile sources emissions is founded upon: (a) developing link-based emissions models based on real-world vehicle operational conditions for conventional and advanced vehicle technologies; (b) coupling emissions models and link-based vehicle activities data from travel demand modeling for estimating emission inventory; and (c) designing multiple scenarios to quantify the impacts of advanced technologies on regional mobile sources emissions over a long term.

8.3.1 Emission Factors Estimation

Vehicle emission factor estimates are affected by many factors including vehicle fuel and technology, vehicle class and age, speed, facility type, vehicle fleet distribution, emission control standards, vehicle inspection and maintenance (I/M) program, calendar year. In general, emission factors can be estimated by the following equation:

$$EF_{Y,T,f,V} = BER_{Y,C,f,v} \times SCF_{T,f,V} \times TCF_{T,C} \quad (1)$$

Where:

EF	= emission factor (grams/sec);
BER	= basic emission rate (grams/sec);
SCF	= speed correction factor for time-based emission factor;
TCF	= technology correction factor relative to conventional technology for emission rates;
Y	= calendar year;
T	= vehicle fuel and technology (conventional or alternative);
f	= facility type (freeway, arterial, local roadway, ramp);
V	= actual vehicle speed (mph);
C	= conventional technology (light-duty gasoline vehicles, diesel trucks and buses);
v	= average driving cycle speed (mph).

Basic Emission Rates for HC, CO, and NO_x Emissions

Basic emission rates for HC, CO and NOx are derived from MOBILE6 at average cycle speed. For light-duty gasoline vehicles (LDGVs), average cycle speed is 19.6 mph for freeways and arterials, 34.6 mph for ramp and 12.9 mph for local roadway (EPA, 2001); for heavy-duty diesel vehicles (HDDVs), average cycle speed is 20.0 mph (EPA, 1995). Since MOBILE6 does not identify emission rates for on-ramp versus off-ramp, basic emission rates for freeways or arterials are used as references and combine with on- and off- ramp speed correction factors for on- and off- ramp emission factors estimates. For LDGVs, heavy-duty diesel trucks (HDDTs) and buses (HDDBs), BERs are estimated based on MOBILE6 modeling for each pollutant. In addition, light-duty diesel vehicles (LDDV) are also derived from MOBILE6.

In general, travel demand models (TDMs) produce link-based vehicle activity data for a specified time period. Therefore, in addition to speed and facility type, BERs are adjusted for temperature and humidity conditions during the modeled hours. Emission control programs and standards including I/M program, Tier 2 emission standards and 2007 heavy-duty vehicle emission standards are also considered in estimating BERs in order to account for their impacts on regional mobile source emissions, especially for a future year. BER may also vary with vehicle age. Therefore, final basic emission rates are average values weighted by the fractions of vehicle of various age groups for a given vehicle class:

$$BER_{Y,C,f,v}(Temp, H, P) = \sum_{i}^{24} a_i \times BER_{Y,C,f,v,i}(Temp, H, P) \tag{2}$$

Where:

BER = basic emission rate (gram/sec);

Y = calendar year;

i = vehicle age group (0, 1, 2…, 24);

C = conventional technology;

f = facility type;

v = average driving cycle speed (mph);

$Temp$ = temperature (^{o}F);

H = relative humidity;

P = barometric pressure (inches of mercury);

a_i = fraction of vehicles in age group (i) for a given vehicle class;

Distance-based emission rates derived from MOBILE6 are converted to time-based emission rates using the corresponding average driving cycle speed.

For advanced light-duty vehicle technologies including ethanol 85 (E85), compressed natural gas (CNG), and hybrid electric vehicles (HEVs), emission rates are estimated from EPA's annual certification tests from 2001 through 2007 based on Federal Test Procedure (FTP) test cycle.

Basic Emission Rates for CO_2

Basic emission rates for CO_2 are estimated based on fuel carbon content and fuel economy. For light-duty vehicles, fuel economies are tested through FTP and highway fuel economy test (HFET), in which FTP can represent driving conditions on the city roadway and HFET can represent driving conditions on freeways. Average cycle speed is 21.2 mph for FTP cycle and 48.3 mph for HEFT cycle. For a given type of fuel, BERs for CO_2 are estimated:

$$BER_{CO_2} = \frac{c\,\dfrac{gram\ C}{gallon\ Fuel} \times \dfrac{44\ gram\ CO_2}{12\ gram\ C} \times \alpha}{FE_{cycke}\,\dfrac{mile}{gallon\ Fuel}} \times v\,\frac{mile}{hr} \times \frac{1\ hr}{3600\ \sec} \tag{3}$$

Where:

FE_{cycle} = fuel economy for FTP or HFET cycle (mpg);

BER_{CO_2} = basic emission rate of CO_2 (grams/sec);

c = amount of carbon content in a given fuel;

α = oxidation factor;

v = average cycle speed (mph).

Once speed correction factors for CO_2 are characterized by facility type, speed, vehicle fuel and technology, CO_2 emission factors for a given light-duty vehicle can be adjusted for facility type and speed as with other pollutants. However, for heavy-duty vehicles, BERs for CO_2 are from MOBILE6 as no comprehensive fuel economy data are available. As there are no speed profiles available on on- and off- ramps available for heavy-duty vehicles, BERs from MOBILE6 are directly used.

Speed Correction Factors Estimation

The speed correction factor (SCF) is defined as the ratio of average emission rate for any speed of interest to the link average emission rate at a base speed on a specified roadway type, and for a given vehicle technology. SCFs for a given vehicle technology are estimated based on speed- and facility- specific average link emission rates.

Link-based emission rates are estimated for LDGVs, LDDVs, E85 and CNG cars, HDDBs and HDDTs based on PEMS data prior to estimating SCFs (Frey *et al*., 2006; Zhai *et al*., 2006; Zhai *et al*., 2007; Frey *et al*, 2008). For HEVs, average emission rates for each speed range are estimated based on dynamometer tests (Nam *et al*., 2005). Link-based emissions models are developed based on vehicle specific power or speed-acceleration modes, which are constructed from link speed profiles measured under real-world traffic conditions by PEMS. Vehicle specific power (VSP) takes into account aerodynamic drag, tire rolling resistance, speed, acceleration and road grade (Jiménez-Palacios, 1999) and estimated for a generic light duty vehicle (Frey *et al*., 2006):

$$VSP = \mathrm{v} \times [1.1 \times a + 9.81 \times (\sin(\mathrm{atan}(\varphi))) + \psi] + \zeta \times \mathrm{v}^3 \qquad (4)$$

Where:

VSP	= vehicle specific power (m^2/s^3);
v	= vehicle speed (m/s);
a	= acceleration (m/s^2);
φ	= road grade;
ψ	= rolling resistance term coefficient (0.132 m/s^2);
ζ	= drag term coefficient (0.000302 m^{-1}).

Fourteen VSP discrete modes were defined for light-duty vehicles in a previous study (Frey et al., 2002). For second-by-second link speed profiles classified by facility type and mean link speed, VSP value is calculated at each second, and time spent in each VSP mode on a link are then determined. Similarly, time spent in speed-acceleration mode can be determined when a speed-acceleration modal approach is used. For a given vehicle technology, modal emission rates are estimated based on corresponding PEMS data. Link average emission rate were estimated as the product of the fraction of link travel time spent in each mode multiplied by the corresponding modal emission rates. Speed ranges for each facility type for light-duty vehicles are given in Table 3. VSP modal emissions models are developed for LDGVs, LDDVs, diesel buses, E85 cars, and CNG cars for link emission rates estimates; speed-acceleration modal emissions model are developed for heavy-duty trucks. For HEVs, modal emissions model based only on speed bins are generated as no data at higher VSP modes were available. Finally, link emission rates are characterized by vehicle technology, mean link speed and facility type as possible. SCFs are also specified by these factors.

When base link emission rates are determined, SCFs can be easily calculated. For LDGVs, average driving cycle speed for estimating BERs for HC, CO, and NO_x is 19.6 mph for freeways and arterials, and 12.9 mph for local roadways. Therefore, base speed ranges for SCFs estimation are 18.6-24.9 mph for freeways and arterials, and 12.4-18.6 mph for local roadways. Since no speed profiles for speed range of 18.6-24.9 mph on freeways were available, the link-based emission rates of HC, CO, and NO_x for speed range of 18.6-24.9 mph on arterials are used as the basis to estimate SCFs on freeways, arterials, on- and off-ramps. Link-based emission rates for speed range of 12.4-18.6 mph on local roadways are used as the basis to estimate SCFs on local roadways. For HDDTs and HDDBs, average driving cycle speed for estimating BERs for HC, CO, and NO_x is 20.0 mph. Therefore, average emission rates for link-based emission rates for both speed ranges of 10-20 mph and 20-30 mph on arterials are used as the basis to estimate SCFs for HDDTs and HDDBs on freeways, arterials, and local roadways. As no speed profiles on freeways are available for diesel buses, speed correction equations in MOBILE6 for heavy-duty vehicles were used for diesel buses (EPA, 1995).

For those advanced light-duty vehicle technologies relying on EPA's annual certification FTP tests and LDDVs, emission rates for speed range of 18.6-24.9 mph on arterials were used as the basis to estimate SCFs on any facility type for these vehicles. The average driving cycle speed for these data is 21.2 mph.

For CO_2, average cycle speed of fuel economy test cycle is 21.2 mph for surface streets and 48.3 mph for highways. Therefore, link-based emission rates for speed range of 18.6-24.9 mph on arterials are used as the basis to estimate SCFs on arterials, local roadway, on- and off- ramps, whereas link-based emission rates for speed range of 43.5-49.7 mph on freeways are used as the basis to estimate SCFs on freeways. However, no real-world speed profiles were available for this speed range. Emission rates for HFET cycle are estimated using VSP modal approach and used as the substitution to estimate SCFs on freeways.

Technology Correction Factors

Technology correction factors (TCFs) are set at 1.0 for conventional light-duty gasoline vehicles, diesel trucks and buses.

TCF is set to zero for electric and fuel cell vehciels as they produce no tailpipe emissions. For advanced light-duty vehicles including E85, CNG and HEV, average cycle emission rates for vehicles from model years 2001 through 2007 are used. Based on the FTP test results for advaned technologies, TCFs are estimated as:

$$TCF = \frac{CER_{T,f,v}}{BER_{C,f,v}} \tag{5}$$

Where:

TCF = technology correction factor;

BER = basic emission rate for conventional gasoline cars from MOBILE6 (grams/mile);

CER = average cycle emission rate based on EPA's certification tests (grams/mile);

T = index of advanced technology (E85, HEV, and CNG cars);

C = index of conventional fuel and technology (light-duty gasoline vehicles);

f = facility type (arterial);

v = average driving cycle speed (21.2 mph).

Replacing TCF in Equation (1) with Equation (5), the BER term cancels out, which shows that emission factors estimates for those advanced light-duty vehicles relies strictly on EPA' certification tests.

For advanced heavy-duty vehicles, TCFs are borrowed from the technical literature on emission comparisons for biodiesel-20 versus diesel trucks, and CNG versus diesel buses as no database is available for estimating fleet-based emission factors.

8.3.2 Emission Inventory (EI) Estimation

Emissions models are coupled with estimates of link-level vehicle activity from TDMs to estimate high-resolution emission inventories. Time-based emission factor is a function of facility type, vehicle technology, and link mean speed. In general, on-road emissions are typically estimated as the product of emission factor and activity indicator. The total emissions for a single link on a facility type are estimated as:

$$t_{i,ct} = \frac{L_i}{v_{i,ct}} \times 3600 \tag{6}$$

$$TE_{i,f} = \sum_{ct}^{CT} \left(EF\{Y, f, ct, v_{i,ct}\} \cdot t_{i,ct} \cdot vol_{i,ct} \right) \tag{7}$$

Where:

EF = emission factors (gram/sec);

$TE_{i,f}$ = total emissions on link i for facility f (grams/period);

Y = calendar year;

i = link ID;

f = facility type index;

ct = vehicle class and technology;

$v_{i,ct}$ = mean link speed of vehicle in class ct on link i (mph);

L_i = link i distance (mile);

$t_{i,ct}$ = travel time of vehicle class ct on link i (second/veh);

$vol_{i,ct}$ = flow rate of vehicle class ct on link i (veh/period).

TDM generates outputs such as: link characteristics (link ID, link origin and destination, link facility type and distance), vehicle class, free flow speed and congested speed, and traffic volume by vehicle class. These link-based vehicle activities are used to estimate link-based mobile source emission inventory. Network travel activity data were derived from the Triangle Region Model in North Carolina to serve as an illustrative case study.

8.3.3 Regional Emissions Estimation Scenarios

Multiple scenarios for vehicle fuel and technology fleet penetration were used to investigate the influence of advanced vehicle technologies on the magnitude and spatial characteristics of vehicle emissions. Essentially, there are three sets of scenarios: baseline scenarios, alternative scenarios, and future scenarios. The assumed model years are 2005 for the baseline and alternative scenarios and 2030 for the future scenarios. The baseline scenarios only consider conventional technologies and current emissions standards for a base year; the alternative scenarios consider conventional and advanced vehicle technologies at current market penetration levels, and current emission standards for the base year; future scenario considers conventional and advanced vehicle technologies, emission control standards and programs projected for a future year 2030. Changes in the alternative and future scenarios relative to baseline scenario are intended to quantify the influence of advanced vehicle technologies on regional emissions over a long term. Sensitivity analysis of emission changes to varying market penetration levels of advanced vehicle technologies is carried out to evaluate the potentials of emissions reductions on a regional scale.

8.4 Database

Regional emissions estimation relies on basic emission rates, speed correction and technology correction factors, and link traffic volume. Sources of data for key components in developing the emission inventory are summarized in Table 1.

Basic emission rates for HC, CO and NO_x are derived from MOBILE6 for conventional LDGVs, HDDTs, and HDDBs. Basic emission rates for CO_2 are estimated from fuel economy (EPA, 2006, Fuel Economy Guide, 2007).

To estimate modal emission rates for conventional and advanced technology including LDGVs, HDDTs, HDDBs, E85 cars, HEVs, CNG cars, LDDVs, second-by-second emission rates of HC, CO, NO_x and CO_2 were measured by PEMS under real-world traffic conditions or dynamometer test conditions.

For E85 and CNG cars, and HEVs, average cycle emission rates of HC, CO, and NO_x from EPA's certification tests are used to estimate emission factors for these advanced technologies. For LDDVs, these BERs are also derived from MOBILE6.

For heavy-duty biodiesel-20 (B20) trucks and CNG-fueled buses, TCFs are from literature reviews.

The Triangle Region Model (TRM) produces link-based activity data during a four-hour period around the morning peak. Vehicle activity data are summarized in Table 2. Local roadways and collectors have a much larger number of links than other facility types. Freeways (including freeway ramps) have higher average speed and vehicle kilometer traveled (VKT), compared to arterials, local roadways and collectors.

8.5 Results and Discussion

Emission factors for conventional and advanced vehicle technologies are estimated and coupled with outputs from the TRM to estimate regional mobile sources emission inventory. The impacts of advanced vehicle technologies on regional emissions are quantified through multiple scenarios modeling.

8.5.1 Emission Factors Estimates

Basic Emission Rates Estimates

Basic emission rates of HC, CO and NO_x on each facility type are derived from MOBILE6 for LDGVs, HDDTs and HDDBs. The evaluation month is July as TRM models vehicle activities in the summer. The calendar year considered is 2005 for baseline and alternative scenarios and 2030 for future year. Local hourly average temperature and humidity are given in the input file to account for their impacts on emission rates during peak hours. An RVP of 7.8 pounds per square inch (psi) is applied in this analysis for the Triangle

Area in North Carolina (NC). The default Federal Tier 2 and 2007 heavy-duty vehicle emission standards are used. North Carolina has implemented a vehicle emissions inspection program, and onboard diagnostics (OBD) in 48 counties (Abraczinskas *et al.*, 2007). Test and Repair Computerized (TRC) and evaporative I/M programs are activated. The OBD compliance rate used is 95 percent and the waiver rate is 5 percent. In addition, the local vehicle age distribution from NC Division of Air Quality is used in estimating BERs (Abraczinskas *et al.*, 2007).

In the EPA annual certification FTP tests, there are 59 E85 cars, 67 CNG cars and 12 HEVs for model years from 2001 to 2007. Similar to estimation for LDGVs on arterials, basice emission rates for LDDVs are also derived from MOBILE6. EVs and fuel cell vehicles are considered no tailpipe emissions. For CNG buses and heavy-duty biodiesel trucks, TCFs of emission rates are borrowed from the literature as no comprehensive emissions data are available for both types of advanced heavy-duty vehicles. For biodiesel versus diesel trucks, average ratios of emission rates are 0.79, 0.89, 1.00, 1.01 for HC, CO, NO_x and CO_2 (EPA, 2002; McCormick *et al*., 2006; Frey *et al*., 2008). For CNG versus diesel buses with after-treatment equipments, average ratios of emission rates are 7.58, 0.69, 0.57,0.85 for HC, CO, NO_x and CO_2 (Chandler *et al*., 1996; Ayala *et al*., 2002; Melendez *et al*., 2005).

BERs for CO_2 are estimated for light-duty vehicles on city roadway and highway based on FTP and HFET cycles, using Equation (3). As shown in Table 2, fuel economy is normally higher on highway than on city streets. However, fuel economies for HEVs are similar on both city streets and highways. Among light-duty vehicles, HEVs have the highest fuel economy, which implies lower CO_2 emissions. BERs of CO_2 are larger on highway than on city roadway due to high speeds associated with driving cycle. For E85, theoretical and empirical ratios of CO_2 emission rates are 0.98 for E85 versus gasoline (Zhai *et al*., 2007). When BERs are estimated for LDGVs, BERs are determined for E85 using this ratio.

Speed Correction Factors Estimates

SCFs are estimated based on speed- and facility- specific link emission rates for each vehicle technology when data are available. For example, the average driving cycle speed is 31.5 km/h (19.6 mph) for basic HC, CO and NO_x emission rates generated by MOBILE6 on arterials, and 34.1 km/h for city roadway fuel economy test. Base speed range for estimating speed correction factors is 30-40 km/h on arterials. As show in Figure 2, SCFs for time-based emission factors for LDGVs on arterials increase with speed. Speed- and facility-specific SCFs were estimated for advanced light-duty technology and are shown in Tables 3and 4 for all pollutants. SCFs consistently increase with speed, except for HEVs possibly due to their complicated engine operation rules under various driving conditions. As shown in Table 4, SCFs are very close to each other on arterials and local roadways. However, SCFs for on-ramp versus off- ramp are significantly different as vehicles mostly accelerate at on-ramps and decelerate at off-ramps, thus yielding considerably different emission rates from one another (Frey *et al*., 2006).

Speed- and Facility- Specific Emission Factors for A Given Technology

BERs are adjusted by SCFs for each vehicle technology to estimate speed- and facility-specific emission factors, using Equation (1). However, emission factors for low speed ranges on freeways were interpolated as no link speed profiles were available for those speed ranges. For example, emission factors for light-duty vehicles including LDGVs, LDDVs, E85 and CNG cars, and HEVs on arterials are shown in Figure 3. Emission factors are sensitive to speed variations for all technologies. LDGVs have the largest emission rates of HC, CO and CO_2, compared to other vehicle technologies. However, NO_x emission rates for a given speed range are larger for LDDVs than LDGVs for the current year. Among conventional and advanced technologies, HEVs have the lowest emission rates for all pollutants.

8.5.2 Emission Inventory Estimates

Scenario Simulation for Regional Mobile Source Emissions

As shown in Table 5, regional mobile sources emissions are estimated for three classes of scenarios: baseline, alternative and future. According to the Annual Energy Outlook 2007 by (EIA) of the U.S. Department of Energy, advanced technology vehicles are projected to exceed 27% of light-duty vehicle sales by 2030 in the national range (EIA, 2007). Thus, in the alternative and future scenarios, total market penetration share of alternative vehicle technologies is assumed to be 27% for each vehicle type in order to investigate their potentials in reducing regional emissions in the current and future. EIA predicted the sale amount of advanced light-duty vehicles for each of technologies including flex-fuel vehicles, hybrid electric, diesel, gas, electric and fuel cell. In the alternative and the future scenarios, the assumption regarding fleet distribution for light-duty vehicles is based on sales of advanced light-duty vehicles in 2030 predicted by EIA. Vehicle fleet distributions are also given in Table 5 for each scenario. The distribution of light-duty vehicles' age is shown in Figure 4. In addition, EIA predicted that fuel economy average fuel economy for new light-duty vehicles in 2030 may increase by 15.9%, compared to 2005. This ratio is used to adjust CO_2 emission factors for light-duty vehicles in the future scenarios.

TRM produces link-based activity data during a four-hour period around the morning peak. Using Equation (7) and the vehicle fleet distributions shown in Table 5, total emissions for each link are estimated, and summed up for all links in the network to obtain regional on-road vehicle emissions. Total network emissions for all scenarios are given in Table 6 and emissions comparisons between scenarios are summarized in Table 7. Total emissions in Alternative Scenario 1 are compared with those in Baseline Scenario 1 to evaluate the effects of advanced technologies on current regional emissions. HC emissions decrease by 12% and CO emissions decrease 22%, whereas NO_x and CO_2 emissions show less than 4% reductions when 5 years old advanced technologies substitute for 27% of the current vehicle fleet. When the 27% of conventional vehicles in the current fleet are replaced by new advanced technology vehicles, emission reductions of up to 20%, 24%, 16% and 4% are observed for HC, CO, NO_x and CO_2, respectively.

As shown in Table 5, we assume that for Baseline Scenarios 2 and 3, the current vehicle fleet completely consists of 5 years old or brand new conventional vehicles. Emission changes are given in Table 7 when the conventional vehicle fleet is completely replaced by old or new advanced vehicles. For the substitution of new conventional vehicles with advanced technology vehicles, HC emissions increase by 10%, CO emissions decrease by 21%, NO_x emissions decrease by 5%, and CO_2 emissions decrease by 4%. However, the substitution of old conventional vehicles with old advanced technology vehicles results in HC emissions dropping by 37%. On the other hand, emission reductions increase up to 80% for CO, 10% for NO_x, and 11% for CO_2.

Comparing the Future Scenario 2 with the Baseline Scenario 1 for evaluating the effects of advanced technologies on regional emissions in the future, HC and CO emissions are reduced by over 75%. NO_x emissions show significant reductions up to 92% in the future. CO_2 emissions decrease by 10% in the future. Compared to total emissions based on a completely conventional vehicle fleet in the future, advanced vehicle technologies may lead to minor decreases in HC, NO_x and CO_2 emissions, and large emissions reductions up to 20% in CO emissions when advanced technology vehicles constitute 27% of the vehicle fleet in the future. In either the short-term or the long-term, advanced vehicle technologies have potentials to reduce regional mobile sources emissions in a significant way.

Regional Mobile Source Emissions Characterization

Total link emissions are estimated and normalized by link length and time to illustrate the spatial characteristics of vehicle emissions. As shown in Figure 5, normalized link emissions for baseline scenario are classified by quantile for all links into three groups. Emission “hotspots” mostly occur on freeways, which are due to heavy traffic loads and high speeds during peak hours. Emissions for the Baseline 1 scenario are classified by facility type. As shown in Figure 6a, the largest fraction of emissions occurs on freeways including ramps in the morning peak hours, followed by arterials. Freeways contribute 37% of total VKT in the network, which is very close to the fraction of HC emissions emitted on freeways. However, for other pollutants, the fractions of emissions emitted on freeways exceed their VKT contribution. Arterials contribute 34% of total VKT, which is close to the emissions fractions for all pollutants emitted on arterials. Local roadways and collectors have relatively lower emissions for all pollutants, compared to freeways and arterials.

Transportation network emissions are also characterized by vehicle type. The contributions of the total VKT are 73%, 26% and 0.7% from cars, trucks, and buses respectively. As shown in Figure 6b, although trucks contribute a smaller percentage of the VKT than passenger cars, trucks dominate emissions of NO_x and CO_2 in the individual emission inventory scenarios due to higher emission rates of NO_x and CO_2 from diesel engine, whereas cars dominate CO emissions for either the short-term or the long-term. For HC, cars can dominate emissions in the short-term. However, trucks may dominate emissions of HC in the future.

Sensitivity Analysis of Regional Mobile Source Emissions

A sensitivity analysis of regional emissions is carried out on the alternative scenarios in order to investigate the potential impacts of various fleet penetrations of advanced technologies with old and new mixed vehicle fleet. The relative fractions of advanced vehicle technologies are kept the same as the Alternative 1 scenario. Regional total emissions are calculated when the total fleet penetration of advanced vehicle technologies varies from 0 to 100%, in increments of 10%. As shown in Figure 7, regional emissions are sensitive to total fleet penetration fraction for advanced technologies and consistently decrease. For a given fleet penetration fraction, HC and CO emissions show larger reductions than NO_x and CO_2 emissions. When conventional current vehicle technologies are totally replaced with advanced vehicle technologies, emissions reductions would be 48% for HC, 82% for CO, 13% for NO_x and 12% for CO_2. Compared to HC and CO, NO_x and CO_2 emissions show relatively lower reductions.

8.6 Findings and Conclusions

Emission factors are estimated for conventional and advanced technologies based on link-based driving cycles measured under real-world traffic conditions. These are characterized by facility type, speed and vehicle technology. Emission factors are generally sensitive to speed variation. In general, the ratio of the highest to the lowest mean value for a given pollutant is approximately a factor of up to 3 for light-duty gasoline vehicles. Emission rates for arterials and local roadways are quite close for a given speed range. However, emission rates are significantly different for on- and off-ramp due to their different vehicle driving modes.

Link-based emission factors were coupled with vehicle activity parameters from the Triangle Regional Model to estimate regional emission inventory. Spatial analysis shows that emission hotspots occur on freeways during the peak hours. The largest fraction of pollutants is emitted on freeways during peak periods, followed by arterials. During the morning peak hours, passenger cars were the major sources for HC and CO emissions, whereas trucks were the major sources for NO_x and CO_2 emissions. Increased market penetration of advanced vehicle technologies has the potential to decrease emissions. In the short term, HC and CO emissions have larger reduction potentials than NO_x and CO_2. In addition to HC and CO, NO_x emissions show potential for significant reductions of up to 92% over the long term. CO_2 emission reductions may exceed 10% over the long term. Increases in the market penetration of advanced technologies may reduce regional emissions.

The distribution of HC emission fractions by facility type is close to the distribution of VKT by facility type. Freeways contribute larger fractions of CO, NO_x and CO_2 emissions than their overall VKT share. However, the fractions of emissions for all pollutants emitted on arterials are close to their overall VKT share. For local roadways and collectors, the emissions fractions for CO, NOx and CO_2 are lower than the corresponding VKT fraction.

8.7 Recommendations for Future Research

There are three additional general lines of investigation worth pursuing:

1) For light-duty vehicles, additional speed profiles on freeways under congested traffic conditions are needed in order to fill up the gaps in vehicle activity data and more accurately quantify the sensitivity of link emission rates to speed variations on freeways.
2) Additional PEMS data for advanced heavy-duty vehicle technologies and hybrid electric vehicles need to be collected in order to quantify the impacts of vehicle activities on emissions and estimate speed correction factors, and more accurately

quantify emission factors at various levels of services under real-world traffic condition, and

3) Future land use/transportation network simulation scenario is recommended to ensure that activities that can reduce VKT on a regional network are considered. This study looked only at the effect of fleet change on emissions. The long range impacts of "smart growth" on energy and emissions are an area of research.

8.8 Acknowledgements

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8.9 References

Abraczinskas, M., P. Jones, V. Chandler and P. Bello (2007), "Emissions and Air Quality Analysis of the California Low Emission Vehicle II (CA LEV-II) Standards in NC," The 16th Annual International Emission Inventory Conference Emission Inventories: Integration, Analysis, and Communications, May 14-17, Raleigh, NC.

Ayala, A., N.Y. Kado, R.A. Okamoto, B.A. Holmén, P.A. Kuzmicky, R. Kobayashi and K.E. Stiglitz (2002), "Diesel and CNG Heavy-duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview," Paper 2002-01-1722, Society for Automotive Engineers, Spring Fuels & Lubricants Meeting & Exhibition, Reno, NV.

Bai, S., Y-C, Chiu and D.A. Niemeier (2007), "A Comparative Study of Using Trip-based versus Link-based Traffic Data for Regional Mobile Source Emissions Estimation," *Atmosphere Environment*, doi: 10.1016/j.atmosenv. 2007.05.051.

Caliper Corporation (2000), TransCAD User's Guide, Newton, MA.

CDOT (2005), Conformity Analysis and Determination Report for the Cabarrus-Rowan MPO, the Gaston Urban Area MPO, and the Mecklenburg-Union MPO 2030 Long Range Transportation Plans and the FY 2004-2010 Transportation Improvement Programs and for Non-MPO Areas of Lincoln County,Iredell County, Gaston County, and Union County. Charlotte Department of Transportation at North Carolina, June 2005. http://www.mumpo.org/2030_LRTP.htm.

Chandler, K., Malcosky, N., R. Motta, P. Norton, K. Kelly, L. Schumacher and D. Lyons (1996), "Alternative Fuel Transit Bus Evaluation Program Results," Society for Automotive Engineers, International Spring Fuels and Lubricants Meeting, May, Dearborn, MI.

Cook, R., J.S. Touma, A. Beidler, and M. Strum (2006), "Preparing Highway Emissions Inventories for Urban Scale Modeling: A Case Study in Philadelphia," *Transportation Research Part D: Transport and Environment*, 11(6):396-407.

EIA (2007), "Annual Energy Outlook 2007 with Projections to 2030," DOE/EIA-0383, Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy, Washington, DC, February.

EPA (1995), "AP-42 Volume II, Compilation of Air Pollution Emission Factors, Mobile Sources, Appendix H," Environment Protection Agency, Ann Arbor, MI, June 30.

EPA (2001), "Final Facility Specific Speed Correction Factors," EPA420-R-01-060, M6.SPD.002, Environment Protection Agency, Ann Arbor, MI, November.

EPA (2002), "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions," EPA-420-P-02-001, Environmental Protection Agency, Ann Arbor, MI, October.

EPA (2004), "Technical Guidance on the Use of MOBILE6.2 for Emission Inventory Preparation," EPA420-R-04-013, Environment Protection Agency, Ann Arbor, MI, August.

EPA (2006), "Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2006," EPA420-R-06-011, Environmental Protection Agency, Ann Arbor, MI, July.

EPA (2007), "National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data: 1970 - 2006 Average Annual Emissions, All Criteria Pollutants," Environment Protection Agency, July 2007. Http://www.epa.gov/ttn/chief/trends/index.html. Accessed on September 23.

Frey, H.C., N.M Rouphail, A. Unal and J.D. Colyar (2001), "Emissions Reduction Through Better Traffic Management: An Empirical Evaluation Based Upon On-Road Measurements," Prepared by North Carolina State University for North Carolina Department of Transportation, North Carolina State University; December, Raleigh, NC.

Frey, H.C., A. Unal, J. Chen, S. Li and C. Xuan (2002), "Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle & Equipment Emission System," EPA420-R-02-027, Prepared by North Carolina State University for U.S. Environmental Protection Agency, August, Ann Arbor, MI.

Frey, H.C., A. Unal, N.M. Rouphail and J.D. Colyar (2003), "On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument," *Journal of the Air and Waste Management Association,* 53:992-1002.

Frey, H.C., N.M. Rouphail and H. Zhai (2006), "Speed- and Facility-Specific Emission Estimates for On-Road Light-Duty Vehicles on the Basis of Real-World Speed Profiles," *Transportation Research Record: Journal of the Transportation Research Boar*, 1987:28-137.

Frey, H.C., N.M. Rouphail and H. Zhai (2008), "Emissions Estimates for Heavy-Duty Trucks Based on Real-World Activity," Paper No.08-1311. *The 87th Annual Meeting of the Transportation Research Board*, January, Washington, DC, January.

Fuel Economy Guide (2007). http://www.fueleconomy.gov/feg/download.shtml. Accessed in September.

Jiménez-Palacios, J. (1999), "Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing," PhD Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Lave, L. B., H. L. MacLean, C. Hendrickson and R. Lankey (2000), "Life-Cycle Analysis of Alternative Automobile Fuel/Propulsion Technologies," *Environ. Science & Technology*, 34(7):3598-3605.

McCormick, R.L., A. Williams, J. Ireland, M. Brimhall and R.R. Hayes (2006), "Effects of Biodiesel Blends on Vehicle Emissions," NREL/MP-540-40554, National Renewable Energy Laboratory, October.

Melendez, M., J. Taylor, J. Zuboy, W.S. Wayne and D. Smith (2005), "Emission Testing of Washington Metropolitan Area Transit Authority Natural Gas and Diesel Transit Buses," NREL/TP-540-36355, National Renewable Energy Laboratory, December.

Miller, C. A.,G. Hidy, J. Hales, C.E. Kolb, A.S. Werner, B. Haneke, D. Parrish, H. C. Frey, L. Rojas-Bracho, M. Deslauriers, B. Pennell, J.D. Mobley and A. Miller (2006), "Air emission inventories in North America: A critical assessment," *Journal of the Air and Waste Management Association*, 56(8):1115-1129.

Nam, E.K. and A. Mitcham (2005), "Dynamometer and On-board Emissions Testing of the Honda Insight and Toyota Prius," Paper 2005-01-0681, 2005 Society of Automotive Engineers World Congress & Exhibition, Detroit, MI, April.

Romm, J. (2006), "The Car and Fuel of the Future," *Energy Policy*, 34(17):2609-2614.

Rykowski, R.A., E.K. Nam and G. Hoffman (2005), "On-Road Testing and Characterization of Fuel Economy of Light-Duty Vehicles," *Journal of Fuels and Lubricants*, 114(4):276-285.

Younglove, T., G. Scora and M. Barth (2005), "Designing On-Road Vehicle Test Programs for the Development of Effective Vehicle Emission Models," *Transportation Research Record: Journal of the Transportation Research Board*, 1941:51-59.

Unal, A., N.M. Rouphail and H.C. Frey (2003), "Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions," *Transportation Research Record, Journal of the Transportation Research Board*, 1842:47-56.

Wang, M.Q. (1999), "Fuel-Cycle Greenhouse Gas Emissions Impacts of Alternative Transportation Fuels and Advanced Vehicle Technologies," *Transportation Research Record, Journal of the Transportation Research Board*, 1664:9-17.

Zhai, H., H.C. Frey and N.M. Rouphail (2006), "Speed- and Facility-Specific Emissions Estimates for Transit Bus based on Real-World Speed Profiles," Paper 2006-A-195, *Proceedings of 99th Annual Meeting of the Air & Waste Management Association*, June 20-23, New Orleans, LA.

Zhai, H., H.C. Frey, N.M. Rouphail, T.L. Farias and G. A. Gonçalves (2007), "Fuel Consumption and Emissions Comparisons between Ethanol 85 and Gasoline Fuels for Flexible Fuel Vehicles," Paper 2007-A-444, *Proceeding of the 100th Annual Meeting of the Air & Waste Management Association*, June 26-29, Pittsburgh, PA.

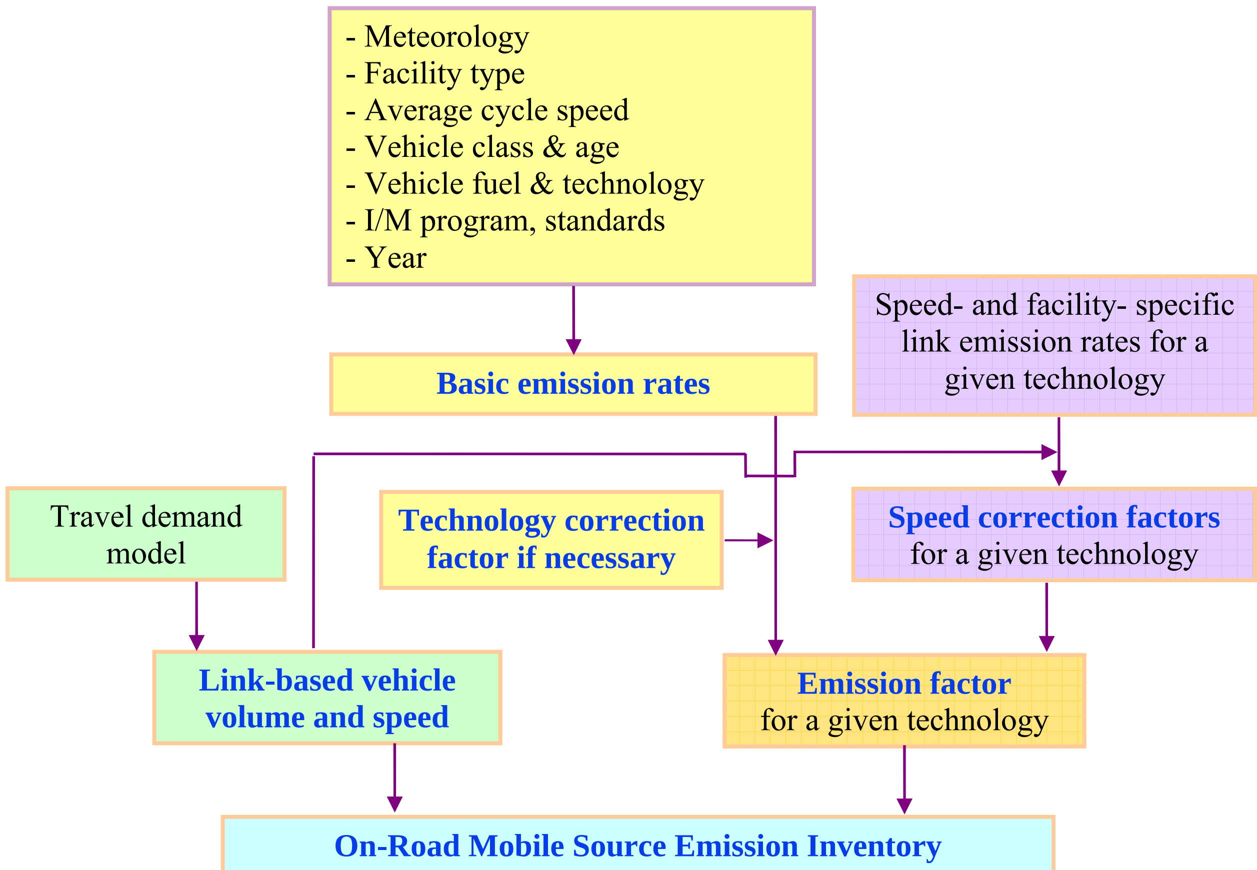


Figure 1. Conceptual Modeling Approach for Emission Factors and Emission Inventory Estimation

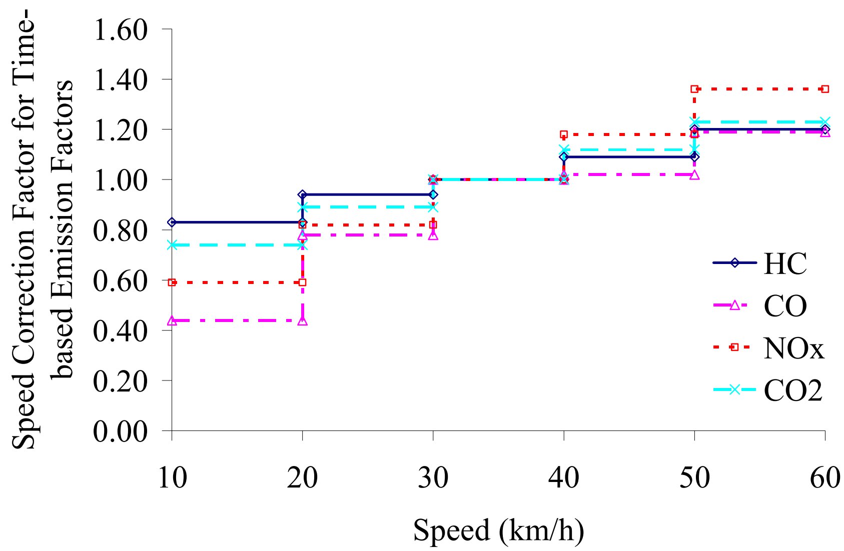


Figure 2. Example of Speed Correction Factors for Time-based Emission Factors for LDGVs on Arterials (Baseline speed range 30-40 km/h)

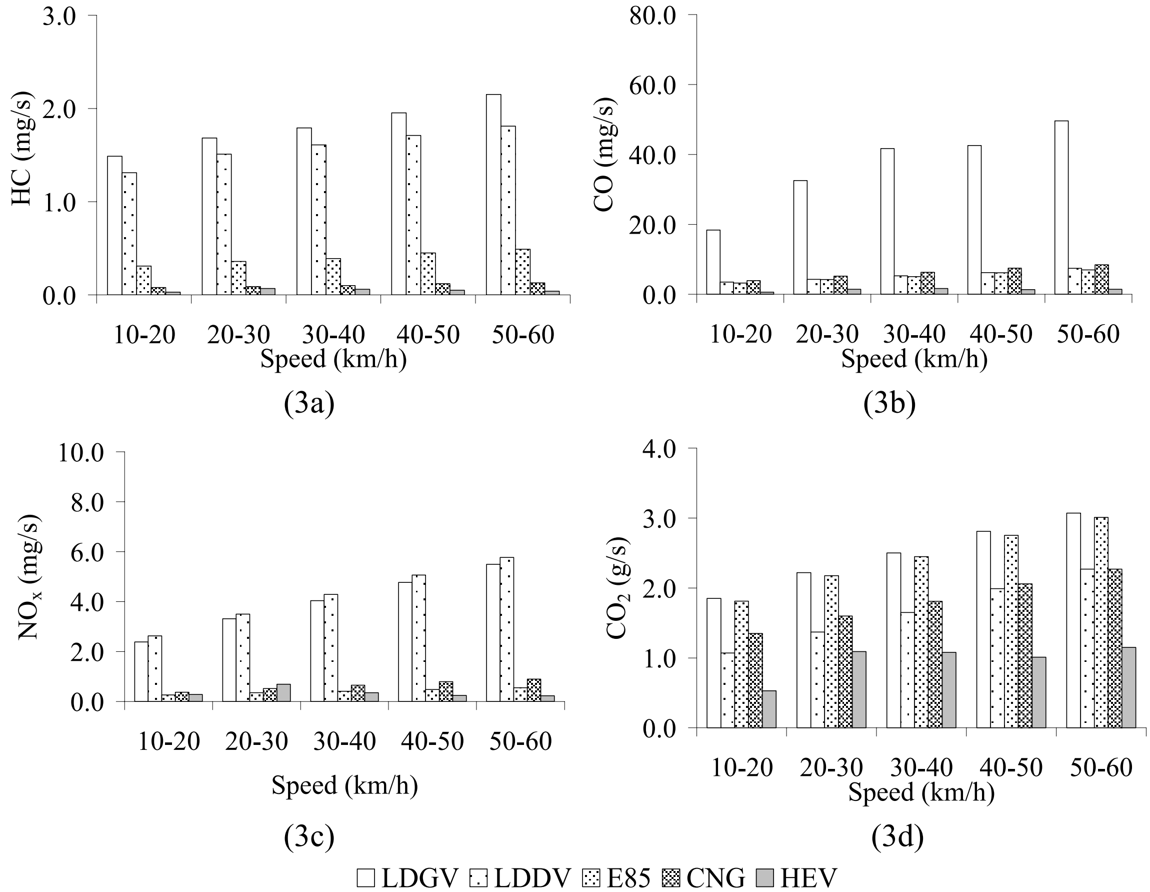


Figure 3. Example of Emission Factors for Light-Duty Vehicle on Arterials [a]

[a] Basic emission rates for LDGVs and LDDVs derived from MOBILE6 for calendar year 2005.

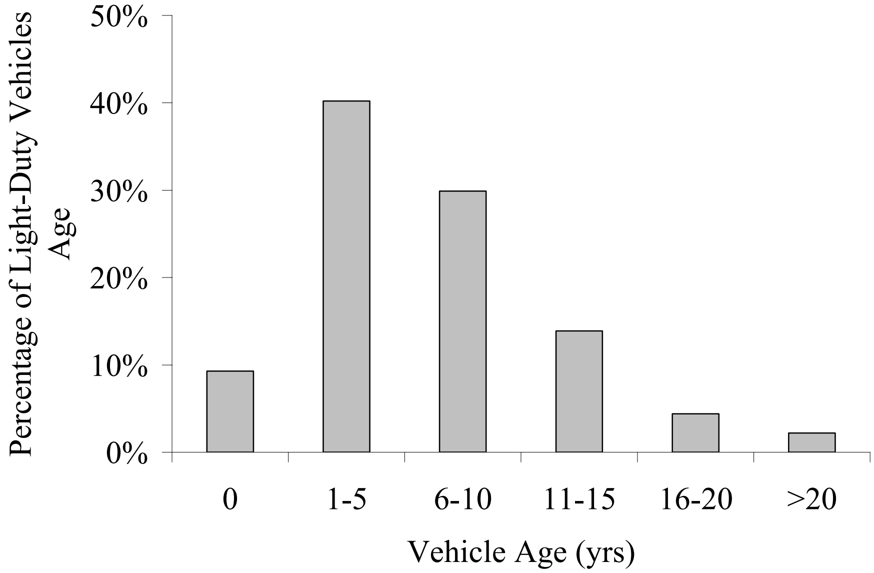


Figure 4. Distribution of Vehicle Age for Light-Duty Vehicles

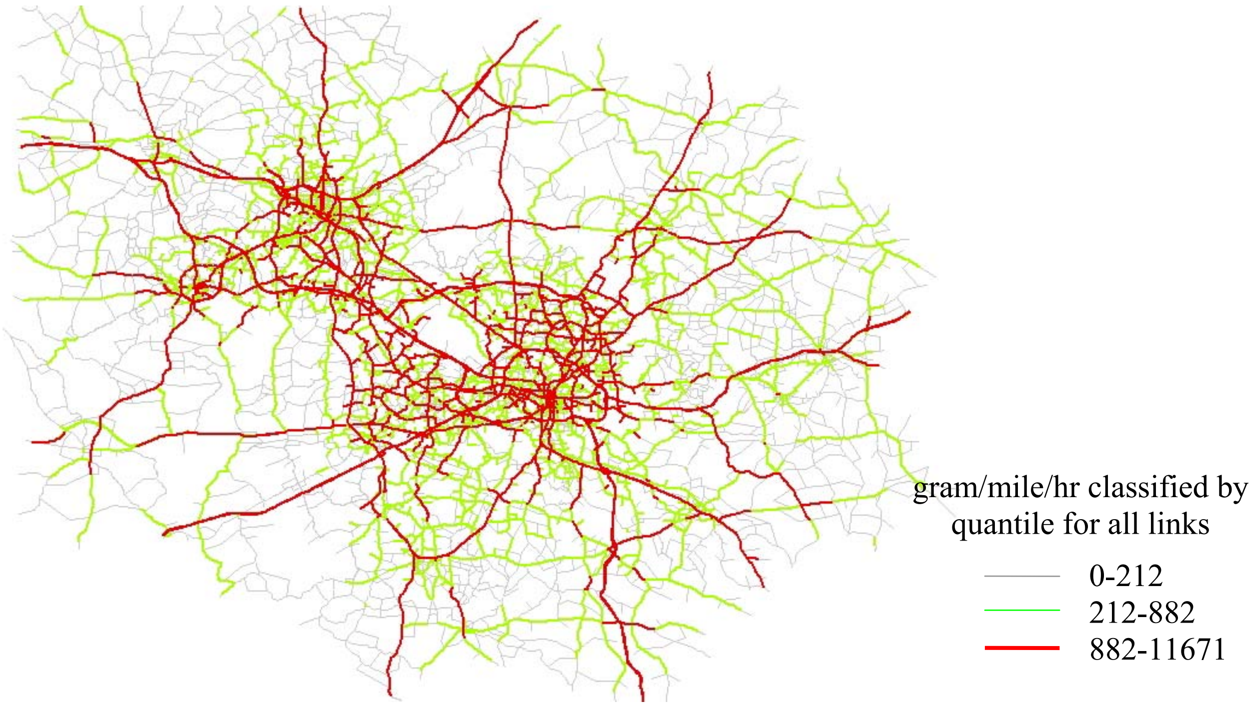
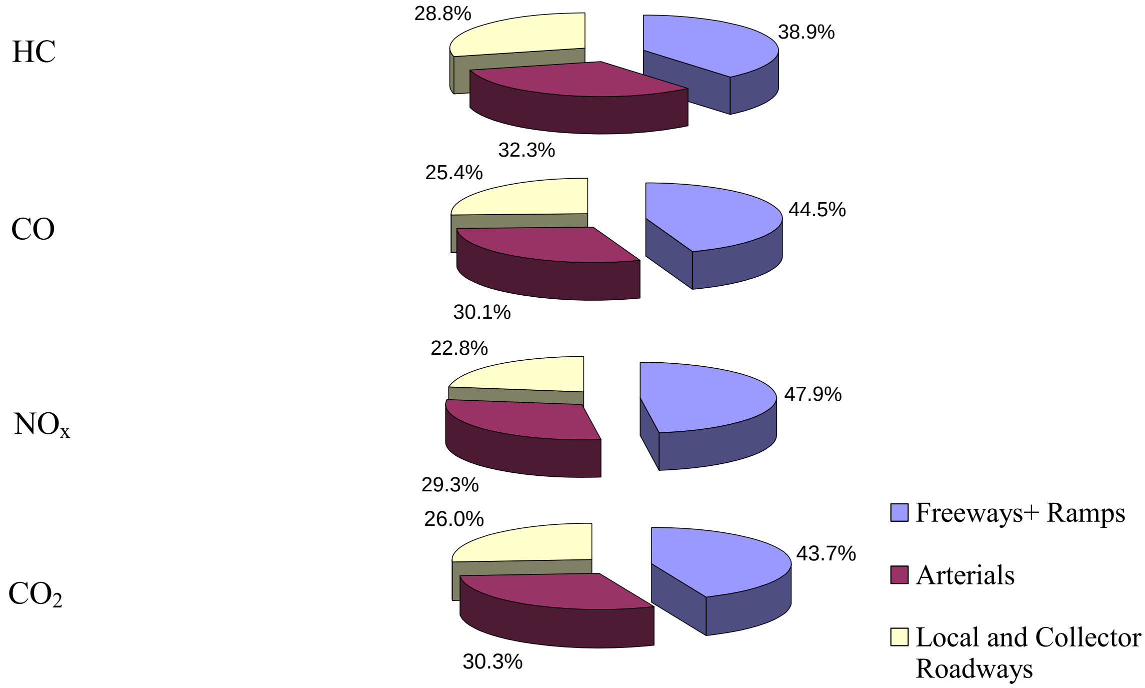
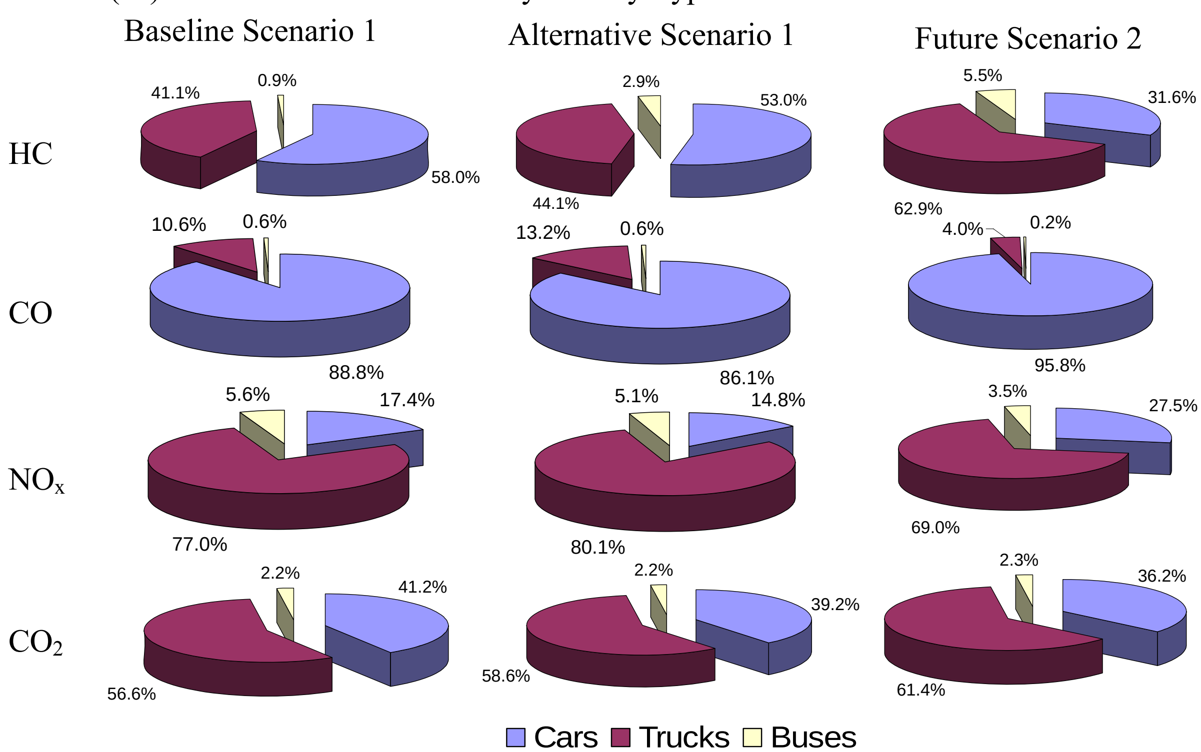


Figure 5. Spatial Characterization of Normalized Link NOx Emissions during AM Peak Hours for Baseline Scenario 1



(6a) Distribution of Emissions by Facility Type for Baseline Scenario 1



(6b) Distribution of Emissions by Vehicle Type for Selected Scenarios

Figure 6. Triangle Regional Model Emissions Distribution by Facility and Vehicle Type

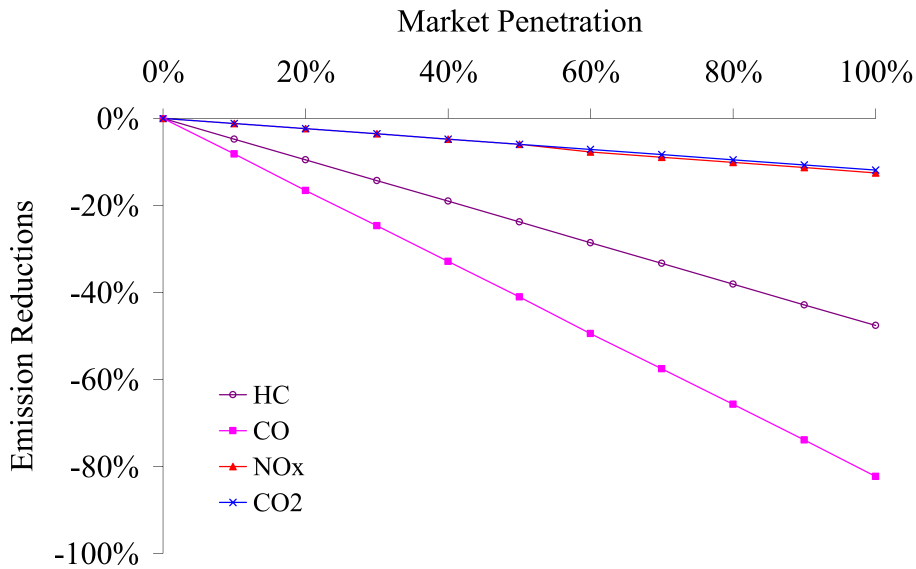


Figure 7. Sensitivity of Emissions Reductions to Advanced Vehicle Total Market Penetration for Alternative Scenario 1

Table 1. Listing of Data Sources for Emission Factors' Estimation

Parameter	Vehicle Fuel & Technology	Source
Basic Emission Rates	LDGV, LDDV,HDDT, HDDB	MOBILE6
Speed Correction Factors	LDGV, HDDT, B20 Trucks	NCSU PEMS
	HDDB, HEV	EPA
	LDDV, E85, CNG Cars	Portugal PEMS
Fuel Economy	LDGV, E85	EPA
	LDDV, HEV, CNG Cars	Fuel Economy Guide by EPA & DOE
Technology Correction Factors	E85, HEV, CNG Cars	EPA Certification Tests
	B20 trucks, CNG Buses	Literature about comparison studies(B20 vs. Diesel, CNG vs. Diesel)
Traffic Demand	Triangle Regional Model	ITRE, NCSU

Table 2. Triangle Regional Model Vehicle Activity Database for 4-hour Morning Peak Simulation [a]

Item	Vehicle Class[b]	Facility Type			Total
		Freeway/Ramp	Arterial	Local and Collector	
Link Average Speed (km/h)		92	68	47	
Number of Links in Model		1,580	3,990	9,510	15,080
Vehicle Kilometers Traveled (10^3 VKT)	Car	3,589	3,775	3,185	10,548
	Truck[c]	1,687	1,060	997	3,744
	Bus	46	23	26	95
	(sum)	5,322	4,858	4,208	14,388
Percentage of Total VKT (%)	Car	24.9	26.2	22.1	73.3
	Truck[c]	11.7	7.4	6.9	26.0
	Bus	0.3	0.2	0.2	0.7
	(sum)	37.0	33.8	29.3	100.0

[a] TRM simulation year is 2005.
[b] Percentages of vehicle counts by vehicle class and facility types are estimated based on national average distributions (Charlotte DOT, 2005).
[c] Assume that the fraction of total VMT for trucks is the same as the percentage of trucks in the stream.

Table 3. Basic Emission Rates and Speed Correction Factors for Time-based CO_2 Emission Factors for Alternative Light-Duty Vehicles

Vehicle Technology	# of Units	Fuel Economy (mpg)		Basic Emission Rate (g/sec)		Speed Correction Factor							
						Facility Type	Speed Range (km/h)						
		City Road	Highway	City Road	Highway		10-20	20-30	30-40	40-50	50-60	60-70	90-100
CNG	16	22[a]	30[a]	1.81	3.02	Freeway[b]					1.03		1.33
						Arterial[c]	0.74	0.89	1.00	1.14	1.26		
						Local Rd.[c]		0.89	1.01	1.11			
						On/Off Ramp[b]						1.51/ 0.56	
LDDV	47	36	44	1.65	3.07	Freeway[b]					1.04		1.55
						Arterial[c]	0.65	0.83	1.00	1.21	1.38		
						Local Rd.[c]		0.86	1.01	1.18			
						On/Off Ramp[b]						1.82/ 0.36	
HEV	28	48	49	1.08	2.41	Freeway[d]					0.34		1.03
						Arterial[d]	0.49	1.01	1.00	0.93	1.07		
						Local Rd.[d]	0.49	1.01	1.00	0.93	1.07		
						On/Off Ramp[d]						1.00	

[a] For CNG, fuel economy is equivalent value. One equivalent gallon is equal to 121.5 cubic feet of CNG.

[b] The average speed is 48.3 mph for HFET cycle. Link emission rates on freeways for speed range 70-80 km/h are regarded as the base to estimate speed correction factors on freeways. However, no link emission rate based on real-world speed data is available for this speed range. Average emission rate for HFET cycle is 2.70 g/sec, which is estimated using VSP modal approach. As an alternative option, average emission rate for HFET cycle is used as the basis to calculate speed correction factors on freeways, on- and off- ramps.

[c] The average speed is 21.2 mph for FTP. Therefore, link emission rates on arterials for speed range 30-40 km/h are regarded as the base to estimate speed correction factors on arterials and local roadways.

[d] For HEV, second-by-second dynamometer tests data are available. Average emission rate for each speed ranges is estimated only by speed bins instead of vehicle specific power modal approach as no emission data at high speeds are available to estimate modal emission rates for higher VSP modes. Emission rates for speed range 70-80 km/h is used as the base to estimate speed correction factors on freeways and ramps, whereas emission rates for speed range 30-40 km/h is used as the base to estimate speed correction factors on arterials and local roadways.

Table 4. Speed Correction Factors for Time-based HC, CO and NO_x Emission Factors for Alternative Light-Duty Vehicles (continued)

Vehicle Technology	Pollutant	Facility Type	Speed Ranges (km/h)						
			10-20	20-30	30-40	40-50	50-60	60-70	90-100
E85	HC[a]	Freeway					1.35		1.76
		Arterial	0.78	0.90	1.00	1.14	1.24		
		Local Rd.		0.91	1.01	1.12			
		On/Off Ramp						1.99/0.70	
	CO	Freeway					1.57		2.30
		Arterial	0.64	0.84	1.00	1.22	1.38		
		Local Rd.		0.86	1.02	1.20			
		On/Off Ramp						2.66/0.58	
	NO_x	Freeway					1.67		2.54
		Arterial	0.63	0.86	1.00	1.19	1.35		
		Local Rd.		0.83	1.00	1.22			
		On/Off Ramp						2.88/0.59	
CNG	HC[a]	Freeway					1.36		1.78
		Arterial	0.75	0.89	1.00	1.15	1.25		
		Local Rd.		0.89	1.02	1.11			
		On/Off Ramp						2.02/0.75	
	CO	Freeway					1.57		2.31
		Arterial	0.62	0.83	1.00	1.19	1.34		
		Local Rd.		0.84	1.01	1.17			
		On/Off Ramp						2.73/0.66	
	NO_x	Freeway					1.65		2.48
		Arterial	0.57	0.81	1.00	1.22	1.39		
		Local Rd.		0.82	1.02	1.19			
		On/Off Ramp						2.90/0.65	
HEV	HC	Freeway					0.62		1.69
		Arterial	0.56	1.19	1.00	0.86	0.62		
		Local Rd.	0.56	1.19	1.00	0.86	0.62		
		On/Off Ramp						0.48	
	CO	Freeway					0.87		0.75
		Arterial	0.37	0.89	1.00	0.81	0.87		
		Local Rd.	0.37	0.89	1.00	0.81	0.87		
		On/Off Ramp						4.06	
	NO_x	Freeway					0.67		4.30
		Arterial	0.79	1.98	1.00	0.67	0.67		
		Local Rd.	0.79	1.98	1.00	0.67	0.67		
		On/Off Ramp						1.00	

[a] Speed correction factors for fuel consumption are used here as no HC data were available.

Table 4 Continued

Vehicle Technology	Pollutant	Facility Type	Speed Ranges (km/h)						
			10-20	20-30	30-40	40-50	50-60	60-70	90-100
LDDV	HC	Freeway					1.19		1.44
		Arterial	0.81	0.94	1.00	1.06	1.13		
		Local Rd.		0.94	1.00	1.06			
		On/Off Ramp						1.56/0.88	
	CO	Freeway					1.48		2.11
		Arterial	0.67	0.81	1.00	1.19	1.41		
		Local Rd.		0.85	1.00	1.19			
		On/Off Ramp						2.48/0.52	
	NO_x	Freeway					1.55		2.61
		Arterial	0.61	0.82	1.00	1.18	1.35		
		Local Rd.		0.81	0.94	1.15			
		On/Off Ramp						3.02/0.51	

Table 5. Simulated Scenarios for Conventional versus Alternative Vehicle Technologies [g]

Scenario	Scenario Function	Fleet Characterization										Calendar Year
		LDVs by Technology (%)						Buses by Technology (%)		HDVs by Technology (%)		
		LDGV	E85	HEV	LDDV	CNG	EV/Fuel Cell	Diesel	CNG	Diesel	Biodiesel	
Baseline 1	Total emissions (TEs) based on current conventional vehicle fleet [h]	100	0	0	0	0	0	100	0	100	0	2005
Baseline 2	TEs based on all 5 years old conventional vehicle fleet	100	0	0	0	0	0	100	0	100	0	
Baseline 3	TEs based on completely new, but conventional vehicle fleet	100	0	0	0	0	0	100	0	100	0	
Alternative 1 [a]	TEs based on current fleet with penetration of 5 years old alternative vehicle technologies replacing 27% of current conventional vehicle fleet [c]	73	9.9	9.9	5.9	1.2	0.1	73	27	73	27	2005
Alternative 2	TEs based on current fleet with penetration of new alternative vehicle technologies replacing 27% of current conventional vehicle fleet [b,d]	73	9.9	9.9	5.9	1.2	0.1	73	27	73	27	
Alternative 3 [b]	TEs based on all 5 years old alternative vehicle fleet [d]	0	36.6	36.7	21.8	4.6	0.3	0	100	0	100	
Alternative 4	TEs based on completely new alternative vehicle fleet [e]	0	36.6	36.7	21.8	4.6	0.3	0	100	0	100	
Future 1	TEs based on future conventional vehicle fleet [h]	100	0	0	0	0	0	100	0	100	0	2030
Future 2 [a]	TEs based on future fleet with penetration of alternative vehicle technologies replacing 27% of future conventional vehicle fleet [f, h]	73	9.9	9.9	5.9	1.2	0.1	73	27	73	27	

[a] For E85 and CNG cars, and HEVs, basic emission rates (BERs) are estimated based on EPA' emission certification tests projected to vehicle useful life of 50,000 miles.

[b] For E85 and CNG cars, and HEVs, BERs are estimated based on EPA' emission certification tests for vehicle useful life of zero-mile.

[c] For LDDVs, BERs are estimated based on current mix of the old and new mixed vehicle fleet for diesel cars in 2005; for CNG buses and B20 trucks, their BERs are estimated based on HDDTs and HDDBs' BERs for current mix of the old and new mixed vehicle fleet in 2005and emission change rates of CNG versus diesel buses, and B20 versus diesel trucks.

[d] For LDDVs, emission factors are estimated for 5 years old diesel cars; for CNG buses and B20 trucks, their BERs are estimated based on 5 years old HDDTs and HDDBs' BERs and emission change rates of CNG versus diesel buses, and B20 versus diesel trucks.

[e] For LDDVs, BERs are estimated for new diesel cars; for CNG buses and B20 trucks, their BERs are estimated based on new HDDTs and HDDBs' BERs and emission change rates of CNG versus diesel buses, and B20 versus diesel trucks.

[f] For LDDVs, BERs are estimated based on future mix of the old and new mixed vehicle fleet for diesel cars in 2030; for CNG buses and B20 trucks, their BERs are estimated based on HDDTs and HDDBs' BERs for future mix of the old and new mixed vehicle fleet in 2030 and emission change rates of CNG versus diesel buses, and B20 versus diesel trucks.

[g] The 2005 transportation network is used for all scenarios.

[h] Figure 4 gives fleet age distribution for light-duty gasoline vehicles.

Total 6. Total Triangle Regional Model Running Exhaust Emissions during Four-Hour Morning Peak (tons)

Scenario	HC	CO	NO_x	CO_2
Baseline 1	2.07	35.58	16.80	4479
Baseline 2	1.49	25.38	15.61	4370
Baseline 3	0.48	4.73	7.05	4325
Alternative 1	1.82	27.69	16.17	4335
Alternative 2	1.66	26.98	14.08	4311
Alternative 3	0.94	5.14	14.06	3873
Alternative 4	0.53	3.75	6.72	3856
Future 1	0.53	10.09	1.24	4173
Future 2	0.52	8.11	1.22	4049

Table 7. Pairwise Relative Change in Total Running Exhaust Emissions by Scenario

Scenario Comparison	Emissions Changes (%)			
	HC	CO	NO_x	CO_2
Alternative 1 vs. Baseline 1	-12	-22	-4	-3
Alternative 2 vs. Baseline 1	-20	-24	-16	-4
Alternative 3 vs. Baseline 2	-37	-80	-10	-11
Alternative 4 vs. Baseline 3	10	-21	-5	-11
Future 1 vs. Baseline 1	-74	-72	-93	-7
Future 2 vs. Baseline 1	-75	-77	-93	-10
Future 2 vs. Future 1	-2	-20	-2	-3

PART IX CONCLUSIONS AND RECOMMENDATIONS

This chapter gives key findings, conclusions and recommendations.

9.1 Findings

This section presents key findings regarding light-duty and heavy-duty vehicles emissions, comparisons of fuel use and emissions between conventional and advanced vehicle technologies, and regional mobile sources emissions characterization.

9.1.1 Link-level Emission Rates Estimates for Light-Duty Vehicles

This VSP modal approach was applied to both conventional and alternative light-duty vehicle. The average emission rates vary significantly and increase with mean link speed for various vehicle technologies.

The ratio of the highest to the lowest mean value for a given pollutant is approximately a factor of up to 3 for light-duty gasoline vehicles. However, when comparing the highest to lowest emission rate among the 14 VSP modes, the variability is typically an order-of-magnitude. This implies some loss of information associated with the use of a highly aggregate measure of vehicle activity such as mean speed.

Benchmark comparison of link emission rates derived from the VSP approach versus MOBILE6 indicated substantial concordance in results.

9.1.2 Link-level Emission Rates Estimates for Diesel Transit Buses

For transit buses, link average emission rates are shown to increase with link mean speed. ANOVA test results indicated that for link average emission rates, facility type did not appear to be a major explanatory variable when compared with speed.

The ratio of the highest to the lowest link-based average emissions was about a factor of 2.0, 1.8, 1.7 and 1.2 respectively for CO_2, CO, NO_x and HC. Compared with the ratios of the VSP modal average emission rates, the variability of link-based average emissions explained by link mean speed was significantly lower. This result is consistent with findings from the study for light-duty gasoline vehicle emissions estimates.

9.1.3 Link-level Emission Rates Estimates for Heavy-Duty Trucks

Modal emission rates for heavy-duty diesel trucks were found to be highly sensitive to acceleration variation, but not as much to speeds, especially for CO and HC. Link-based emission rates of CO_2 for both chassis types and NO for tandem trucks increased with link mean speed. However, link-based emission rates for CO and HC were not significantly different from each other for various link mean speeds, especially on arterials. Link-based PM emission rates for both chassis types on arterials were also not sensitive to differences in link mean speed. However, they tended to increase with mean speed on freeways.

Link-based emission rates differ for both chassis types. Vehicle load resulted in increases of approximately 34% for diesel and 36% for biodiesel in emissions, compared to the unloaded condition. Link-based emission rates of PM, NO, CO and HC for B20 biodiesel fuel were found to be lower than those for diesel fuel. However, both types of fuels generated similar CO_2 emissions.

9.1.4 Comparing Fuel Consumption for Diesel- and Hydrogen- Fueled Transit Buses

The VSP modal approach produced trip fuel consumption estimates that are accurate to within plus or minus 10%. The modal approach can be improved by further stratification based on passenger load.

The fuel life-cycle analysis shows that the fuel life cycle energy consumption may increase by 51% if diesel fuel is replaced with hydrogen obtained from steam reforming of methane. Based on single driving cycle, substitution of hydrogen versus diesel buses may significantly decrease emissions by 92%, 96% and 65% for of CO, NO_x and HC although CO_2 emissions may increase by 12%.

9.1.5 Comparing Fuel Consumption and Tailpipe Emissions for E85 versus Gasoline

Theoretical and empirical analyse show that vehicles operating on E85 consume approximately 49% more mass fuel, compared to gasoline fueled vehicles. However, the two fuels produce similar CO_2 tailpipe emissions on an energy basis. On the fleet basis, replacing gasoline with E85 will reduce CO tailpipe emissions by 22%; however, NO_x tailpipe emissions will not significantly change, and HC tailpipe emissions may increase by 12%.

In addition, on a fuel life cycle basis for corn-based ethanol versus gasoline, CO emissions decrease by 18%. Emission reductions are 25% for total CO_2 and 50% for fossil CO_2. However, HC and NO_x emissions increase by 18% and 82% respectively.

9.1.6 Regional Mobile Source Emissions Characterization

Link-based emission factors are characterized by facility type, speed and vehicle technology. Emission factors are generally sensitive to speed variation. The effects of facility type on emission rates were found to be not as significant as speed. However, emission rates for on-ramp versus off-ramp are significantly different because of their inherent different driving modes (dominant accelerations versus decelerations).

The link-based emission factors are coupled with transportation demand model outputs to estimate regional emission inventory. Emission hotspots occurred on freeways during morning peak hours. Because of larger VMT and high travel speed, the largest fraction of pollutants emits on freeways during peak period, followed by arterials. Passenger cars are the major emission sources for HC and CO, whereas trucks are the major emission sources for NO_x and CO_2. For the current scenario, 58% of HC emissions and 89% of CO emissions come from passenger car; 77% of NO_x and 57% of CO_2 emissions come from heavy-duty trucks.

Currently, the distribution of HC emission fractions by facility type is close to the distribution of the VMT by facility type. Freeways contribute 38% of total VMT. However, freeways contribute 44% or more of emissions for CO, NO_x and CO_2. For arterials, the fractions of emissions for all pollutants emitted on arterials are more close to the VMT fraction. For local roadways and collectors, the emissions fractions for CO, NO_x and CO_2 are less than the corresponding VMT fraction.

In the short term, HC and CO emissions have larger reduction potentials than NO_x and CO_2. In addition to HC and CO, NO_x may also have significant emissions reductions up to 92% over the long term, compared to the baseline scenario. CO_2 emission reductions will increase up to 10% in the future. Regional mobile source emissions are sensitive to the penetration fraction for alternative vehicle technologies.

9.2 Conclusions

This section presents key conclusions regarding light-duty and heavy-duty vehicles emissions, comparisons of fuel use and emissions between conventional and alternative vehicle technologies, and regional mobile sources emissions characterization.

9.2.1 Light-Duty and Heavy-Duty Vehicles Fuel Use and Emission Rates

The modal approach enables the conversion of microscale information regarding vehicle dynamics to an average speed for conventional and alternative technologies including light-duty and heavy-duty vehicles. Real-world link speed profiles are stratified by facility type and a link mean speed. The second-by-second speed profiles can be used to estimate time-based distributions of discrete modes, which in turn can be used to explain a substantial portion of variability in second-by-second vehicle fuel use and emissions. This methodology links the aggregate vehicle activity output of transportation models with micro-scale profiles that affect actual fuel use and emissions.

Although there is some loss of information associated with the use of a highly aggregate measure of vehicle activity such as mean speed, the use of link emission rates aggregated by link mean speed can achieve reasonable fleet-based total emissions estimation. These types of link-based emission estimates from real-world activity and emissions data can be coupled with transportation demand models to improve the accuracy of emissions estimates. This comparison with MOBILE6 provides a degree of comfort that the modal approach can be used to aggregate micro-scale data to produce driving cycle-based estimates.

Vehicle load affects fuel consumption and emission rates for heavy-duty vehicles.

Link emission rates are generally sensitive to speed variations. However, compared with speed, facility type excluding on-ramp versus off-ramp did not appear to be a major explanatory variable for emission rates.

9.2.2 Fuel Consumption and Tailpipe Emissions Comparisons between Conventional versus Alternative Vehicle Technologies

The substitution of diesel with biodiesel for heavy-duty trucks may reduce tailpipe emissions in PM, NO, CO and HC. However, both types of fuels generate similar CO_2 emissions.

On a fuel life-cycle basis for a case study, the substitution of hydrogen versus diesel buses increases the fuel life cycle energy consumption and CO_2 emissions, but significantly decreases emissions for of CO, NO_x and HC.

Vehicles operating on E85 consume more fuel, compared to gasoline fueled vehicles. However, both E85 and gasoline generate similar CO_2 emissions. The substitution of E85 versus gasoline has the mixed effects on tailpipe emissions and air quality, depending on pollutants. On a fuel life-cycle basis, replacing gasoline with corn-based ethanol decreases CO_2 and CO emissions, but increases NO_x and HC emissions.

9.2.3 Characterization for Regional Mobile Sources Emissions

The spatial pattern and quantity of emissions are affected by facility type because of inherent activity characteristics during the morning peak. The magnitudes of contribution to regional emissions are affected by vehicle class for different pollutants.

Market penetration of alternative vehicle technologies into the current and future vehicle fleet will tend to decrease emissions in either a short term or a long term. Regional mobile source emissions decrease with an increase of the penetration fraction for alternative vehicle technologies in the vehicle fleet.

9.3 Recommendations

Key recommendations and future research needs are summarized below.

9.3.1 Conduct Additional PEMS Measurement to Address Vehicle Activity Gaps

For light-duty vehicles, there are needs for additional speed profiles on freeways under various levels of service, especially for more congested traffic conditions, to more accurately quantify the sensitivity of link emission rates to speed variations on freeways. For hybrid electric vehicles, engine on/off and emissions modeling approaches are recommended for further application as additional data, particularly for real-world traffic conditions become available.

For heavy-duty transit buses, link emission rates on freeways were not included when evaluating the effects of facility type on link emission rates. For the future work, link speed profiles on freeways should be measured for transit buses using the PEMS.

For heavy-duty trucks, there is a need for data on additional driving cycles at various facility types and for the inclusion of other types of heavy-duty trucks in order to develop more comprehensive fleet-based estimates. In addition, similar to light-duty vehicles, CO_2 emission factors for heavy-duty vehicles should be specified by facility type and speed.

9.3.2 Conduct PEMS Studies for Heavy-Duty Vehicle Technologies

Emissions changes for biodiesel versus diesel fueled heavy-duty trucks, diesel versus CNG fueled buses are estimated based on a literature review rather than PEMS data, which are used to estimate emissions for alternative heavy-duty vehicle technologies. PEMS data should be collected for additional types of alternative heavy duty vehicle technologies in order to (a) quantify the impacts of vehicle activities on emissions; (b) estimate speed correction factors; (c) provide more accurate emission factors at various levels of service; and (d) estimate emission inventory for alternative heavy-duty vehicle technologies.

9.3.3 Expand the Comparison of Fuel Use and Emissions for Alternative Fuel Vehicles

The VSP-based modal approach is useful for characterizing bus trips and their fuel consumption. The comparison of fuel consumption for diesel versus hydrogen is based on only one driving cycle. Empirical data and analytical comparisons are needed for additional driving situations.

Comparisons of emission rates between biodiesel and diesel fuels indicate that the substitution of biodiesel for diesel can bring about environmental benefits in tailpipe emissions reductions. However, there is a need for a life cycle inventory comparison when substituting one fuel for another.

The use of ethanol reduces dependence on fossil energy and greenhouse gas (GHG) emissions. This study quantifies changes of tailpipe and life cycle emissions for corn-based ethanol85 versus gasoline and contributes to the understanding of the effects of ethanol85 on air quality. Quantification of tailpipe emissions changes for E85 versus gasoline can be used in emission inventory estimation and/or projection for evaluating the impacts of alternative transportation fuel on emissions and urban air quality. Mixed effects for ethanol85 indicate a tradeoff between GHG reductions and air quality management, especially for ozone pollution. In addition, ethanol production may bring adverse agricutural environmental impacts and compete for resource use with agriculture and food. With sustainable agriculture, improved ethanol production and vehicle technology, ethanol85 has the potential to supply a share of transportation energy.

9.3.4 Evaluate Individual and Integrated Effects of Landuse and Vehicle Technologies on Regional Emissions

The alternative vehicle technologies are recommended to reduce regional mobile sources emissions. However, the future land use or transportation network scenario simulation should be coupled with emissions models to evaluate individual and integrated effects of land use and vehicle technology on regional emissions and air quality in the future.

Quantification of such impacts on regional emissions for land use and vehicle technology can provide support for decision-making regarding land use and transportation planning policy, and air quality management.

In addition, in future scenario modeling, the effect of replacing conventional light-duty or heavy-duty vehicle technologies with only one of alternative vehicle technologies on regional emissions is evaluated. Thus, the potentials for each alternative technology in regional emissions reductions should be quantified.

9.3.5 Conduct Uncertainty Analysis for Emission Inventory Estimation

Point estimates have been carried out for emission inventory. However, as there are uncertainties associated with emission factors and modeling scenarios, uncertainty analysis should be conducted for emission inventory estimation. Emission factors are estimated by basic emission rate, speed profile correction factor and technology factor, each of which has uncertainties. There are uncertainties associated with vehicle fleet distributions in scenario modeling, especially for future scenario. Uncertainties in emission factors and vehicle fleet characterization should be quantified. Numerical methods such as Monte Carlo simulation should be applied to determine uncertainty ranges for emission inventory estimates.

APPENDIX

Appendix A Supporting Information for Part IV

A Vehicle Specific Power Approach to Speed- and Facility- Specific Emissions Estimates for Diesel Transit Buses

Supporting Information

This supporting information (SI) provides supplemented texts, tables and figures to further describe the VSP-based model development and validation, and speed- and facility- specific average emission rates estimates and their evaluation. The issues contained are:

(1) Bus link speed profiles to get insights on link-based bus activity patterns and their association with mean speeds and emissions;

(2) Data division to investigate the representative of model calibration and validation datasets;

(3) Exploring the relationship between VSP and emissions before model development;

(4) Assessing the effects of autocorrelation on modal emissions model;

(5) Inter-vehicle variability in VSP mode average emission rates;

(6) Effects of acceleration on CO VSP modal emission rates;

(7) Validation of the VSP modeling approach and uncertainty analysis;

(8) Time distributions of VSP modes for multiple links with the same attributes; and

(9) ANVOA test on the effect of facility type and link mean speed on transit bus emission rates.

S1. Link Speed Profiles of Transit Buses

Various vehicle activities such as deceleration and acceleration produce different levels of vehicle emissions. Link speed profiles of transit buses were analyzed in order to get insights on link-based activities patterns for transit buses and their association with link mean speeds and emissions. For transit buses, a link was defined as the road segment between two bus stops. The defined links were characterized by the segment attribution such as roadway type. Link classes included principal arterials, minor arterials, local and collector streets. There were two types of bus speed profiles as shown in Figure S-1: (I) the one that had no traffic control stops; and (Π) the other that had traffic control stops. As shown in Table S-1, the speed profile (I) had lower mean speed than speed profile (Π). However, CO_2, CO and NO_x emission rates based upon the distance (g/mile) from speed profile (Π) were larger than from speed profile (I) whereas its average emission for HC was lower than from speed profile I, which implied that traffic control stops can affect bus activities and emissions.

S2. PEMS Database Division

The PEMS database was divided into two parts: a calibration dataset and a validation dataset for model development and validation. Because driving modes affect vehicle emission rates, the similarity of bus activities between both datasets was investigated prior to using them in order to evaluate whether both datasets were representative or not. The cumulative distribution function (CDF) plots of vehicle speeds and accelerations were generated for the calibration and validation datasets to ensure that activities in both datasets were comparable. As shown in Figure S-2, the values of CDF for a given speed or acceleration were very close to each other for both datasets, which indicates that there are similar patterns of vehicle activities between the calibration and validation datasets and that both datasets were representative of each other.

S3. Relationship between VSP and Emission Rates

The relationship between VSP and emissions was explored through the use of scatter plots. As shown in Figure S-3, emission rates were very low and were almost the constant for VSP less than -10 m^2/s^3. However, emission rates gradually increased with the VSP values when VSP values were in the range from -10 to 0 m^2/s^3. There was generally a monotonic increase in emissions with positive VSP for all pollutants, with the exception of CO emission rates which tended to decrease when VSP values were above about 10 m^2/s^3 (see paper for an explanation as to why this may be the case) In general, monotonic relationships motivated the development of the VSP binning approach.

Examination of the data showed that there were positive VSP values in previous seconds for the current data point whose VSP value was in the range from -10 to 0 m^2/s^3. Therefore, it is necessary to further investigate the randomness in the dataset. The randomness in the dataset is ascertained by computing autocorrelations for data values at varying time lags. The sample autocorrelation plot in Figure S-4 showed that the time series of emissions had an autocorrelation between current and adjacent observations in previous several seconds. The autocorrelation explained the reason that emission rates corresponding to VSP values from -10 to 0 m^2/s^3 displayed increasing trends.

As shown in Figure S-5a, CO emissions are sensitive to bus acceleration. During heavy acceleration, more fuel is injected and more incomplete combustion may occur, which result in high CO emissions. There are fewer samples with heavy acceleration for Mode 8 than Modes 6 and 7, which are shown in Figure S-5b.

S4. Effects of Autocorrelation on Modal Emissions Model

As shown in Figure S-4a for Bus 1, for the time lag up to 2 seconds for CO, NO_x, and HC and 6 seconds for CO_2, the autocorrelation is larger than 0.50. There are similar situations for other buses. Thus, the effect of autocorrelation on the VSP modal emissions model needs to be evaluated.

Before evaluating the effect of autocorrelation on emission rates, the averaging duration per VSP mode event for typical speed profiles is investigated, as shown in Figure S-6. These two speed profiles are typical. During the vehicle driving, one speed profile has traffic control stops, and the other has no traffic stops. These two speed profiles were on different links. The duration per VSP event ranged from 1.0 second to more than 30.0 second for two speed profiles. The average duration per VSP mode event for each mode for typical speed profiles are summarized in Table S-2. The average duration per VSP mode event for each mode ranged from 1.2 seconds to 5.0 seconds for two speed profiles. The overall average duration per event across modes for the original datasets are 1.7 seconds and 2.0 seconds for two speed profiles. Compared to the average duration per VSP mode event for two speed profiles, consecutive average are close.

Given average duration per VSP mode event of real-world link speed profiles, the second-by-second data are averaged using consecutive averages of 2, 3 and 5 seconds in order to evaluate the implications of autocorrelation on the VSP modal modeling. Modal models involve averaging of the data. Therefore, it is useful to evaluate the effect of averaging on autocorrelation. Consecutive averaging was applied to the calibration datasets. A 2, 3 or 5 second average VSP was used. The modal emission rates were estimated for each version of the calibration data, based on each averaging time.

As an example, the autocorrelation coefficients for the 2-, 3- and 5-second consecutive moving average datasets for Bus 1 are shown in Figure S-4. Compared to the original second-by-second dataset, the autocorrelation coefficients for both consecutive average datasets decrease for all pollutant as expected, especially for the larger second consecutive average dataset.

The 2-, 3- and 5-second consecutive average calibration datasets were used individually to re-estimate the VSP modal emission rates. The differences for modal emission rates based on consecutive average dataset and the original calibration dataset are given in Table S-3. Such differences of modal emission rates are classified into three ranges (≤±5%, ≤±10%, >±10%), and number of VSP modes for each range is summarized for each pollutant in Figure S-7.

The overall average differences in modal emission rates for eight modes is not more than 3% for CO_2, NO_x and HC, and not more than 5% for CO, when comparing second-by-second and consecutive averages. For CO_2, NO_x and HC, the absolute differences in modal emission rates are not more than 10% for the 2- and 3-second consecutive average datasets;

however, for the 5-second consecutive average dataset, there is one mode for each of these pollutants, for which the absolute differences in modal emission rates are more than 10% and less than 16%. For CO, there are two modes for the 2-second consecutive average dataset, three modes for the 3-second consecutive average dataset and four modes for the 5-second consecutive average dataset, for which such absolute differences are more than 10% for CO, and even up to 29%. These results indicate that the consecutive averages have relatively larger effects on individual modal emission rates for CO than those for other pollutants.

Using the fleet validation dataset, modal models based on 2-, 3- and 5- second consecutive average datasets are evaluated. Total emissions are estimated using these new modal emission rates and compared to total measured emissions. The estimation errors for all trips emissions are given in Table S-4 and compared for different versions of consecutive average-based models. The average difference of estimation errors in total emissions estimated for 12 trip speed profiles is 0.1 to 1.3 percent for CO_2, HC and NO_x, and 1.4 to 4.1 percent for CO when comparing each of 2, 3 and 5 second consecutive average-based models to the original modal model based on second-by-second data. Therefore, autocorrelation is found to have no significant effects on trips emissions predicted by the VSP modal emissions model.

S5. Inter-Vehicle Variability in VSP Modal Average Emission Rates

Vehicle activities affect emissions. The CDFs of vehicle speed were plotted for individual buses. As shown in Figure S-8, buses had different activities patterns. For example, Buses 7, 9 and 10 were related to low speed activities. However, Buses 11, 14 and 15 are related to high speed activities. For Buses 7, 9 and 10, there are 65 to 70 percent of speeds less than 20 mph, and 60 percent of speed less than 20 mph for Bus 6, whereas there are 40 percent of speeds less than 20 mph for Bus 11, and 50 to 54 percent of speeds less than 20 mph for Buses 14 and 15. Trip average speed was 12 mph and 14 mph for Buses 9 and 10, which are much lower than average speeds of 24 mph for Bus 11 and 21 mph for Bus 14.

Inter-vehicle variability in VSP modal average emission rates was investigated before combining data from different vehicles to estimate fleet average emission rates. The modal average emission rates were estimated based upon individual vehicle data. As summarized in Table S-5, the number of samples for each of eight VSP modes for individual vehicle is more than 100, except for VSP Mode 8 for Buses 1, 11 and 15, which indicates that there are sufficient samples to estimate modal average emission rates. As shown in Figure S-9, in general, VSP modal average emission rates of CO_2, NO_x and HC monotonously increased with the VSP mode for all buses except for modal average emission rates of HC from Buses 14 and 15.

There were similar varying trends for CO emissions for all buses. For CO, modal average emission rates increased with VSP mode up to Modes 5 or 6 or 7 and then decreased.

Comparisons of multiple buses emissions indicated that there was a large inter-vehicle variability in emissions for HC. Compared with modal average HC emission rates of other vehicles, each of the eight modal average emission rates for Bus 10 were almost all the lowest. For Buses 14 and 15, modal average emission rates for the VSP Modes 1, 2 and 3 are larger than those for high VSP modes, which are also much larger than modal average emission rates of the VSP Modes 1 and 2 of other buses. Different from other buses, the correlation coefficients between HC emission rates and VSP for Buses 14 and 15 were 0.04 and -0.18, which indicated low correlation between two variables.

For diesel vehicles, HC emissions have a dependence on equivalence ratio. Equivalence ratio is defined as actual fuel versus air ratio normalized with respect to the stoichiometric fuel versus air ratio:

$$\phi = \frac{\left(m_f / m_a \right)_{actual}}{\left(m_f / m_a \right)_{stoichiometric}} \quad \text{(S-1)}$$

Where:

ϕ = equivalence ratio;

f = index of fuel;

a = index of air;

m = the mass;

m_f / m_a = fuel versus air mass ratio.

As shown in Figure S-10(a), the high HC emission rates in gram per second occurred at highly fuel lean equivalence ratio. As an alternative, HC emission rates were normalized by brake horse power. As shown in Figure S-10(b), there is a more clear relationship between equivalence ratio and normalized HC emissions. Similar to results by Frey *et al*, 2002, the high HC emission rates occurred at low values of equivalence ratio less than 0.40. High HC emission rates were also observed when equivalence ratio was more than 1.30, which did not appear in Frey *et al.*, 2002 due to no samples available for equivalence ratios more than 1.30. High equivalence ratios are for fuel-rich combustion, which results in incomplete combustion and HC emission rates. As shown in Figure S-10(c), equivalence ratio and VSP are weakly related as correlation coefficient between them is 0.30. Thus, the VSP modal approach does not explain a large portion of the variability in HC emission rates. On the other hand, HC emission rates and total emissions from on-road diesel engine are small relative to gasoline engine.

There was a smaller inter-vehicle variability in modal average emission rates on a relative basis for CO_2 and NO_x than for HC and CO.

S6. Effects of Acceleration on CO VSP Modal Emission Rates

CO emissions are sensitive to acceleration. Quantification of heavy acceleration in individual VSP modes helps illustrate the trends that CO modal emission rate for VSP Mode 8 is smaller than for VSP Mode 6 or 7 for some vehicles shown in Figure S-9b. Percentages of data for heavy acceleration events in individual high VSP modes for each vehicle are summarized in Table S-6. As shown in Figure S-11, the ratio of modal emission rates for VSP Mode 8 versus 6 or 7 increases with the ratio of percentage of heavy acceleration more than 3 mph/s. For vehicles with the modal emission rates ratios less than 1.0 for VSP Mode 8 versus 6 or 7, there are higher percentages of samples with heavy acceleration for VSP Modes 6 and 7 than for VSP Mode 8, which account for lower modal emission rate for VSP Mode 8; for vehicles with the modal emission rates ratios more than 1.0, there are higher percentages of heavy acceleration events associated with VSP Mode 8.

S7. Validation for VSP modeling approach with Uncertainty Estimates

Once VSP mode average emission rates were estimated based upon the model calibration dataset, validation was carried out. The validation database consisted of 12 subsets, each of which was selected from individual vehicles and was ten minutes in length as described in the main paper. Using modal average emission rates with 95% confidence intervals shown in Figure 2 of the main paper, total emissions of individual subsets were estimated for each of buses and then compared with corresponding measured total emissions. Subsequently, estimation errors were calculated for each bus.

Because VSP mode average emission rates had large confidence intervals, especially for CO and HC, uncertainty estimates of total emissions were included in the model validation. Total emissions for each bus are estimated with uncertainty ranges as follows:

$$TE = \sum_{i=1}^{8} T_i \times ER_i \tag{S-2}$$

$$TE^{Lower} = \sum_{i=1}^{8} T_i \times (ER_i - \frac{t(11,0.025) \times SD_i}{\sqrt{12}}) \tag{S-3}$$

$$TE^{Upper} = \sum_{i=1}^{8} T_i \times (ER_i + \frac{t(11,0.025) \times SD_i}{\sqrt{12}}) \tag{S-4}$$

Where:

TE = Total estimated emissions for a bus trip (g);

TE^{Lower} = Lower boundary of total estimated emissions for a bus trip (g);

TE^{Upper} = Upper boundary of total estimated emissions for a bus trip (g);

i = Index of VSP mode, 1, 2, …, 8;

ER_i = Modal average emission rate of Mode i (g/s);

SD_i = Standard deviation of modal average emission rates of 12 buses for Mode i (g/s);

T_i = Time spent in Mode i (s);

t = t-value of Student's distribution with 11 degrees of freedom for 95% confidence intervals.

Total emissions were estimated based on individual data subset. Uncertainty ranges of estimation errors for 12 buses are given in Figure S-12. The average values of mean estimation errors of 12 buses for selected pollutants are displayed in Figure S-13. The results show that the VSP modeling approach generated different estimation errors for different pollutants. The mean estimation error for CO_2 for one bus was less than +/- 20%. For CO, NO and HC, estimation errors substantially decreased when emissions increased. However, for HC emissions, the approach exhibited significantly different performance for different vehicles. Zero estimation error was enclosed by the uncertainty ranges of estimation errors for many buses. The average values of the 12 mean estimation errors with 95% CIs shown in Figure S-13 indicated that VSP modeling has good ability to predict CO_2, NO_x and CO emissions from diesel transit buses. However, it had a larger estimation error for HC emissions due to relatively larger inter-vehicle variability in HC emissions from transit buses.

S8. Time Distributions of VSP Modes for Multiple Links with the Same Attributes

Emission estimates based on the VSP-modeling approach and measured speed profiles were determined by the fraction of travel time spent in each VSP mode. It was necessary to investigate whether patterns of VSP mode time distributions were similar among multiple links with the same speed ranges and facility type before data from multiple links (in the same speed mode and roadway type) were combined to estimate link-based speed- and facility-specific average emission rates. For example, time distributions of VSP modes for selected link speed profiles on principal arterials were calculated for mean link speed from 25 mph to 30 mph. As shown in Figure S-14a, about 37 % of the time on average was spent in VSP Mode 1, and less than 12 % was spent in any other mode. As shown in Figure S-14b, the CV value for the percentage of time distribution is 0.25 for VSP Mode 1 and ranges from 0.41 to 0.72 for other modes. Time distribution was similar among multiple links for this speed mode and data from multiple links with the same attributes were combined.

S9. ANOVA Test on the Effects of Facility Type and Mean Speed on Buses Emissions

An ANOVA test was carried out to evaluate the effect of facility type and mean speed on transit buses emissions for each of selected pollutants. Three speed ranges (10-15 mph, 15-20 mph and 20-25mph) and three facility types (major arterial, minor arterial, local and collector) were included in the ANOVA test. As shown in Table S-7, all p-values corresponding to facility type were more than .05 and p-values corresponding to mean speed were less than .001, which implied that facility type did not appear to be a major explanatory variable when compared with speed.

List of Figures and Tables in Supporting Information

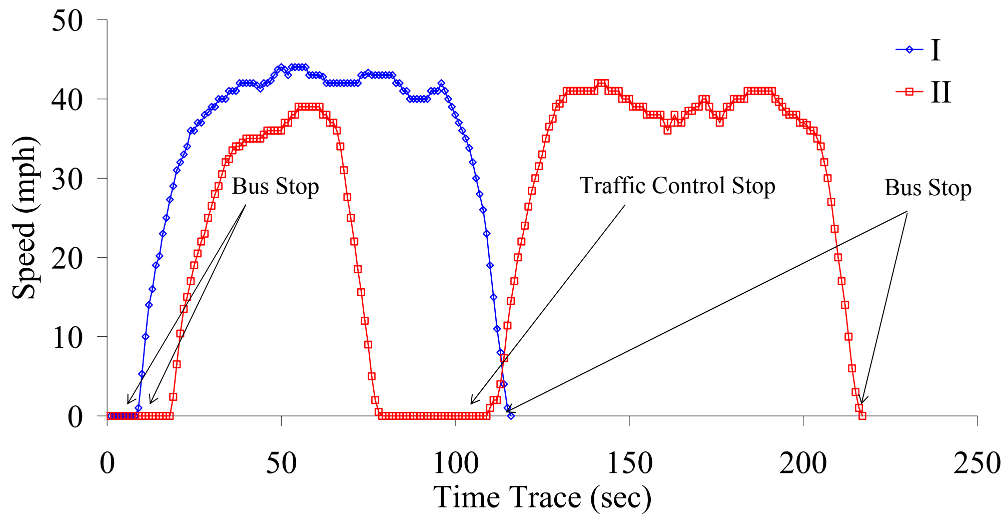
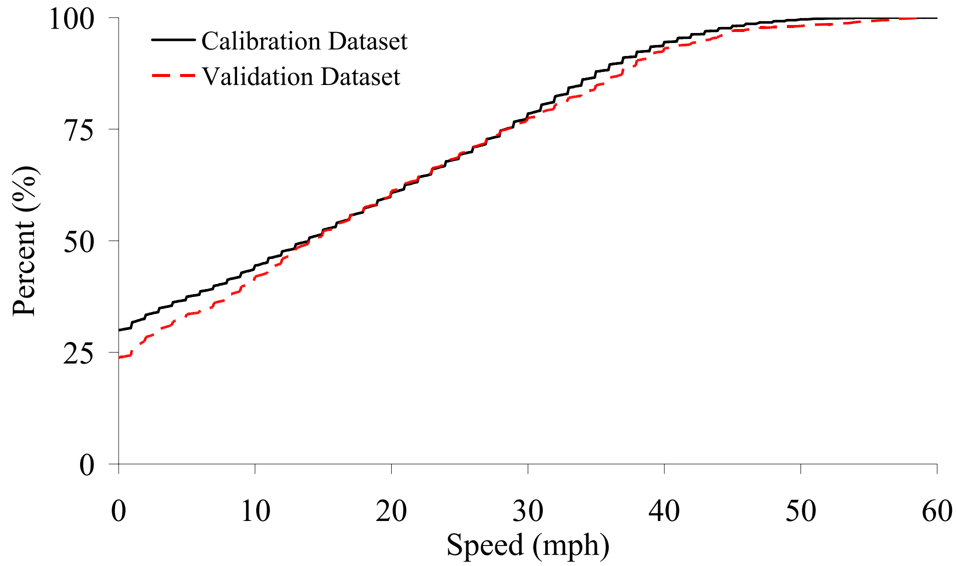
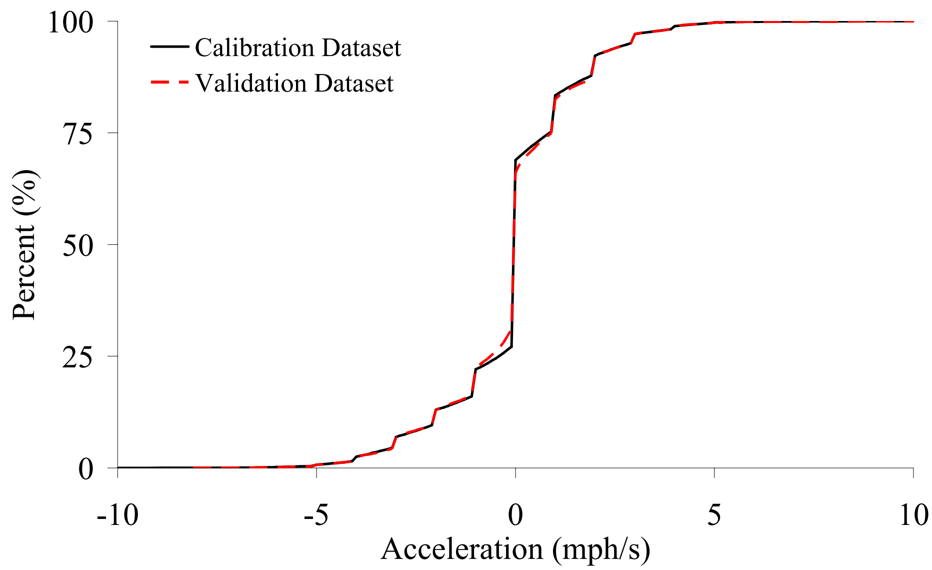


Figure S-1 Typical Speed Profiles for Transit Buses

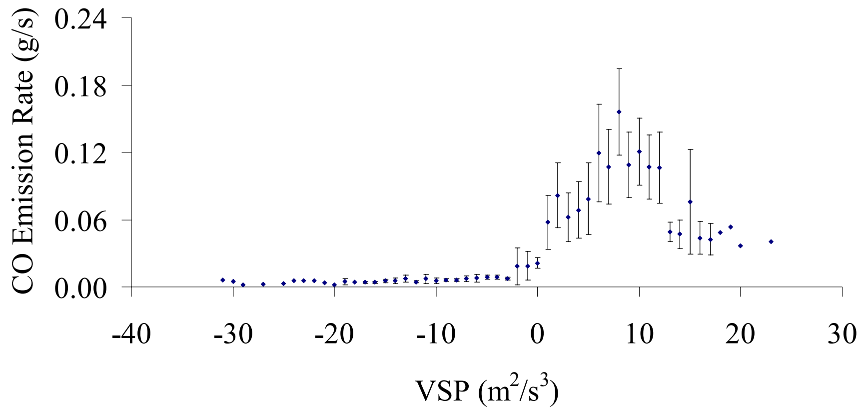


(a) Speed

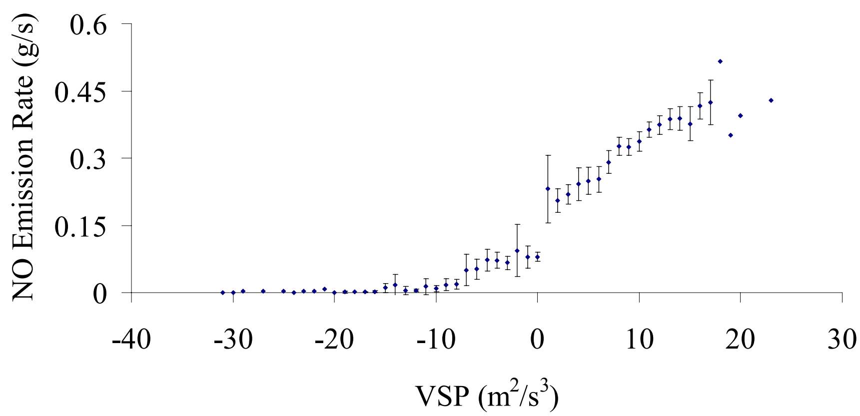


(b) Acceleration

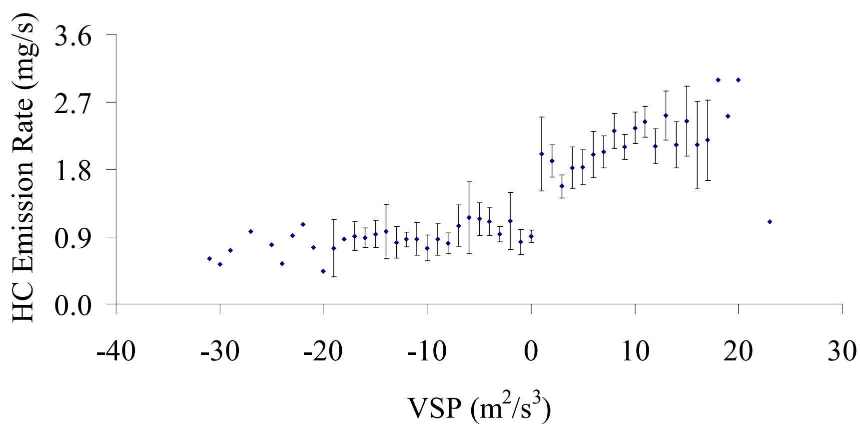
Figure S-2 Empirical Cumulative Distribution Functions for Calibration and Validation Datasets



(a) CO

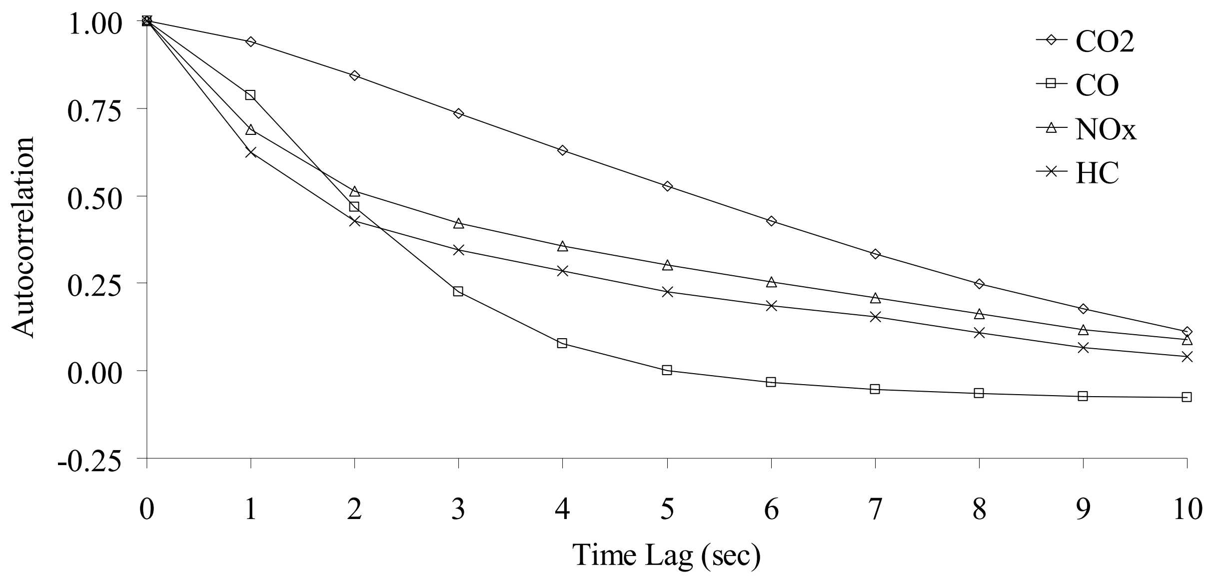


(b) NO

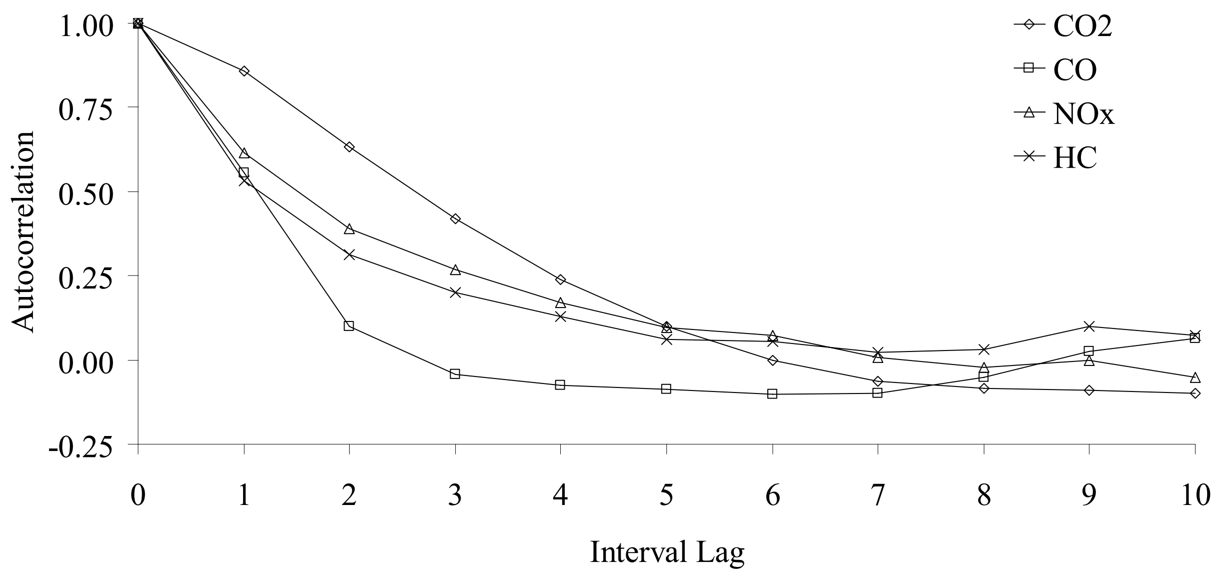


(c) HC

Figure S-3 Emission Rates vs. Vehicle Specific Power based on Bus 1 Data

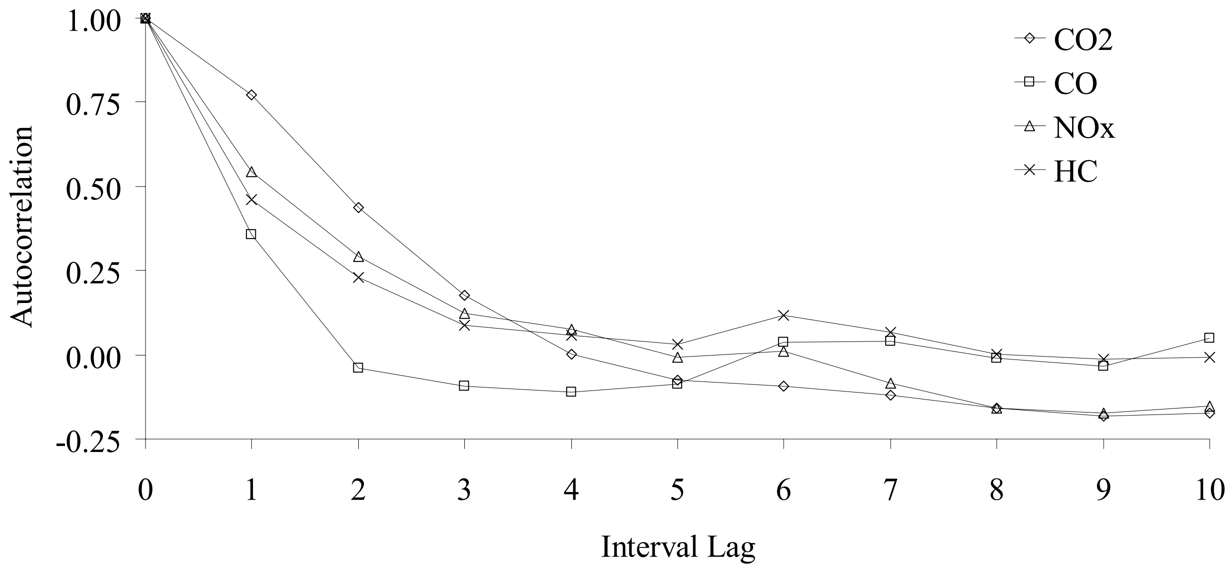


(a) Original dataset

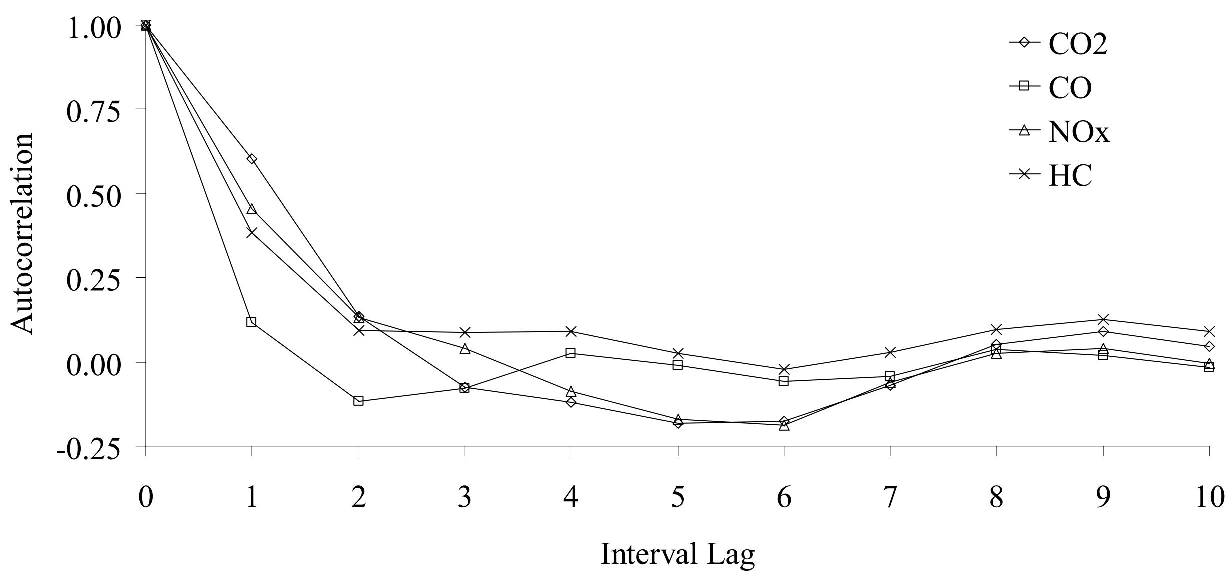


(b) 2-second consecutive moving average dataset

Figure S-4 Autocorrelation Coefficient of Instantaneous Emissions based on Bus11 Data Including All VSP Values. Continued on next page

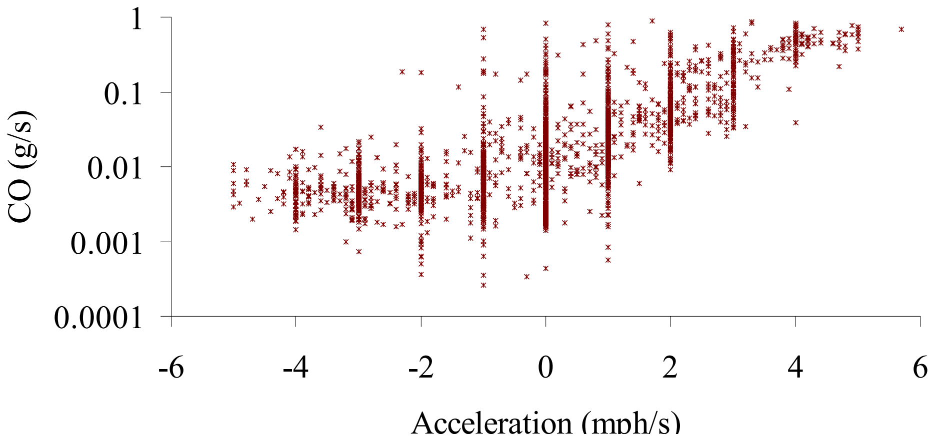


(c) 3-second consecutive moving average dataset

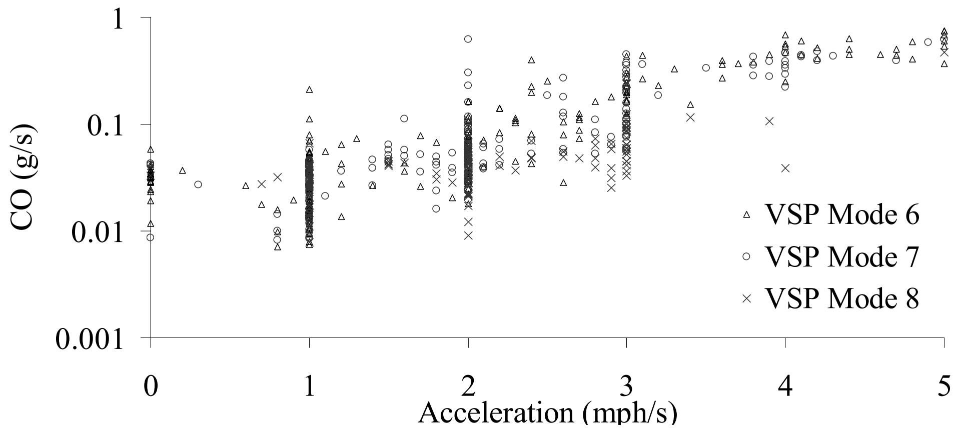


(d) 5-second consecutive moving average Dataset

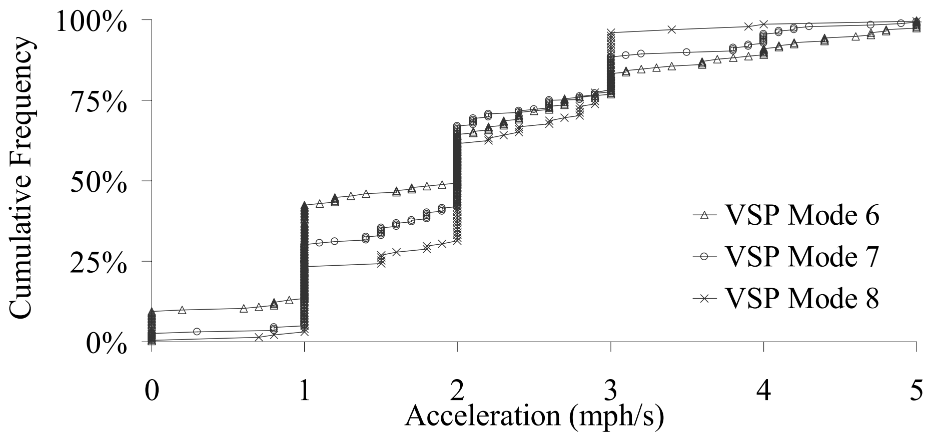
Figure S-4 Continued



(a) CO versus acceleration based on all Bus 1 data

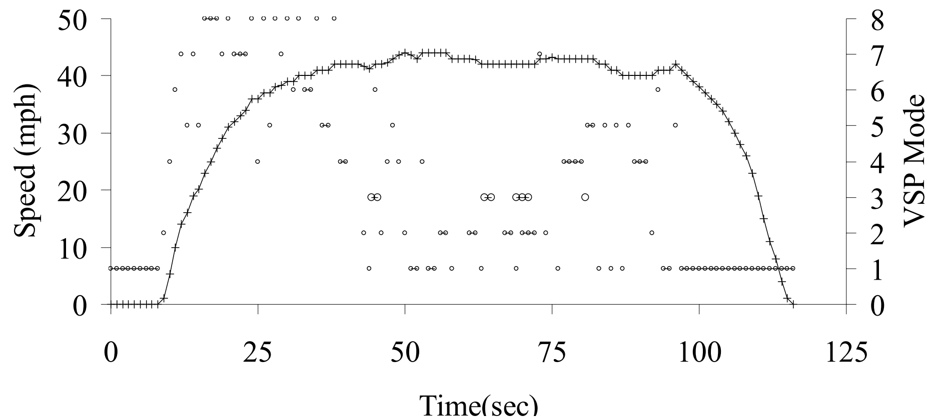


(b) CO versus acceleration based on VSP modes 6, 7 and 8 data

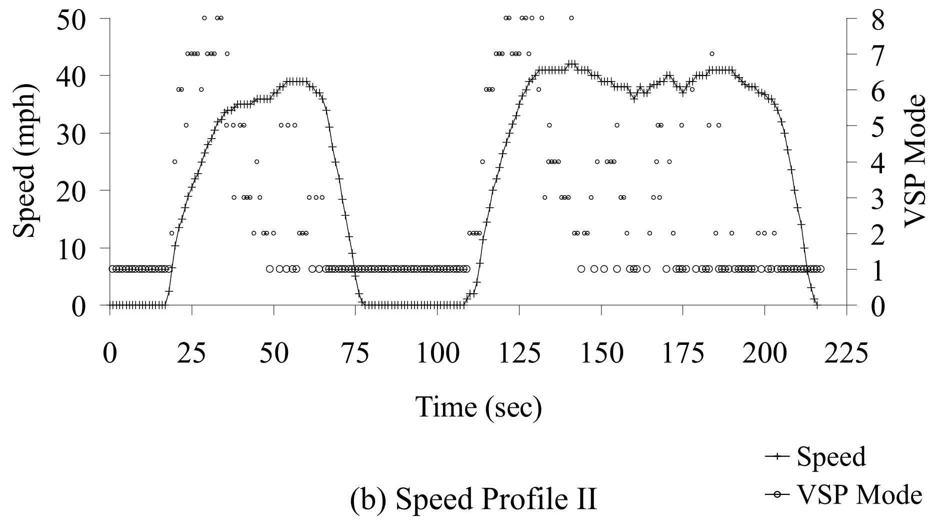


(c) Cumulative frequency of acceleration for VSP Modes 6, 7 and 8

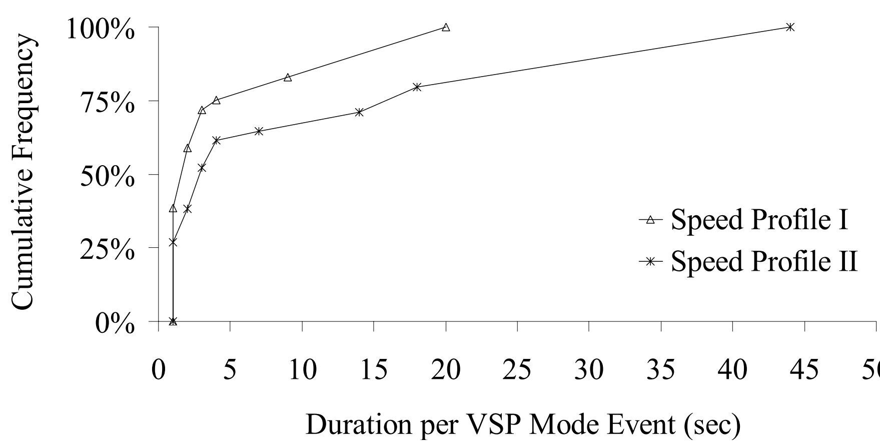
Figure S-5 CO Emission Rate and Bus Acceleration based on Bus 1 Data



(a) Speed Profile I

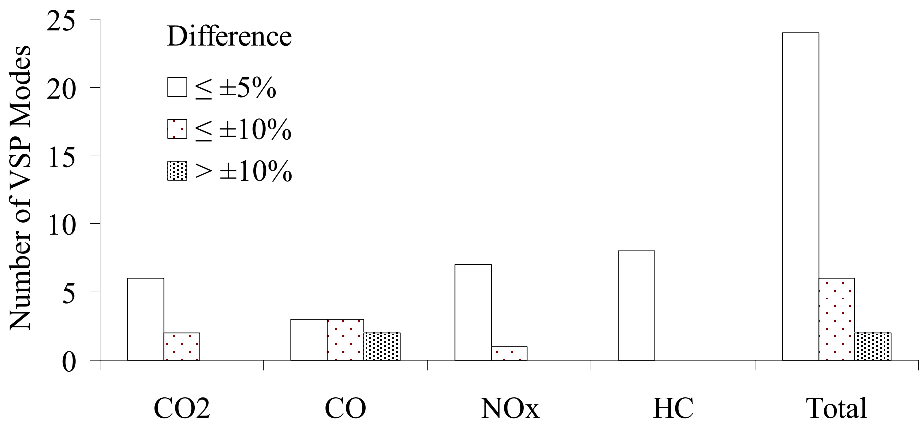


(b) Speed Profile II

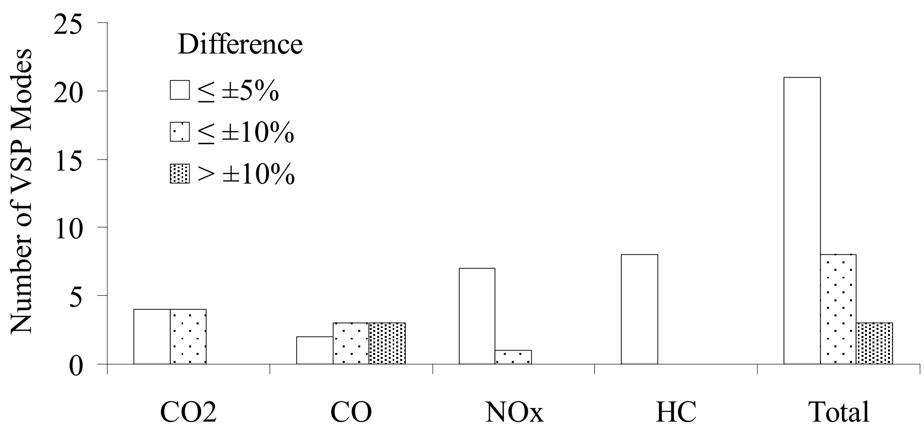


(c) Cumulative time-weighted frequency of duration per VSP mode event for two speed profiles

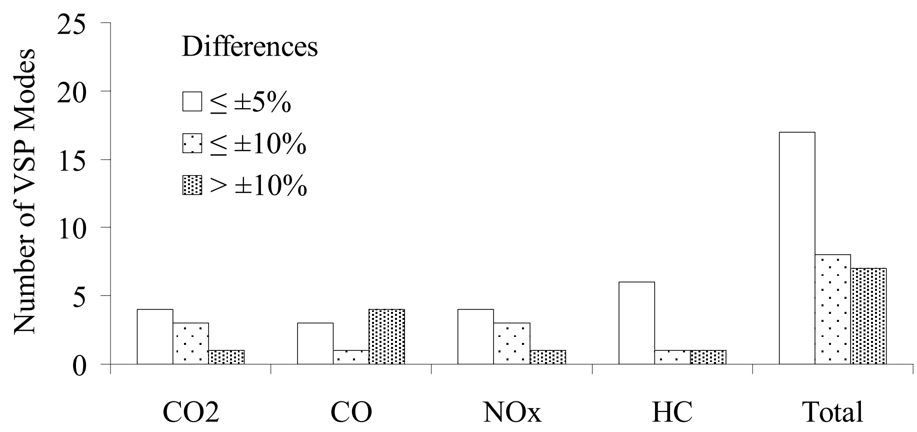
Figure S-6 VSP Mode Events for Typical Speed Profiles



(a) Original versus 2-second consecutive average-based models



a) Original versus 3-second consecutive average-based models



(c) Original versus 5-second consecutive average-based models

Figure S-7 Number of VSP Modes Classified by The Differences of Modal Emission Rates based on The Original and Consecutive Averages Calibration Dataset

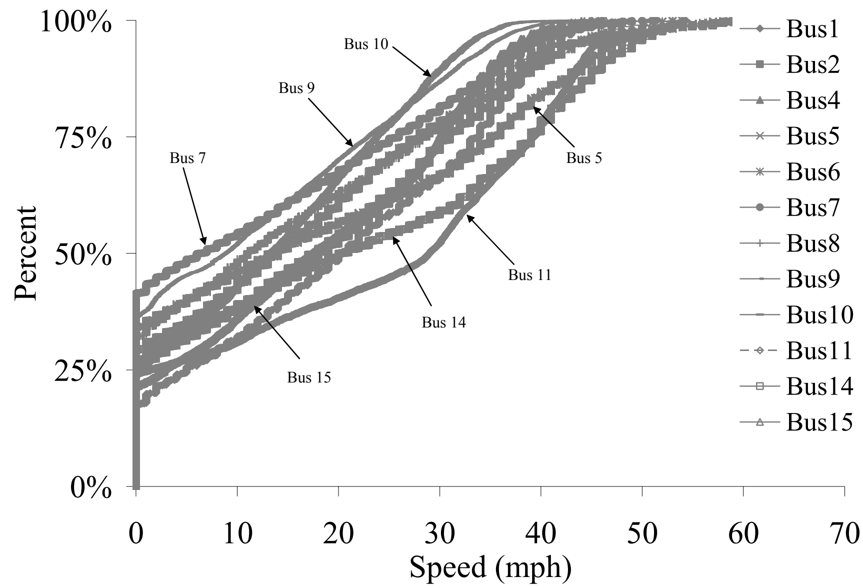
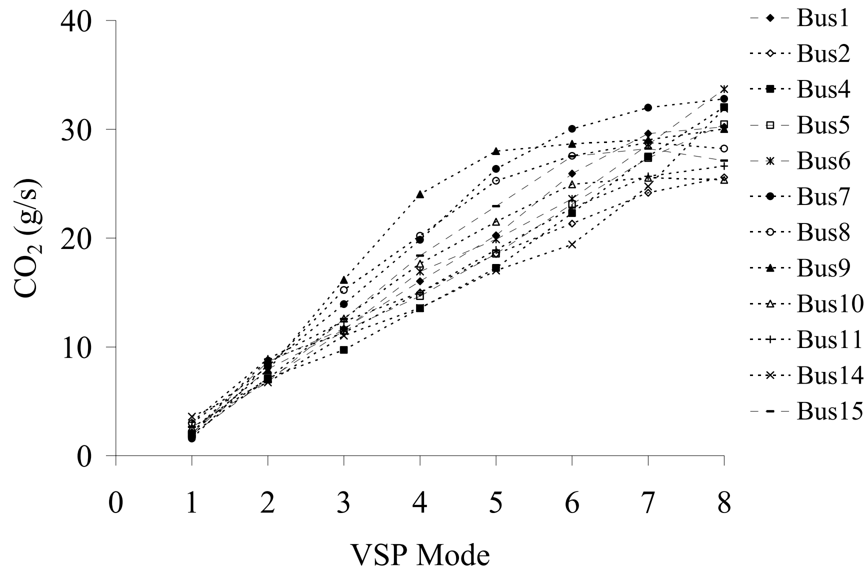
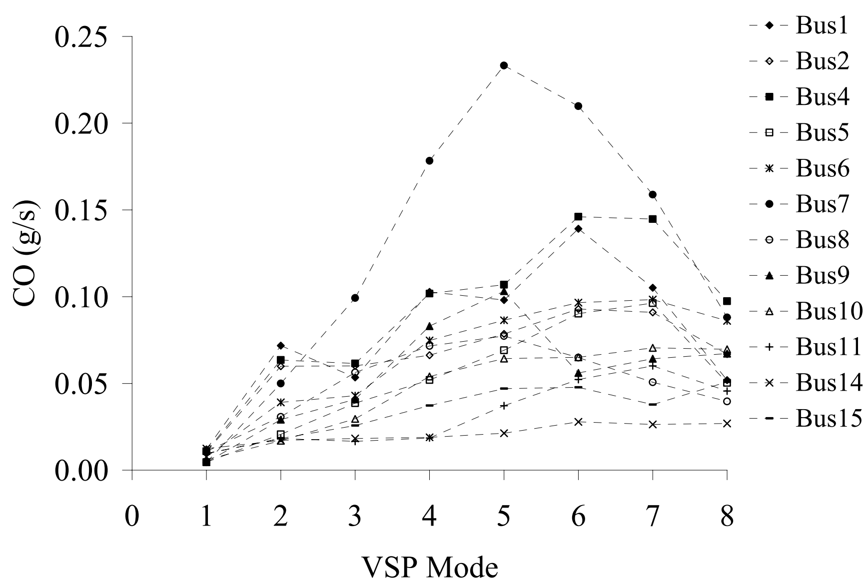


Figure S-8 Empirical Cumulative Distribution Function of Speeds for Individual Buses



(a) CO_2



(b) CO

Figure S-9 Inter-Vehicle Variability in Modal Average Emission Rates.

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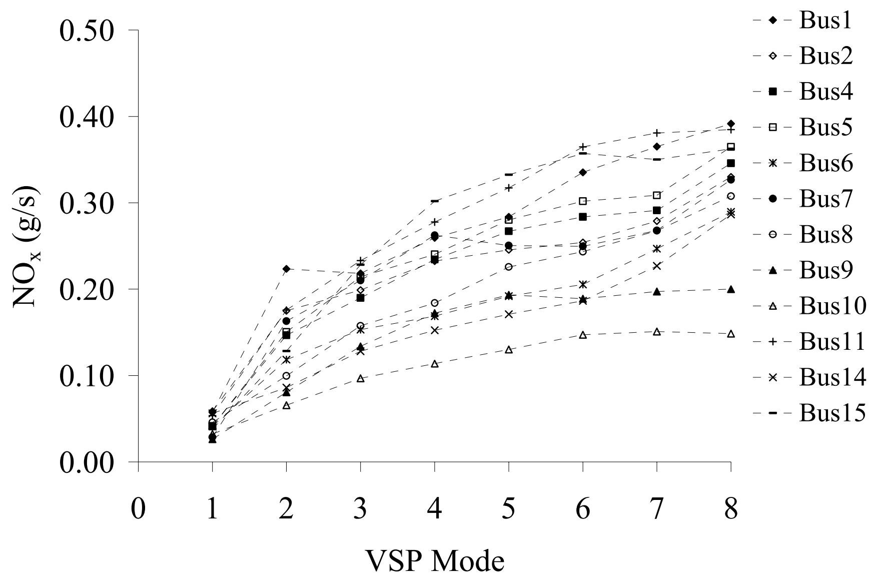
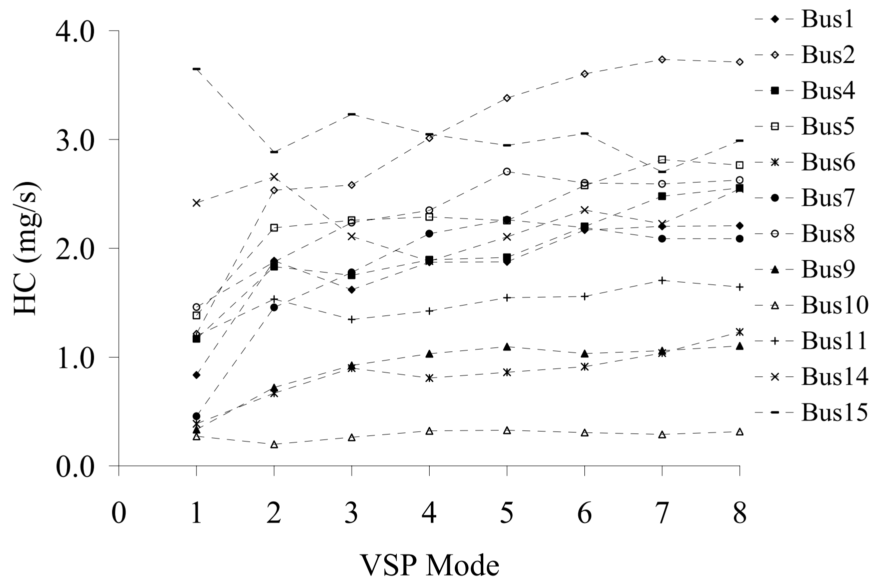
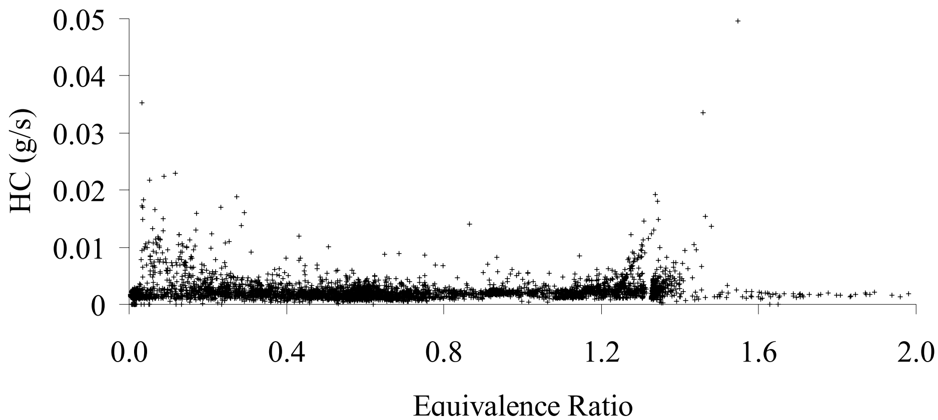


(c) NO_x

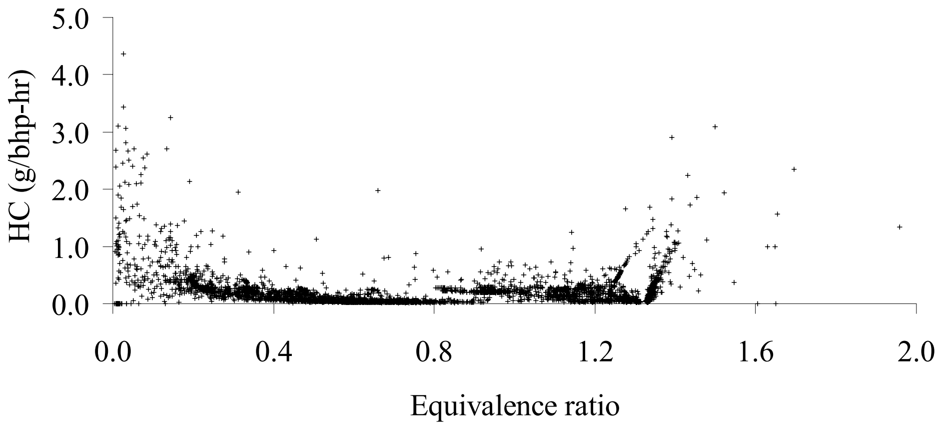


(d) HC

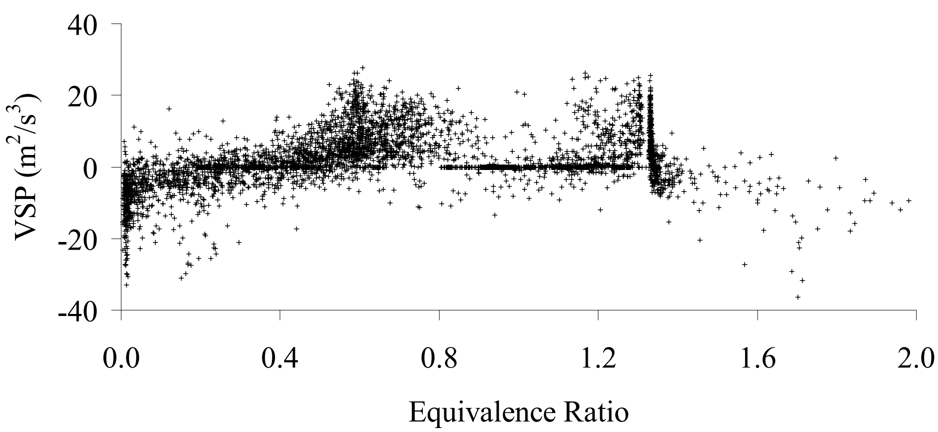
Figure S-9 Continued



(a) Equivalence ratio versus HC emission rate (in g/s)



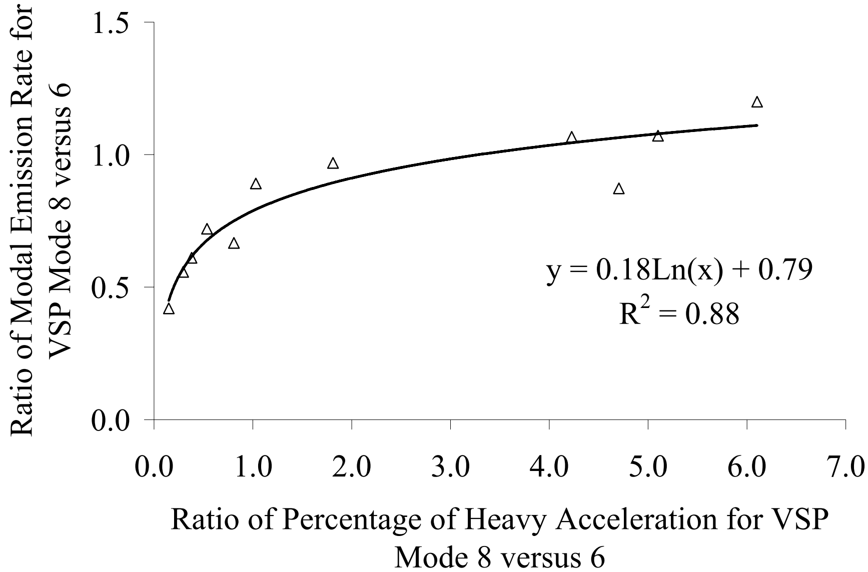
(b) Equivalence ratio versus HC emission rate (in g/bhp-hr)[a]



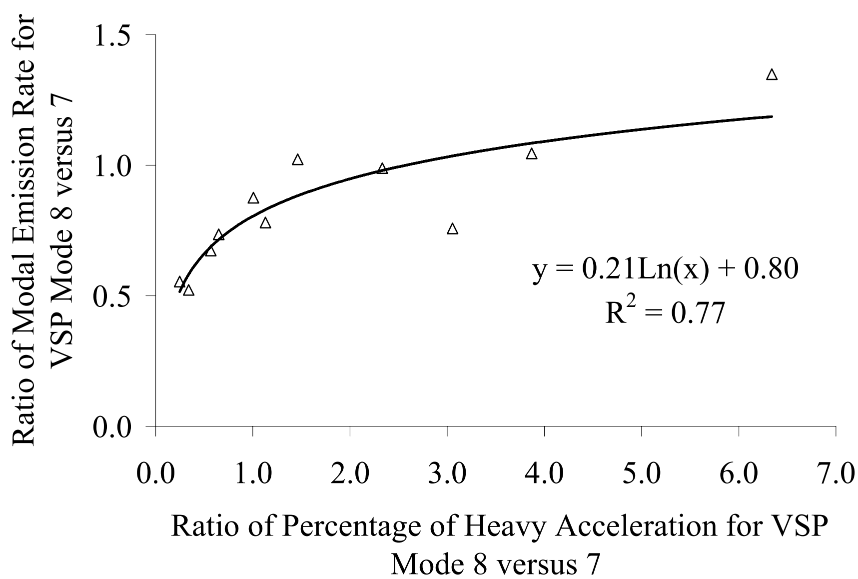
(c) Equivalence ratio versus VSP

Figure S-10 Relations of Equivalence ratio with HC Emission Rate and Vehicle Specific Power based on One Bus Trip Data

[a] Some HC emission rates in g/bhp-hr were missing for equivalence ratios more than 1.60.

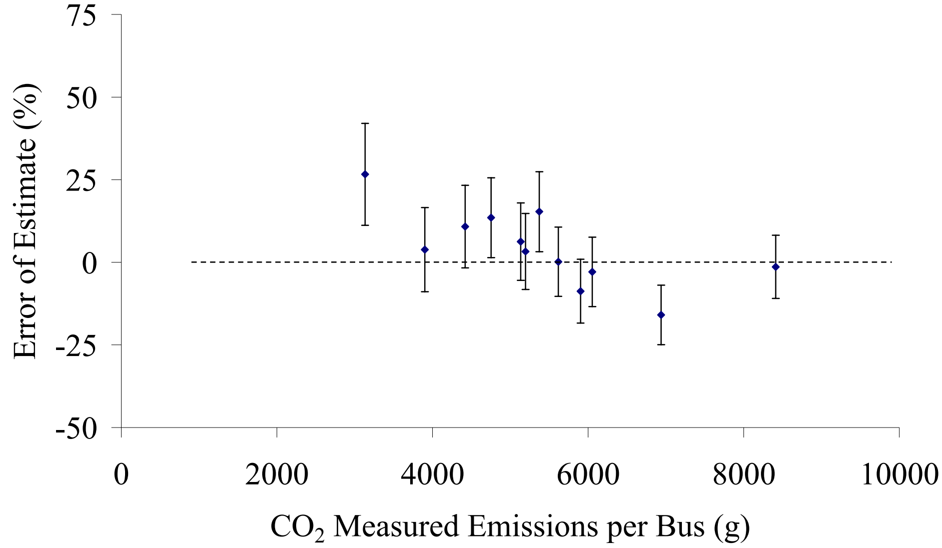


(a) Ratio of percentage of heavy acceleration for VSP Mode 8 versus 6

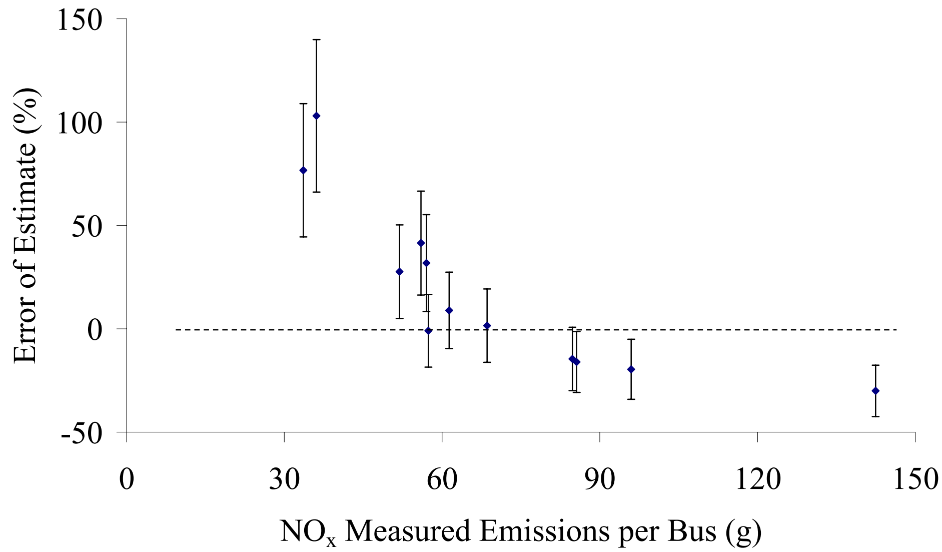


(b) Ratio of percentage of heavy acceleration for VSP Mode 8 versus 7

Figure S-11 Relationship between Ratio of Percentage of Heavy Acceleration and Ratio of Modal Emission Rates for VSP Mode 8 versus 6 and 7

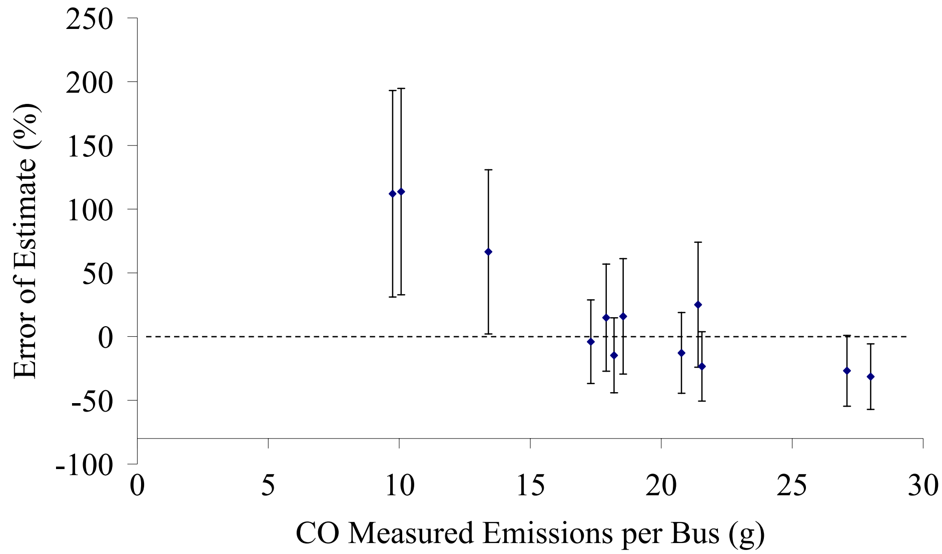


(a) CO_2

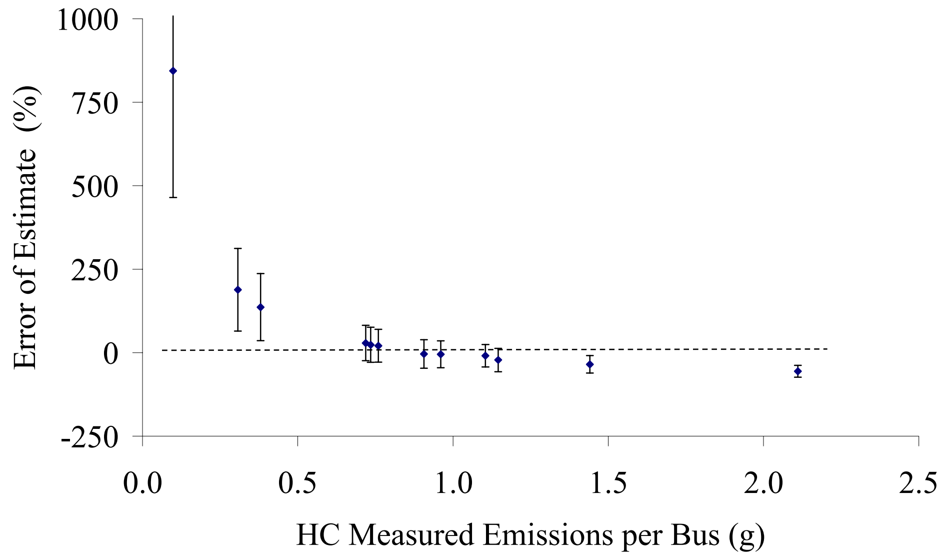


(b) NO_x

Figure S-12 Errors of Estimates of Total Emissions based upon Individual Validation Data Subsets.[a] Continued on next page



(c) CO



(d) HC

Figure S-12 Continued [a]

[a] represents uncertainty ranges of errors of emission estimate

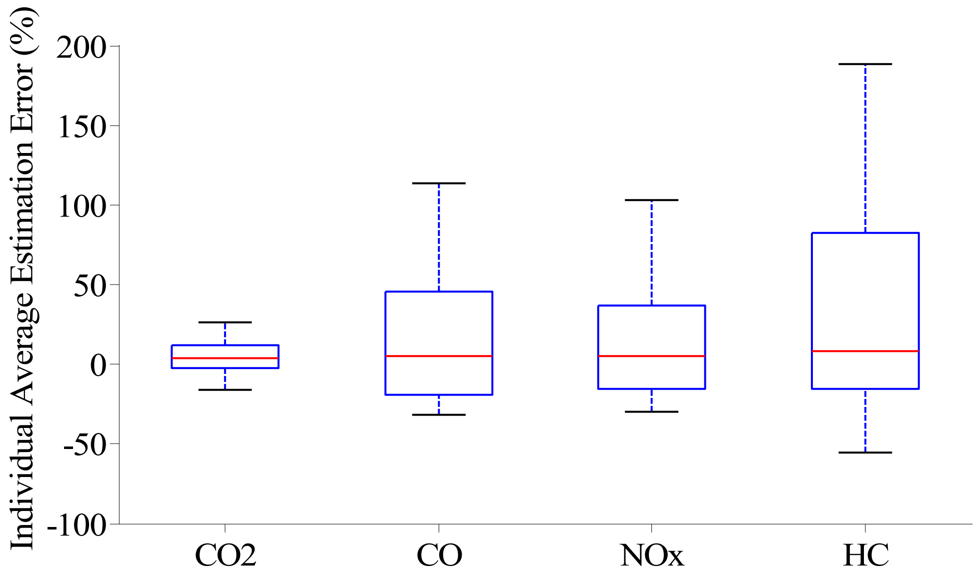
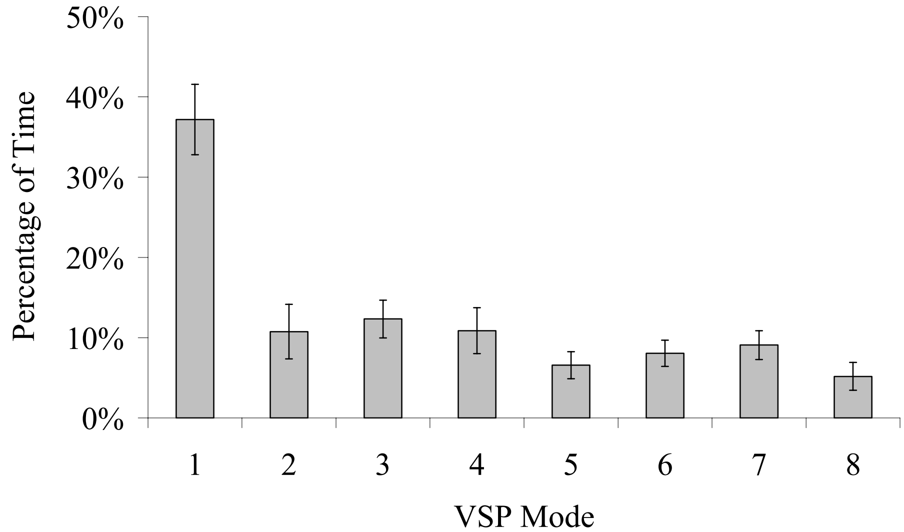
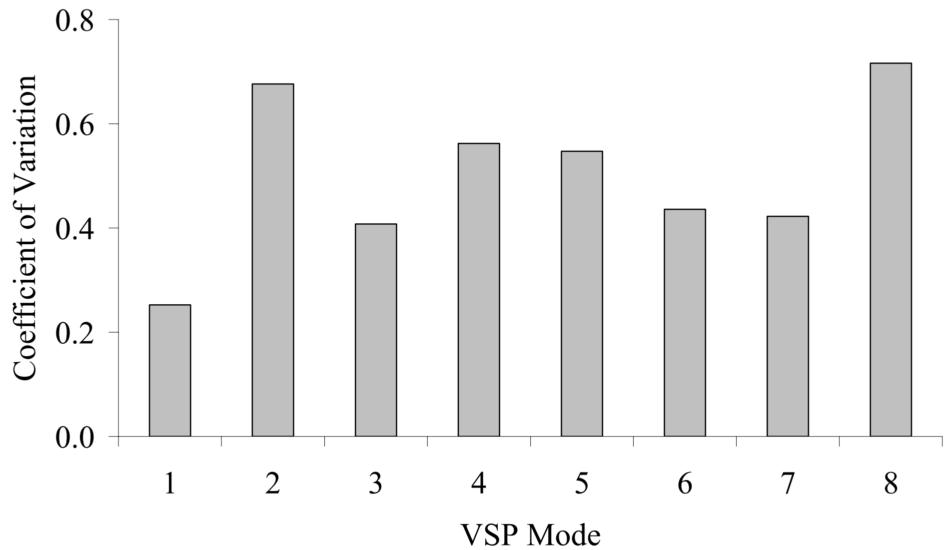


Figure S-13 Individual Bus Average Estimation Errors for Trip Emissions [a]

[a] The boxplot has lines at the smallest observation, lower quartile, median, upper quartile and largest observation. Any data observation which lies more than 1.5*IQR (interquartile range, subtracting the lower quartile from the upper quartile) lower than the first quartile or 1.5*IQR higher than the third quartile is considered an outlier.



(a) Average percentage of time for a given VSP mode and 95% confidence interval on mean



(b) Coefficient of variation for the percentage of time

Figure S-14 Average Time distributions of VSP Modes on The Links of Principal Arterials for Average Speed 25-30 mph

Table S-1 Link Mean Speed and Average Emissions for Selected Speed Profiles

Speed Profile	Link Mean Speed (mph)	Average Emission (g/mile)			
		CO_2	CO	NO_x	HC
I	32.9	1322.5	3.68	20.44	0.25
Π	24.3	1360.5	5.65	21.07	0.17

Table S-2 Averaging Length of Time per VSP Mode Event

VSP Mode	Speed Profile I		Speed Profile II	
	Number of Instantaneous Events	Average Length of Time per Event (sec)	Number of Instantaneous Events	Average Length of Time per Event (sec)
1	13	3.3	23	5.0
2	10	1.5	15	1.5
3	4	2.0	12	1.4
4	8	1.8	8	1.6
5	10	1.2	12	1.2
6	5	1.2	5	1.6
7	6	1.3	7	2.3
8	9	1.2	7	1.4
Max.	13	3.3	23	5.0
Min.	4	1.2	5	1.2
Overall average	8	1.7	11	2.0

Table S-3 Differences of Modal Emission Rates based on The Original and Consecutive Average Calibration Datasets (%)

VSP Mode	CO_2			CO			NO_x			HC		
	2-Sec	3-Sec	5-Sec	2-Sec	3-Sec	5-Sec	2-Sec	3-Sec	5-Sec	2-Sec	3-Sec	5-Sec
1	-6	6	-1	-2	3	7	-3	5	0	2	-1	4
2	-5	8	-12	-7	9	-12	-7	8	-16	-4	5	-11
3	-2	3	-4	9	-7	13	1	3	-6	2	3	-1
4	-4	5	-3	-11	8	5	-2	2	-4	-4	2	-3
5	0	-2	2	0	-4	-3	2	-3	3	-1	2	-4
6	3	-5	6	8	-11	-5	2	-4	5	-1	-1	1
7	6	-7	8	2	14	-19	4	-5	8	5	-2	1
8	5	-6	7	-11	13	-29	2	-1	9	1	1	-10
Average across modes	0	0	0	-2	3	-5	0	1	1	0	1	-3

Table S-4 Estimation Errors for Total Emissions based on The Fleet Validation Dataset Using Modal Models Developed from The Original and Consecutive Average Calibration Datasets (%)[a]

Pollutant	Calibration Dataset			
	Original Dataset	2-Sec Moving Average Dataset	3-Sec Moving Average Dataset	5-Sec Moving Average Dataset
CO_2	2.6	2.5	2.4	3.3
CO	5.9	4.5	2.7	1.8
NO_x	4.3	3.7	3.0	3.4
HC	3.0	3.6	2.7	1.8

[a] Based on the fleet validation dataset, total emissions estimates using modal models are compared to total measured emissions to calculate estimation errors.

Table S-5 Sample Size for VSP Modes for Individual Vehicles

VSP Mode	Bus Number												Sum
	1	2	4	5	6	7	8	9	10	11	14	15	
1	991	1577	3874	4286	3801	4743	4037	4503	4162	2097	2570	2704	39345
2	213	415	960	678	643	364	786	538	1142	627	455	685	7506
3	221	306	760	514	491	254	465	324	646	772	379	472	5604
4	164	266	549	426	384	250	484	550	555	704	298	386	5016
5	154	206	491	355	335	269	509	606	412	425	225	336	4323
6	170	166	462	369	281	417	471	356	253	177	168	240	3530
7	166	161	496	403	343	606	400	254	150	115	217	165	3476
8	98	124	252	279	409	419	118	206	146	55	371	97	2574
Sum	2177	3221	7844	7310	6687	7322	7270	7337	7466	4972	4683	5085	71374

Table S-6 Percentage of Samples for Heavy Acceleration Events in Individual High VSP Modes for Each Vehicle (%)

Vehicle Number	Percent of Samples for Acceleration > 3 mph/s in Given VSP Modes		
	Mode 6	Mode 7	Mode 8
2	9	7	5
4	15	21	12
5	10	8	3
6	11	12	12
7	13	8	2
8	4	2	2
9	9	14	55
10	11	23	54
11	7	11	35
14	6	7	11
15	10	7	42

Table S-7 ANOVA Tests for Effects of Facility Type and Mean Speed on Link Average Emission Rates

Pollutant	Source	DF	Sum of Squares	F Ratio	Prob. > F
CO_2	Mean Speed	2	2.94E+02	4.69E+01	<.001
	Facility Type	2	1.84E+00	2.94E-01	0.75
CO	Mean Speed	2	3.45E-03	5.61E+01	<.001
	Facility Type	2	7.21E-05	1.17E+00	0.31
NO	Mean Speed	2	3.46E-02	6.07E+01	<.001
	Facility Type	2	2.25E-04	3.94E-01	0.67
HC	Mean Speed	2	5.15E-07	6.23E+01	<.001
	Facility Type	2	1.14E-08	1.38E+00	0.25

Appendix B Development of Modal Emissions Model for A Hybrid Electric Vehicle [‡‡]

[‡‡] This manuscript is in preparation for submission to *Environmental Science & Technology*.

DEVELOPMENT OF MODAL EMISSIONS MODEL FOR A HYBRID ELECTRIC VEHICLE

ABSTRACT

This research quantifies engine on/off strategies and modal emission rates for a selected HEV under hot stabilized conditions. A second-by-second dynamometer database for tests of a series-parallel Toyota Prius HEV was used. Engine on/off operation rules were identified using a classification and regression tree (CART). In previous work, vehicle specific power (VSP) has been identified as a useful exploratory variable for emissions. A VSP-based modal approach was assessed as a method for modeling emissions for HEVs. VSP-based modal average emission rates were estimated using the second-by-second dynamometer database. Evaluation of model predictions for when the engine is on or off demonstrates close agreement between the model and the independent evaluation data. Specifically, the engine is found to be off only under threshold conditions of engine power demand that are speed and acceleration dependent. Emissions for a driving cycle or a trip are estimated as the product of modal average emission rates multiplied by time spent in the corresponding VSP mode while the engine is on, summed over all modes. Predicted CO_2 emissions for a selected driving cycle agree closely with the independent data. The predicted cycle emissions of CO, NO_x and HC are subject to large relative errors, but are small on an absolute basis compared to conventional gasoline vehicle emissions. Engine operation rules and modal average fuel consumption rates are applied to various driving cycles for estimating average emissions. Engine on/off and emissions modeling approaches are

recommended for further application as additional data, particularly for real-world traffic conditions become available.

INTRODUCTION AND RESEARCH OBJECTIVES

Hybrid electric vehicles (HEVs) are at the forefront of advanced vehicle technology development as they are more efficient, pollute less and reduce dependence on foreign oil. In the near future, the HEVs are not only an interim solution for implementation of zero emissions vehicles but a practical solution for commercialization of super-ultra-low-emission vehicles (Chau *et al.*, 2002). Recent achievements of research and development in advanced batteries further help facilitate the commercialization of HEVs (Weinstock, 2002).

A HEV uses a combination of an internal combustion engine and electric motor to improve fuel economy and reduce emissions of vehicles (Kheir *et al.*, 2004). However, there is a trade-off for HEV's engine control strategy to optimize the fuel economy and reduce the emissions. In order to determine the ideal operating point of the engine and motor, the control strategy considers all possible engine-motor torque pairs (Johnson *et al.*, 2000). The driver inputs, the state of charge (SOC) of the energy storage, the motor/generator speed, the current gear ratio and vehicle speed, are variables affecting the determination of the power split between the internal combustion engine and the electric motor (Kheir *et al.*, 2004). In general, there are two basic hybrid electric designs: parallel and series, classically used to categorize HEVs (Duoba *et al.*, 2001), which have different hybrid powertrain configurations. In the series-parallel hybrid, the features of series and parallel hybrids are incorporated in the powertrain configuration. An electric motor for the parallel HEV assists vehicle propulsion and acts as a generator to recapture energy during decelerations and to provide power for the auxiliary systems. In the series hybrid, engine mechanical output is first converted into electricity using a generator. The converted electricity either charges the battery or can bypass the battery to propel the wheels via the same electric motor and mechanical transmission (Chau *et al.*, 2002). The series-parallel Toyota Prius has a dual-mode hybrid and a planetary gear set allowing for the engine and electric motor to synergistically drive the wheels or the electric motor to individually drive the wheels (Kelly *et al.*, 2001). For the parallel Honda Insight, engine is off only during slow speed decelerations and vehicle stops. However, the series hybrid vehicle engine is off at many situations, including electric start and decelerations (Kelly *et al.*, 2001). For the series-parallel hybrid control, during startup and driving at light load, the electric motor propels the vehicle, while the engine is off operation; during full throttle acceleration and normal driving, both the engine and electric motor work together to propel the vehicle (Chau *et al.*, 2002). The U.S. National Renewable Energy Laboratory developed an Advanced Vehicles Simulator (ADVISOR) to analyze the performance and fuel economy for HEVs (Kelly *et al.*, 2001, Senger *et al.*, 1998). The ADVISOR can also evaluate the effect of parameter changes on vehicle performance, fuel economy and emissions.

Many institutes such as Argonne National Laboratory, National Renewable Energy Laboratory and the U.S. Environmental Protection Agency (EPA), measured emissions from the HEVs using standardized dynamometer tests (Kelly *et al.*, 2001, Duoba *et al.*, 2000, Nam *et al.*, 2005). For instance, the U.S. EPA has carried out an in-use vehicle emissions compliance program in which two hybrid vehicles were tested (Nam *et al.*, 2005). However, few studies quantified engine activities and emissions characterized under various driving conditions, especially in real-world traffic conditions. In practice, there is a need to develop emission factors for the HEVs in order to evaluate emissions impacts on air quality along with their increasing market penetration in the vehicle fleet.

Thus, the specific objectives of this research are to: (1) quantify engine on/off operation rules and then develop modal emissions model for a selected HEV under hot stabilized conditions; and (2) apply engine rules and emissions model to characterize vehicle activities and predict emissions during selected standard driving cycles and real-world traffic conditions for the HEVs.

DATABASE

Modal emissions model for hybrid electric vehicles are developed using second-by-second dynamometer test database that were provided by EPA. Dynamometer test data were collected via multiple 4-bag Federal Test Procedure (FTP) test cycles in EPA-Office of Transportation and Air Quality (OTAQ)'s in-use emissions surveillance program (Nam *et al.*, 2005). In-use test vehicle is 2001 Toyota Prius that has 1.5 liter gasoline engine and a series-parallel hybrid configuration. Tests showed that there was large test-to-test variability in emissions. However, vehicles functioned properly and met emissions standard. Four independent test cycles were used in the study, in which three cycle data were used as the calibration dataset and one cycle data used for validating vehicle engine operation rules and emissions model. Vehicle activity data in the hot-stabilized conditions were identified in term of exhaust temperatures for engine operation rules exploration and in-use emissions model development. Dynamometer test recorded gasoline engine RPM, vehicle speed, exhaust temperature, pollutant emissions of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO) and hydrocarbon (HC), and so on.

Gasoline engine on/off operation rules and emissions model are applied to standard driving cycles such as FTP-75 and NYCC, and second-by-second link speed profiles measured in real-world traffic conditions on the major arterials using Portable Emissions Measurement System (PEMS) from the previous project (Frey *et al.*, 2001) for emissions predictions. Two levels of speed profiles were selected for use on the same link. The mean speed ranges of these speed profiles are individually 10-20 km/h and 30-40 km/h. There were ten speed profiles measured in the major arterial for each level of speed ranges.

METHODOLOGY

The methodology employed in this study consists of: (a) identifying vehicle engine on/off operation rules; (b) developing a microscopic VSP-based modal emissions model based on high resolution dynamometer test data; and (c) applying engine operation rules and emissions model to predict emissions for selected driving cycles.

Classification and Regression Tree to Identify Engine On/Off Operation Rules

The HEVs use internal combustion engines with emissions-free electric motor to achieve fuel economy and emissions reductions. The HEVs have the potential to operate completely in "electric only" or “engine-off” mode, in which the vehicle can operate without any emissions. Therefore, it is necessary to identify when gasoline engine is on or off operation before emissions model is developed for the HEVs. Engine operating strategy relies on vehicle driving conditions (Kelly *et al.*, 2001). For example, in idling and deceleration conditions, engine may be shut down.

Classification and regression tree (CART) is a nonparametric and nonlinear technique (Breiman *et al.*, 1984). CART produces accurate predictions or predicted classifications based on few logical if-then conditions, which is very simple to interpret the underlying relationships between the predictor variables and the dependent variable.

Engine speed can be an indictor of engine on or off operation. Typically a modern vehicle runs with the engine speed from 1800RPM to 2400 RPM at full throttle (Heywood, *et al.*, 1988), and engine speed is more than 500 RPM even during the idling (Zhang, 2006). Therefore, the RPM value of 500 is a critical value to judge when the engine is on or off operation. Engine speed is used as a dependent variable in CART. Exploratory correlation analysis can help identify key variables affecting engine operation rules as predictors of CART. The purpose of tree-building is to determine a set of if-then logical conditions that accurately predict engine operation rules for the HEVs under various complicated driving conditions. In principal, tree splitting could continue until all cases are perfectly classified or predicted. However, this would not make much sense. In fact, the way to control splitting is to allow splitting to continue until the average RPM values with 95 percentage confidence intervals of all terminal nodes are significantly different from 500 because the engine can be considered being off-operation when engine RPM is less than that value.

VSP-based Modeling Approach

Vehicle specific power (VSP) has been identified as a useful exploratory variable for emissions, which takes into account aerodynamic drag, tire rolling resistance and road grade (Jiménez-Palacios, 1999). Based on coefficient values for a generic light duty vehicle, VSP is calculated using the following equation (Frey *et al.*, 2002, Frey *et al.*, 2006):

$$VSP = \mathrm{v} \times [1.1 \times a + 9.81 \times (\sin(\mathrm{atan}(\theta))) + \varphi] + \zeta \times \mathrm{v}^3 \quad (1)$$

Where:

a = acceleration (m/s^2);

θ = road grade;

φ = rolling resistance term coefficient (0.132 m/s^2);

ζ = drag term coefficient (0.000302 m^{-1});

v = vehicle speed (m/s);

VSP = vehicle specific power (m^2/s^3).

Fourteen discrete VSP modes were defined for light-duty gasoline vehicles (LDGVs) in a previous study (Frey *et al.*, 2002). For LDGVs, the idling mode lies inside VSP Mode 3. However, no emissions are produced for the HEVs under the idling driving mode. The HEVs use the same VSP modes definition as LDGVs except for Mode 3 from which the idling mode is extracted as another independent VSP mode. So, there are 15 VSP modes defined for HEVs. Using the second-by-second speed profiles, acceleration and road grade, VSP was computed from Equation (1) and then categorized into VSP modes. Thus, modal average emission rates for HEVs were estimated using the dynamometer database. Such a VSP-based modal approach was assessed as a method for modeling emissions for the HEVs.

For a driving cycle, total cycle emissions are the product of modal average emission rates multiplied by time spent in corresponding VSP mode while the engine is simultaneously on operation, summed over all modes.

Engine on/off operation rules are first evaluated by using the validation dataset. These rules are applied to the driving cycle in the validation dataset for recognizing engine operation status. Cycle emissions are then estimated by HEVs' modal emissions model and then compared with the measured emissions for model capacity assessment.

Application to Predict Emissions of Real-world Speed Profiles and Driving Cycles

The EPA's FTP-75 driving cycle is used for emission certification of light duty vehicles and has three segments: cold start phase, transient phase and hot start phase. The EPA's NYCC driving cycle is developed for chassis dynamometer testing of light-duty vehicles, which simulates low speed urban driving with frequent stops. Engine on/off operation rules and emissions model are applied to standard driving cycles including the FTP-75 and NYCC for predicting emissions from these cycles. In addition, two levels of speed profiles measured in the real-world traffic conditions were also investigated in order to reflect emissions of hybrid electric vehicles in the real world.

The continuous estimates of VSP values for driving cycles and speed profiles were grouped into discrete modes. Time distributions of VSP modes featured by engine on/off operation were determined for a given driving cycle or link speed profile. As shown in Equation (2), emissions for a driving cycle or a speed profile are estimated as the product of modal average emission rates multiplied by the fraction of time spent in the corresponding VSP mode while the engine is on, summed over all modes.

$$E_j = \sum_{i=1} \left\{ \frac{t_{i,j}}{T_j} \times ER_i \right\} \tag{2}$$

$$\overline{E} = \frac{1}{J} \sum_{j=1}^{J} E_j \tag{3}$$

Where:

E_j = average emission rate for speed profile or driving cycle *j* (g/s);

$\overline{E}$ = average emission rate for a given mean speed (g/s);

ER_i = VSP modal average emission rate (g/s);

i = mode index;

j = speed profile or driving cycle index;

J = number of the speed profiles or driving cycles with the close mean speed;

$t_{i,j}$ = time spent in VSP mode *i* for speed profile or driving cycle *j*, while the engine is on;

T_j = total travel time for speed profile or driving cycle *j* (sec).

RESULTS AND DISCUSSION

Engine on/off operation rules were identified for hybrid electric vehicle. Modal emissions models were then developed and validated. Engine rules and emissions models were subsequently applied to predict emissions for standard driving cycles and selected speed profiles measured in real-world traffic conditions.

Engine On/Off Operation Rules

Vehicle speed and acceleration determine driving modes. Exploratory analysis was carried out based upon calibration dataset using Spearman rank correlation. The coefficients were 0.42 and 0.32 for acceleration and speed, respectively with engine RPM, which showed that vehicle speed and acceleration were variables affecting engine control strategies. Therefore, speed and acceleration were used as predictors in CART to predict engine RPM. As shown in Figure 1, engine operation patterns were identified under various driving conditions. Engine rules for off operation are summarized in Table 1. The engine is found to be off operation only under threshold conditions of engine power demand that are speed and acceleration dependent. In general, the engine is shut down in the idling mode and startup, and in the deceleration and cruise modes, the engine may also be off operation, especially for low vehicle speed, which implies that in the environmental perspective, the HEVs are optimal for the congested areas as no tailpipe emissions may be produced. The prediction of engine on or off operation based on validation dataset showed that the engine spent 60.8% of total driving cycle time in the off-operation, which was much close to 59.5% of the observation, which indicated that engine on/off rules were well identified for this type of the HEV.

VSP Modes and Modal Average Emission Rates Estimates

The driving patterns for the HEV were modeled based on the joint distribution of time spent in each VSP modes and engine on/off operations. Modal average emission rates were estimated based upon the calibration dataset while the engine was on operation and are shown in Figure 2. Due to the limitation of sample sizes, no data were available for VSP Modes 12-14. In general, modal average emission rates increased with the VSP mode. However, modal average emission rates of NO_x and HC associated with higher modes were not significantly different from each other. There were no data regarding how much power drawn from the engine versus the battery are available, which may account for some inconsistent trends at high VSP. There were larger uncertainties in modal average emission values associated with VSP Mode 11 for all pollutants as only 5 second-by-second samples were available. For HC and NO_x, modal average emission rates had larger confidence intervals, especially for higher VSP modes, mainly because of large inter-test cycle variability in HC and NO_x emissions.

Modal average emission rates for LDGVs were estimated based on a number of vehicles in the previous study (Frey *et al.*, 2002). Modal average emission rates of a HEV were compared with those of LDGVs. Ratios of modal average emission rates for HEV versus LDGV are given in Table 2. The HEV has much lower emission rates than LDGVs for a given mode, especially for NO_x and HC emissions. This implies that pollution may become less if the HEVs substitute the LDGVs. However, only one HEV is used to make a comparison with LDGVs. There is a need for more data for a larger number of HEVs to further evaluate the potentials of their emissions reductions.

Engine rules and emissions model were evaluated based upon the validation dataset. Engine on/off operations for dataset driving cycle were identified by following rules shown in Figure 1 based upon speed and acceleration. Meanwhile, VSP values and time distribution of VSP modes were calculated. As shown in Table 3, the predictions of the joint distributions of time spent in each VSP modes and engine on/off operations well agree with the observations. Overall estimate absolute errors are less than 2% for the prediction of engine on/off operation status, which demonstrates that these rules identified through CART can represent engine actual operation status. Total emissions for the driving cycle were estimated using modal emissions models. Predicted CO_2 emissions for the selected driving cycle agree closely with the measured emissions. The predicted cycle emissions of CO, NO_x and HC are subject to large relative errors, but are small on an absolute basis compared to conventional gasoline vehicle emissions. Large inter-test cycle variability in emissions, especially for HC and NO_x, is the main source of emissions prediction error.

Emissions Predictions for Standard Driving Cycles and Real-world Speed Profiles

As shown in Table 5, cycle or link mean speeds are close between the NYCC and real-world speed profiles group A, and for the FTP-75 driving cycle with real-world speed profile group B. Before emissions estimation, engine operation rules were used to identify instantaneous engine operation status of standard driving cycles and link speed profiles. Based upon second-by-second speed profiles and acceleration, and road grade for real-world driving cycles, VSP values were calculated, and time spent in each VSP mode for each driving cycle and speed profile was determined. So, joint time distributions of VSP modes and engine-on operations were determined for these cycles and speed profiles and are shown in Figure 3. Using the Equation (2), cycle or link average emissions were estimated for each cycle and speed profile. Since no data were available for VSP Mode 12-14, average emissions rates of VSP Mode 11 was regarded as modal emission rates for VSP Mode 12-14. As shown in Figure 3, less time was spent in VSP Mode 12 up to 14. So, this assumption could not result in big estimate errors. As shown in Table 3, average emissions for all selected pollutants were sensitive to cycle or link mean speeds. For a given mean speed level, emissions from real-world speed profiles were somewhat higher than from standard driving cycles as more time spent in the higher VSP modes would produce more emissions. For example, real-world speed profiles group B had more percentage of time spent in Mode 8 up to 14 than the FTP-75 driving cycle, which explained the reasons of high emissions associated with real-world speed profiles.

Similar to NYCC cycle, deceleration and idling driving modes for congested urban areas often happen. Time spent in lower VSP modes becomes much more, meanwhile the engine is off operation. In this situation, less tailpipe emissions are generated, which would be very beneficial to urban environment.

IMPLICATION AND RECOMMENDATIONS

The engine is off operation during the idling and startup. The engine may be shut down and the electric motor only propels hybrid vehicle during the deceleration and cruise, especially in the conditions of low vehicle speeds and light load, which rely on vehicle speed and acceleration. For an urban area, the engine may be frequently shut-down because of congested level of service and traffic signal control. Therefore, the use of the HEVs in these areas is helpful to reduce emissions and improve air quality.

Comparisons of modal average emission rates between the HEV and conventional gasoline vehicles imply that the use of the hybrid vehicles can significantly reduce vehicle tailpipe emissions. However, there are needs for more HEVs for this comparison.

Emissions from the HEV were predicted under real-world traffic conditions using engine rules and VSP modal emissions model. Average emissions characterized by link mean speed are recommended to be used as emission factors for the HEV in emission inventory estimation.

Although emissions in real-world traffic conditions are predicted in this study, no actual emissions data are available. In addition, road grade such as uphill and downhill may affect engine operation for the HEVs in the real-world traffic conditions, which are not included in the classification and regression tree. Engine and emissions modeling are recommended for further application as more data for a large number of HEVs are available, particularly in real-world traffic conditions.

When the engine is on operation, the power may be provided together by both the gasoline engine and electric motor to propel vehicle, or by the gasoline engine alone. Data regarding battery charging and discharging, and use of the electric motor, are needed in order to develop an improved model. Therefore, additional variables need o be measured for the purpose of modeling, in which the battery state of charge (SOC) measurement may be necessary for emissions adjustments as the use of the internal combustion engine and electric motor depend on battery SOC.

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SUPPORTING INFORMATION AVAILABLE

Text and figures pertaining to inter-test variability in the VSP modal emission rates, real-world link speed profiles and standard driving cycles.

REFERENCES

Breiman, L., J. Friedman, C.J. Stone and R.A. Olshen (1984), Classification and Regression trees, Wadsworth, Belmont, CA.

Chau, K.T. and Y.S. Wong (2002), "Overview of Power Management in Hybrid Electric Vehicles," *Energy Conversion and Management*, 43(15): 1953-1968.

Duoba, M., J. Anderson and H. Ng (2000), "Issues in Emissions Testing of Hybrid Electric Vehicles", Proceedings of the 2000 Global Powertrain Congress, Detroit, MI, June.

Duoba, M., H. Ng and R. Larsen (2001), "Characterization and Comparison of Two Hybrid Electric Vehicles (HEVs) – Honda Insight and Toyota Prius," Paper 2001-01-1335, Society of Automotive Engineers 2001 World Congress, Detroit, Michigan, March 5-8.

Frey, H.C., N.M. Rouphail, A. Unal and J. Colyar (2001), "Emissions Reduction through Better Traffic Management: An Empirical Evaluation Based Upon On-Road Measurements," Report FHWY/NC/2002-001, Prepared by North Carolina State University for North Carolina Department of Transportation, 2001.

Frey, H.C., A. Unal, J. Chen, S. Li and C. Xuan (2002), "Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle & Equipment Emission System," EPA420-R-02-027, Prepared by North Carolina State University for U.S. Environmental Protection Agency, Ann Arbor, MI. August.

Frey, H.C., N.M. Rouphail and H. Zhai (2006), "Speed- and Facility-Specific Emission Estimates for On-Road Light-Duty Vehicles on the Basis of Real-World Speed Profiles," *Transportation Research Record: Journal of the Transportation Research Board*, 1987: 128-137.

Heywood, J.B. (1988), Internal Combustion Engine Fundamentals, McGraw-Hill:New York.

Jiménez-Palacios, J.(1999), "Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing," PhD Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1999.

Johnson, V.H., K.B. Wipke and D.J. Rausen (2000), "HEV Control Strategy for Real-Time Optimization of Fuel Economy and Emissions," Paper 2000-01-1543, 2000 Society of Automotive Engineers, Future Car Congress, Crystal City, VA, April.

Kelly, K.J. and A. Rajagopalan(2001), "Benchmarking of OEM Hybrid Electric Vehicles at NREL," NREL/TP-540-31086, National Renewable Energy Laboratory, August.

Kelly, K.J., M. Zolot, G. Glinsky and A. Hieronymus (2001), "Test Results and Modeling of the Honda Insight Using ADVISOR," NREL/CP-540-31085, National Renewable Energy Laboratory, August.

Kheir, N.A., M.A. Salman and N. J. Schout (2004), "Emissions and Fuel Economy Trade-off for Hybrid Vehicles Using Fuzzy Logic," *Mathematics and Computers in Simulation*, 66(2-3):155-172.

Nam, E.K. and A. Mitcham (2005), "Dynamometer and On-board Emissions Testing of the Honda Insight and Toyota Prius," Paper 2005-01-0681, Society of Automotive Engineers 2005 World Congress & Exhibition, Detroit, MI, April.

Senger, R.D., M.A. Merkle and D.J. Nelson (1998), "Validation of ADVISOR as A Simulation Tool for A Series Hybrid Electric Vehicle," Society of Automotive Engineers Special Publications, *Technology for Electric and Hybrid Vehicles*, 1331:95-115.

Weinstock, I.B.(2002), "Recent Advances in the US Department of Energy' Energy Storage Technology Research and Development Programs for Hybrid Electric and Electric Vehicles," *Journal of Power Sources*, 110(2): 471-474.

Zhang, K. (2006), “Microscale On-Road Vehicle-Specific Emissions Measurement and Modeling,” PhD Dissertation, Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC.

List of Tables and Figures

Table 1. Summary of Series-Parallel Hybrid Vehicle Engine-off Rules

Driving Condition	Speed (mph)	Acceleration (mph/s)	Threshold Power [a] (mph ^{2}/s)
1	0.0- 9.1	a<2.5	22.8
2	9.1-18.4	a<0.7	12.9
3	18.4-36.0	a<0.1	3.6
4	36.0-40.5	a<-0.1	-4.1

[a] Power is the product of speed and acceleration.

Table 2. Ratios of Modal Average Emission Rates for HEV versus LDGV [a]

VSP Mode	VSP Range (m^2/s^3)	CO_2	CO	NO_x	HC
1	VSP<-2	0.30	0.07	0.02	0.05
2	$-2 \leq$ VSP<0	0.39	0.26	0.03	0.05
3[b]	$0 \leq$ VSP<1	0.76	0.34	0.07	0.07
4	$1 \leq$ VSP<4	0.45	0.28	0.02	0.08
5	$4 \leq$ VSP<7	0.53	0.34	0.02	0.22
6	$7 \leq$ VSP<10	0.63	0.25	0.03	0.20
7	$10 \leq$ VSP<13	0.69	0.32	0.05	0.20
8	$13 \leq$ VSP<16	0.73	0.16	0.03	0.18
9	$16 \leq$ VSP<19	0.84	0.29	0.02	0.12
10	$19 \leq$ VSP<23	0.86	0.29	0.01	0.08
11	$23 \leq$ VSP<28	0.62	0.13	0.01	0.02

[a] Modal average emission rates for LDGV come from Frey *et al.*, 2002

[b] For hybrid electric vehicle, Mode 3 range is 0<VSP<1.

Table 3. Percentage of Joint Time Distributions of Engine Control and VSP Modes based upon Validation Data From 4-Bag FTP Cycle

VSP Mode	Percentage of Time Distributions of Engine Control and VSP Modes (%)			
	Engine On (RPM $\geq$ 500)		Engine Off (RPM < 500)	
	Observed	Predicted	Observed	Predicted
1	1.6	1.1	14.6	15.2
2	0.6	0.2	9.7	10.1
3 [a]	0.7	0.3	5.1	5.5
4	8.7	7.4	13.3	14.6
5	13.2	14.6	1.5	0.1
6	8.5	8.6	0.1	0.0
7	3.2	3.2	0.0	0.0
8	2.1	2.1	0.0	0.0
9	0.9	0.9	0.0	0.0
10-14[b]	0.6	0.6	0.0	0.0
Idle[c]	0.2	0.2	15.3	15.3
Total	40.5	39.2	59.5	60.8

[a] VSP mode range is $0 < VSP < 1$.
[b] No data available for VSP Modes 12-14.
[c] VSP is equal to zero for the idling mode.

Table 4. Emissions Estimate Using VSP-based Model based upon Validation Data

Type	Total Cycle Emissions (g)			
	CO_2	CO	NO_x	HC
Measurement	1776	2.33	0.087	0.031
Model Estimate	1728	3.72	0.056	0.102
Estimation Error	-2.7%	59.3%	-36.1%	228.5%

Table 5. Predicted Average Emission Rates for Selected Driving Cycles and Real-World Speed Profiles

Speed Profile	Average Speed (km/h)	Average Emission Rates			
		CO_2(g/s)	CO(mg/s)	NO_x(mg/s)	HC(mg/s)
NYCC	11.4	0.66	1.50	0.020	0.035
Real-World A	14.8	0.71	1.59	0.020	0.034
FTP75	34.1	1.17	2.55	0.038	0.065
Real-world B	36.1	1.77	4.12	0.052	0.077

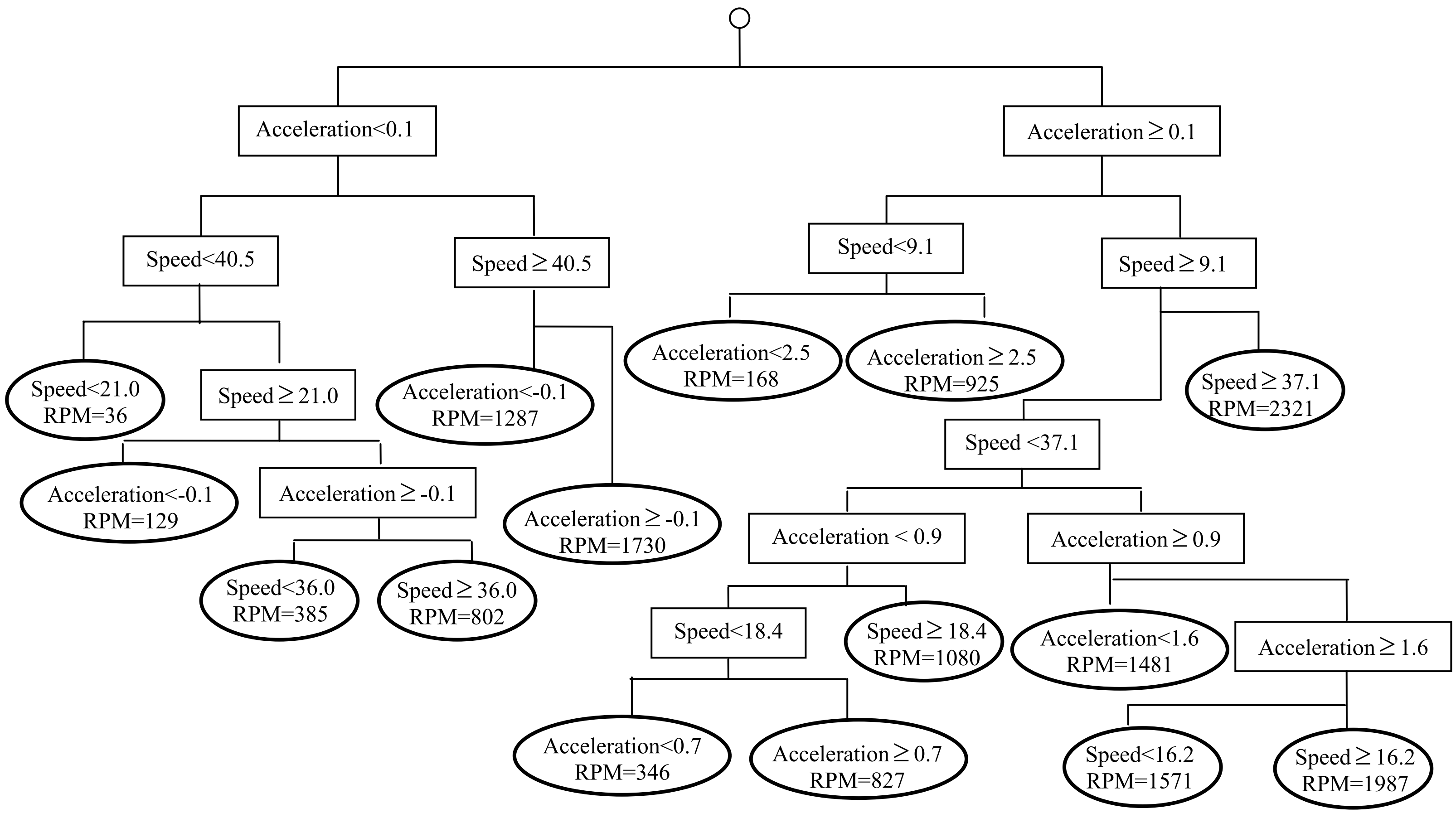


Figure 1. Classification and Regression Tree Modeling for Hybrid Vehicle Engine based upon Dynamometer Tests

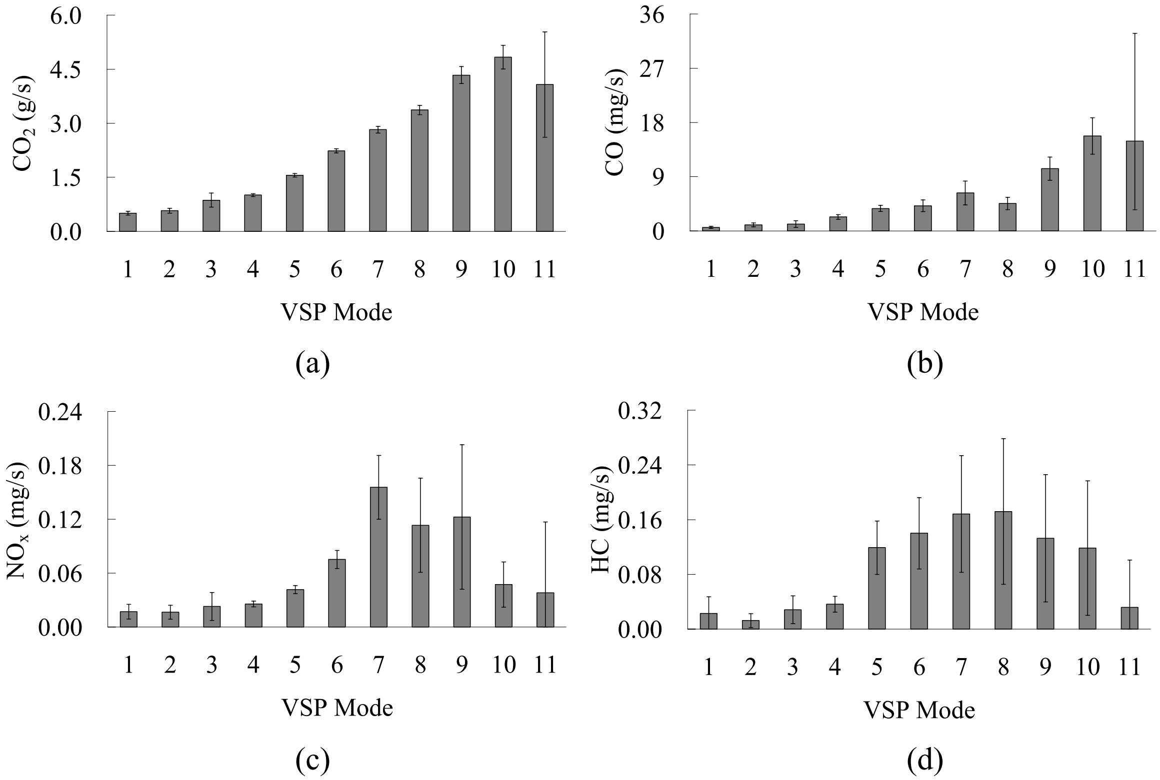


Figure 2. VSP Modal Average Emission Rates of Hybrid Electric Vehicle based upon Dynamometer Tests [a,b]

[a] No data were available for VSP Modes 12-14.

[b] Empirical and parametric bootstrap simulation was applied to estimate the 95% confidence intervals of VSP Mode 11 average emission rates for NO_x and HC, and for CO respectively, which ranged from the 2.5th and 97.5th percentiles of the bootstrap replicates.

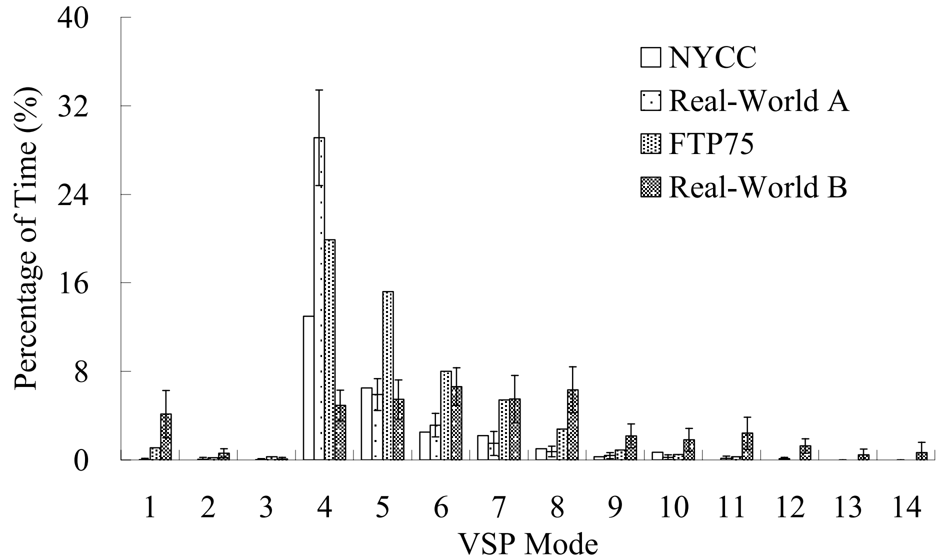


Figure 3. Predicted Percentages of Joint Time Distributions of VSP Modes and Engine On Operation for Selected Driving Cycles and Real-World Speed Profiles

Development of Modal Emissions Model for A Hybrid Electric Vehicle

Supporting Information

Supporting information (SI) provides supplement materials to support the VSP-based emissions model and application. The issues contained in SI are: (1) assessment on inter-test variability in emissions; and (2) real-world link speed profiles and standard driving cycles.

S1. Assessment on Inter-Test Variability in Emissions

Inter-test variability in emissions is evaluated to explore the error source of model emissions estimates. The modal average emission rates were estimated based upon each individual test cycle data to investigate inter-test variability in modal average emissions for all pollutants. As shown in Figure S-1, there is no significant difference for CO_2 emissions among multiple test cycles; For CO emissions, modal emission rates for Test 4 are significantly larger than those of other test cycles for VSP Mode 4 up to 7; For NO emissions, modal emission rates for Test 1 are generally lower than for other tests, especially for VSP Modes 10 and 11. In general, there is a large inter-test variability in modal average emission rates for multiple tests; and for HC emissions, modal emission rates for Test 4 have large uncertainties on the mean. Furthermore, their emission rates associated with VSP Mode 5 up to 8 are significantly huge, compared with other test cycles. In the main paper, Test 3 was used as validation dataset. Table 3 in the main paper shows that there is about 40% of time for engine on-operation, most of which was spent in VSP Mode 4 up to 6 ranging from 7.4% to 14.6%. Larger inter-test variability in emissions of CO, NO and HC associated with those modes is the main source of emissions estimate errors.

S2. Real-world Link Speed Profiles and Standard Driving Cycles

The speed profiles are visualized to get insight into the variation of driving conditions as it directly affects engine operation status. So, second-by-second speeds are plotted out for real-world link speed profiles, and NYCC and FTP-75 driving cycles and shown in Figure S-2. The link has 72.4 km/h (35 mph) speed limit. For speed profiles with low link mean speeds, vehicles frequently stopped for all runs. However, vehicle experienced similar driving modes: deceleration, idling and acceleration for runs with link mean speeds from 30 km/h to 40km/h. Compared with runs with low mean speeds, these runs with high speeds only stopped one time. For standard driving cycles, NYCC has frequent stops. Frequent stop and idling implied that the engine would spend more time on the status of off-operation.

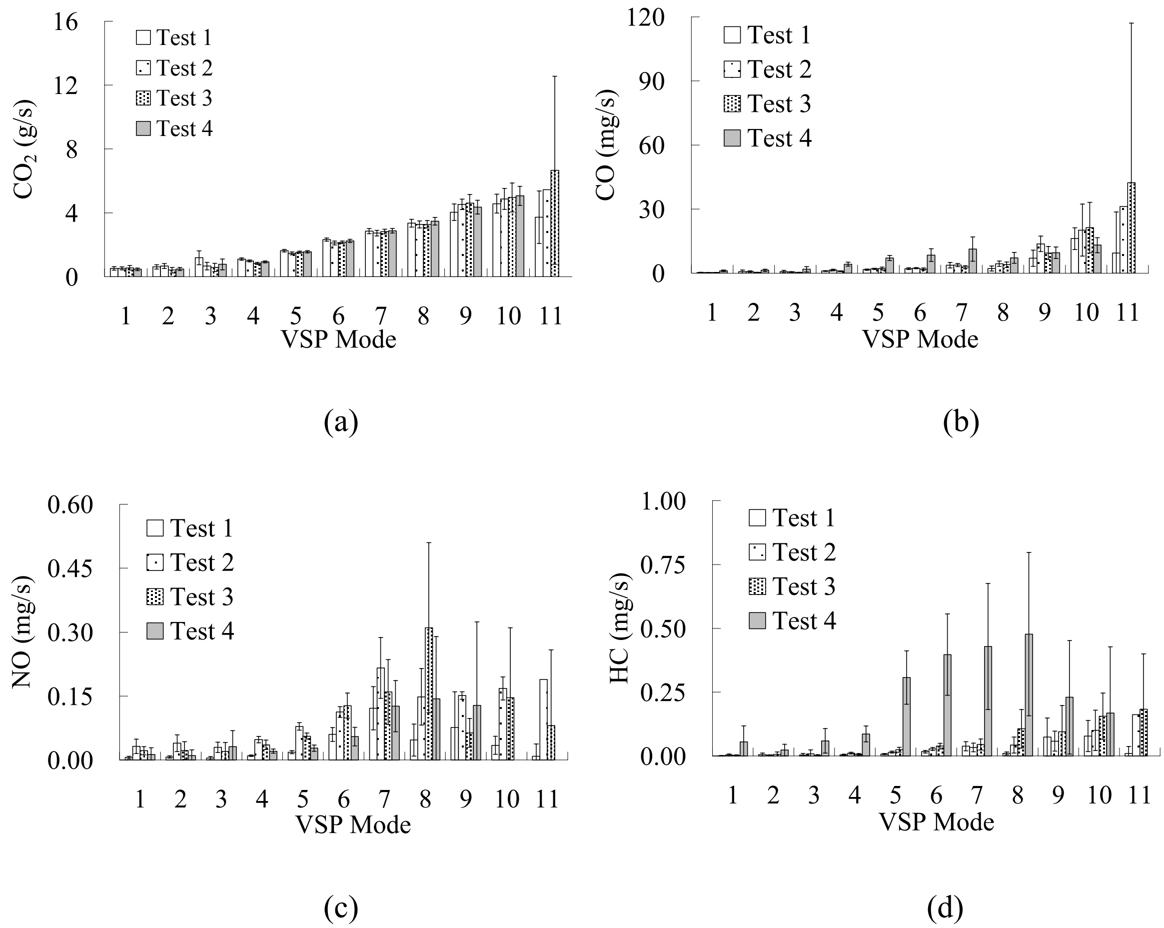
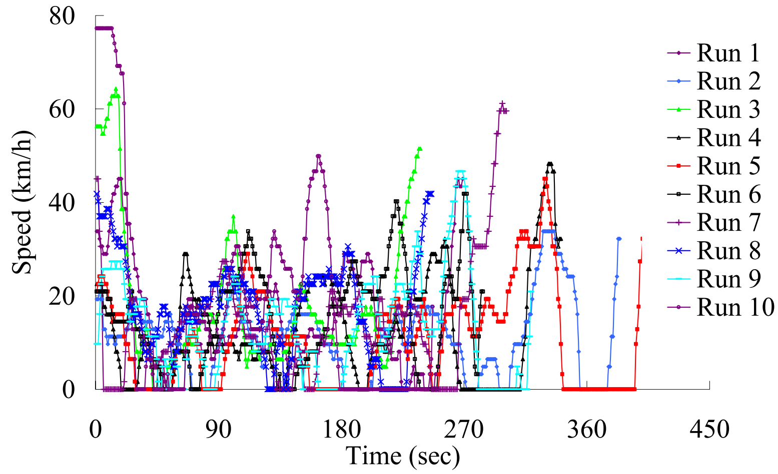
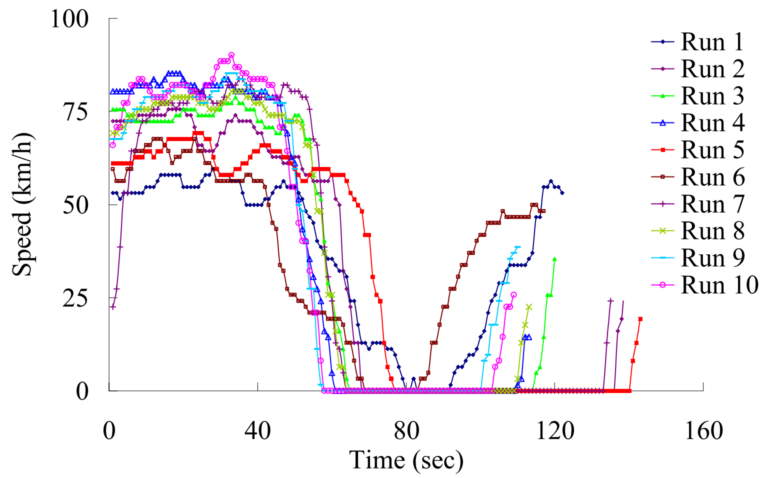


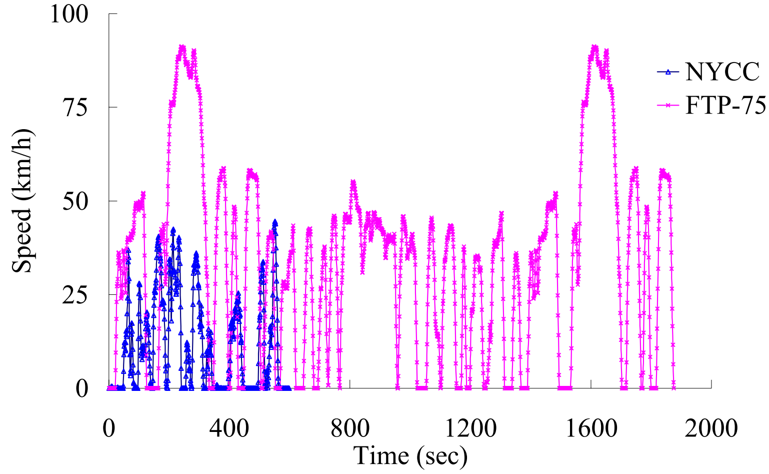
Figure S-1. Inter-Test Variability in Modal Average Emission Rates



(a) Speed Profiles with Link Mean Speeds: 10-20 km/h



(b) Speed Profiles with Link Mean Speeds: 30-40 km/h



(c) Standard Driving Cycles: NYCC and FTP-75

Figure S-2. Real-World Link Speed Profiles and Standard Driving Cycles

Appendix C MATLAB Code for Emission Inventory

```
% Baseline Emission Inventory Estimation
tic
load TDMOutputs
TRANUS(:,:)=TDMOutputs;
% [TRANUS]=xlsread('TranusOuputs', 'DATA');
% Load transportation data file- link level

load BERLDGVStart
load BERLDGVSoakHC
% Load emission factors of start and hot soak emissions for LDGV.

% Emission factors are characterized by vehicle technology, roadway type and link mean speed.

% ----------------------Indictors---------------------------------------
% Indictors to give the position/column in the data matrix "TRANUS" for each parameter of concern.
ID=1;           % Link ID
Dist=2;         % Link Distance (miles)
FinSpeed=5;   % Congested Link Speed (mph)
Operator=7;    % Type of Operators
RoadType=4;  % Type of Link Roadway/ Facility Type
Volume=6;      % Travel Volume for a Given Operator, Number of Vehicles
% ------------------------------------------------------------------

% ------------------ Operator Type -------------------------------------
        % SOV                      -1
        % Carpool                  -2
        % Transit Bus              -3
        % Walk                     -4 Ignore Walk as they are not vehicles
        % Express Bus              -5
        % P&R                      -6 Ignore P&R as they are not vehicles
        % Truck                    -7
% -------------------Roadway Type -------------------------------------
```

```
        % Freeway                 1
        % Arterial                2
        % Local & Collector       3
        % Ramp                    4
        % Connector WTF           5
        % Connector OTF           6
        % Connector other         7
        % P&R Connector           8
        % P&R Artifical           9
        % Connector_WTF           10
        % Connnector_Airport      11
        % Connector UNCC          12
        % Pedestrian              13
        % Arterial Vehicle        14
        % Connector Vehicle       15
        % Connector Vehicle       16
% ----------------------------------------------------------------------
% Emissions Type Included:
%               Running Exhaust Emissions
%               Running Evaporative Loss Emissions of VOC for LDGV
%               Start Emissions for LDGV
% ----------------------------------------------------------------------

% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% To calculate link emissions for each operator on each link
% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
[M,N]=size(TRANUS);
OperatorEmissions=zeros(M,5);
% Link ID, and Emissions of CO2, CO, NOx and HC in order for a given operator
% The first column is record of link ID.
% The columns from the second to the fifth are emissions records.
```

```
LDGVEvapHC=zeros(M,2);
% The first column records link ID.
% The second column is running evaporative emissions of HC.

LDGVSoakHC=zeros(M,2);
% The first column records link ID.
% The second column is hot soak emissions of HC.

for i=1:M
    switch TRANUS(i,Operator)
        case -1  % SOV
            [SOVEmissions, EvapHCLDGV, SoakHCLDGV]
=BaselineSOVHOVEmissions(TRANUS(i,:));
            OperatorEmissions(i,1)=TRANUS(i,ID);
            OperatorEmissions(i,2:5)=SOVEmissions;

            LDGVEvapHC(i,1)=TRANUS(i,ID);   % Running Evaporative HC Emissions
            LDGVEvapHC(i,2)=EvapHCLDGV;

            LDGVSoakHC(i,1)=TRANUS(i,ID);   % Hot Soak Emissions at Link 8 & 9
            LDGVSoakHC(i,1)=SoakHCLDGV;
        case -2  % Carpool
           [CarpoolEmissions, EvapHCLDGV,
SoakHCLDGV]=BaselineSOVHOVEmissions(TRANUS(i,:));
            OperatorEmissions(i,1)=TRANUS(i,ID);
            OperatorEmissions(i,2:5)=CarpoolEmissions;

            LDGVEvapHC(i,1)=TRANUS(i,ID);   % Running Evaporative HC Emissions
            LDGVEvapHC(i,2)=EvapHCLDGV;

            LDGVSoakHC(i,1)=TRANUS(i,ID);   % Hot Soak Emissions at Link 8 & 9
            LDGVSoakHC(i,1)=SoakHCLDGV;
```

```
        case -3  % Transit Bus
           [BusEmissions]=BaselineBUSmissions(TRANUS(i,:));
            OperatorEmissions(i,1)=TRANUS(i,ID);
            OperatorEmissions(i,2:5)=BusEmissions;
            LDGVEvapHC(i,1)=TRANUS(i,ID);
        case -4 % Walk (No emissions)
            OperatorEmissions(i,1)=TRANUS(i,ID);
            LDGVEvapHC(i,1)=TRANUS(i,ID);
        case -5 % Express Bus
           [ExpressBusEmissions]=BaselineBUSmissions(TRANUS(i,:));
            OperatorEmissions(i,1)=TRANUS(i,ID);
            OperatorEmissions(i,2:5)=ExpressBusEmissions;
            LDGVEvapHC(i,1)=TRANUS(i,ID);
        case -6 % P&R (No Emissions)
            OperatorEmissions(i,1)=TRANUS(i,ID);
            LDGVEvapHC(i,1)=TRANUS(i,ID);
        case -7 % Truck
           [TruckEmissions]=BaselineTRUCKEmissions(TRANUS(i,:));
            OperatorEmissions(i,1)=TRANUS(i,ID);
            OperatorEmissions(i,2:5)=TruckEmissions;
            LDGVEvapHC(i,1)=TRANUS(i,ID);
        otherwise
            OperatorEmissions(i,1)=TRANUS(i,ID);
            LDGVEvapHC(i,1)=TRANUS(i,ID);
       end
end

% ~~~~~~~~~ Characterize network emissions by facility type ~~~~~~~~~~
NetworkEmissions=zeros(M,N+4);
NetworkEmissions(:,1:N)=TRANUS;
NetworkEmissions(:,(N+1):(N+4))=OperatorEmissions(:,2:5);
```

```
FreewayEmissions=zeros(1,4);
ArterialEmissions=zeros(1,4);
LocalEmissions=zeros(1,4);
RampEmissions=zeros(1,4);

for i=1:M
   switch NetworkEmissions(i,RoadType)
      case 1
         FreewayEmissions=FreewayEmissions+NetworkEmissions(i,(N+1):(N+4));
      case 2
         ArterialEmissions=ArterialEmissions+NetworkEmissions(i,(N+1):(N+4));
      case 3
         LocalEmissions=LocalEmissions+NetworkEmissions(i,(N+1):(N+4));
      case 4
         RampEmissions=RampEmissions+NetworkEmissions(i,(N+1):(N+4));
   end
end
% ----------------------------------------------------------------------

% ~~~~~~~ Characterize network emissions by operator type ~~~~~~~~~~
CarsEmissions=zeros(1,4);
TrucksEmissions=zeros(1,4);
BusesEmissions=zeros(1,4);

for i=1:M
   switch NetworkEmissions(i,Operator)
      case -1
         CarsEmissions=CarsEmissions+NetworkEmissions(i,(N+1):(N+4));
      case -2
         CarsEmissions=CarsEmissions+NetworkEmissions(i,(N+1):(N+4));
      case -3
         BusesEmissions=BusesEmissions+NetworkEmissions(i,(N+1):(N+4));
```

```
        case -5
          BusesEmissions=BusesEmissions+NetworkEmissions(i,(N+1):(N+4));
        case -7
          TrucksEmissions=TrucksEmissions+NetworkEmissions(i,(N+1):(N+4));
    end
end
% ---------------------------------------------------------------------

% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% To calculate total running tailpipe and evaporative emissions for each link including all operators
% Attention: The coding algorithm to identify all operators on the same
%              link is based on format of TRANSUS output file that all operators
%              on the same link are continuously recorded together in the column.

NumLink=80000;  % Number of links in the networks
LinkEmissions=zeros(NumLink, 5);
LinkLength=zeros(NumLink, 2);
   % The first column records link ID, and 2nd~5th columns record total emissions for each link

LinkEvpHC=zeros(NumLink,1);

j=1;
for i=1:NumLink
        LinkEmissions(i,1)=OperatorEmissions(j,1);   % Tailpipe Emissions
        LinkLength(i,1)=OperatorEmissions(j,1);
        LinkLength(i,2)=TRANUS(j,Dist);                  % record link length

        LinkEvpHC(i)=LDGVEvapHC(j,1);                % Evaporative HC Emissions
         while LinkEmissions(i,1)==OperatorEmissions(j,1) & j< M
              LinkEmissions(i,2:5)=LinkEmissions(i,2:5)+OperatorEmissions(j,2:5);
              LinkEvpHC(i)=LinkEvpHC(i)+LDGVEvapHC(j);
              j=j+1;
```

```
            NumL=i; % To finally record the actual number of links
        end
        if (j==M) & LinkEmissions(i,1)==OperatorEmissions(j,1)
            LinkEmissions(i,2:5)=LinkEmissions(i,2:5)+OperatorEmissions(j,2:5);
            LinkEvpHC(i)=LinkEvpHC(i)+LDGVEvapHC(j);
        end
end
% -------------------------------------------------------------------

% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% To get total running tailpipe emissions for the whole transportation network
%
TotalRunEmissions=zeros(1:4);
TotalRunEmissions=sum(LinkEmissions(1:NumL,2:5));
% or calculate in this way:
RunTotalEmissions=sum(OperatorEmissions(:,2:5));
RunError=TotalRunEmissions-RunTotalEmissions; % Check that, should be zero
% -------------------------------------------------------------------

% ~~~~~~~~~~~~ To get total emission per link length at peak period ~~~~~~
LinkEmissionsPerLength=zeros(NumL,5);

for i=1:NumL
    LinkEmissionsPerLength(i,1)=LinkEmissions(i,1);
    LinkEmissionsPerLength(i,2:5)=LinkEmissions(i,2:5)/LinkLength(i,2)/4;
    % To record emissions per mile and hour at peak hours
end
% --------------------------------------------------------

% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
[TripMatrix]=xlsread('TRIPS', 'Sheet1');
[R,C]=size(TripMatrix);
```

```
% Load zonal trip data file
% Note: 1. This is a square matrix. The diagonal elements represent
%            intrazonal trips; and the off-diagonal elements represent the interzonal trips.
%        2. The first row and the first column record zone IDs.
%        3. TripMatrix(1,1) records the series number of category.
%---------------------------------------------------------------------

% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% To calucalte start emissions for SOV+Carpool /Light-Duty Gasoline Vehicles
% StartEmissions= gram/start* # of trip starts
TripStartHC=zeros(R,C);
TripStartCO=zeros(R,C);
TripStartNOx=zeros(R,C);

TripStartHC(1,:)=TripMatrix(1,:);
TripStartCO(1,:)=TripMatrix(1,:);
TripStartNOx(1,:)=TripMatrix(1,:);
TripStartHC(:,1)=TripMatrix(:,1);
TripStartCO(:,1)=TripMatrix(:,1);
TripStartNOx(:,1)=TripMatrix(:,1);
 % The first row and the first column record zone IDs.

TripStartHC(2:R,2:C)=BERLDGVStart(1)*TripStartHC(2:R,2:C);
TripStartCO(2:R,2:C)=BERLDGVStart(1)*TripStartCO(2:R,2:C);
TripStartNOx(2:R,2:C)=BERLDGVStart(1)*TripStartNOx(2:R,2:C);

% ---------------------------------------------------------------------

% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% To calculate hot soak emissions for SOV+Carpool /Light-Duty Gasoline Vehicles
% Attention: Hot soak emissions come from two type locations: P&R connectors and artificial,
%              and internal zones.
```

```
% HotSoakEmissions=gram/end * # of trip ends

InterZonalTripMatrix(:,:)=TripMatrix;
for i=2:R
   InterZonalTripMatrix(i,i)=0; % Exclude intrazonal trips from Trip Matrix
end
TripSoak=zeros(R,C);
TripSoak(1,:)=TripMatrix(1,:);
TripSoak(:,1)=TripMatrix(:,1);
TripSoak(2:R,2:C)=BERLDGVSoakHC *InterZonalTripMatrix(2:R,2:C);
       % The first row and the first column record zone IDs.

% ---------------------------------------------------------------------

save FreewayEmissions FreewayEmissions -ascii
save ArterialEmissions ArterialEmissions -ascii
save LocalEmissions LocalEmissions -ascii
save RampEmissions RampEmissions -ascii

save CarsEmissions CarsEmissions -ascii
save TrucksEmissions TrucksEmissions -ascii
save BusesEmissions BusesEmissions -ascii

save LinkEmissionsPerLength LinkEmissionsPerLength -ascii

toc
TimeElapsed= toc;
% To give the time spent in running program


% ------------------------------------------------------------------------------------------------------------------------
```

```
function [SOVHOVEmissions,EvapHCLDGV,
SoakHCLDGV]=BaselineSOVHOVEmissionsEmissions(TRANUS);

% Load Emission Factors [g/s]
load BEFLDGVFreeway
load BEFLDGVArterial
load BEFLDGVLocal
load BEFLDGVOnramp
load BEFLDGVOfframp

load BRatioEvapTail
load BERLDGVStart
load BERLDGVSoakHC

SOVHOVEmissions=zeros(4,1);
EvapHCLDGV=0;
SoakHCLDGV=0;
% ----------------------Indictors---------------------------------------
% Indictors to give the position/column in the data matrix "TRANUS" for each parameter of concern.
ID=1;           % Link ID
Dist=2;         % Link Distance (miles)
FinSpeed=5;  % Congested Link Speed (mph)
Operator=7;  % Type of Operators
RoadType=4; % Type of Link Roadway/ Facility Type
Volume=6;     % Travel Volume for a Given Operator, Number of Vehicles
% ---------------------------------------------------------------------

LinkTravelTime=TRANUS(1, Dist)/TRANUS(1, FinSpeed)*3600;  % the unit of [sec]
% -------------------Roadway Type --------------------------------------
        % Freeway                1
        % Arterial               2
        % Local & Collector     3
```

```
     % Ramp              4
% -----------------------------------------------------------------------

% ~~~~~~~~~ To Calculate link emissions for each type of operator for a
% given speed level on a given facility type ~~~~~~~~~~~~~~~~~~~~

 switch TRANUS(1,RoadType)
    case 1  % Freeway
     if (TRANUS(1,FinSpeed) <=(40/1.609) )   % 30-40 km/h
       SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVFreeway(1:4,1);
     end

     if (TRANUS(1,FinSpeed) >(40/1.609) & TRANUS(1,FinSpeed)<= (50/1.609))   % 40-50 km/h
       SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVFreeway(1:4,2);
     end

     if (TRANUS(1,FinSpeed) >(50/1.609) & TRANUS(1,FinSpeed)<= (60/1.609))  % 50-60 km/h
       SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVFreeway(1:4,3);
     end

     if (TRANUS(1,FinSpeed) >(60/1.609) & TRANUS(1,FinSpeed)<= (70/1.609))  % 60-70 km/h
       SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVFreeway(1:4,4);
     end

      if (TRANUS(1,FinSpeed) >(70/1.609) & TRANUS(1,FinSpeed)<= (80/1.609)) % 70-80 km/h
       SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVFreeway(1:4,5);
      end

      if (TRANUS(1,FinSpeed) >(80/1.609) & TRANUS(1,FinSpeed)<= (90/1.609)) % 80-90 km/h
       SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVFreeway(1:4,6);
      end
```

```
  if (TRANUS(1,FinSpeed) >(90/1.609))   % 90-100 km/h
   SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVFreeway(1:4,7);
  end

case 2    % Arterial

  if (TRANUS(1,FinSpeed) <=(20/1.609))    % 10-20 km/h
    SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVArterial(1:4,1);
  end

  if (TRANUS(1,FinSpeed) >(20/1.609) & TRANUS(1,FinSpeed)<= (30/1.609))  % 20-30 km/h
    SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVArterial(1:4,2);
  end

  if (TRANUS(1,FinSpeed) >(30/1.609) & TRANUS(1,FinSpeed)<= (40/1.609))  % 30-40 km/h
    SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVArterial(1:4,3);
  end

  if (TRANUS(1,FinSpeed) >(40/1.609) & TRANUS(1,FinSpeed)<= (50/1.609)) % 40-50km/h
    SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVArterial(1:4,4);
  end

  if (TRANUS(1,FinSpeed) >=(50/1.609))      % >50 km/h
    SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVArterial(1:4,5);
  end

case 3 % Local & Collector  3

  if (TRANUS(1,FinSpeed) <=(20/1.609))     % 10-20 km/h
    SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVLocal(1:4,1);
  end
```

```
    if (TRANUS(1,FinSpeed) >(20/1.609) & TRANUS(1,FinSpeed)<= (30/1.609)) % 20-30 km/h
      SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVLocal(1:4,2);
    end

    if (TRANUS(1,FinSpeed) >(30/1.609) & TRANUS(1,FinSpeed)<= (40/1.609))  % 30-40 km/h
      SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVLocal(1:4,3);
    end

    if (TRANUS(1,FinSpeed) >(40/1.609) & TRANUS(1,FinSpeed)<= (50/1.609))   % 40-50km/h
      SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVLocal(1:4,4);
    end

    if (TRANUS(1,FinSpeed) >=(50/1.609))    % >50 km/h
      SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*BEFLDGVLocal(1:4,5);
    end

  case 4  % Ramp
      % Average Emission Rates of On- and Off- Ramp BERs as Emission Factors for Ramps

SOVHOVEmissions(1:4)=LinkTravelTime*TRANUS(1,Volume)*(BEFLDGVOnramp(1:4)+BEFL
DGVOfframp(1:4))/2;
 end
  % ---------------------------------------------------------------------------

%~~~~~~~~ Running Evaporative Emissions for LDGVs~~~~~~~~~~~~~~
x=TRANUS(1,FinSpeed);
switch TRANUS(1,RoadType)
  case 1 % Freeway
       EvapHCLDGV=SOVHOVEmissions(1)*(2.37e-4*x^2-3.05e-2*x+1.21);
  case 2 % Arterial
       EvapHCLDGV=SOVHOVEmissions(1)*(2.40e-4*x^2-3.26e-2*x+1.31);
  case 3  % Local Roadway
```

```
        EvapHCLDGV=SOVHOVEmissions(1)*(2.40e-4*x^2-3.26e-2*x+1.31);
    case 4  % Ramp
        EvapHCLDGV=SOVHOVEmissions(1)*BRatioEvapTail(4);
end

% ~~~~~~~~~~ Hot Soak Emissions at P&R Connector and Artifical ~~~~~~~~
  switch TRANUS(1,RoadType)
    case 8 %
        SoakHCLDGV=TRANUS(1,Volume)*BERLDGVSoakHC;
    case 9 %
        SoakHCLDGV=TRANUS(1,Volume)*BERLDGVSoakHC;
  end



% ---------------------------------------------------------------------------------------------------------------------
function [BusEmissions]=BaselineBUSmissions(TRANUS);
load BEFHDDBFreeway
load BEFHDDBArterial
load BEFHDDBLocal
load BEFHDDBRamp

BusEmissions=zeros(4,1);
% ----------------------Indictors---------------------------------------
% Indictors to give the position/column in the data matrix "TRANUS" for each parameter of concern.
ID=1;           % Link ID
Dist=2;         % Link Distance (miles)
FinSpeed=5;  % Congested Link Speed (mph)
Operator=7;   % Type of Operators
RoadType=4; % Type of Link Roadway/ Facility Type
Volume=6;     % Travel Volume for a Given Operator, Number of Vehicles
% ---------------------------------------------------------------------
```

```
LinkTravelTime=TRANUS(1, Dist)/TRANUS(1, FinSpeed)*3600;  % the unit of [sec]

% For diesel transit buses, emission factors are not sensitive to facility type but link mean speed.

% ~~~~~~~~~ To calculate link emissions for each type of operator for a  given speed level on a
%        given facility type ~~~~~~~~~~~~~~~~~~~~~~~~~~~

switch TRANUS(1,RoadType)
   case 1 % Freeway
      %  ATTENTION: no emission rates estimates based on PEMS are available
      %                       for diesel buses on freeways. Speed correction factor
      %                       equations in MOBILE5&6 are applied to get emission
      %                       factors for diesel buses on freeways.

        RatioTo20mph=TRANUS(1,FinSpeed)/20; % <ATTENTION>
        BEFHDDBFreeway(1)=BEFHDDBFreeway(1)*RatioTo20mph*exp(0.924-
0.055*(20*RatioTo20mph)+0.00044*(20*RatioTo20mph)^2);
        BEFHDDBFreeway(2)=BEFHDDBFreeway(2)*RatioTo20mph*exp(1.396-
0.088*(20*RatioTo20mph)+0.00091*(20*RatioTo20mph)^2);
        BEFHDDBFreeway(3)=BEFHDDBFreeway(3)*RatioTo20mph*exp(0.676-
0.048*(20*RatioTo20mph)+0.00071*(20*RatioTo20mph)^2);
        BEFHDDBFreeway(4)=BEFHDDBFreeway(4);

        BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBFreeway(1:3);
        BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBFreeway(4);

   case 2 % Arterial
     if (TRANUS(1,FinSpeed) <=10 )  % 5-10 mph
        BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBArterial(1:3,1);
        BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBArterial(4,1);
     end
```

```
if (TRANUS(1,FinSpeed) >10 & TRANUS(1,FinSpeed)<= 15)    % 10-15 mph
  BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBArterial(1:3,2);
  BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBArterial(4,2);
end

if (TRANUS(1,FinSpeed) >15 & TRANUS(1,FinSpeed)<= 20)
   % 15-20 mph
  BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBArterial(1:3,3);
  BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBArterial(4,3);
end

if (TRANUS(1,FinSpeed) >20 & TRANUS(1,FinSpeed)<= 25)  % 20-25 mph
  BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBArterial(1:3,4);
  BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBArterial(4,4);
end

if (TRANUS(1,FinSpeed) >25 & TRANUS(1,FinSpeed)<= 30)    % 25-30 mph
  BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBArterial(1:3,5);
  BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBArterial(4,5);
end

if (TRANUS(1,FinSpeed) >30 & TRANUS(1,FinSpeed)<= 35)  % 30-35 mph
  BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBArterial(1:3,6);
  BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBArterial(4,6);
end

if (TRANUS(1,FinSpeed) >35 & TRANUS(1,FinSpeed)<= 40)  % 35-40 mph
  BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBArterial(1:3,7);
  BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBArterial(4,7);
end

if(TRANUS(1,FinSpeed) >40) % mph   EF for 40-45 mph
```

```
    BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBArterial(1:3,8);
    BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBArterial(4,8);
  end

case 3 % Local
  if (TRANUS(1,FinSpeed) <=10 ) % 5-10 mph
    BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBLocal(1:3,1);
    BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBLocal(4,1);
  end

  if (TRANUS(1,FinSpeed) >10 & TRANUS(1,FinSpeed)<= 15)  % 10-15 mph
    BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBLocal(1:3,2);
    BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBLocal(4,2);
  end

  if (TRANUS(1,FinSpeed) >15 & TRANUS(1,FinSpeed)<= 20)  % 15-20 mph
    BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBLocal(1:3,3);
    BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBLocal(4,3);
  end

  if (TRANUS(1,FinSpeed) >20 & TRANUS(1,FinSpeed)<= 25)   % 20-25 mph
    BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBLocal(1:3,4);
    BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBLocal(4,4);
  end

  if (TRANUS(1,FinSpeed) >25 & TRANUS(1,FinSpeed)<= 30)   % 25-30 mph
    BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBLocal(1:3,5);
    BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBLocal(4,5);
  end

  if (TRANUS(1,FinSpeed) >30 & TRANUS(1,FinSpeed)<= 35)   % 30-35 mph
    BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBLocal(1:3,6);
```

```
        BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBLocal(4,6);
      end

      if (TRANUS(1,FinSpeed) >35 & TRANUS(1,FinSpeed)<= 40)  % 35-40 mph
        BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBLocal(1:3,7);
        BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBLocal(4,7);
      end

      if(TRANUS(1,FinSpeed) >40)   % 40-45 mph
        BusEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDBLocal(1:3,8);
        BusEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBLocal(4,8);
      end

    case 4 % Ramp
       % Emission factors from MOBILE6 are used for diesel buses on ramps
       BusEmissions=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDBRamp;
end

% -----------------------------------------------------------------------------------------------------------------
function [TruckEmissions]=BaselineTRUCKEmissions(TRANUS);
load BEFHDDTFreeway
load BEFHDDTArterial
load BEFHDDTLocal
load BEFHDDTRamp
TruckEmissions=zeros(4,1);

% ----------------------Indictors---------------------------------------
% Indictors to give the position/column in the data matrix "TRANUS" for each parameter of concern.
ID=1;             % Link ID
Dist=2;           % Link Distance (miles)
FinSpeed=5;  % Congested Link Speed (mph)
Operator=7;   % Type of Operators
```

```
RoadType=4; % Type of Link Roadway/ Facility Type
Volume=6;    % Travel Volume for a Given Operator, Number of Vehicles
% ------------------------------------------------------------------------

LinkTravelTime=TRANUS(1, Dist)/TRANUS(1, FinSpeed)*3600;  % the unit of [sec]

% ~~~~~~~~~~ To calculate link emissions for each type of operator for a
% given speed level on a given facility type ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

switch TRANUS(1,RoadType)
  case 1 % Freeway
    if (TRANUS(1,FinSpeed) <=15 )    % 10-15 mph
      TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,1);
      TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,1);
    end

    if (TRANUS(1,FinSpeed) >15 & TRANUS(1,FinSpeed)<=20)     % 15-20 mph
      TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,2);
      TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,2);
    end

    if (TRANUS(1,FinSpeed) >20 & TRANUS(1,FinSpeed)<=25)   % 20-25 mph
      TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,3);
      TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,3);
    end

    if (TRANUS(1,FinSpeed) >25 & TRANUS(1,FinSpeed)<=30)   % 25-30 mph
      TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,4);
      TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,4);
    end

    if (TRANUS(1,FinSpeed) >30 & TRANUS(1,FinSpeed)<=35)    % 30-35 mph
```

```
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,5);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,5);
  end

  if (TRANUS(1,FinSpeed) >35 & TRANUS(1,FinSpeed)<=40)    % 35-40 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,6);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,6);
  end

  if (TRANUS(1,FinSpeed) >40 & TRANUS(1,FinSpeed)<=45)   % 40-45 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,7);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,7);
  end

  if (TRANUS(1,FinSpeed) >45 & TRANUS(1,FinSpeed)<=50)  % 45-50 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,8);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,8);
  end

  if (TRANUS(1,FinSpeed) >50 & TRANUS(1,FinSpeed)<=55)  % 50-55 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,9);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,9);
  end

  if (TRANUS(1,FinSpeed) > 55)        % 55-60 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTFreeway(1:3,10);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTFreeway(4,10);
  end

case 2    % Arterial
  if (TRANUS(1,FinSpeed) <=15 )     % 10-15 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTArterial(1:3,1);
```

```
  TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTArterial(4,1);
end

if (TRANUS(1,FinSpeed) >15 & TRANUS(1,FinSpeed)<=20)   % 15-20 mph
  TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTArterial(1:3,2);
  TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTArterial(4,2);
end

if (TRANUS(1,FinSpeed) >20 & TRANUS(1,FinSpeed)<=25)   % 20-25 mph
  TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTArterial(1:3,3);
  TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTArterial(4,3);
end

if (TRANUS(1,FinSpeed) >25 & TRANUS(1,FinSpeed)<=30)  % 25-30 mph
  TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTArterial(1:3,4);
  TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTArterial(4,4);
end

if (TRANUS(1,FinSpeed) >30 & TRANUS(1,FinSpeed)<=35)   % 30-35 mph
  TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTArterial(1:3,5);
  TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTArterial(4,5);
end

if (TRANUS(1,FinSpeed) >35 & TRANUS(1,FinSpeed)<=40)  % 35-40 mph
  TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTArterial(1:3,6);
  TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTArterial(4,6);
end

if (TRANUS(1,FinSpeed) >40 )  % 40-45 mph
  TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTArterial(1:3,7);
  TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTArterial(4,7);
end
```

```
case 3 % Local
  if (TRANUS(1,FinSpeed) <=15 )     % 10-15 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTLocal(1:3,1);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTLocal(4,1);
  end

  if (TRANUS(1,FinSpeed) >15 & TRANUS(1,FinSpeed)<=20)   % 15-20 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTLocal(1:3,2);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTLocal(4,2);
  end

  if (TRANUS(1,FinSpeed) >20 & TRANUS(1,FinSpeed)<=25)   % 20-25 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTLocal(1:3,3);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTLocal(4,3);
  end

  if (TRANUS(1,FinSpeed) >25 & TRANUS(1,FinSpeed)<=30)   % 25-30 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTLocal(1:3,4);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTLocal(4,4);
  end

  if (TRANUS(1,FinSpeed) >30 & TRANUS(1,FinSpeed)<=35)   % 30-35 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTLocal(1:3,5);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTLocal(4,5);
  end

  if (TRANUS(1,FinSpeed) >35 & TRANUS(1,FinSpeed)<=40)   % 35-40 mph
    TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTLocal(1:3,6);
    TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTLocal(4,6);
  end
```

```
    if (TRANUS(1,FinSpeed) >40 )   % 40-45 mph
      TruckEmissions(1:3)=LinkTravelTime*TRANUS(1,Volume)*BEFHDDTLocal(1:3,7);
      TruckEmissions(4)=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTLocal(4,7);
    end

  case 4 % Ramp
      % Emission factors from MOBILE6 are used for diesel trucks on ramps
      TruckEmissions=TRANUS(1,Dist)*TRANUS(1,Volume)*BEFHDDTRamp;

end
```