High Automobile Emissions: Modeling Impacts and Developing Solutions

by

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Abstract

In the last few years, scientific consensus is that emission of greenhouse gases (GHGs) into the atmosphere is contributing to changes in the earth's climate. While uncertainty remains over the pace and dimensions of the change, a consensus on the need for action has grown among the public and elected officials. In part, this shift has been accelerated by concern over energy security and rising fuel prices. The new political landscape has led many cities, states, and regions to institute policies aimed at reducing GHG emissions. These policies and emerging initiatives have significant implications for the transportation planning process. The transportation sector accounts for approximately 27% of GHG production in the U.S. (as of 2003) and while the U.S. accounts for only roughly 5% of the world's population, it is estimated that it produces over 20% of the world's GHG emissions. Note that this does not include "lifecycle" emissions that result from the processes undertaken to extract, manufacture, and transport fuel. Carbon dioxide represents approximately 96% of the transportation sector's radiative forcing effects. Unlike conventional air pollutants, carbon dioxide emissions are directly tied to the amount of fuel consumed and its carbon intensity. Therefore, emissions reductions can be achieved by increasing the use of low-carbon fuels, improving fuel economy, or reducing total vehicle miles of travel – often called the three legged stool. (A fourth leg is congestion reduction, at certain optimal speeds). These same factors are related to our use of imported oil, so actions taken to reduce GHG emissions may actually produce benefits in both policy areas. The climatic risks of additional emissions associated with capacity projects must be balanced against the mobility, safety, and economic needs of a community or region. Consequently, this dissertation attempts to quantify the impacts of high-emitting vehicles on the environment and to propose solutions to enhance the currently-used high-emitting vehicle detection procedures. In addition, fuel consumption and emission models for high-speed vehicles are developed in order to provide more reliable estimates of vehicle emissions and study the impact of vehicle speeds on vehicle emissions.

The dissertation extends the state-of-the-art analysis of high emitting vehicles (HEVs) by quantifying the network-wide environmental impact of HEVs. The literature reports that 7% to 12% of HEVs account for somewhere between 41% to 63% of the total CO emissions, and 10% are responsible for 47% to 65% of HC emissions, and 10% are responsible for 32% of NO_x emissions. These studies, however, are based on spot measurements and do not necessarily reflect network-wide impacts. Consequently, the research presented in this dissertation extends the state-of-knowledge by quantifying HEV contributions on a network level. The study uses microscopic vehicle emission models (CMEM and VT-Micro model) along with pre-defined drive cycles (under the assumption that the composite HEV and VT-LDV3 represent HEVs and NEVs, respectively) in addition to the simulation of two transportation networks (freeway and arterial) to quantify the contributions of HEVs. The study demonstrates that HEVs are responsible for 67% to 87% of HC emissions, 51% to 78% of CO emissions, and 32% to 62% of the NO_X emissions for HEV percentages ranging from 5% to 20%. Additionally, the traffic simulation results demonstrate that 10% of the HEVs are responsible for 50% to 66% of the I-81 HC and 59% to 78% of the Columbia Pike HC emissions, 35% to 67% of the I-81 CO and 38% to 69% of the Columbia Pike CO emissions, and 35% to 44% of the I-81 NO_X and 35% to 60% of the Columbia Pike NO_X emissions depending on the percentage of the normal-emitting LDTs to the total NEVs. HEV emission contributions to total HC and CO emissions appear to be consistent with what is reported in the literature. However,

the contribution of NO_X emissions is greater than what is reported in the literature. The study demonstrates that the contribution of HEVs to the total vehicle emissions is dependent on the type of roadway facility (arterials vs. highways), the background normal vehicle composition, and the composition of HEVs. Consequently, these results are network and roadway specific. Finally, considering that emission control technologies in new vehicles are advancing, the contribution of HEVs will increase given that the background emission contribution will decrease.

Given that HEVs are responsible for a large portion of on-road vehicle emissions, the dissertation proposes solutions to the HEV screening procedures. First, a new approach is proposed for estimating vehicle mass emissions from concentration remote sensing emission measurements using the carbon balance equation in conjunction with either the VT-Micro or PERE fuel consumption rates for the enhancement of current state-of-the-art HEV screening procedures using RSD technology. The study demonstrates that the proposed approach produces reliable mass emission estimates for different vehicle types including sedans, station wagons, full size vans, mini vans, pickup trucks, and SUVs. Second, a procedure is proposed for constructing on-road RS emission standards sensitive to vehicle speed and acceleration levels. The proposed procedure is broadly divided into three sub-processes. In the first process, HE cut points in grams per second are developed as a function of a vehicle's speed and acceleration levels using the VT-Micro and CMEM emission models. Subsequently, the HE cut points in grams per second are converted to concentration emissions cut points in parts per million using the carbon balance equation. Finally, the scale factors are computed using either ASM ETW- and model-year-based standards or engine-displacement-based standards. Given the RS emissions standards, the study demonstrated that the use of on-road RS cut points sensitive to speed and acceleration levels is required in order to enhance the effectiveness of RS.

Finally, the dissertation conducted a study to develop fuel consumption and emissions models for high-speed vehicles to overcome the shortcomings of state-of-practice models. The research effort gathered field data and developed models for the estimation of fuel consumption, CO_2, CO, NO, NO_2, NOx, HC, and PM emissions at high speeds. A total of nine vehicles including three semi-trucks, three pick-up trucks, and three passenger cars were tested on a nine-mile test track in Pecos, Texas. The fuel consumption and emission rates were measured using two portable emission measurement systems. Models were developed using these data producing minimum errors for fuel consumption, CO_2, NO_2, HC, and PM emissions. Alternatively, the NO and NO_x emission models produced the highest errors with a least degree of correlation. Given the models, the study demonstrated that the newly constructed models overcome the shortcomings of the state-of-practice models and can be utilized to evaluate the environmental impacts of high speed driving.

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I dedicate my dissertation to my lovely wife, Bosle Shin, who always understands, believes, and supports me and to my baby, who will be born in December 2008.

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Chapter 1: Introduction

Since the transportation sector is a major contributor to the air pollution problem, various strategies to reduce on-road vehicle emissions in a cost-effective manner have been identified to achieve the national ambient air quality standard (NAAQS). The literature identifies one of the most cost-effective strategies to reduce vehicle emissions as the identification and repairing of high-emitting vehicles (HEVs). HEVs are responsible for a large portion of on-road vehicle emissions. HEVs are vehicles whose emissions of hydrocarbons (HCs), oxides of nitrogen (NO_x) are two and/or carbon monoxide (CO) emissions are three times higher than the certification emissions level *(1)*. Accordingly, high emitting vehicles are considered as big contributors to the national emissions of the Environmental Protection Agency's (EPA) six criteria pollutants, although they comprise only a small fraction of the vehicle fleet. Consequently, significant research and efforts are devoted to screening high emitting vehicles. Most of the states in the U.S. are operating their own inspection and maintenance (IM) programs to identify and repair HEVs. Additionally, supplementary programs such as remote sensing of on-road vehicles' emissions and roadside emission tests are used to enhance the effectiveness of IM programs. Therefore, HEV issues including the use of remote sensing devices should be systematically studied to reduce mobile-source emissions.

Since mobile-source emissions are considered as one of the significant contributors to air pollution, the estimation of mobile-source emissions is critical, especially for on-road vehicles, in order to assess the impact of various transportation activities on the environment *(2)*. Accordingly, the EMPAC model for California and the MOBILE model for other states have been developed for the emission inventory assessment *(2, 3)*. Also, the Comprehensive Modal Emission Model (CMEM) and the VT-Micro fuel consumption and emission models are currently available to assess the impact of vehicle activities on energy use and exhaust emissions at the microscopic level; instantaneous fuel consumption rates and emissions rates at specific engine load conditions *(4, 5)*.

Although each of these vehicle emission models has been constructed using a different framework/structure, they are common in that they are developed based on a database of emissions and vehicle speed measurements. The EMFAC and MOBILE models were constructed from a database of vehicle emission rates at speeds of up to 65 mi/h *(3, 6)*. The CMEM and VT-Micro models were built from a set of emission rates at speeds up to 80 mi/h and 75 mi/h, respectively *(4, 5)*. This limitation of the models in the training data demonstrates the need to develop new vehicle fuel consumption and tailpipe-exhaust emission models for vehicle speeds that exceed 80 mi/h given that this is not uncommon on existing freeways. For example, some sections of I-10 in West Texas have a speed limit of 80 mi/h. Additionally, the state of Texas has a plan to construct high speed corridor systems, whose design criteria is up to speeds of 100 mi/h in or near nonattainment areas. Thus, there is a need for the development of new models.

1.1 Identification of Problem

As the ultimate objective of reducing mobile-source emissions is to secure public health and the environment, a number of questions need to be addressed. These questions include:

1. What is the network-wide contribution of HEVs to air pollution?
2. How can the screening of HEVs be enhanced?
3. How can HEVs be identified in the field using remote sensing cut-points sensitive to vehicle engine loads?
4. How can the impact of high speeds on vehicle emissions be assessed?

In an attempt to answer these questions, numerous research efforts have been conducted, focusing on the studying the impact of HEVs on the environment, methods and technologies to identify

HEVs, the modeling of HEV emissions, and developing models to account for high vehicle speeds on vehicle emissions.

The literature identifies a number of studies that have attempted to answer some of the questions that were raised. For example, some studies concluded that a small fraction of HEVs were responsible for a large fraction of the total mobile-source emissions. One study indicated that 7.8 percent of the fleet are responsible for 50 percent of the total emissions *(7)*. Another study concluded that 5 percent of the vehicles emitted 80 percent of the emissions *(8)*. However, both studies relied on IM240 test data or remote sensing measurements at a single location to derive their conclusions, and thus the results are limited both temporally and spatially. Consequently, there is a need to assess the network-wide environmental impact of HEVs.

Second, many of the states in the U.S. operate their own Inspection and Maintenance (I/M) Program, in order to identify and repair HEVs. In addition, other supplementary devices, such as RSDs (remote sensing devices), are used to identify HEVs. Several states are now using RSDs because they can collect on-road emission data from the in-use vehicle fleet. In this context, there is a need to evaluate the efficiency of remote sensing for the screening of HEVs and to enhance and optimize these screening procedures.

Third, the remote sensing cut points used currently are constant regardless of vehicle engine loads although the vehicle emissions are significantly affected by vehicle speed and acceleration levels. Consequently, remote sensing cut points sensitive to vehicle speed and acceleration levels need to be developed to enhance the effectiveness of remote sensing.

Finally, the current state-of-practice emission modeling tools do not provide reliable emission estimates for vehicle speeds greater than 80 mi/h since the models do not have supporting data at these high speeds. This limitation of the models in the training data demonstrates the need to develop new vehicle fuel consumption and tailpipe-exhaust emission models for vehicle speeds that exceed 80 mi/h given that this is not uncommon on existing freeways. For example, some sections of I-10 in West Texas have the speed limit of 80 mi/h. Additionally, the state of Texas has a plan to construct a high speed corridor system, whose design criteria is speeds up to 100 mi/h in or near nonattainment areas. Thus, there is a need for the development of new models.

1.2 Research objectives

The objectives of this research effort are to:

1. Quantify the network-wide environmental impact of HEVs,
2. Develop robust algorithms for the optimum screening of HEVs,
3. Develop remote sensing cut points sensitive to vehicle speed and acceleration levels, and
4. Construct high speed vehicle fuel consumption and emissions models.

1.3 Dissertation Layout

In achieving the above objectives the dissertation is composed of seven chapters. The first chapter provides an overview of the problem, the research objectives, and an overview of the research approach. The second chapter provides a synthesis of the literature on the topic and identifies research needs that require addressing in a comprehensive manner. The third chapter uses pre-defined drive cycles and traffic simulation to evaluate the network-wide impacts of HEVs along with utilizing vehicle emission models. Specifically, different types and percentages of HEV vehicles are modeled for an arterial and freeway network for differing levels of congestion. The network-wide contribution of HEV vehicle emissions is quantified. The forth chapter introduces the various challenges that need to be addressed in the screening of HEVs. In addition, the chapter introduces proposed solutions to enhance RSD HEV screening. The fifth chapter develops an approach for the identification of HEV cut points. In the sixth chapter, the emission models for high speed vehicles are constructed to provide tools for quantifying the impact of high speed vehicles on the environment and energy since high speed vehicles are another potential big contributor to mobile-source emissions. Finally, chapter seven provides the dissertation conclusions in addition to recommendations for further research.

Chapter 2: Literature Review

In this chapter the literature related to mobile-source emissions are presented for establishing the basis for the proposed research effort. First, a brief introduction to air pollution is presented including the history of various environmental regulations. Second, the literature on automobile emissions is presented followed by a description of automobile emission modeling. Finally, the literature related to high emitting vehicles is presented.

2.1 Introduction to Air Pollution

In this section an introduction to air pollution is presented to provide basic knowledge of the issue. First, the source of air pollution is presented to provide the relationship between source emissions and air pollution. Second, pollutants of interest that are considered to be seriously harmful to human health and the environment are presented. Finally, regulations that have been enacted for air pollution control are introduced.

2.1.1 Source of Air Pollution

Although the sources of air pollution could be defined with respect to their various characteristics, both stationary sources and mobile sources are presented in this review.

Stationary sources are defined as fixed facilities or areas that emit air pollution which are divided more specifically into either point-sources or area-sources as well. Point-sources are facilities that emit greater than 10 tons per year of a criteria pollutant or hazardous pollutant or 25 tons per year of a combination of hazardous pollutants such as power plants, oil refineries, and so on. Alternatively, area-sources are sources emitting less than 10 tons per year of a criteria pollutant or hazardous pollutant or less than 25 tons per year of a mixture of pollutants. Area-sources include smaller emission sources in comparison to point-sources which include commercial buildings, residential buildings, gas stations, dry cleaners, auto body paint shops, etc.

Mobile-sources are classified into either on-road vehicles or non-road vehicles. On-road vehicles include cars, trucks, and buses. Non-road vehicles include ships, airplanes, locomotives, lawn and garden equipment, construction, agricultural, and industrial equipment *(9)*.

In terms of Emissions Contribution at a national level, transportation sector including both on-road and non-road emissions accounts for 82 percent of all carbon monoxide (CO) emissions, 56 percent of all oxides of nitrogen (NO_X) emissions, and 45 percent of all volatile organic compounds (VOC) emissions in 2002, as illustrated in Figure 2.1 *(10)*.

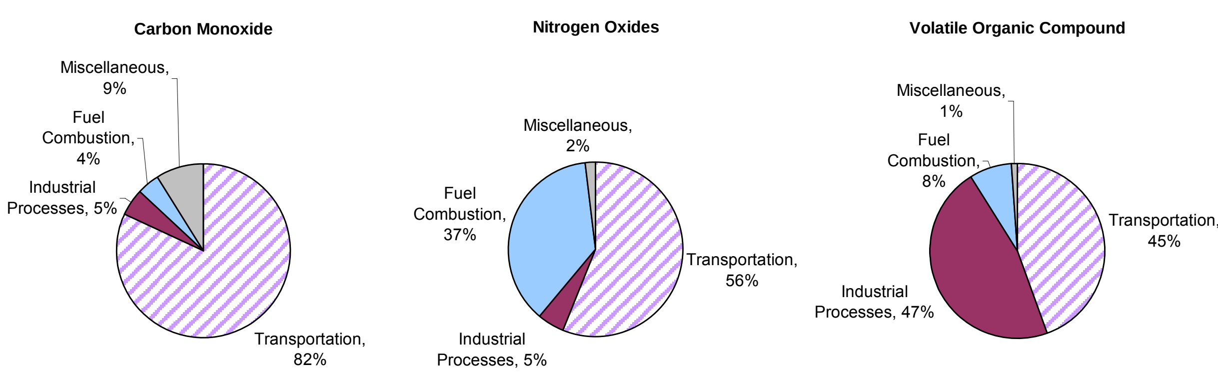


Figure 2.1 Emissions Contributions by source category, 2002

2.1.2 Pollutant of Interest

The most concerned air pollutants are defined as carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, particulate matter, and lead which are called six criteria pollutants. The National Ambient Air Quality Standards (NAAQS) for the six criteria pollutants were promulgated for the determination of attainment. NAAQSs consist of primary standards and secondary standards. The primary standard was designed to protect public health, while the secondary standard was set to secure public welfare.

Carbon monoxide mainly results from incomplete combustion processes due to the lack of oxygen, although it is produced by natural processes as well. Since it interrupts the delivery of oxygen to body tissues, exposure to CO can result in mind symptoms such as disorientation and headache to serious conditions such as coma and death depending on the degree of concentration of CO *(11, 12)*.

Sulfur dioxide primarily results from sulfur in coal. More than 65% of sulfur dioxide emitted to the air comes from electrical utilities from coal fired power plants. Exposure to sulfur dioxide causes respiratory irritation and aggravates existing lung and heart diseases. Additionally, SO_2 causes reduction in visibility since it helps form airborne particles. Finally, SO_2 contributes to the creation of acid rain and the concomitant results may include corrosion of materials, damage of trees and crops, and acidification of soils, and natural water sources *(12, 13)*.

Of the oxides of nitrogen, nitric oxide (NO) and nitrogen dioxide (NO_2) are referred together to as NO_X. Around 50 percent of nitrogen oxides come from the operation of automobiles. Other primary sources include electric utilities, industrial, commercial, and residential fuel uses. NO_X causes respiratory problems and contributes to the formation of ground level ozone, brown haze, and acid rain *(14)*.

Ozone as a criteria pollutant is commonly referred to as ground level ozone which is produced by a chemical reaction between volatile organic compounds, such as hydro carbon, and nitrogen oxides in the presence of sun light. While ground level ozone is harmful to human health causing respiratory problems, ozone in stratosphere is beneficial to the earth by means of blocking the sun's harmful rays *(15)*.

Particulate matter is a combination of enormously small solid and liquid particles floating in the air. The most concerned size of particles is 10 micrometer in diameter or smaller because these particles can be inhaled through the throat and nose and enter the lungs. Specifically, these particles are categorized into two groups, namely; inhalable coarse particles and fine particles. The size of inhalable coarse particles are larger than 2.5 micrometers in diameter and smaller than 10 micrometers in diameter, while the size of fine particles is smaller than 2.5 micrometers in diameter *(16)*. Health problems caused by inhaling these particles may include respiratory irritation and cardiovascular disease since some particles may enter the lungs deeply and/or bloodstream *(17)*. Alternatively, reductions in visibility, environmental damages, and aesthetic damages have been known to be caused by particulate matters.

Lead is a metal defined as a criteria pollutant. The primary sources of lead have been motor vehicles and industrial sources. But more than 50 percent of the total lead emissions comes from metal processing after the phase out of leaded gasoline. Exposure to lead causes anemia, organ damages, brain and nerve damages, and affects animals, plants and fish *(18)*.

Other air pollutants of concern are Hazardous Air Pollutants (HAPs), also known as air toxics, which cause or may cause cancers and/or deadly health problems such as damages to the immune system, neurological, reproductive, developmental, and respiratory problems *(19)*. EPA is required to control 188 HAPs working with state and local governments. The original list of hazardous air pollutants is available at EPA's Technology Transfer Network Air Toxics Web Site *(20)*.

2.1.3 History of Regulation

As mankind has been consuming a tremendous amount of coal since the Industrial Revolution, anthropogenic air pollution has worsened. The incredible increases in automobile use has accelerated the consumption of petroleum fuel as well and concomitant air pollutants have been released into the air. Consequently, air pollution became a more serious problem and a number of disastrous events in history have demonstrated the severity of the problem. For example, in 1873 a total of 268 death toll was reported in London, England. In 1931, 592 deaths were recorded from a nine-day fog in Manchester, England. In 1966, almost 168 deaths were estimated in New York from air pollution. The recognition of seriousness of air pollution derived a need to enact laws which attempt to control human activities that create air pollutants. The following sections briefly address legislation and regulatory efforts related to air quality control in the United States.

In 1955 the Air Pollution Control Act was first enacted by the U.S. Congress. The act began research on air pollution effects and provided technical assistance to the states. In 1960 and 1962 the Air Pollution Control Act was amended which required the Surgeon General to conduct a study assessing the effects of vehicle exhaust emissions on human health. In 1963 the Clean Air Act was enacted to provide federal grants for research and technical assistance to state and local governments. Additionally, it provided for defining air quality criteria. In 1965 the Motor Vehicle Air Pollution Control Act was enacted, which was actually an amendment of the Clean Air Act of 1963, in response to the need for the control of automobile emissions. The act directed the Department of Health, Education, and Welfare to establish automobile emissions standards. In 1967 the Air Quality Act was enacted and provided a structure for the designation of Air Quality Control Regions (AQCRs) within the U.S. based on meteorology, topography, and climate data. In 1970 the Clean Air Act was amended. The act provided National Ambient Air Quality Standards (NAAQSs), New Source Performance Standards (NSPSs), and National Emission Standards for Hazardous Air Pollutants (NESHAPS) and transferred all the administrative authorities and responsibilities to the Environmental Protection Agency (EPA). In 1977 the Clean Air Act was amended and required to review NAAQSs. In 1990 the Clean Air Act Amendments were enacted, which were the most important and practical regulations since the CAAAs of 1970. The amendments consisted of 11 main divisions, which are briefly described in Table 2.1 *(12, 21)*.

Table 2.1 Titles for CAAA of 1990

Title I	Provisions for attainment and maintenance of national ambient air quality standards
Title II	Provisions relating to mobile sources
Title III	Air toxics
Title IV	Acid deposition control
Title V	Permits
Title VI	Stratospheric ozone and global climate protection
Title VII	Provisions relating to enforcement
Other Titles	Provisions relating to research, development and air monitoring
	Provisions to provide additional unemployment benefits
	Provisions to improve visibility

2.2 Automobile Emissions

2.2.1 History of Automobile Emissions Controls

After World War II California was the first state in the U.S. that recognized automobile emission problems and the need to control them. In response to this need, the Los Angeles County Motor Vehicle Pollution Control laboratory was instituted in 1955 and the Motor Vehicle Pollution Control Board was established in 1960. Additionally, the Motor Vehicle Act was federally enacted in 1960 and funded research on automobile emissions. The California Motor Vehicle State Bureau of Air Sanitation mandated Positive Crankcase Ventilation (PCV) to control hydrocarbon emissions in 1961. The Department of

Health, Education, and Welfare was directed to establish automobile emissions standards by the Motor Vehicle Air Pollution Control Act of 1965. In 1966 the California Motor Vehicle Pollution Control Board adopted auto tailpipe emission standards for HC and CO. In 1967 the California Motor Vehicle Pollution Control Board and the Bureau of Air Sanitation were unified into the California Air Resources Board (CARB). In 1970 the Environmental Protection Agency (EPA) was established and initiated a 90 percent reduction in automobile emissions through the Clean Air Act Amendments of 1990. In 1971 CARB adopted auto tailpipe emission standards for NO_X. In 1972 Exhaust Gas Recirculation (EGR) valves came to use to control NO_X emissions. In 1975 the CARB's Motor Vehicle Emission Control Program used the first two-way catalytic converter. In 1976 lead in gasoline was limited by CARB. In 1977 the first three-way catalytic converter was adopted to control HC, NO_X, and CO emissions by Volvo's "Smog-Free" vehicle. In 1983 64 cities in the nation established Inspection and Maintenance (I/M) programs. In 1988 on-board computer systems were required to be installed to 1994 model year vehicles or newer vehicles by CARB. In 1990 the CAAA of 1990 established a series of programs to control automobile emissions. These programs included more stringent standards and test procedures; expansion of I/M programs; new automobile technologies and clean fuel programs; and provisions relating to transportation management. In 2004 the Greenhouse Gas Rule was approved by CARB to require automobile manufacturers to sell vehicles that exhaust less greenhouse gas emissions from model year 2009 *(12, 21)*.

2.2.2 Type of Automobile Emissions

Automobile emissions result from the combustion process and fuel evaporation. Exhaust emissions are the resultants of the combustion process. If gasoline and diesel fuels are perfectly combusted, all hydrocarbons in the fuel are converted into carbon dioxide and water. Since the combustion process, however, is typically not perfect, the hydrocarbons in the fuel are converted to unburned hydrocarbons, nitrogen oxides, carbon monoxide, carbon dioxide and water *(22)*. For the purposes of automobile emissions modeling, the mode of automobile operation is classified into Cold Start, Hot Start, Hot Stabilized, and Idle. The reason for using the classification is that exhaust emissions rates depend on the operating conditions.

Alternatively, evaporative emissions come from the evaporation of fuel. The type of evaporative emissions from automobile is classified into Diurnal, Resting Loss, Hot Soak, Running Loss, Refueling Loss and Crankcase emissions. Diurnal emissions result from the evaporation of fuel caused by ambient temperature rise during the day, which heats motor vehicles. Resting loss emissions are also diurnal emissions but the ambient temperature drops. Hot Soak emissions occur after the engine is turned off because the engine still remains hot. Running Loss emissions happen while the car is running because the engine is hot. Refueling Loss emissions are the gasoline vapors forced out when the fuel tank is being filled. Crankcase emissions leak from the engine crankcase ventilation system *(22, 23)*.

2.2.3 Automobile Engine and Combustion Process

Automobile engines are commonly internal combustion engines that burn fuel and air in a combustion chamber. The combustion process creates the gases at high temperature and pressure and the expansion of the gases moves the engine pistons. The reciprocating force generated by piston movement is changed to rotary motion. The most commonly used internal combustion engine in automobiles is the four-stroke cycle also referred to as the OTTO cycle engine. The engine has one complete cycle that consists of four strokes, namely; intake, compression, combustion, and exhaust stroke, which means two revolutions of the crankshaft is required. Specifically, a mixture of vaporized fuel and air is drawn into the cylinder during the intake stroke as the piston moves downward. Then the mixture is compressed by the upward movement of the piston created by the flywheel during the compression stroke. At the end of the compression stroke a spark occurs and the fuel is combusted. During the combustion stroke the gases expand, moving the piston downward. At the end of the combustion stroke the exhaust valve begins to open. Finally the combusted fuel and gases are exhausted as the piston moves upward *(24, 25)*.

Gasoline used as fuel in the internal combustion engine is a mixture of liquids extracted from petroleum, consisting of both aliphatic hydrocarbons and aromatics such as benzene and toluene. The combustion that occurs inside the engine is a chemical reaction of hydrocarbons in gasoline and oxygen from air. Theoretically the reaction converts carbon to CO_2 and hydrogen to H_2O, which is referred to as the stoichiometric reaction and/or the complete combustion. The most important factor to achieve the complete combustion is to make a stoichiometric mixture of air and fuel and maintain the air to fuel ratio. In other words, it is a key to supply the exact amount of air (oxygen) required for the complete combustion depending on the quantity of fuel. When an air to fuel ratio is greater than the stoichiometric ratio, air is being supplied more than required. Adversely, when an air to fuel ratio is less than the stoichiometric ratio, air is being supplied less than required. The former is former is referred to as a fuel lean condition and the latter is a fuel rich condition. Generally fuel rich conditions result in unburned CO and HC. A study conducted by the General Motors (GM) Corporation analyzed the effects of air to fuel ratio on HC, CO, and NO emissions. Based on the results, HC and CO emissions were minimized at a value near the stoichometric air to fuel ratio but NO emissions were maximized at the value *(12, 26)*.

2.2.4 Automobile Emissions Control Technology

A number of Emission control technologies have been invented in the past and nowadays intensive efforts are being made in various areas to control automobile emissions. In this section, these technologies are briefly described.

Positive Crankcase Ventilation (PCV)

Positive crankcase ventilation systems were introduced by the GM Corporation in the early 1960s to reduce HC exhaust emissions. Automobile unburned fuel, mostly hydrocarbon, pollutes air when it is being emitted into the air. Additionally it corrodes critical parts because it contaminates the engine oil. In order to eliminate this problem, PCV systems were designed to route the gases from the crankcase into the intake manifold *(27)*.

Exhaust Gas Recirculation (EGR) boxes

Exhaust gas recirculation systems were introduced in the early 1970s to reduce exhaust NO_X emissions from both gasoline and diesel engines. Since high temperatures in the chamber promote the formation of NO_X emissions, the gases exhausted from the engines are partially recirculated into the engine cylinders to dilute the mixture of air and fuel, resulting in reducing NO_X formation. Typically 5 to 15 percent of the exhaust gas is recirculated to the chamber in a spark-ignited engine to avoid misfires and partial burns. Alternatively the gases are recirculated up to 50 percent in a diesel engine *(28, 29)*.

Catalytic Converter

Since the first generation of catalytic converters was invented in the mid-1970's, catalytic converters are being used as the core vehicle emission control system by the automobile manufacturers to meet the emissions standards. There are two types of catalytic converters mostly used; three-way and two-way catalytic converters. A three-way catalytic converter, which is mostly used on spark ignition engines, is designed to oxidize CO and HC and to reduce NO_x emissions simultaneously. A two-way catalytic converter, which is widely used on diesel engines, is used to reduce HC and CO by means of the oxidization of HC and CO. The precious metals used as the catalyst include platinum, palladium, rhodium, cerium, iron, manganese, and nickel *(30)*.

On-Board Diagnostic

On-Board Diagnostics is a computer-based system monitoring the performance of some of the engine's major components, including emission controls. OBD is built into all model year 1996 and newer light-duty cars and trucks as mandated by the 1990 Clean Air Act. A large number of states have already employed OBD checks into their I/M programs, or prepare for OBD checks *(31)*.

Hybrid Vehicles

Vehicles that use more than one power source to propel it are called hybrid vehicles in a broad sense. In most cases, hybrid-electric vehicles that use gasoline engines and electric motors are commonly referred to as hybrid vehicles. Since the hybrid vehicle has a higher fuel economy than conventional vehicles by means of storing wasted power during braking, it produces fewer emissions. Specifically, the captured power is stored in an on-board rechargeable energy storage system (RESS) and the gasoline engine is shut down during the vehicle stops or while it is coasting or idling. Since city driving involves frequent stops, coasting and idling, the hybrid vehicle is more efficient for city driving than highway driving *(32)*. Additionally, the hybrid vehicle achieves the reduction of noise emissions at idling and low speed driving. However, one concern is a fact that the battery utilized in the hybrid vehicle's RESS is toxic and can lead to various health problems *(33)*.

Electric Vehicles

Electric vehicles (EVs) are defined as vehicles that have one or more electric motor powered by a battery system to propel it. Since EVs do not generate tailpipe emissions during their operation, EVs have been referred to as "zero-emissions vehicles". However, they are sometimes called "emissions-elsewhere vehicles" because generating the electricity from non-renewable sources to charge the battery system is commonly accompanied by producing emissions. Although EVs have several advantages such as higher energy efficiency, environmentally friendliness, energy dependency reduction, and smooth operation with less maintenance than conventional vehicles, the wide use of EVs is hindered by several issues. The low energy density of the battery system is one of the most serious issues because most of EVs can only travel less than 150 miles without recharging. Another challenge is a fact that it takes 4 to 8 hours to recharge the battery system. Also, the high price of a new battery pack is one of the concerns *(34-37)*.

Fuel Cell Vehicles

Fuel cell vehicles (FCVs) use electric engines to propel like EVs but they generate electricity by themselves. Since FCVs use hydrogen gas to generate electricity, they are also referred to as hydrogen vehicles. FCVs are directly fueled with pure hydrogen gas or with hydrogen-rich fuels to convert to hydrogen gas *(38, 39)*.

Alternative Fuels

Alternative fuels are developed for the reduction of energy dependency on the petroleum imported from foreign countries and for the protection of the environment. Ethanol and bio-diesel are the most well known alternative fuels. Ethanol is made by fermenting and distilling corn and/or other crops such as sugar cane, sugar beet, and switchgrass *(40, 41)*. In Brazil, it is made from sugar cane and is widely used as car fuel. Bio-diesel is commonly made by processing vegetable oils or animal fats *(42)*.

2.2.5 Automobile Emissions Control Programs (Exercises)

2.2.5.1 I/M program

I/M programs used in most states can be categorized into three types in terms of their implementation structure, which include Centralized, Decentralized and Hybrid network types *(43)*. These criteria are based on the scale, number and function of stations. The status of I/M program implementation can be found in the EPA's document *(44)*.

The general procedure of the I/M program has several steps. First, a basic visual inspection, known as a visual anti-tampering check, is conducted by the inspector. The inspector checks the presence of emission control components such as catalytic converter, exhaust gas recirculation (EGR) valve, positive crankcase ventilation (PCV) valve, fuel inlet restrictor, air pump, and vapor canisters. After a visual inspection, the inspector conducts a gas gap pressure test, which tests whether harmful evaporative emissions are leaking from a vehicle's gas tank. Second, the vehicle is tested under real-world simulated conditions to test whether vehicle exhaust emissions exceed cut points. Otherwise, the inspector checks the vehicle's On-Board Diagnostics (OBD) system.

Emission tests are divided into mass emissions and concentration measurement tests, in terms of measurement methods. Mass emission tests directly measure the mass of emitted emissions from the vehicle's tailpipe. Emission measurements are usually expressed as the mass of emissions divided by the distance-traveled by the testing vehicle under a simulated road condition *(43)*. The Federal Test Procedure (FTP), IM240, BAR31, IM93/CT93, and IM147 all fall into this categorization. On the other hand, concentration tests measure the relative concentrations of vehicle exhaust emissions. Idle speed and Acceleration Simulation Mode (ASM) tests fall into this categorization *(43)*.

2.2.5.2 Clean Screening

Clean screening can be used as a supplemental program included in inspection and maintenance (I/M) programs for the enhancement of the efficiency and cost-effectiveness of the I/M programs. It identifies vehicles that are clean enough to pass the emissions test scheduled by IM programs and exempting the vehicles from the test. Specifically, three types of clean screening are described in the draft guidance published by the EPA. The first type is remote sensing clean screening, which uses roadside remote sensing to screen clean vehicles. The second is vehicle emissions profiling, which uses statistics on historical vehicle emission test results. In order words, the historical test results are ranked based on the vehicles' failure rates and the ranking can be used to screen low emitters or high emitters. The third is model year exemptions, which exempts vehicles based on their model years for a specific period. For example, vehicles that are four or five years old are exempted in many states *(45)*.

2.2.5.3 Roadside Inspection Program

The Bureau of Automotive Repair (BAR) initiated a roadside inspection program in 1985. The program was aimed to collect data on vehicle tailpipe emissions, emission control systems, and tampering rates from on-road vehicles, and to compare these data to that from inspection stations. For the selection of vehicles, a stratified sampling and random sampling is used. The selected vehicle takes the ASM test on a dynamometer *(46)*.

2.2.5.4 Oxygenated Fuel Program

Oxygenated fuel programs were mandated by the Clean Air Act Amendments of 1990 to reduce CO emissions in nonattainment areas that exceeded the national ambient air quality standard for CO. Since on-road vehicles are responsible for a large portion of CO emissions and CO emissions are easily generated when insufficient oxygen is supplied in combustion processes, oxygenated gasoline was used in nonattainment areas especially during the cold weather months to promote the combustion efficiency. For the oxygenation, methyl tertiary butyl ether (MTBE) or ethanol is used as oxygenate *(47)*.

2.2.6 Automobile Emissions Tests and Drive Cycles

This section describes methodologies to identify high emitting vehicles. I/M programs are mainly discussed and other methodologies are introduced, in order to describe how high emitters are identified.

2.2.6.1 Federal Test Procedure

The federal test procedure (FTP) is not used in I/M programs but used to certify the compliance of new vehicles, light duty vehicles (LDVs) and light duty trucks (LDTs), with federal emission standards. In addition, the base emission rates of the MOBIEL emission factor model was developed based on the FTP test results *(48)*. It was designed to measure concentrations of HC, CO, NO_X, and CO_2 emissions for the vehicles, while the vehicles are being driven on a simulated typical urban driving. Since the driving cycle was developed based on actual driving data collected in Los Angeles during the late 1960s, it is referred to as "LA4" or the urban dynamometer driving schedule (UDDS) *(49)*. The FTP driving cycle is divided into three segments: a cold-start segment (known as bag1 phase), a hot-stabilized segment (known as bag2 phase), and a hot-start segment (known as bag3 phase). The vehicle is preconditioned and soaked in a room controlled 68 to 86°F overnight prior to testing. The composite emissions rates for FTP are calculated using Equation [2-1]. However, a shortcoming with the FTP is that it does not inlcude high engine load conditions such as aggressive driving behavior and air conditioning use. Consequently, the supplemental federal test procedure (SFTP) was designed to address the shortcoming and was implemented beginning with the 2000 model year *(43)*. The driving cycles for the SFTP include "US06" and "SC03": the US06 was designed to measure emissions under aggressive driving behavior while the SC03 was designed to measure emissions following start-up and air conditioning use *(48)*. The FTP, US06, and SC03 drive schedules are illustrated in Figure 2.2.

$$\text{Composite FTP}_{(\text{grams/mile})} = \frac{[(0.43 \times Bag1) + (0.57 \times Bag3)] + Bag2}{7.5} \quad [2\text{-}1]$$

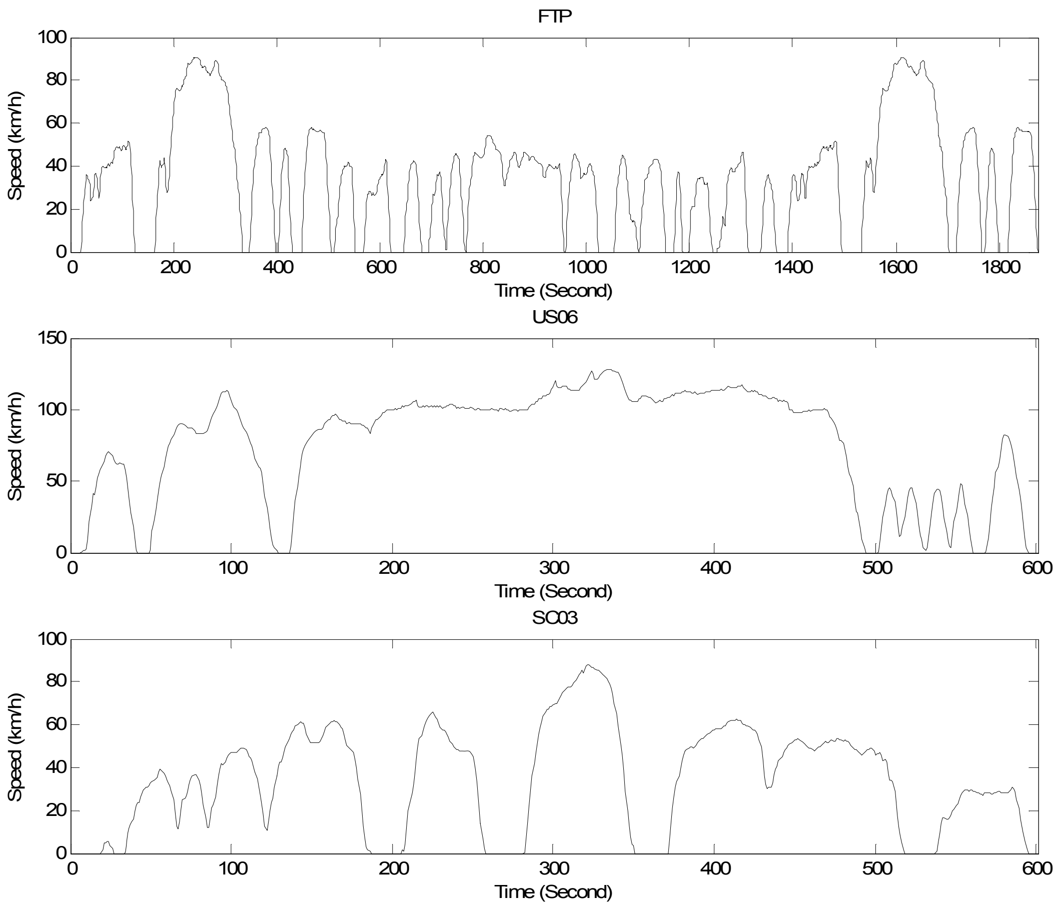


Figure 2.2 FTP, US06, and SC03

2.2.6.2 IM240

Since the FTP cycle requires several minutes to execute, it was hard to utilize the FTP as the standard procedure for inspection and maintenance programs. Consequently, several shortened versions of the FTP test were developed. The IM240 test is one of these shortened models that originated from the FTP test in which a vehicle is driven on a dynamometer over a 240-second (2-mile) cycle which corresponds to the first 240 seconds of the FTP's hot-stabilized segment *(43)*. The compliance of the vehicle is determined after comparing the emissions test result with the emission standards. A large number of states in the U.S. have utilized this test in their I/M programs. The IM240 test utilizes the emission standards for hydrocarbons, carbon monoxide, and oxides of nitrogen in grams per mile by vehicle type and model year. The vehicle types include light duty vehicles, high-altitude light duty vehicles, light duty trucks 1, high-altitude light duty trucks 1, light duty trucks 2, high-altitude light duty trucks 2, and heavy duty trucks *(43)*.

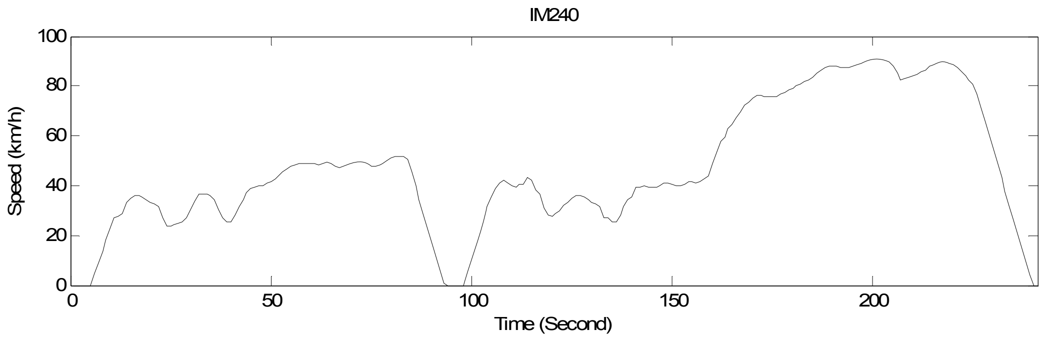


Figure 2.3 IM240

2.2.6.3 ASM Test

Austin et al. *(50)* proposed a new emission test procedure, the *Acceleration Simulation Mode* (ASM) test, that can correctly and economically identify 90% of vehicles that emit excessive NO_x emissions for I/M programs. In the study, they concluded that the ASM 5015 test is best for identifying high NO_X emitting vehicles and the 2500 rpm test could correctly identify high CO and/or HC emitting vehicles. As this is a loaded-mode steady-state test, exhaust concentrations are measured from a vehicle driven on a dynamometer under a loaded condition. The widely used ASM tests can be divided into two types in terms of vehicles' speed levels and load conditions. The ASM5015 test employs 50% of the maximum load conditions in the FTP test at a 15 mi/h speed. The ASM2525 test utilizes 25% of the maximum load conditions in the FTP at a 25 mi/h speed *(43)*.

2.2.6.4 Remote Sensing Test

Remote sensing devices (RSD) are tools that measure the concentration of pollutants emitted by on-road vehicles. The key technology in remote sensing is an infrared absorption principle. The amount of infrared light reflected and absorbed is translated into the concentration of exhaust pollutant. Also, RSD has the capability of capturing vehicle speeds, acceleration levels, and license plate numbers. Different tailpipe exhaust emission measurements and remote sensors are not directly used in I/M programs. However, it is considered a supplementary tool to enhance the efficiency of I/M programs. The feasibility of employing remote sensing as a complementary part of I/M programs has been evaluated in many states. A number of states are starting to utilize RSDs in their State Implementation Plans (SIPs) such as "clean screen program" and "evaluation of I/M program performance".

2.2.6.5 Other EPA Dynamometer Drive Schedules

The New York City Cycle (NYCC) is a cycle representing congested urban driving at low speeds and involving frequent stops as the name implies. It represents a 1.18 mile driving with an average speed of 7.1 mph over a 598 second duration. The Highway Fuel Economy Driving Schedule (HWFET) is designed by EPA to determine the fuel economy of light duty vehicles. The vehicle is driven over 10.26 miles with an average speed of 48.3 mph over a 765 second duration.

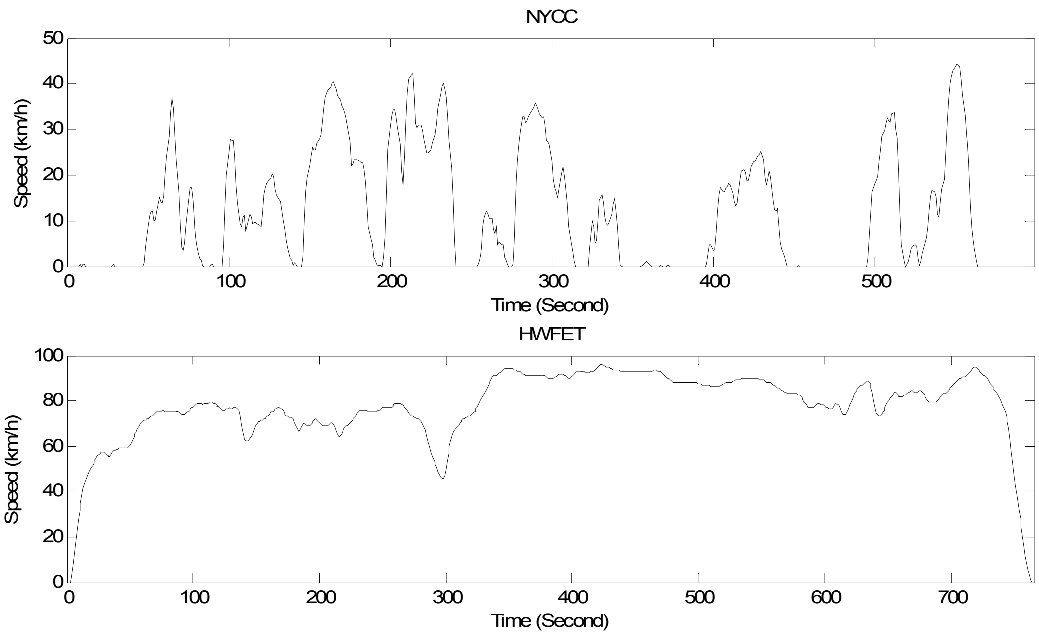


Figure 2.4 NYCC and HWFET

2.3 Automobile Emission Models

2.3.1 Usage of Vehicle Emission Models

Vehicle emission models fall into four categories depending on the model usage. The first category includes models that are directly used to assess the effectiveness of control strategies at the national level. The second level of modeling includes models that are used to develop regional emission inventories in conjunction with transportation planning models. On-road emission inventories are estimated by taking the product of emission rates derived from vehicle emission models with the vehicle miles of travel estimated using travel-demand models. In this level, the emission inventories are used to help develop state implementation plans (SIPs) and conduct transportation conformity analyses. The third level of modeling is used to estimate regional emission concentrations. In this level, in addition to the vehicle emission and travel-demand models, other air-quality models such as dispersion models are utilized for the determination of attainment of national ambient air quality standards (NAAQS). The fourth level of modeling includes models that are used to quantify the impacts on public health caused by emission exposure. In this level, all the models used in the third level are used in addition to exposure models to quantify the health impacts of such exposure *(51)*. This purpose is the ultimate objective of air pollution modeling and the procedure is illustrated in Figure 2.5. Specifically, mobile-source emissions in the figure are practically estimated using the MOBILE and non-road models. Pollutant emissions from other sources are estimated using emission factors obtained from AP42, the compilation of air pollutant emission factors *(52)*. For the modeling of air pollution dispersion, the EPA's guideline on air quality models recommends two modeling systems: the AERMOD modeling system and CALPUFF. The AERMOD system is a steady-state plume model, while CALPUFF is a non-steady-state puff dispersion model that considers the effects of the temporal and spatial meteorological variation. For the estimation of the dispersion of on road vehicle emissions, CALINE3, CAL3QHC, and CAL3QHCR can be used *(53)*. Given the concentrations of criteria pollutant emissions, the human exposure model (HEM) can be used to estimate the cancer and non-cancer hazard associated with vehicle emissions. There are two versions of the HEM: HEM-Screen and HEM-3 *(54)*.

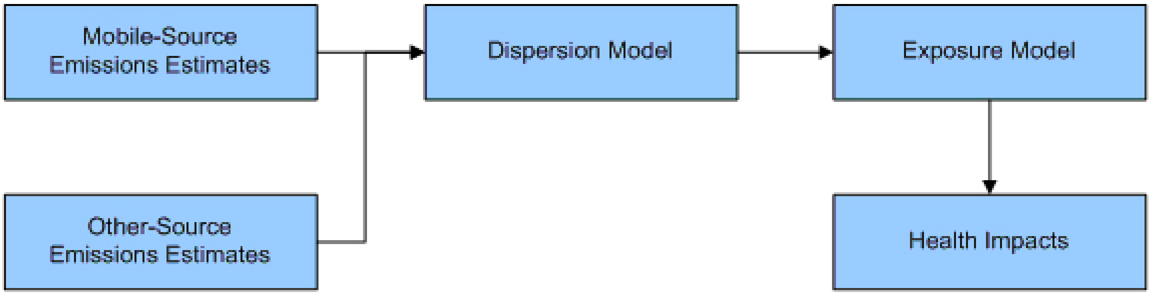


Figure 2.5 Health Impacts Estimates

2.3.2 Vehicle Emission Models

Vehicle emission models fall into two categories in terms of their scale. The first category is macroscopic models that use average speed as a critical input variable. The second is microscopic models that utilize instantaneous vehicle speed and acceleration levels as input variables *(55)*.

The macroscopic models include the EPA MOBILE model and the CARB (California Air Resources Board) EMFAC (EMission FACtor) model. The emission rates are estimated using input parameters such as vehicle type, age, average speed, ambient temperature, and vehicle operating mode *(56)*. First, the base emission rates, which are derived from the FTP test data, are determined by vehicle types. Then, the base emission rates are adjusted based on other correction factors. This type of model has been mainly used in constructing regional emission inventories and estimating on-road mobile-source emissions. A problem with macroscopic models is that the models are not sensitive to transient vehicle behavior associated with operational-level transportation projects.

The microscopic models include the Comprehensive Modal Emission Model (CMEM) and the VT-Micro emission model. This type of models are capable of quantifying the environmental impact of operational level projects, such as ramp metering, signal coordination, and many Intelligent Transportation System (ITS) strategies, since both models estimate second-by-second emission rates. The CMEM model is a modal emission and a physical, power-demand model, while the VT-Micro model is a statistical model.

2.3.2.1 MOBILE 6

The first version of the MOBILE model was developed in the late 1970s by the U.S. Environmental Protection Agency to estimate on-road vehicle emission factors *(51)*. Since the first appearance of the MOBILE model, the model has been continuously updated. The history of the MOBILE model development is described in the literature *(57)*. The MOBILE6.2 model is currently available as a result of a series of efforts updating the model *(58)*.

Since mobile-source emissions contribute to a large portion of emission inventories, the precise assessment of on-road vehicle emission trends is critical to establishing effective air-quality control strategies. In the context of this, the MOBILE model has a very important role in air-quality management. Briefly speaking, the purpose of the MOBILE model is to estimate on-road vehicle emission factors based on speed and vehicle type accounting for regional conditions impacting emission factors such as temperature, humidity, and fuel quality *(51, 59)*.

The MOBILE model consists of five major components accounting for emission factors, test conditions, fleet characteristics, fuel characteristics, and emission control programs *(23)*. The "base emission rates" component is the most important part of the model because it provides emission rates for running emissions based on FTP test data as a function of vehicle type, model year, and technology type. The second component deals with test conditions, such as temperature, humidity, and vehicle load, to provide correction factors. The fleet characteristic component includes all model years and vehicle classes. The fuel characteristic component includes differences of oxygen and sulfur content in fuel. The last component includes regional control programs such as Inspection and Management (I/M) programs to adjust “base emission rates”. The fleet-average emission rates are estimated by means of combining those components, as described in Equation [2-2] and Equation [2-3] *(23)*.

$$\text{Fleet-Average Emission Rate}_{\text{Vehicle Class}} = \sum[\text{TravelFraction}] \times \left\{ \begin{array}{l} [\text{LA4 Emission Rate} + \text{Tampering Offset} + \text{Aggressive Driving} + \text{Air Conditioning}] \\ \times[\text{Temperature Adjustment}] \times [\text{Speed Adjustment}] \times [\text{Fuel Adjustment}] \end{array} \right\} \quad [2\text{-}2]$$

$$\text{Fleet-Average Emission Rate} = \sum[\text{VMT Mix}]_{\text{Vehicle Class}} \times [\text{Fleet-Average Emission Rate}]_{\text{Vehicle Class}} \quad [2\text{-}3]$$

The MOBILE model inputs fall into four categories, namely: (1) Inputs related to fuel characteristics such as sulfur content and oxygenate content; (2) Inputs related to vehicle and travel characteristics such as registration distribution, annual mileage accumulation, average speed distribution, distribution of vehicle miles traveled, engine start per day, engine start soak time distribution, trip end distribution, average trip length distribution, and hot soak duration (3); Inputs related to regional controls such as I/M program description, anti-tampering inspection program description, and stage II refueling emissions inspection program description (4); and Inputs related to regional conditions and others such as the calendar year, month (January, July), hourly temperature, altitude (high, low), weekend/weekday, humidity/solar load, natural gas vehicle fractions, HC species output, particle size cutoff, emission factors for particulate matter (PM), and hazardous air pollutants (HAPs), and output format specifications and selections. The detailed description of each input can be found in the literature *(58)*.

The MOBILE model outputs include HC; CO; NO_X; exhaust, tire wear, and brake wear particulate matters; sulfur dioxide (SO_2); ammonia (NH_3); six hazardous air pollutants (HAPs); and CO_2 emission factors for 28 individual vehicle types including gas, diesel, and natural-gas-fueled cars, trucks, buses, and motorcycles. Furthermore the emission factors are estimated for any calendar year between 1952 and 2050. The detailed description of outputs and their format can be found in the literature *(58)*.

2.3.2.2 Motor Vehicle Emission Simulator (MOVES)

EPA has been developing a new integrated system of emission models, entitled the motor vehicle emission simulator (MOVES) to meet various modeling demands from a microscopic analysis to national inventory levels. The model may substitute the MOBILE6 and Non-road emission models. The first implementation of MOVES was termed MOVES2004. Currently, the second implementation of MOVES is available for demonstration purposes, which is termed MOVES-HVI. MOVES-HVI has a capability of estimating national inventories and projections for fuel consumption, CO_2, N_2O, and CH_4 from highway motor vehicles. Additionally, the criteria pollutant emissions, such as HC, CO, NO_X, and PM, can be estimated. In the future, the emission models for non-road mobile sources such as airplanes, locomotives, marine engines, and other equipment will be added into the system *(60)*.

2.3.2.3 Comprehensive Modal Emission Model

The Comprehensive Modal Emission Model (CMEM) was the result of the research sponsored by the National Cooperative Highway Research Program (NCHRP Project 25-11), which was conducted by the College of Engineering-Center for Environmental Research and Technology (CE-CERT) at the University of California-Riverside.

CMEM is a modal emission and a physical, power-demand model based on a parameterized analytical representation of emissions production. The model estimates second-by-second vehicle tailpipe emissions as a function of the vehicle’s operating condition. There are four operating conditions: variable soak time start, stoichiometric operation, enrichment, and enleanment. The model determines the vehicle’s operating condition by comparing the vehicle power demand with power demand thresholds. The tail-pipe emissions are estimated through three components, which are fuel rate (FR), engine-out emission indices (grams of emissions/grams of fuel), and time-dependent catalyst pass fraction (CPF) *(4)*.

$$\text{Tailpipe Emission} = FR \times \left(\frac{g_{emission}}{g_{fuel}} \right) \times CPF \qquad [2\text{-}4]$$

The model has six modules, which include the engine power demand, engine speed, fuel/air ratio, fuel-rates, engine-out emissions, and catalyst pass fraction. The input parameters for the model are divided into two groups. The first group includes operating variables such as roadway grades, accessory power, speed trace, soak time, and specific humidity. The second group includes model parameters, which are divided into two sub-groups. The first sub-group includes readily-available parameters such as vehicle mass, idle speed of engine, and number of gears. The second sub-group includes calibrated parameters related to fuel, engine-out emission, enleanment, enrichment, soak-time, cold-start, and hot catalyst.

2.3.2.4 VT-MICRO Vehicle Emission Model

The VT-Micro fuel consumption and emission rates are estimated based on vehicle-specific speed and acceleration levels. In order to construct the VT-Micro model, chassis dynamometer data measured at the Oak Ridge National Laboratory (ORNL) were utilized. Specifically, nine normal emitting vehicles, six light duty vehicles, and three light duty trucks, were included into the ORNL data to represent an average vehicle that had average characteristics such as engine displacement, vehicle curb weight, and vehicle type considering average vehicle sales. The ORNL data included a total of between 1,300 to 1,600 individual measurements for each vehicle with the corresponding speed and acceleration levels. In the ORNL data, the vehicle acceleration and speed ranged from -1.5 to 3.7 m/s^2 and from 0 to 33.5 m/s (0 to 121 km/h), respectively. Consequently, the VT-Micro model finally incorporated a combination of linear, quadratic, and cubic speed and acceleration terms, and was separated into two models for positive and negative accelerations, as illustrated in Equation [2-5] *(61)*.

$$MOE_e = \begin{cases} e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}^{e} \times u^i \times a^j)} & \text{for } a \geq 0 \\ e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(M_{i,j}^{e} \times u^i \times a^j)} & \text{for } a < 0 \end{cases} \qquad [2\text{-}5]$$

Where $L^e_{i,j}$ and $M^e_{i,j}$ represent model regression coefficients for MOE "*e*" at speed power "*i*" and acceleration power "*j*". The final VT-Micro model produced emission produced good fits to the ORNL data (R^2 in excess of 0.92 for all MOEs).

In addition, models for five light duty vehicles and two light duty trucks were constructed within the VT-Micro model framework by using data from 60 light duty vehicles and trucks. In the construction, Classification and Regression Tree Algorithms (CART) were used to group vehicles into homogenous categories *(61)*. Also, high emitting vehicle emission models, which had four different high emitting vehicle categories, were incorporated into the VT-Micro model. The HEV model was demonstrated that it introduced a margin of error of 10 percent when compared to in-laboratory bag measurements *(62)*.

2.4 High Emitting Vehicles

2.4.1 Definition of High Emitting Vehicles

High emitting vehicles have received much attention from researchers and regulators after the promulgation of federal regulation in the 1970s. The EPA defines high emitters as vehicles whose emissions of HCs, NO_x are two and/or CO are three times higher than the national standards for new vehicles *(1)*. OBD-II equipment is programmed to identify when vehicle emissions exceed 1.5 times certification standards *(43)*. As can be seen, high emitting vehicles are defined as vehicles having emissions greater than cut-points or standards.

From the 80's, several definitions of high emitters could be found. These definitions can be categorized into three types in terms of methodologies used. The first type utilizes the mean and standard deviation of the sampled vehicle fleet. For example, GM researchers, Haskew and Gumbleton, suggested defining high emitters as vehicles exceeding six standard deviations from the mean of the sampled FTP data *(63)*.

The second type is to define the dirtiest 10% of the fleet or vehicles responsible for 50% of the total emissions as high emitters. For example, Stedman, who developed a remote sensor, defined gross emitters as the proportion of vehicles responsible for 50% of the CO emissions *(64)*.

The third type is to employ specific values in the unit of gram/mile or % concentration as the cut points. However, the reason that these cut points were employed was not mentioned in the literatures. In 1990, Lawson et al. provided the criteria for classifying low-emitting, high emitting, and super-emitting vehicles, in terms of CO concentration. For their study, they defined a low-emitting car as emitting 1.3% CO concentrations, a high-emitting car as emitting 8.5% CO, and a super-emitting car as emitting 17% CO *(7)*.

2.4.2 Regulations Related to High Emitting Vehicles

2.4.2.1 Inter-modal Surface Transportation Efficiency Act (ISTEA)

The ISTEA of 1991 was made into law to provide a new vision for surface transportation *(65)*. This act allowed highway funds to be transferred to activities that contribute to achieving air quality standards, and it provided authorizations for highway construction, highway safety, and mass transportation expenditures. The Congestion Mitigation and Air Quality Improvement (CMAG) program was authorized by the ISTEA to provide funds for the projects that contribute to air quality improvements and reduce congestion.

2.4.2.2 State Implementation Plan Submissions (SIPs)

Each state is responsible for preparing and submitting a State Implementation Plan that demonstrates how the National Ambient Air Quality Standards (NAAQS) will be achieved, maintained, and enforced under the Clean Air Act. In addition, the state must obtain EPA approval of the SIP *(66)*. In SIPs, mobile source emission inventories should be projected and the impacts of transportation plans, programs, and projects on emissions should be quantified.

2.4.2.3 Conformity Process

Transportation conformity requires EPA, DOT, and a variety of regional agencies to incorporate the air quality and transportation planning development process under the Clean Air Act. Metropolitan Planning Organizations (MPOs) and DOTs must demonstrate that new violations or delays in the attainment of standards will not be caused or contributed by transportation activities *(56)*. Specifically, MPOs are responsible for demonstrating that higher emission levels beyond the 1990 baseline year will not happen because of regional transportation improvement programs that include both federal and nonfederal projects. The construction of these projects should have emission levels lower than before *(56)*.

2.4.3 Impacts of High Emitting Vehicles

The fact that a small proportion of high emitting vehicles are responsible for a large amount of emissions was identified in a number of studies. The utilized cut points to identify high emitters vary depending on the objectives of the studies, as was demonstrated earlier in the previous section. Thus, the magnitude of high emitter impacts on overall vehicle emissions depends on how high emitters are defined. Also, the quantified impacts were varied depending on the type of employed data such as mass emission measurements or concentration measurements by remote sensors. However, in these studies, the high emitter impacts were computed in a similar manner. First, all measurements are sorted in the order of emission rates. Second, the ratio of high emitters to the vehicle fleet is calculated based on the cut points. Third, the aggregated contribution of high emitters is computed to find the percentage of the emissions emitted by high emitters relative to the total emissions.

One of the famous studies addressing high emitter impacts is Wayne and Horie's study in 1983. They evaluated the in-use vehicle surveillance program in California. In this study, they concluded that 47% of the CO emissions were produced by only 12% of the vehicles tested *(67)*. Another famous study is Stedman's study in 1989. He analyzed the effectiveness of the state's oxygenated fuels program by using remote sensing measurements, and concluded that 10% of the vehicles produce more than 50% of the CO emissions *(64)*. In 1999, McClintock analyzed RSD and IM240 test data from 1997 and 1998 to develop high-emitter identification criteria. In his study, the worst-polluting 10% of vehicles for each pollutant emitted 63% of total CO, 47% of total HC, and 32% of total NO emissions *(68)*.

2.4.4 Modeling of High Emitting Vehicles

Since the ultimate objective of air pollution modeling is to assess the impacts of air pollutions on public health, this section presents firstly the use of vehicle emission models to assess health impacts. Secondly, the type of vehicle emission models is presented in terms of the characteristics and scale of the models. Finally, the MOBILE6 and the comprehensive modal emission model (CMEM) are presented in more detail, since they are state-of-practice macroscopic and microscopic models, respectively. In addition, the feature of modeling of high emitting vehicles within the models is presented.

2.5.3.2 Modeling of High Emitting Vehicles in MOBILE 6

MOBILE6 does not estimate emissions directly; instead emission factors for high emitting vehicles for 28 different vehicle types are used. MOBILE 6 does not include emission models for high emitting vehicles but considers the impacts of high emitting vehicles in its base emission rates. Since a large number of sample vehicle's FTP test data are required to develop base emission rates, vehicles at I/M test stations were asked to participate voluntarily by providing some incentives to the owners. MOBIEL 6 is assumed to have enough number of high emitting vehicles that represent in-use vehicle fleet in developing base emission rates. However, in the process of recruiting vehicles, it is not easy to get some high emitting vehicles, tampered vehicles, and luxury vehicles *(51)*. Consequently, this would cause significant bias in emissions factors estimations because high emitting vehicles are believed to be big contributors of on-road emissions even though they are a small fraction of the vehicle fleet.

2.5.4.2 Modeling of High Emitting Vehicle in CMEM and VT-MICRO models

The CMEM model defines four types of high emitting vehicles and the impacts of these vehicles are included in the model. High emitting vehicles fall into four types as a result of laboratory measurements of second-by-second engine-out and tailpipe emissions *(4)*. A small number of model year 90 – 94 high emitting vehicles were tested under the FTP bag3 condition. Their categorizations were based on the evaluation of the relationship between fuel rate and engine-out and tailpipe emissions, rather than on mechanical examination or any consequent emissions reduction due to the repair or replacement of vehicles' components *(69)*.

The first type of high emitting vehicles has the lean fuel-ratio at moderate power, and emits low CO and HC emissions but high NO_X emissions, relative to emissions of clean vehicles. The reasons leading to type 1 are not specific but considered inappropriate signal from the oxygen sensor or functioning of the electronic engine control. The second type of high emitting vehicles has the rich fuel-ratio at moderate power, and emits typically normal engine-out HC emissions. Alternatively, type 2 produces high tailpipe CO emissions because the CO emission index and catalyst pass fraction are high. The third type of high emitting vehicles involves a high engine-out HC emissions index, mild enrichment and a catalyst with poor performance, and has the profile of moderate to slightly-high tailpipe CO, very high HC, and moderate to low NO_X emissions relative to normal vehicles. High engine-out HC is probably resulted in incomplete combustion due to a physical mechanism such as a bad spark plug or an injector related problem. The fourth type of high emitting vehicles has poor catalyst performance for all three pollutants at moderate power, and produces high tailpipe emissions for CO, HC, NO_X relative to clean vehicles. These characteristics result from chronically poor catalyst performance, due to burned-out of missing catalyst, or transiently poor catalyst performance.

Chapter 3: Environmental Impacts of High-Emitting Vehicles

Sangjun Park and Hesham Rakha, submitted for peer review at the 88th Transportation Research Board Annual Meeting.

3.1 Introduction

Since it has been reported that high-emitting vehicles (HEVs) are responsible for a large amount of the total emissions from on-road vehicles, significant research efforts have focused on HEV issues *(70, 71)*. The most relevant issue is how to define and identify HEVs in order to repair their malfunctions or retire them early. Another issue is quantifying the environmental impacts of HEVs because this is essential for assessing the sensitivity of air quality control strategies. For example, all states in the U. S. are required to prepare State Implementation Plans (SIP) to demonstrate how they achieve National Ambient Air Quality Standards (NAAQS). For the preparation of a SIP, if a state plans to implement a roadside emissions test program for the detection of HEVs using remote sensing devices, it is impossible to assess the benefit without quantifying the reductions in emissions exhausted by the HEVs.

The definition of HEV is found in the literature where the impacts of HEVs on the mobile-source emissions were quantified. Most studies quantified the impacts utilizing emission measurement data collected from IM programs or roadside emissions tests *(1, 7, 63, 64, 67, 68, 70-74)*. Therefore, the quantified impacts of HEVs are very limited in space and time depending on where and when the measurements were taken, although they are valuable. Specifically, the impacts change over time as the traffic flow conditions vary. Furthermore, the operating conditions of on-road vehicles, such as lean or rich conditions, result from the combination of driver's characteristics, roadway physical conditions such as roadway grade and curvature, and operating conditions such as speed limit and traffic signals. Consequently, the objective of this paper is to quantify the impacts of HEVs on the vehicle exhaust emissions, focusing on HC, CO, NO_X, while considering various possible roadway traffic conditions using vehicle emission and traffic simulation models. The paper quantifies the impacts by estimating hot-stabilized vehicle emissions, not including other types of vehicle emissions such as Cold-Start, Hot-Start, and evaporative emissions.

In terms of paper organization, initially, the definition and impacts of HEVs are presented from the literature. Secondly, the modeling of high-emitting vehicles used for the development of the Comprehensive Modal Emission Models (CMEMs) and VT-Micro Emission Models is presented because the models are utilized to assess the impacts of HEVs. The following section presents the methodologies that utilize pre-defined drive cycles and the results that were derived. Additionally, another approach is presented which utilizes microscopic traffic simulation software together with the VT-Micro emission models. This section describes the networks used for the simulation as well as results from the simulation runs. Finally, the conclusions of the study are presented.

3.2 Literature REVIEW of High-Emitting Vehicles

HEVs are namely the vehicles that emit a higher amount of pollutant tailpipe emissions during the course of their operation when compared to normal-emitting vehicles (NEVs). Generally, HEVs are defined as the vehicles with tailpipe emissions of interest that exceed the thresholds that are dependent upon the vehicle emission test type that the vehicles are subjected to, such as IM240 or ASM tests. In other words, the vehicles failing the designated emission test are defined as HEVs. For example, the U.S. Environmental Protection Agency (EPA) defined HEVs as vehicles having two or three times the emission standards of new vehicles in terms of HC, CO, and NO_X emissions from the FTP tests during the MOBILE6 model development *(1)*. However, there have been several different approaches to define HEVs in previous studies *(63, 64, 70)*. For example, General Motors (GM) researchers found vehicles that exhausted abnormally high emissions and defined vehicles as outliers once their idle IM emissions exceeded ten times the Federal standard for CO and HC *(63, 70)*. In 1989, Stedman reported that 10% of the vehicles produced more than 50% of the CO measured during his study. In his study, HEVs were defined as a percentage of vehicles that accounted for 50% of the CO *(64, 70)*.

Beginning in the 1980s, the contribution of HEVs to total vehicle emissions has been quantified. The earliest study that quantified the impacts of HEVs was Wayne and Horie's 1983 study, which reported that 12% of the vehicles were responsible for 47% of the total CO emissions based on the idle IM test *(67, 70)*. In 1990, Bishop and Stedman conducted a study using remote sensing devices and reported that a range of 7% to 10% of the vehicles were responsible for 50% of the CO emissions *(7, 70)*. In 1991, Stephens also quantified the contribution of HEVs using remote sensing devices. He reported that 50% of the CO emissions were emitted by 8% to 9% of the vehicles. He also reported that 10% of the vehicles were responsible for 58% ofthe CO and 65% of the HC emissions *(70, 72, 73)*. In 1995, Beaton et al. reported that 50% of the CO and HC emissions came from 7% to 10% of the vehicles, respectively *(70, 74)*. In 1995, Lawson analyzed IM240 test data and concluded that 10% of the test-failing vehicles were responsible for 41% of CO and 61% of the HC emissions *(7, 70)*. In 1999, McClintock conducted a study using both remote sensing data and IM240 test data and concluded that 10% of the vehicles were responsible for 63% of CO, 47% of HC, and 32% of NO emissions *(68, 70)*. In summary, 7% to 12% of the vehicles accounted for a range of 41% to 63% of the total CO emissions, and 10% of the vehicles were responsible for a range of 47% to 65% of HC emissions and 32% of NO emissions. As addressed here, all the previous studies that quantified the contribution of HEVs to the total vehicle emissions analyzed remote sensing data and/or IM test data, which means that the datasets utilized in the studies were very confined both temporally and spatially. Consequently, there is a need to investigate the network-wide impacts of HEVs on the environment.

3.3 Modeling of High-Emitting Vehicles

For the quantification of the impacts of HEVs, the study uses the CMEM and VT-Micro vehicle emission models. Consequently, this section describes the modeling of HEVs utilized to build the CMEM and VT-Micro HEV models.

Wenzel and Ross identified a total of 107 vehicles as high emitters from the 343 total tests based on the FTP bag emission results and classified them into four categories as a result of laboratory measurements of second-by-second engine-out and tailpipe emissions, in order to include HEV models within the CMEM framework *(4, 69)*. The first type of HEV (HEV-1) is a vehicle that has a lean A/F ratio at moderate power and emitting low CO and HC but high NO_X emissions, relative to the emissions of clean vehicles. The second type of HEV (HEV-2) is a vehicle that has a rich A/F ratio at moderate power and emitting normal engine-out HC and high tailpipe CO emissions. The third type of HEV (HEV-3) is a vehicle involved in a high engine-out HC emission index caused by incomplete combustion, mild enrichment and a poor catalyst performance, and having the profile of moderate to slightly-high tailpipe CO, very high HC, and moderate to low NO_X emissions. The fourth type of HEV (HEV-4) is a vehicle with a poor catalyst performance for all three pollutants at moderate power, and exhausting high tailpipe emissions for CO, HC, and NO_X *(4, 62)*. Given the vehicles, the CMEM #19, - #20, - #21, - #22, and - #23 models were constructed within the modeling structure of CMEM.

For the development of the VT-Micro HEV models, a total of 36 high-emitting vehicles that were identified based on the FTP emission results were utilized. For the HEV classification, the CMEM categorization of four types was applied to the procedures of classifying the HEVs. Consequently, the four VT-Micro HEV models were constructed within the VT-Micro model framework. The models were validated by comparing the emission estimates with in-laboratory bag measurements and proved to estimate vehicle emissions with a margin of error of 10%. In addition, the models were incorporated within the INTEGRATION microscopic traffic simulation software *(62)*.

3.4 Impacts of high-emitting vehicles

Two methodologies were used to quantify the environmental impacts of HEVs. The first utilizes pre-defined drive schedules, also referred to as drive cycles, along with the CMEM and VT-Micro vehicle emission models. The second approach simulates two roadway networks, an arterial and freeway network, using microscopic traffic simulation software (INTEGRATION) along with the VT-Micro emission models.

3.4.1 Using Pre-defined Drive Cycles

For the quantification of the HEV impacts, the study utilizes five pre-defined drive cycles: The Federal Test Procedure (FTP), US06, IM240, New York City Cycle (NYCC), and the Highway Fuel Economy Test Driving Schedule (HFETDS). The selection of those drive cycles is aimed to simulate different driving conditions.

The first drive cycle selected is the FTP cycle which was designed to certify newly manufactured light-duty vehicles and ensure that they comply with the emission standards. The cycle was developed to simulate average urban driving in the late 1960s and is divided into three parts: Bag1, Bag2, and Bag3. Bag1 is normally referred to as the “Cold Start” bag since the vehicle is soaked over a specified duration prior to testing. During Bag1, the vehicle runs 5.8 km (3.6 mi) with an average speed of 41 km/h (25.6 mi/h) over a 505-second period. Bag2 is referred to as “Stabilized” and represents a 6.3 km (3.9 mi) route with an average speed of 26.1 km/h (16.2 mi/h) over an 864-second period. Bag3 is referred to as “Hot Start” and is exactly the same as the Bag1’s speed schedule. The US06 cycle is one of the supplement FTP cycles that is designed to address the shortcomings of the FTP cycle. It is especially designed to represent aggressive driving patterns such as high speed and/or high-acceleration driving behavior. Specifically, the vehicle runs 12.9 km (8.01 mi) with an average speed of 77.9 km/h (48.4 mi/h) and a maximum speed of 129.2 km/h (80.3 mi/h) over a 596-second period *(51, 75, 76)*. The IM240 cycle is widely used in IM programs implemented in a number of states to test if in-use light-duty vehicles comply with the emission standards. It is known as a shortened FTP cycle since it is a 240-second cycle representing 3.2 km (1.96 mi) of urban driving with an average speed of 47.3 km/h (29.4 mi/h). NYCC is a cycle representing congested urban driving causing low speeds and frequent stops, as the name implies. It represents 1.9 km (1.18 mi) of driving with an average speed of 11.4 km/h (7.1 mi/h) over a 598-second period. The HFETDS cycle was designed by EPA to determine the fuel economy of light-duty vehicles. The vehicle is driven 16.5 km (10.26 mi) with an average speed of 77.7 km/h (48.3 mi/h) over a 765-second period *(6, 51, 75, 76)*.

The distribution of vehicle specific power (VSP) and speed profiles for each of the drive cycles is illustrated in Figure 3.1. As can be seen in Figure 3.1, US06 has the highest median VSP of 11.4 kW/tonne and NYCC has the smallest median VSP of 0.0 kW/tonne. Given those drive cycles, the VT-Micro models for LDV1, LDV3 are utilized to estimate normal-emitting light-duty vehicles’ emissions, which are used as background vehicles’ emissions. The VT-Micro models for HEV1 through HEV4 and CMEM models for Category19 through Category22 are also utilized to estimate HEVs’ emissions.

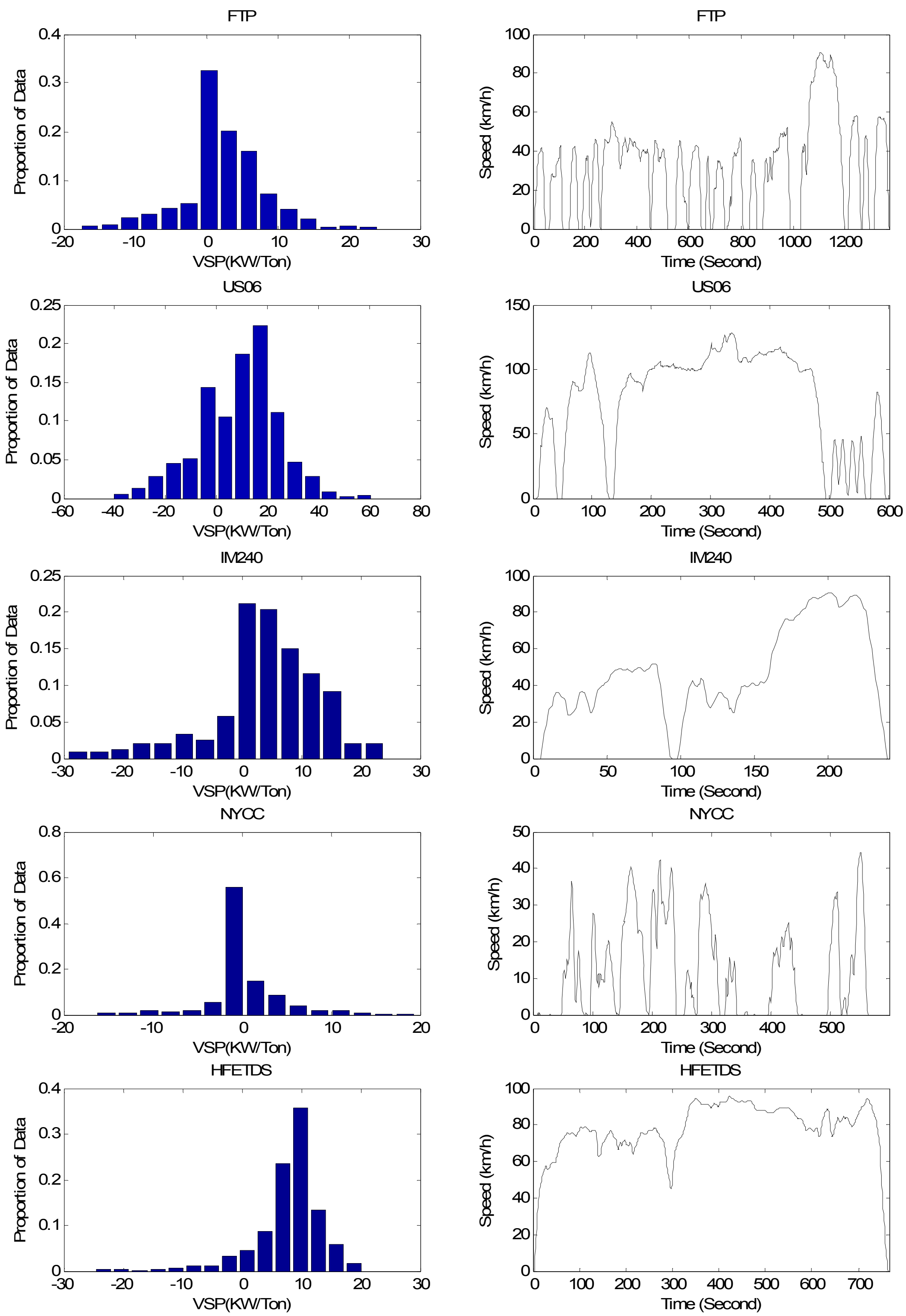


Figure 3.1 Pre-defined drive cycles.

Comparison of VT-Micro and CMEM Model Estimates

The CMEM and VT-Micro model estimates are compared in this section using the emissions estimates of the drive cycles. Specifically, the amount of tailpipe emissions of the individual HEVs is compared to normal vehicle emissions, VT-LDV1 and VT-LDV3, for each of the drive cycles. In addition, differences between the VT-Micro and CMEM model results were analyzed by comparing second-by-second emission rates. Please note that all the emission rates in Table 3.1 are standardized by the fuel use to normalize the data and exclude the effect of engine size.

Prior to the comparison, the characteristics of the representative normal-emitting light-duty vehicles, VT-LDV1 and VT-LDV3, are described. The reason to utilize the two NEVs is to demonstrate how the contribution of HEVs would change if the average emission rates of NEVs varied due to the advances in emission control technologies. As can be seen in Table 3.1, all of the emissions rates for VT-LDV1 are higher than those for VT-LDV3 because the model years of the vehicles categorized as VT-LDV1 are older than 1990 and those of the vehicles categorized as VT-LDV3 are later than 1995. Please remember that the individual HEVs have different characteristics as addressed in the section on HEV modeling. For example, VT-HEV4 and CMEM-22 are vehicles that release higher HC, CO, NO_X emissions, while VT-HEV3 and CMEM-21 are those that only release higher HC and CO emissions.

In the case of HC emissions, VT-HEV3, -HEV4, CMEM-21, and -22 are classified as HEVs. VT-HEV3 and -HEV4 have a range of 9.15 grams per liter of fuel (g/l) to 23.57 g/l as can be shown in Table 3.1. The relative differences range from 326% to 727%, when compared to VT-LDV1, and from 2,308% to 13,765%, when compared to VT-LDV3. Alternatively, the rates for CMEM-21 and -22 range from 7.14 g/l to 20.91 g/l and the relative differences range from 151% to 873%, when compared to VT-LDV1, and from 4,100% to 5,403%, when compared to VT-LDV3.

In the case of CO emissions rates, VT-HEV2, -HEV3, and -HEV4 range from 18.11 g/l to 252.33 g/l and the relative differences range from -48% to 611%, when compared to VT-LDV1, and from 325% to 6,627%, when compared to VT-LDV3. For CMEM-20, -21, and -22, the emission rates range from 45.0 g/l to 284.44 g/l and the relative differences to VT-LDV1 and to -LDV3 range from 19% to 489% and from 888% to 2,799%, respectively.

VT-HEV1, -HEV4, CMEM-19, and -22 are classified as HEVs for NO_X emissions. The emission rates for VT-HEV1 and -HEV4 range from 9.74 g/l to 31.46 g/l and the relative differences to VT-LDV1 and -LDV3 range from 127% to 304% and from 1,133% to 2,427%, respectively. CMEM-19 and -22 have a range of 8.91 g/l and 17.47 g/l and the relative differences to VT-LDV1 and to -LDV3 range from 44% to 215% and from 558% to 2,187%, respectively.

When comparing the individual vehicle emission rates for each of the drive cycles, the US06 cycle's emissions rates turn out to be the highest rates from the results of CMEM runs regardless of the vehicle type. However, different results are drawn when VT-Micro HEV models are utilized. For the HC emissions, NYCC's emission rates for VT-HEV3 and -HEV4 are higher than those for the other drive cycles. For the CO emissions, US06 cycle's emission rates for VT-HEV2 and -HEV3 are higher than those for the other cycles. However, VT-HEV4's NYCC rate is higher than those for the other cycles. For NO_X emissions, the HFETDS cycle's emission rates for VT-HEV1 and -HEV4 are higher than those for the other cycles. But it is impossible to determine which model is superior based on these results because the VT-Micro and CMEM models produce different results due to variations in the characteristics of the vehicles utilized to construct the models. The second-by-second US06 drive cycle emissions rates for CMEM-22 and VT-HEV4 are plotted as a function of time in Figure 3.2. As can be seen in Figure 3.2, the emissions rates for VT-HEV4 are higher than those for CMEM-24 at low VSP levels but much smaller at high VSP levels. All the instantaneous emissions rates and the differences from the results of all drive cycles are plotted as a function of VSP levels in Figure 3.3Figure 3.3. The emissions rates generally increase as the VSP levels increase. In the case of CO and NO_X emissions, the estimates for VT-HEV4 are spread widely for a given VSP level when compared to those for CMEM24. In the case of HC emissions, the CMEM-22 model estimates are spread over a wider range.

Table 3.1 Emission Rates From VT-Micro and CMEM Models

Pollutant	Vehicle Type		FTP	US06	IM240	NYCC	HFETDS
HC (grams per liter of fuel)	NEV*	VT LDV1	2.69	2.19	2.52	2.85	1.83
		VT LDV3	0.21	0.38	0.23	0.17	0.25
	HEV*	VT HE3	13.08	9.09	12.08	13.64	10.98
		VT HE4	19.50	13.85	17.20	23.62	14.58
		CMEM #21	8.35	20.91	11.35	7.14	11.07
		CMEM #22	9.22	20.19	11.76	8.95	9.22
CO (grams per liter of fuel)	NEV	VT LDV1	38.02	52.79	38.39	35.07	34.21
		VT LDV3	4.47	9.61	5.21	3.58	5.12
	HEV	VT HE2	24.20	119.64	23.98	18.42	21.80
		VT HE3	210.92	252.82	225.17	188.58	243.26
		VT HE4	216.77	250.81	207.55	242.91	189.13
		CMEM #20	74.35	284.44	94.66	69.99	89.57
		CMEM #21	45.00	244.57	72.48	50.01	50.59
		CMEM #22	55.41	220.25	65.55	52.40	66.74
NO_X (grams per liter of fuel)	NEV	VT LDV1	5.47	10.42	6.77	3.25	7.86
		VT LDV3	0.91	1.95	1.29	0.45	1.95
	HEV	VT HE1	22.17	25.12	25.23	11.41	31.46
		VT HE4	17.96	23.46	21.41	9.68	27.02
		CMEM #19	11.56	15.29	13.55	10.29	13.41
		CMEM #22	10.6	17.47	12.81	8.91	12.76

*NEV: Normal-Emitting Vehicle

*HEV: High-Emitting Vehicle

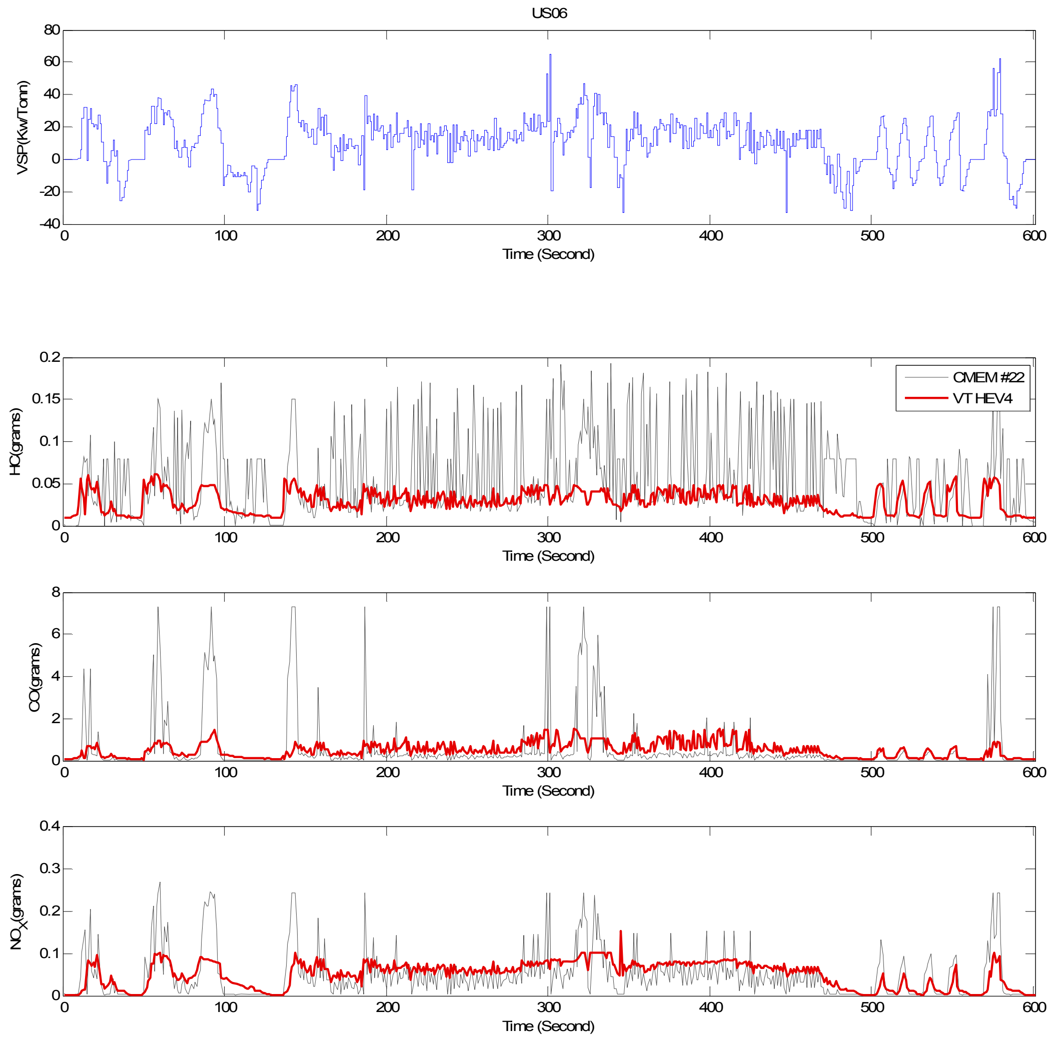


Figure 3.2 Second-by-second US06 emission rates for CMEM-22 and VT-HEV4.

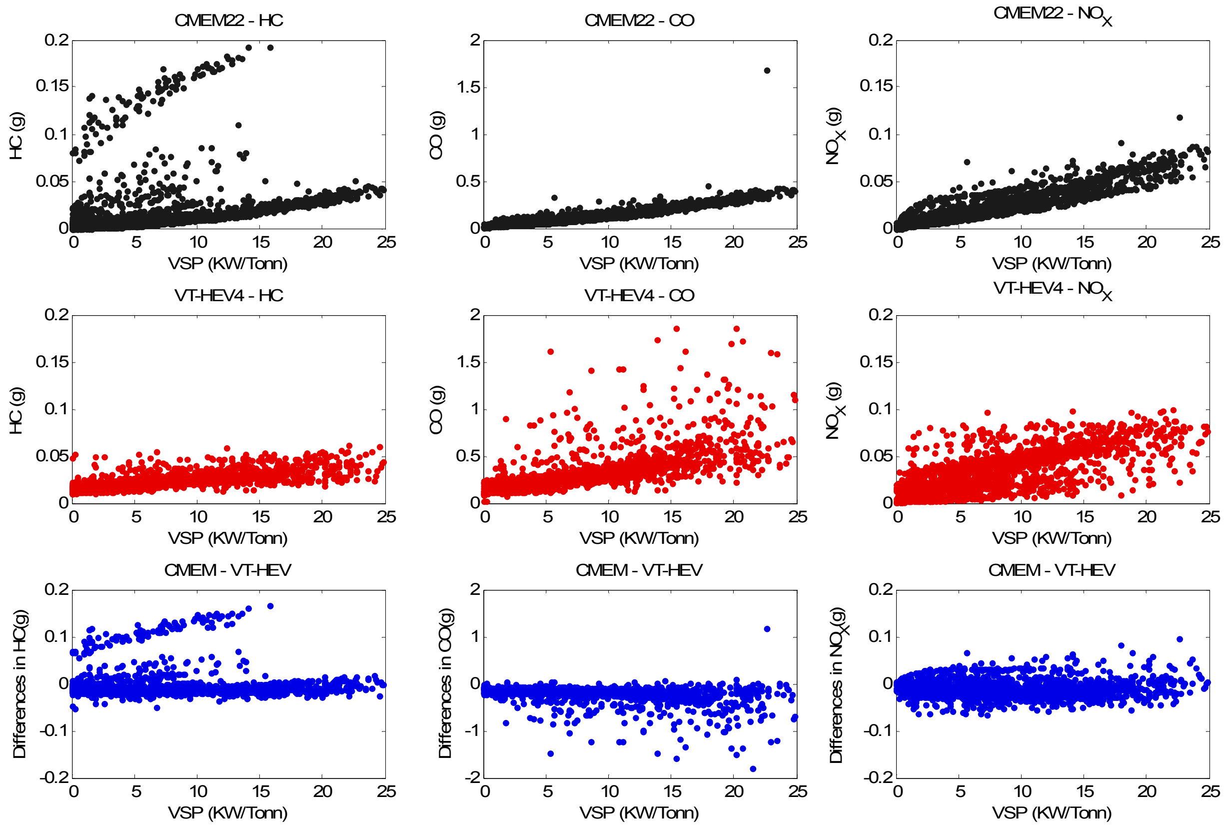


Figure 3.3 Emissions rates for CMEM #22 and VT-HEV4 as a function of VSP.

Results of Drive Cycle Runs

Given all the emissions rates, the contribution of each of the HEVs for each of the drive cycles is computed and summarized in Table 3.2, when VT-LDV1 is assumed to be the base NEV. For example, since VT-HEV1 emits normal HC and CO but high NO_X emissions, the contribution of NO_X emissions increases disproportionally as the proportion of VT-HEV1 to the total fleet increases. For the FTP drive cycle, the contribution of VT-HEV1 ranges from 18% to 50% as the proportion of VT-HEV1 varies from 5% to 20%. Alternatively, for comparison purposes, the HEV contribution relative to the base VT-LDV3 NEV is computed, as summarized in Table 3.3. In addition to each of the HEVs, composite HEVs are also considered to capture real world vehicle composition. The composite vehicles are defined as a combination of the HEVs; the VT-Micro composite vehicle consists of 34.0% of VT-HEV1, 13.4% of -HEV2, 40.2% of -HEV3, and 12.4% of -HEV4. The CMEM composite vehicle consists of 34.0% of CMEM-19, 13.4% of -20, 40.2% of -21, and 12.4% of -22. The proportion is based upon the distribution of high-emitting vehicles that was studied from the Arizona IM240 data, MY1990-1993 *(4)*.

In the case of HC emissions, when VT-LDV1 is considered as the base NEV, a 5% HEVs (including VT-HEV3, -HEV4, CMEM-21, and -22) are responsible for at least 12% and, at most, 33% of the total HC emissions as shown in Table 3.2. Ten percent of the HEVs are responsible for a range of 22% to 51% of HC emissions. Alternatively, when VT-LDV3 is used, 5% of the HEVs account for at least 56% and, at most, 88% of the total HC emissions as shown in Table 3.3. Ten percent of the HEVs account for somewhere between 73% to 94% of HC emissions.

In the case of CO emissions, 5% of the HEVs account for somewhere between 3% to 27% of the total CO emissions relative to the base VT-LDV1 and account for 18% to 78% relative to the VT-LDV3.

Furthermore, ten percent of the HEVs are responsible for 6% to 39% of the total HC emissions relative to the base VT-LDV1 and 10% are also responsible for 32% to 88% relative to the VT-LDV3.

In the case of NO_X emissions, 5% of HEVs are responsible for at least 7% and, at most, 18% of the total NO_X emissions relative to the VT-LDV1, as shown in Table 3.2. Ten percent of HEVs are responsible for 14% to 31% of NO_X emissions. Alternatively, when VT-LDV3 is considered as the base vehicle, 5% of the HEVs account for at least 26% and, at most, 57% of the total NO_X emissions, as shown in Table 3.3. Ten percent of the HEVs account for a range of 42% to 74% of the total emissions.

In conclusion, considering the VT-Micro and CMEM composite HEVs, and a base VT-LDV3, 10% of the HEVs are responsible for 67% to 87% of HC emissions, 51% to 78% of CO emissions, and 32% to 62% of the NO_X emissions. Additionally, it is clearly demonstrated that the contribution of HEVs to the total emissions vary depending on the drive cycle under consideration. Consequently, the use of the IM240 data without any other supplemental data in accessing the impacts of HEVs to calculate the benefit of I/M programs might introduce errors. Also, using only remote sensing data can introduce errors when considering that remote sensing devices are commonly installed only at on- or off-ramps and these results are based on a single observation.

Table 3.2 Contribution of HEVs (Background Vehicle: VT LDV1)

VEHICLE Type	HEV%	HC					CO					NO_X				
		FTP	US06	IM240	NYCC	HFETD	FTP	US06	IM240	NYCC	HFETD	FTP	US06	IM240	NYCC	HFETD
VT HEV1	5%	9%	9%	8%	9%	11%	4%	7%	4%	3%	5%	18%	11%	16%	16%	17%
	10%	17%	17%	16%	17%	21%	8%	13%	9%	6%	9%	31%	21%	29%	28%	31%
	15%	24%	24%	24%	24%	29%	12%	19%	14%	10%	14%	42%	30%	40%	38%	41%
	20%	31%	31%	30%	31%	37%	16%	25%	18%	13%	19%	50%	38%	48%	47%	50%
VT HEV2	5%	3%	5%	2%	2%	3%	3%	11%	3%	3%	3%	6%	6%	7%	6%	7%
	10%	5%	10%	5%	5%	5%	7%	20%	6%	6%	7%	13%	12%	15%	12%	14%
	15%	8%	15%	8%	7%	8%	10%	29%	10%	8%	10%	19%	17%	21%	18%	20%
	20%	11%	21%	11%	10%	11%	14%	36%	14%	12%	14%	25%	23%	28%	24%	26%
VT HEV3	5%	20%	18%	20%	20%	24%	23%	20%	24%	22%	27%	4%	4%	4%	4%	4%
	10%	35%	32%	35%	35%	40%	38%	35%	39%	37%	44%	8%	8%	8%	7%	8%
	15%	46%	42%	46%	46%	51%	49%	46%	51%	49%	56%	12%	12%	12%	11%	12%
	20%	55%	51%	55%	54%	60%	58%	54%	59%	57%	64%	16%	16%	17%	15%	16%
VT HEV4	5%	28%	25%	26%	30%	30%	23%	20%	22%	27%	23%	15%	11%	14%	14%	15%
	10%	45%	41%	43%	48%	47%	39%	35%	38%	43%	38%	27%	20%	26%	25%	28%
	15%	56%	53%	55%	59%	58%	50%	46%	49%	55%	49%	37%	28%	36%	34%	38%
	20%	64%	61%	63%	67%	67%	59%	54%	57%	63%	58%	45%	36%	44%	43%	46%
VT - Micro Composite	5%	16%	14%	15%	16%	18%	15%	15%	15%	15%	17%	11%	8%	10%	10%	11%
	10%	28%	26%	28%	29%	32%	27%	27%	28%	27%	30%	20%	15%	20%	18%	20%
	15%	38%	36%	38%	39%	43%	37%	37%	38%	37%	41%	28%	22%	28%	26%	29%
	20%	47%	44%	46%	47%	52%	45%	45%	46%	45%	50%	36%	28%	35%	34%	36%
CMEM #19	5%	4%	11%	5%	4%	7%	3%	13%	3%	3%	4%	10%	7%	10%	14%	8%
	10%	8%	20%	11%	7%	13%	6%	24%	7%	5%	8%	19%	14%	18%	26%	16%
	15%	13%	29%	16%	11%	20%	8%	34%	10%	8%	11%	27%	21%	26%	36%	23%
	20%	17%	36%	21%	15%	26%	12%	42%	14%	11%	16%	35%	27%	33%	44%	30%
CMEM #20	5%	10%	26%	14%	9%	16%	9%	22%	11%	10%	12%	5%	5%	6%	7%	5%
	10%	20%	43%	25%	18%	29%	18%	37%	22%	18%	23%	11%	10%	11%	13%	10%
	15%	28%	54%	34%	26%	39%	26%	49%	30%	26%	32%	16%	15%	17%	20%	15%
	20%	35%	62%	43%	33%	47%	33%	57%	38%	33%	40%	21%	20%	22%	26%	20%
CMEM #21	5%	14%	33%	19%	12%	24%	6%	20%	9%	7%	7%	2%	2%	2%	3%	2%
	10%	26%	51%	33%	22%	40%	12%	34%	17%	14%	14%	4%	5%	5%	6%	4%
	15%	35%	63%	44%	31%	52%	17%	45%	25%	20%	21%	7%	7%	7%	9%	6%
	20%	44%	70%	53%	38%	60%	23%	54%	32%	26%	27%	9%	10%	10%	13%	9%
CMEM #22	5%	15%	33%	20%	14%	21%	7%	18%	8%	7%	9%	9%	8%	9%	13%	8%
	10%	28%	51%	34%	26%	36%	14%	32%	16%	14%	18%	18%	16%	17%	23%	15%
	15%	38%	62%	45%	36%	47%	20%	42%	23%	21%	26%	25%	23%	25%	33%	22%
	20%	46%	70%	54%	44%	56%	27%	51%	30%	27%	33%	33%	30%	32%	41%	29%
CMEM Composite	5%	11%	26%	14%	9%	17%	5%	18%	7%	6%	7%	6%	5%	6%	9%	5%
	10%	20%	42%	26%	17%	31%	11%	31%	14%	12%	14%	12%	10%	12%	17%	11%
	15%	28%	54%	36%	25%	41%	16%	42%	21%	17%	20%	18%	15%	18%	24%	16%
	20%	36%	62%	44%	32%	50%	22%	51%	27%	23%	26%	24%	20%	24%	31%	21%

Table 3.3 Contribution of HEVs (Background Vehicle: VT LDV3)

VEHICLE Type	HEV%	HC					CO					NO_X				
		FTP	US06	IM240	NYCC	HFETD	FTP	US06	IM240	NYCC	HFETD	FTP	US06	IM240	NYCC	HFETD
VT HEV1	5%	55%	35%	50%	62%	47%	26%	28%	26%	24%	25%	56%	40%	51%	57%	46%
	10%	72%	53%	68%	77%	65%	42%	45%	42%	40%	41%	73%	59%	69%	74%	64%
	15%	80%	64%	77%	85%	75%	54%	56%	54%	51%	52%	81%	69%	78%	82%	74%
	20%	85%	72%	83%	89%	81%	62%	65%	62%	60%	61%	86%	76%	83%	86%	80%
VT HEV2	5%	25%	24%	21%	28%	16%	22%	40%	19%	21%	18%	29%	25%	30%	33%	23%
	10%	41%	40%	36%	45%	29%	38%	58%	34%	36%	32%	47%	42%	47%	51%	39%
	15%	53%	51%	48%	57%	39%	49%	69%	45%	48%	43%	58%	53%	59%	62%	50%
	20%	61%	60%	56%	65%	48%	58%	76%	53%	56%	52%	66%	62%	67%	70%	59%
VT HEV3	5%	77%	56%	73%	81%	70%	71%	58%	69%	73%	71%	19%	18%	18%	21%	14%
	10%	88%	73%	85%	90%	83%	84%	75%	83%	85%	84%	33%	32%	32%	36%	26%
	15%	92%	81%	90%	94%	88%	89%	82%	88%	90%	89%	44%	42%	42%	47%	36%
	20%	94%	86%	93%	95%	92%	92%	87%	92%	93%	92%	53%	51%	51%	56%	44%
VT HEV4	5%	83%	66%	80%	88%	75%	72%	58%	68%	78%	66%	51%	39%	47%	53%	42%
	10%	91%	80%	89%	94%	87%	84%	74%	82%	88%	80%	69%	57%	65%	70%	61%
	15%	94%	86%	93%	96%	91%	90%	82%	88%	92%	87%	78%	68%	75%	79%	71%
	20%	96%	90%	95%	97%	94%	92%	87%	91%	94%	90%	83%	75%	81%	84%	78%
VT - Micro Composite	5%	71%	49%	66%	77%	62%	60%	49%	57%	63%	58%	42%	31%	38%	43%	33%
	10%	84%	67%	81%	87%	77%	76%	67%	74%	78%	75%	60%	48%	56%	62%	51%
	15%	89%	76%	87%	92%	84%	83%	76%	82%	85%	82%	71%	60%	67%	72%	62%
	20%	92%	82%	90%	94%	89%	87%	82%	86%	89%	87%	77%	68%	74%	78%	70%
CMEM #19	5%	36%	41%	38%	40%	34%	19%	46%	20%	21%	21%	40%	29%	36%	54%	27%
	10%	54%	59%	56%	58%	53%	33%	64%	34%	36%	35%	59%	47%	54%	72%	43%
	15%	65%	70%	67%	69%	64%	44%	74%	45%	47%	46%	69%	58%	65%	80%	55%
	20%	73%	77%	74%	76%	71%	53%	80%	54%	56%	55%	76%	66%	72%	85%	63%
CMEM #20	5%	60%	67%	63%	64%	58%	47%	61%	49%	51%	48%	26%	22%	24%	34%	18%
	10%	76%	81%	78%	79%	74%	65%	77%	67%	68%	66%	42%	38%	40%	52%	31%
	15%	83%	87%	85%	86%	82%	75%	84%	76%	78%	76%	54%	49%	52%	64%	42%
	20%	88%	91%	89%	90%	87%	81%	88%	82%	83%	81%	62%	58%	60%	71%	51%
CMEM #21	5%	68%	74%	72%	69%	70%	35%	57%	42%	42%	34%	12%	11%	11%	18%	7%
	10%	82%	86%	84%	83%	83%	53%	74%	61%	61%	52%	22%	21%	20%	32%	15%
	15%	88%	91%	90%	88%	89%	64%	82%	71%	71%	64%	30%	30%	29%	42%	21%
	20%	91%	93%	92%	92%	92%	72%	86%	78%	78%	71%	38%	38%	36%	51%	28%
CMEM #22	5%	70%	74%	73%	74%	66%	39%	55%	40%	43%	41%	38%	32%	34%	51%	26%
	10%	83%	85%	85%	86%	80%	58%	72%	58%	62%	59%	56%	50%	53%	69%	42%
	15%	89%	90%	90%	91%	87%	69%	80%	69%	72%	70%	67%	61%	64%	78%	54%
	20%	92%	93%	93%	93%	90%	76%	85%	76%	79%	77%	74%	69%	71%	83%	62%
CMEM Composite	5%	61%	67%	64%	63%	60%	33%	54%	37%	38%	34%	29%	22%	26%	41%	19%
	10%	76%	81%	79%	79%	76%	51%	71%	55%	57%	52%	46%	38%	42%	59%	32%
	15%	84%	87%	86%	85%	84%	62%	80%	66%	67%	63%	57%	49%	54%	70%	43%
	20%	88%	90%	89%	89%	88%	70%	85%	74%	75%	71%	66%	58%	62%	77%	52%

3.4.2 Results of Traffic Simulation Analysis

In evaluating the network-wide impact of HEVs, two different networks, an interstate highway and an arterial, were considered in this study in an attempt to study the impact of HEVs for a wide range of network configurations. Specifically, a section of the I-81 Interstate Highway and a section of the Columbia Pike arterial are modeled. This section describes the geometry and characteristics of the networks, the development of modeling scenarios, and discusses the results of the analysis.

Network Characteristics

The section of I-81 extends from Christiansburg, VA to Roanoke, VA, which corresponds to mileposts 118 to 143. This section is basically a two-lane per direction highway with three-lane segments at some locations. The study section covers a total of 40 km (25 mi) of interstate highway with eight interchanges and includes truck climbing lanes at specific steep grade locations *(77)*.

Columbia Pike, State Route 244, is a major arterial feeding traffic to the Washington, DC metropolitan area, running through Arlington County. The section of the pike utilized in this study extends over 6.4 km (3.95 mi), running east from Carlin Spring Road to Joyce Street. There are 20 signalized intersections and one freeway-type interchange *(78)*.

Scenario Development

In quantifying the impact of HEVs, each scenario is simulated for one hour during the evening peak considering a variety of fleet compositions by varying the ratio of HEVs to the total fleet population. Specifically, the ratio of each of the VT-HEVs to the total traffic volume is increased from 5% to 20% in increments of 5%. The fleet is composed of light-duty HEVs only because they are believed to be the vehicles most responsible for mobile-source emissions. For the modeling of NEVs, VT-LDV3 is used as the base background vehicle as was done earlier in the pre-defined drive cycle runs. The individual scenarios are repeated considering a total of 10 different random number seeds to introduce. Please note that the roadway grades are not considered in the simulation to exclude their impact.

Simulation Results

Given all the simulation results, the emission rates are calculated by dividing the total HC, CO, and NO_X emissions in grams by the total consumed fuel in liters. The emission rates for the I-81 Interstate Highway were higher than those for Columbia Pike, except the HC emissions for VT-HEV3, -HEV4, and the composite vehicle. Note that the average emission rates do not change significantly as the proportion of HEVs is varied from 5% to 20%. The HC HEV emission rates, including VT-HEV3, -HEV4, and the composite vehicle, are at least 17 times and at most 33 times higher than normal vehicle emissions for the I-81 study network, and at least 32 times and at most 65 times for the Columbia Pike network, when compared the VT-LDV3 vehicle. The CO emissions rates for the HEVs (including VT-HEV2, -HEV3, -HEV4, and the composite vehicle) are at least 12 times and at most 26 times for I-81, and at least 4 times and at most 31 times for Columbia Pike, when compared to the VT-LDV3 vehicle. Noteworthy here is that the CO emission rates for VT-HEV2 for I-81 are much higher (5 times) than those for Columbia Pike. The NO_X emission rates for the HEVs (including VT-HEV1, -HEV4, and the composite vehicle) are at least 7 times and at most 12 times for I-81, and at least 14 times and at most 24 times for Columbia Pike, when compared to the VT-LDV3 vehicle.

For the HC emissions, the contributions of the HEVs vary from 48% to 89% for I-81, and from 63% to 94% for Columbia Pike, as the percentage of the HEVs increases from 5% to 20%. Specifically, 10% of the HEVs (including VT-HEV3, -HEV4, and the composite vehicle) account for 71%, 78%, and 66% of the I-81 emissions and 82%, 88%, 78% of the Columbia Pike emissions, respectively. For the CO emissions, the contribution of 5% to 20% of the HEVs varies from 39% to 87% for I-81 and from 17% to 88% for the Columbia Pike corridor. Ten percent of the HEVs (including VT-HEV2, -HEV3, -HEV4, and the composite vehicle) account for 57%, 74%, 73%, and 67% of the I-81 emissions and 29%, 77%, 76%, and 69% of the

Columbia Pike emissions, respectively. In the case of NO_X emissions, the HEV emission contribution varies from 28% to 75% for I-81 and from 42% to 86% for the Columbia Pike corridor. Ten percent of the HEVs (including VT-HEV1, -HEV4, and the composite vehicle) are responsible for 57%, 55%, and 44% of the I-81 emissions and 73%, 71%, and 60% of the Columbia Pike emissions, respectively.

In summary, the contribution of the HEVs is higher when the vehicles are running on an arterial in comparison to a high speed highway. When the composite vehicle is assumed as the representative vehicle of HEVs, it is demonstrated that 10% of the HEVs are responsible for 66% of the I-81 HC and 78% of the Columbia Pike HC emissions, 67% of the I-81 CO and 69% of the Columbia Pike CO emissions, and 44% of the I-81 NO_X and 60% of the Columbia Pike NO_X emissions.

Table 3.4 Contribution of HEVs From Simulation

HEV TYPE	HEV %	HC		CO		NO_X	
		I-81	PIKE	I-81	PIKE	I-81	PIKE
VT HEV1	5%	33%	49%	25%	30%	39%	56%
	10%	51%	67%	41%	48%	57%	73%
	15%	62%	76%	52%	59%	68%	81%
	20%	70%	82%	61%	67%	75%	86%
VT HEV2	5%	24%	20%	39%	17%	21%	38%
	10%	39%	35%	57%	29%	36%	57%
	15%	51%	46%	68%	40%	47%	68%
	20%	59%	54%	75%	48%	56%	75%
VT HEV3	5%	54%	69%	58%	62%	16%	23%
	10%	71%	82%	74%	77%	29%	39%
	15%	80%	88%	82%	84%	39%	50%
	20%	85%	91%	87%	88%	48%	59%
VT HEV4	5%	63%	77%	56%	61%	36%	53%
	10%	78%	88%	73%	76%	55%	71%
	15%	85%	92%	81%	84%	66%	79%
	20%	89%	94%	86%	88%	73%	84%
VT-Micro Composite	5%	48%	63%	49%	51%	28%	42%
	10%	66%	78%	67%	69%	44%	60%
	15%	75%	85%	76%	78%	56%	71%
	20%	81%	89%	82%	83%	64%	78%

Impacts of Variation in Total Demand

This section analyzes the impacts of variation in traffic volumes on the contribution of the HEVs by quantifying the changes in the contribution as the traffic volume is varied. For the quantification of the impacts of traffic demand changes, the total traffic volume used in the previous section is varied from

50% to 120% of the base demand. However, the ratio of the HEVs to the total traffic volume is set to a constant of 10% and only the VT-Micro composite HEV is considered.

The simulation results demonstrate that the contribution of HEVs to the total HC, CO, and NO_X emissions is not significantly by the changes in traffic demand. For example, the contribution of HEV emissions to the total emissions from the I-81 simulation varies from -4% to +1% when compared to the base scenario. The contribution of HEV emissions in the case of the Columbia Pike simulation varies from -1% to +1%. Specifically, the contribution to the HC, CO, NO_X emissions from the I-81 simulation ranges from 62% to 67%, from 65% to 67%, and from 44% to 45%, respectively. Those from the Columbia Pike simulation range from 77% to 79% for the HC, from 69% to 70% for the CO, and from 60% to 61% for the NO_X, respectively.

Impacts of Inclusion of Normal-Emitting Light Duty Trucks

For the modeling of NEVs, only VT-LDV3 (passenger car) was used in the previous section. Given that light duty trucks (LDTs: including pickup trucks, minivans, CUVs and SUVs) account for a large portion of the total in-use fleet in the U.S. and the sales of light duty trucks were estimated to increase in the near future, the inclusion of normal-emitting light duty trucks to the analysis should be considered. From the literature, the ratio of light duty trucks to the total light duty vehicles (including passenger cars and light duty trucks) was estimated to increase up to 64.1% in the period of 2020 through 2050 *(23)*. Thus, this section conducts a sensitivity analysis by increasing the ratio of light duty trucks from 30% to 60% in increments of 10% with a 10% HEV composite vehicle. For the modeling of normal-emitting light duty trucks, the VT-Micro models for LDTs are utilized. Specifically, the VT-LDT1 models are utilized. The model years of the vehicles categorized as VT-LDT1 in the development of the VT-Micro models are newer than or equal to 1993.

The emission rates standardized by the fuel usage and the contributions of the HEVs are calculated. The total emissions in grams increase significantly as the proportion of VT-LDT1 in the fleet increases. For example, the total HC, CO, and NO_X emissions for I-81 with 30% of the LDTs increase by 20%, 52%, and 22%, respectively, when compared to those for the traffic composed of only VT-LDV3. The emission rates for the NEV increase as well while those for the HEVs do not change significantly. In conclusion, the contribution of the HEVs decreases as the proportion of the LDTs increases because the base emission rates for NEVs are much higher. Specifically, the contribution of 10% of the HEVs for the I-81 decreases from 66% to 50% for the HC, from 67% to 35% for the CO, and from 44% to 35% for NO_X considering a 60% LDT vehicle fleet. Alternatively, the contribution for Columbia Pike decreases from 78% to 59% for HC, from 69% to 38% for CO, and from 60% to 35% for the NO_X.

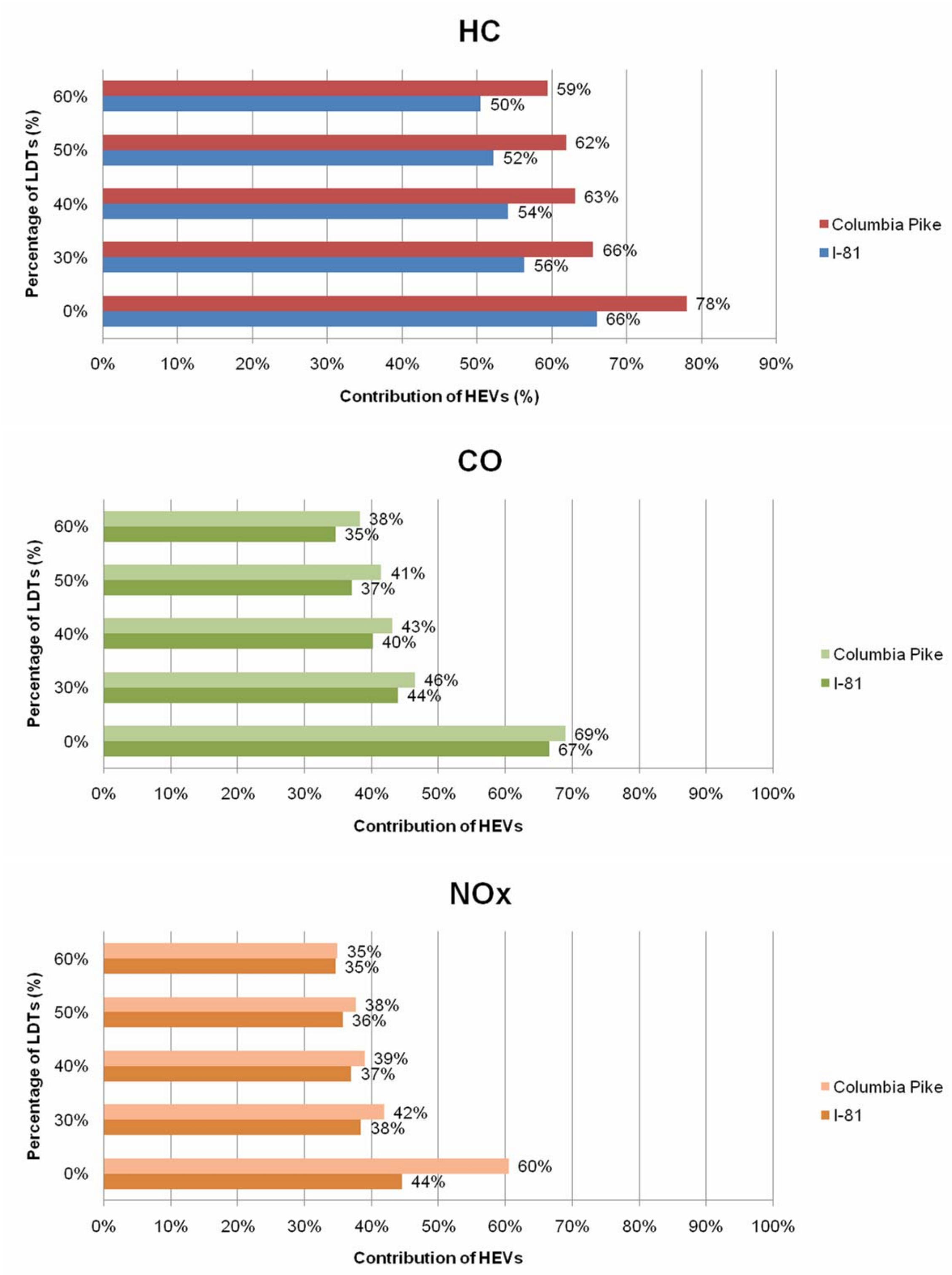


Figure 3.4 Contribution of 10% of the HEVs by the percentage of the LDTs.

3.5 Conclusions

The literature reports that 7% to 12% of HEVs account for somewhere between 41% to 63% of the total CO emissions, and 10% are responsible for 47% to 65% of HC emissions, and 10% are responsible for 32% of NO emissions. These studies, however, are based on spot measurements and do not necessarily reflect network-wide impacts. Consequently, the research presented in this paper extends the state-of-knowledge by quantifying HEV contributions on a network level. The study uses microscopic vehicle emission models (CMEM and VT-Micro model) along with pre-defined drive cycles (under the assumption that the composite HEV and VT-LDV3 represent HEVs and NEVs, respectively) in addition to the simulation of two transportation networks (freeway and arterial) to quantify the contributions of HEVs. The study demonstrates that HEVs are responsible for 67% to 87% of HC emissions, 51% to 78% of CO emissions, and 32% to 62% of the NO_X emissions for HEV percentages ranging from 5% to 20%. Additionally, the traffic simulation results demonstrate that 10% of the HEVs are responsible for 50% to 66% of the I-81 HC and 59% to 78% of the Columbia Pike HC emissions, 35% to 67% of the I-81 CO and 38% to 69% of the Columbia Pike CO emissions, and 35% to 44% of the I-81 NO_X and 35% to 60% of the Columbia Pike NO_X emissions depending on the percentage of the normal-emitting LDTs to the total NEVs.

HEV emission contributions to total HC and CO emissions appear to be consistent with what is reported in the literature. However, the contribution of NO_X emissions is greater than what is reported in the literature. The study demonstrates that the contribution of HEVs to the total vehicle emissions is dependent on the type of roadway facility (arterials vs. highways), the background normal vehicle composition, and the composition of HEVs. Consequently, these results are network and roadway specific. Finally, considering that emission control technologies in new vehicles are advancing, the contribution of HEVs will increase given that the background emission contribution will decrease.

Chapter 4: Solutions for Enhancing Remote Sensing High Emitter Vehicle Screening Procedures

Hesham Rakha, Sangjun Park, Linsey C. Marr, and Richard Olin, presented at the 86th Transportation Research Board Annual Meeting.

4.1 Introduction

To reduce air pollutant emissions to meet the National Ambient Air Quality Standards (NAAQS), many state environmental agencies are focusing their efforts on identifying high emitting vehicles (HEVs). HEVs are vehicles whose emissions of hydrocarbons (HCs) and/or nitrogen oxides (NO_x) are two times higher than the certification emissions level for the vehicle *(1)*, and/or whose emissions of carbon monoxide (CO) are three times higher. Although HEVs comprise only a small fraction of the vehicle fleet, they contribute to a large fraction of total emissions. For example, one study found that 7.8 percent of the fleet is responsible for 50 percent of the total emissions based on a gram of CO per gallon of fuel burned *(7)*. Another study found that 5 percent of the vehicles emitted 80 percent of the emissions *(8)*.

Many of the states in the U.S. operate their own Inspection and Maintenance (I/M) Program, in order to identify and repair HEVs. In addition, other supplementary devices, such as RSDs (remote sensing devices), are used to identify HEVs. Several states are now using RSDs because they can collect on-road emission data from the in-use vehicle fleet. In contrast to some I/M tests that quantify emissions on a mass per time basis over a driving cycle that can last up to four minutes, RSDs report mole fractions, or concentrations, of pollutants in exhaust at a single point in time. The advantage of RSDs is that they are able to capture site-specific measurements under real-world conditions as vehicles are driven on-road. However, several issues remain in screening HEVs and normal emitting vehicles using RSDs, including converting from concentrations to mass emission rates and setting RSD-based standards to identify HEVs.

The objectives of this paper are to validate the use of RSD measurements to predict mass emission rates, to compare and contrast different methods for estimating fuel consumption rates, and to evaluate the accuracy with which RSDs can be used to screen HEVs using the proposed methods.

In terms of the paper layout, the paper first presents the validation of the procedure developed to estimate mass emissions. Secondly, the Physical Emission Rate Estimator (PERE) model that is based on vehicle specific power (VSP) and the VT-Micro model are compared, because these models can be used to estimate fuel consumption rates. The following section presents the mass emission estimations and a comparison of the emission estimates against field measurements. Subsequently, the proposed procedure is applied for screening HEVs and normal emitting vehicles. Finally, the conclusions of the study and recommendations for further research are presented.

4.2 Validation of Mass Emission Procedure

4.2.1 Conversion of Concentration Measurements to Mass Emissions

Measurements of vehicle exhaust emissions are very important because they are used in many air-quality improvement activities such as I/M programs and the development of emission models and inventories. In practice, two test methods are widely used in quantifying vehicle exhaust emissions: mass emission tests and concentration tests. Mass emission tests directly measure the mass of several pollutants emitted from a vehicle running a simulated driving cycle. In these tests, exhaust emissions are reported in units of grams per unit time or grams per unit distance. A group of tests that are named based on the underlying drive cycle fall into this category. The Federal Test Procedure (FTP) is used to certify new vehicle emissions. Other tests used by state I/M programs include the IM240, BAR31, IM93 (CT93), and IM147 *(71)*.

Concentration tests measure the pollutants in vehicle exhaust emissions and report results in units of percentage or parts per million (PPM) of total exhaust volume. Idle and ASM tests fall into this category and are used in I/M programs in several states. Additionally, RSDs measure the concentrations of emissions from on-road vehicles. RSDs are considered a supplemental tool for I/M programs, due to their ability to capture on-road emissions. Consequently, several states in the U.S. are trying to improve their I/M programs using RSDs. However, in order to estimate the mass emissions per time a relationship between concentrations and mass emission rates needs to be developed.

The literature describes two approaches for developing conversion equations. The first approach is based on regression models. Regression models require use of both concentration and mass emission measurements of a sample of vehicles to develop coefficients. For instance, Austin et al. *(50)* proposed a new emission test procedure, the *Acceleration Simulation Mode* (ASM) test, that can correctly and economically identify 90% of vehicles that emit excessive nitrogen oxide (NO_x) emissions for I/M programs. In the study, they concluded that the ASM 5015 test is best for identifying high NO_X emitting vehicles and the 2500 rpm test could most correctly identify high CO and/or HC emitting vehicles. In addition, formulae were developed for the estimation of carbon monoxide (CO), hydrocarbon (HC), and nitrogen dioxide (NO_2) emissions using regression methods. In estimating CO and HC mass emissions, the concentration of CO and HC emissions are measured from the 2500 rpm test based on the engine size and used as the regressors for CO and HC mass emissions. Engine displacement is also used as a regressor for CO and HC mass emissions. On the other hand, the NO_X mass emissions are regressed from the concentration of NO_X emissions measured by the ASM 5015 test and the emission test weight (vehicle weight plus 300 lbs for light duty vehicles) rather than the engine size.

DeFries et al. *(79)* constructed models for simulating Virginia IM240 emissions from concentration measurements taken from ASM 5015 and ASM 2525 test procedures, because Virginia must report emission reductions in terms of mass emissions to the EPA. In this study, a dataset of 1702 paired ASM and IM240 emissions were utilized for the modeling purpose. The models for the conversion were constructed by utilizing full ASM tests, not "fast pass" ASM tests. First, raw emission concentration measurements are corrected for dilution and humidity effects. Using the corrected measurements, the intermediate predictor variables, HC, CO, and NO_X terms, are computed for the input variables. Finally, the IM240 mass emissions are regressed from HC, CO, and NO_X terms, vehicle engine displacement, vehicle age, vehicle type, and a carbureted-or-fuel injected flag. Specifically, the HC term, NO_X term, engine displacement, and vehicle age are used as regressors for IM240 HC emissions. The model for IM240 CO emissions includes the CO term, engine displacement, and vehicle age as the input variables. Lastly, the model for IM240 NO_X emissions utilizes the HC term, CO term, NO_X term, engine displacement, vehicle age, vehicle type, and carbureted-or-fuel injected engine.

The second approach for developing conversion equations is to use carbon balance for converting concentrations to mass emission rates per unit of fuel burned *(71)*. For example, Stedman, developer of the FEAT system (an RSD for on-road vehicle emissions), and his colleagues presented the equations for the conversions *(7, 80)*. Initially, they developed only one equation for CO emissions. This equation was then extended to HC and NO_x emissions when the RSD system was updated to measure these pollutants *(81)*. In addition, Singer and Harley *(82)* proposed a fuel-based methodology for computing motor vehicle emission inventories. In this study, the inventory was estimated as the product of mass-based emission factors with fuel consumption rates. In the process of calculating emission factors, the concentrations of on-road vehicle emissions were converted into mass emissions in units of grams of emissions per fuel consumed. Since the equation that they used is also based on carbon balance, it has the same structure as Stedman's. Specifically, mass emissions per fuel burned are computed by multiplying the number of moles of HC, CO, NO_X emissions per fuel burned and the molecular weight of HC, CO, and NO_X. In order to compute the number of moles for pollutant, the ratio of pollutant to the sum of CO_2, CO, and HC is multiplied by the number of moles of carbon per unit of fuel burned.

4.2.2 Data Description

The study utilizes a dataset of second-by-second IM240 emission measurements that were taken by TESTCOM since a comparison between measured emission rates and estimated emission rates can be done easily for validating a proposed procedure and for testing its effectiveness. The measurements were taken between September 2001 and April 2002. The vehicle model years ranged from 1981 to 2001, and body types included sedans, station wagons, full size vans, mini vans, pickup trucks, and sport utility vehicles.

A second-by-second IM240 emission test reports the vehicle's speed profile, HC, CO, and NO_x emission rates as a function of time, as illustrated in Figure 4.1. The tested vehicle in Figure 4.1 is a 1993 Honda Accord with a 2.4L engine.

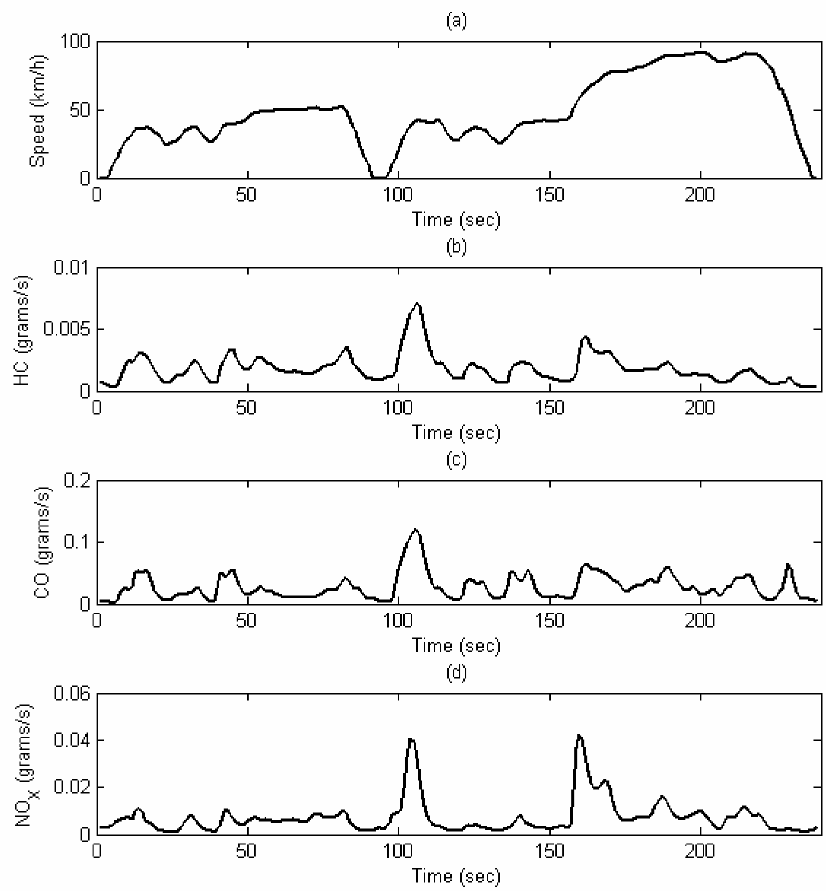


Figure 4.1 Second-by-Second IM240 emission test

4.2.3 Validation Procedure

The mass emission equations that are presented in the literature were validated by first applying them to calculate pollutant concentrations from mass emission rates measured during a sample IM240 test run. The calculated concentrations were then used together with fuel properties and the rate of fuel consumption to predict mass emission rates. The fuel consumption rate was computed using the carbon balance equation, and exhaust concentrations were estimated from the mass emissions using the combustion equation. Finally, predicted mass emission rates were compared to the original mass emission rates.

All carbon that enters the engine as fuel exits in the exhaust in the form of HC (g/s), CO (g/s), CO_2 (g/s), and a typically negligible amount of particulate matter that will be ignored here. Given that the molecular weight of carbon and oxygen are 12 and 16 g/mole, respectively, the molecular weight of CO_2 can be calculated to be 44 g/mole (12+16x2). Therefore, CO_2 contains 27.3 percent (12/44) carbon. Similarly, the molecular weight of CO is 28 g/mole (12+16) yielding 42.9 percent carbon in CO. Also, according to the Code of Federal Regulations Title 40 Part 86 (40 CFR 86), HC emissions from a gasoline powered vehicle contain 86.6 percent carbon by weight. Consequently, the instantaneous carbon emission rate in units of g/s can computed as

$$C = 0.866\,HC + 0.429\,CO + 0.273\,CO_2\,. \qquad [4\text{-}1]$$

Recognizing that average gasoline sold in the US contains 86.4 percent of carbon, and has a density of 738.8 g/L (or 2800 g/gallon), there are 638.31 (0.864x738.8) grams of carbon in a liter of gasoline. Consequently, the fuel consumption rate (L/s) can be computed as

$$F = \frac{0.866\,HC + 0.429\,CO + 0.273\,CO_2}{638.31}\,. \qquad [4\text{-}2]$$

Using the mass emissions of HC, CO, NO_x, and CO_2 available from IM240 test runs, the emission concentrations were computed by first estimating the mass emissions of N_2 through the use of the combustion equation, which can be cast as

$$CH_{1.9} + 1.48(O_2 + 3.76N_2) \rightarrow CO_2 + 0.95H_2O + 5.55N_2\,, \qquad [4\text{-}3]$$

where $CH_{1.9}$ represents gasoline; O_2 + 3.76 N_2 represents air composed of 21% O_2 and 79% N_2 (with argon and other non-oxygen components lumped with N_2); combustion is assumed to be complete with an equivalence ratio of one; and formation of minor species such as NO and CO can be neglected relative to the amount of major species such as N_2 and CO_2 emitted in the exhaust.

Consequently, the mass ratio of N_2 to CO_2 can be computed as

$$\frac{5.55\text{ mol N}_2}{1\text{ mol CO}_2} \times \left(\frac{28\text{ g N}_2}{\text{mol N}_2}\right) \times \left(\frac{\text{mol CO}_2}{44\text{ g CO}_2}\right) = 3.53\,\frac{\text{g N}_2}{\text{g CO}_2}\,. \qquad [4\text{-}4]$$

The N_2 emissions in g/s are then computed as

$$N_2 = 3.53 \times CO_2\,. \qquad [4\text{-}5]$$

In many RSDs, HCs are reported as propane (C_3H_8) equivalents, so the volumetric concentrations of HC, CO, NO_x, and CO_2 can be computed as

$$\%HC = \frac{\frac{HC}{44}}{\frac{HC}{44} + \frac{CO}{28} + \frac{NO_x}{46} + \frac{CO_2}{44} + \frac{N_2}{28}} \times 100\,, \qquad [4\text{-}6]$$

$$\%CO = \frac{\frac{CO}{28}}{\frac{HC}{44} + \frac{CO}{28} + \frac{NO_x}{46} + \frac{CO_2}{44} + \frac{N_2}{28}} \times 100\,, \qquad [4\text{-}7]$$

$$\%NO_x = \frac{\frac{NO_x}{46}}{\frac{HC}{44} + \frac{CO}{28} + \frac{NO_x}{46} + \frac{CO_2}{44} + \frac{N_2}{28}} \times 100 \text{, and} \qquad [4\text{-}8]$$

$$\%CO_2 = \frac{\frac{CO_2}{44}}{\frac{HC}{44} + \frac{CO}{28} + \frac{NO_x}{46} + \frac{CO_2}{44} + \frac{N_2}{28}} \times 100\,. \qquad [4\text{-}9]$$

where NO_x is reported as NO_2.

The estimated mass emissions of HC, CO, NO_x, and CO_2 (HC′, CO′, NO_x′, and CO_2′) are then computed as

$$HC' = 44 \times \frac{\%HC}{\%CO_2} \times \frac{0.864 \times 738.8 \times F}{12\left(1 + \frac{\%CO}{\%CO_2} + 3\frac{\%HC}{\%CO_2}\right)} \qquad [4\text{-}10]$$

$$CO' = 28 \times \frac{\%CO}{\%CO_2} \times \frac{0.864 \times 738.8 \times F}{12\left(1 + \frac{\%CO}{\%CO_2} + 3\frac{\%HC}{\%CO_2}\right)} \qquad [4\text{-}11]$$

$$NO_x' = 46 \times \frac{\%NO_x}{\%CO_2} \times \frac{0.864 \times 738.8 \times F}{12\left(1 + \frac{\%CO}{\%CO_2} + 3\frac{\%HC}{\%CO_2}\right)} \qquad [4\text{-}12]$$

$$CO_2' = 44 \times \frac{0.864 \times 738.8 \times F}{12\left(1 + \frac{\%CO}{\%CO_2} + 3\frac{\%HC}{\%CO_2}\right)} \qquad [4\text{-}13]$$

The mass emission estimates of HC′, CO′, NO_x′, and CO_2′ for a sample vehicle (1993 Honda Accord equipped with a 2.4L engine) were found to be consistent with the field measurements, as clearly demonstrated in Figure 4.2. Specifically, the slope of the line ranges from 1.0011 to 1.0012 with an R^2 of 1.0 for all model estimates. This exercise demonstrates that the mass emission equations that are proposed are valid and thus can be used to estimate mass emissions.

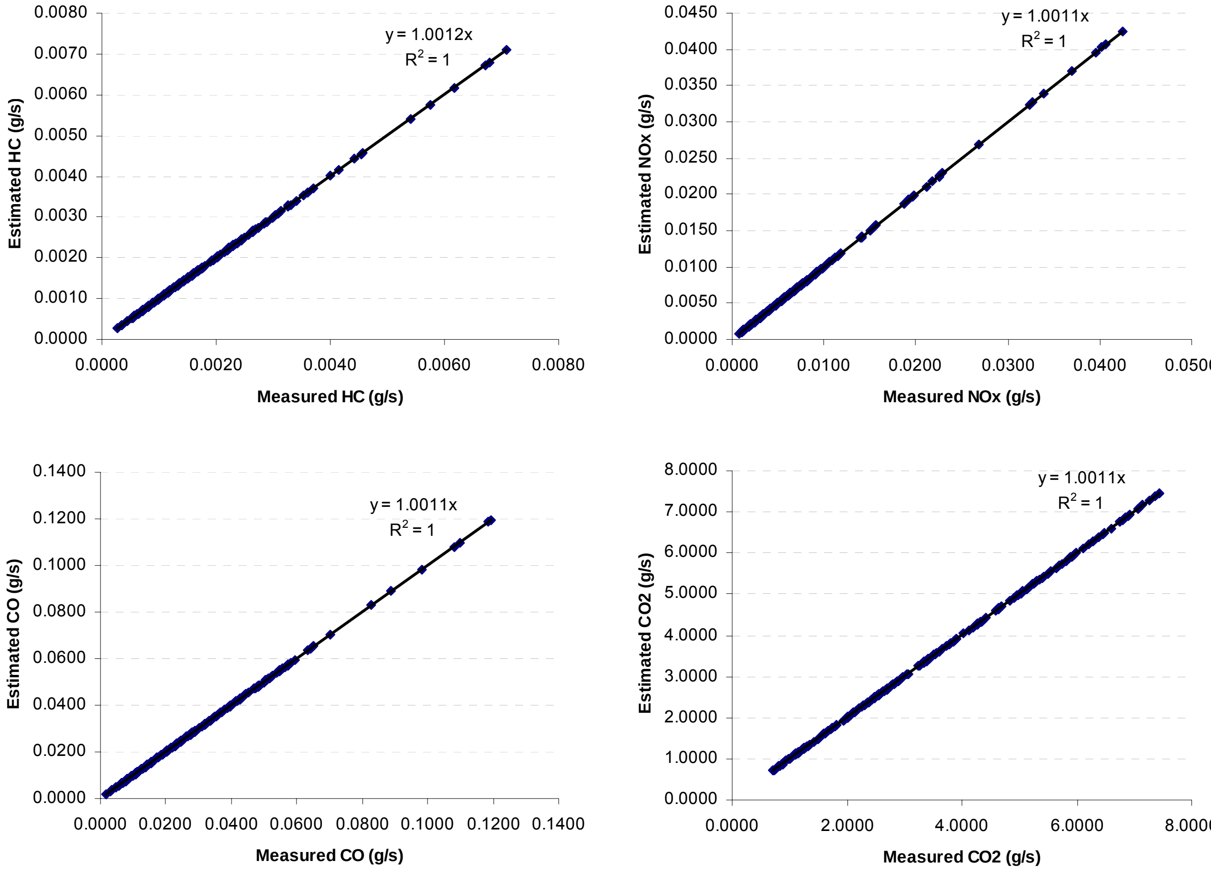


Figure 4.2 Model Validation Results

4.3 Estimation of Mass Emissions

4.3.1 Comparison of VSP and the VT-Micro Model Fuel Consumption Estimates

As demonstrated in the previous section, it is clear that the accuracy of the mass emission estimates hinges on the accuracy of the fuel consumption rates that are used to compute the mass emissions. For purposes of this study we investigated two approaches for estimating a vehicle's instantaneous fuel consumption rate, namely: an approach based on the vehicle specific power (VSP) and the use of the VT-Micro model. Each of these approaches is described in some detail in this section.

VSP is a measure of engine load that has been proposed as a primary causal variable in emissions formation for modeling purposes and has been implemented in the Environmental Protection Agency's Physical Emission Rate Estimator (PERE). One study also suggested an approach using VSP to estimate fuel consumption rates of on-road vehicles *(83)*. However PERE is only is only used to estimate fuel consumption rates in this study. PERE is meant to supplement the data driven portion of Multi-scale mOtor Vehicle and equipment Emission System(MOVES) and fill in gaps where necessary. The model is essentially an effort to simplify, improve, and implement the Comprehensive Modal Emissions Model (CMEM) developed at the University of California, Riverside. PERE is based on the premise that for a given vehicle, (engine out) running emissions formation is dependent on the amount of fuel consumed. As such, it models the vehicle fuel rate as well as CO_2 generation with some degree of accuracy. Being a physically based model, it has the potential (with some modification) to model new technologies (vehicles meeting new emissions standards), deterioration, off-road sources, I/M programs, as well as being able to easily extrapolate to areas where data are sparse.

The VSP approach to emissions characterization was proposed by Jimenez-Palacios *(84)*. VSP is a measure of the road load on a vehicle; it is defined as the power per unit mass to overcome road grade, rolling, and aerodynamic resistance in addition to the inertial acceleration. VSP is computed as

$$VSP = v[a(1+\varepsilon) + gG + gC_r] + \frac{0.5\rho C_D A v^3}{m} \quad [4\text{-}14]$$

where v is vehicle speed (assuming no headwind) in m/s, a is the vehicle acceleration in m/s^2, ϵ is a mass factor accounting for the rotational masses (~4%), g is the acceleration due to gravity, G is the roadway grade, C_r is rolling resistance coefficient (~0.0135), C_D is aerodynamic drag coefficient, A is the frontal area, and m is vehicle mass in metric tonnes.

The equation can also have an added vehicle accessory loading term (air conditioner being the most significant) added to it. Moreover, higher order terms in rolling resistance can be added to increase the accuracy of the model *(85)*. Using typical values for coefficients, in SI units the equation and assuming $C_D A/m$ ~ 0.0005, the equation can be written as

$$VSP(\text{kW/metric Ton}) = (1.04a + 9.81G + 0.132)v + 0.00121v^3 \quad [4\text{-}15]$$

The introduction of future technologies such as low rolling resistance tires and more aerodynamic forms can be reflected by adjusting the coefficients in the equation. It should be noted that the while it may be reasonable to assume typical values for rolling and aerodynamic resistance constants, it may pose a problem to assume a single mass for all cars (or vehicle types). There is approximately a factor of 2 difference in $C_D A/m$ between an empty compact car and a full large passenger car *(84)*. Using a single value for all LDVs (for example) can result in a significant error (in VSP) at high speeds when the aerodynamic resistance term dominates and when feed gas emissions are relatively high.

The fuel rate in L/s can be computed as

$$F = \frac{\varphi\left[K(N)\times N(v)\times V_d + \frac{VSP\times m}{\eta} + \frac{P_{acc}(T,N)}{\eta}\right]}{LHV} \quad [4\text{-}16]$$

where φ is the fuel air equivalence ratio (mostly = 1), $K(N)$ is the power independent portion of engine friction (dependent on engine speed), $N(v)$ is the vehicle engine speed, V_d is the engine displacement volume, η is a measure of the engine efficiency (~0.4), $P_{acc}(T,N)$ is the power drag of accessories such as air conditioning (AC), which is a function of the ambient temperature and the humidity level. Without an AC it is some nominal value (~1 kW), and LHV is the factor lower heating value of fuel (~11.6 kJ/L)*(86, 87)*.

The fuel rate is relatively insensitive to K; consequently VSP remains the primary driver of vehicle fuel consumption. The model of [4-16] represents the Physical Emission Rate Estimator (PERE), which is implemented within EPA's MOVES *(86, 87)*. This model was used to estimate the fuel consumption for the same sample vehicle that was described earlier. Currently, the PERE models are only implemented into spreadsheets. "PEREld.xls" was utilized since it is for light duty conventional vehicles. The parameters of a 1993 Honda Accord were input to the model and the fuel consumption estimates were compared to the in-laboratory measurements over the entire IM240 drive cycle, as illustrated in Figure 4.3. The figure clearly demonstrates that the PERE model tends to under-estimate the fuel consumption rate (slope of line 0.8418) with a R^2 of 0.8043.

Using the fuel consumption rates that were estimated by the PERE model, the vehicle emissions were computed and compared to in-laboratory measurements, as demonstrated in Figure 4.4. As was the case with the fuel consumption estimates, the figure clearly demonstrates that the model tends to under-estimate vehicle emissions but has a small amount of prediction error (R^2 ranges from a minimum of 90% to a maximum of 97%).

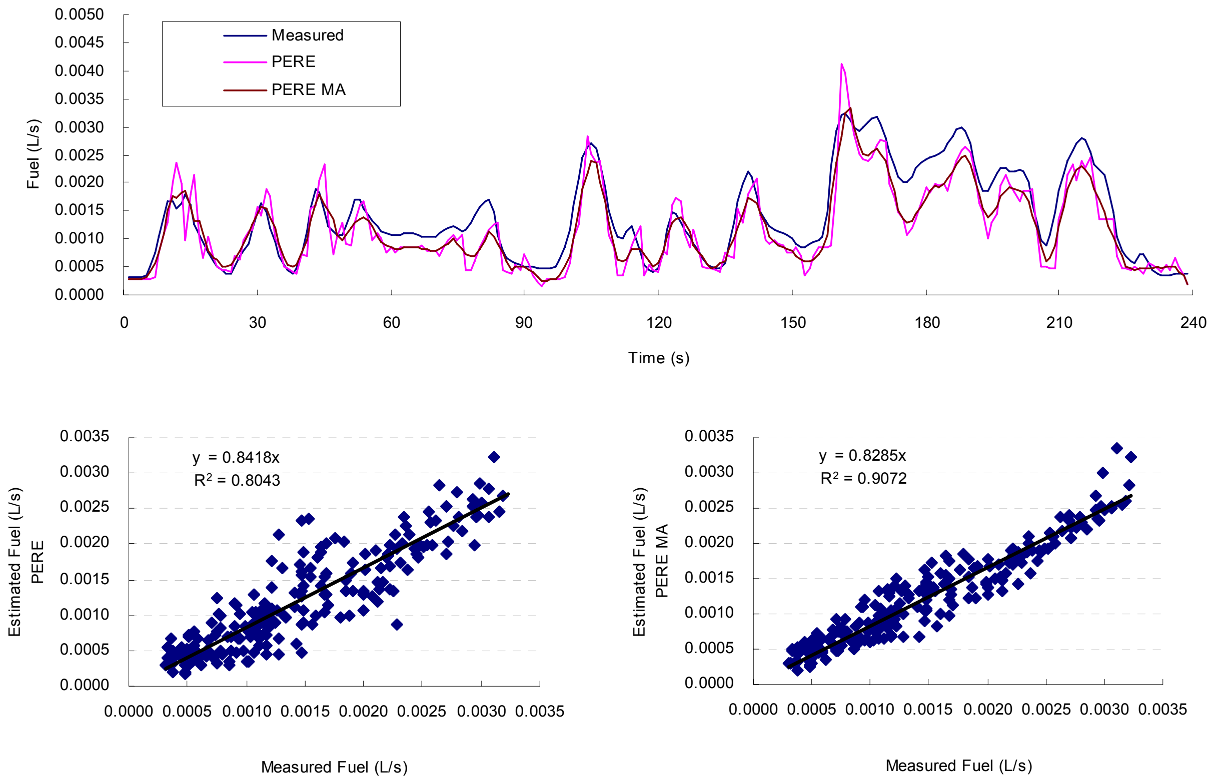


Figure 4.3 PERE Estimated vs. In-laboratory Measured Fuel Consumption Rates

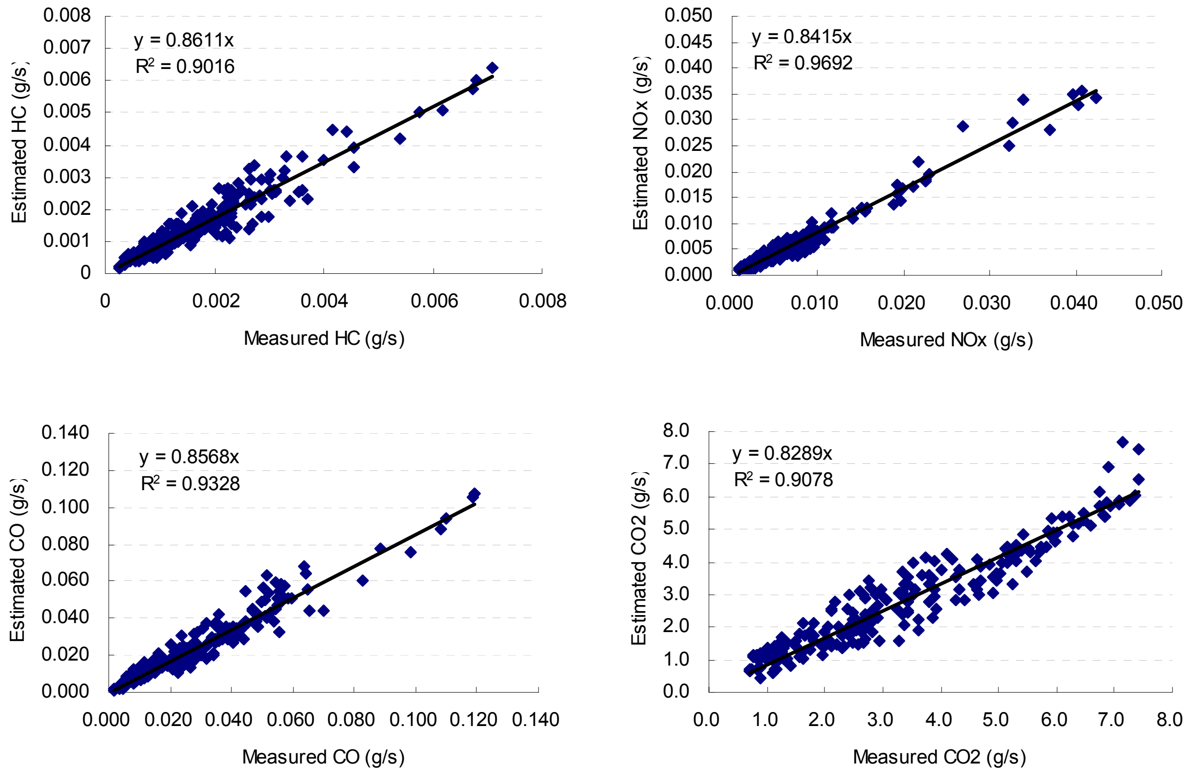


Figure 4.4: Estimated Emission Rates from Fuel Rates Estimated Using PERE vs. In-laboratory Measured Emission Rates

In addition to the PERE model, the VT-Micro model was tested as an alternative tool for predicting the vehicle fuel consumption rate. The VT-Micro model, unlike the PERE model, is a statistical as opposed to a physical model. The model estimates vehicle fuel consumption and emission rates using a combination of speed and acceleration levels by means of a dual-regime model as

$$MOE_e = \begin{cases} e^{\sum_{i=0}^{3}\sum_{j=0}^{3} L_{i,j}^{e} \times u^i \times a^j} & \text{for a} \geq 0 \\ e^{\sum_{i=0}^{3}\sum_{j=0}^{3} M_{i,j}^{e} \times u^i \times a^j} & \text{for a} < 0 \end{cases}, \qquad [4\text{-}17]$$

where $L^e_{i,j}$ and $M^e_{i,j}$ represent model regression coefficients for MOE *e* (HC, CO, NO_X, CO_2, fuel) at speed exponent *i* and acceleration exponent *j (5, 88, 89)*. The model was developed using a sample of 101 light duty vehicles (LDVs). The data were gathered by EPA on a chassis dynamometer at the Automotive Testing Laboratories, Inc. (ATL) in Ohio, and EPA's National Vehicle and Fuels Emission Laboratory (NVREL) in Ann Arbor, Michigan in the spring of 1997. All vehicles at ATL were drafted as a stratified random sample at Inspection and Maintenance lanes utilized by the State of Ohio. The vehicles tested at the EPA laboratory were recruited randomly. All vehicles were tested under as-received condition (without repairs). Of the total 101 vehicles 62 vehicles were tested at ATL and 39 vehicles were tested at NVREL. Of the 101 vehicles, 96 vehicles had complete datasets. Furthermore, of these 96 vehicles, 60 vehicles were classified as normal vehicles. These 60 normal vehicles were grouped into homogenous groups using a Classification and Regression Tree (CART) algorithm. The CART algorithm is a datamining technique that uses a regression tree method that automatically searches for important patterns and relationships and quickly finds hidden structures in highly complex data. Tree structured classifiers or binary tree structured classifiers are built by repeating splits at active nodes. An active node is divided into two sub-nodes based on a split criterion and a split value. The splitting process is generally continued until (a) the number of observations in a child node has met a minimum population criteria or (b) a minimum deviance criteria at a node is met, where the deviance criteria D is defined as the Sum of Squared Error (SSE) *(8, 90, 91)*.

The dependent variable (Y) was a 60-by-4 matrix that included 4 dependent variables for 60 normal vehicles. The dependent variables included HC, CO, CO_2, and NO_x emissions averaged over 15 drive cycles. Similarly, the independent variable (X) was a 60-by-n matrix that included a number of vehicle attributes, including the vehicle model year, engine technology, engine size, and vehicle mileage. Alternatively, the X matrix can be thought of as a set of vectors X_k, each composed of 60 elements, where k is the vehicle attribute index under consideration in the CART algorithm.

The vehicles were classified into 5 LDV and 2 LDT categories, as demonstrated in Table 4.1. The Honda Accord vehicle would fit in category LDV2 because its mileage was 81,360. However LDV5 was the closest to the sample vehicle in terms of fuel consumption. Thus the VT-Micro LDV2 and LDV5 models were utilized to estimate fuel consumption rates.

Table 4.1 CART Algorithm Vehicle Classification

Vehicle Category	Number of Vehicles
Category for Light Duty Vehicles	
LDV1: Model Year < 1990	6
LDV2: 1990<=Model Year<1995, Engine Size < 3.2 liters, Mileage < 83653,	15
LDV3: Model Year >= 1995, Engine Size < 3.2 liters, Mileage < 83653,	8
LDV4: Model Year >=1990, Engine Size < 3.2 liters, Mileage >= 83653	8
LDV5: Model Year >=1990, Engine Size >= 3.2 liters	6
LDV High Emitters	24
Category for Light Duty Trucks	
LDT1: Model Year >= 1993	11
LDT2: Model Year < 1993	6
LDT High Emitters	12
Total Vehicles	96

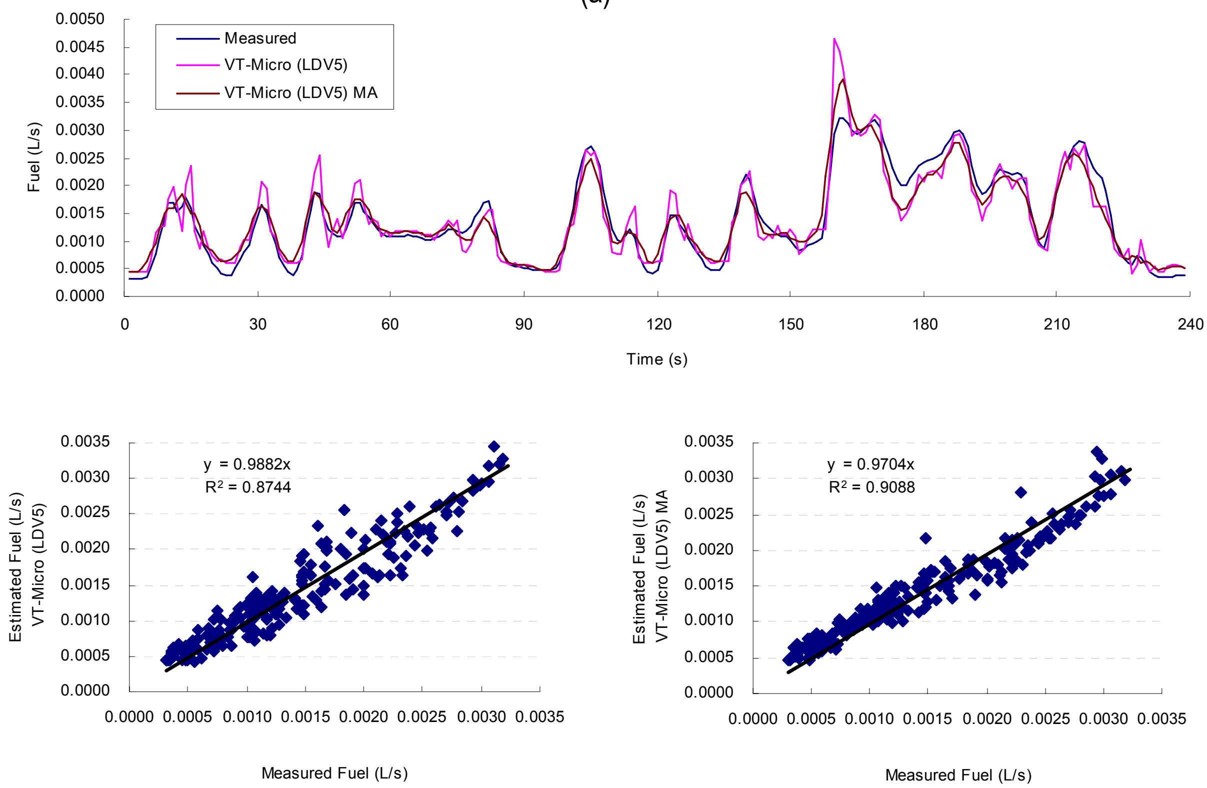
The results of the analysis demonstrate a high degree of correlation between the estimated instantaneous fuel consumption rate and the measured rate. In addition, the LDV5 model produced closer fuel consumption rates than the LDV2 did, as demonstrated in

Figure 4.5. The impact of the use of a moving average (MA) size 5 on a degree of correlation and errors is also demonstrated in

Figure 4.5. The MA is used to smooth some of the peaks in the model estimates and to account for the historical effects on vehicle fuel consumption and emission rates. The estimated and smoothed VT-Micro LDV5 model fuel consumption rates in conjunction with the emission concentrations were then utilized to estimate the vehicle emissions of HC, CO, NOx, and CO2. The results clearly demonstrate a minimum systematic error (slope of line close to 1) and a high degree of correlation (R2 in excess of 90%), when using the VT-Micro LDV5 model.

Comparing Figure 4.3 to Figure 4.5, both of the VT-Micro and PERE models appear to provide reliable estimates of vehicle fuel consumption since all the R^2 values are greater than 0.80. In terms of errors, the VT-Micro LDV5 model produced closer fuel estimates to the measured fuel consumption rates, while the VT-Micro LDV2 and PERE models under-estimated fuel consumption rates.

(a)



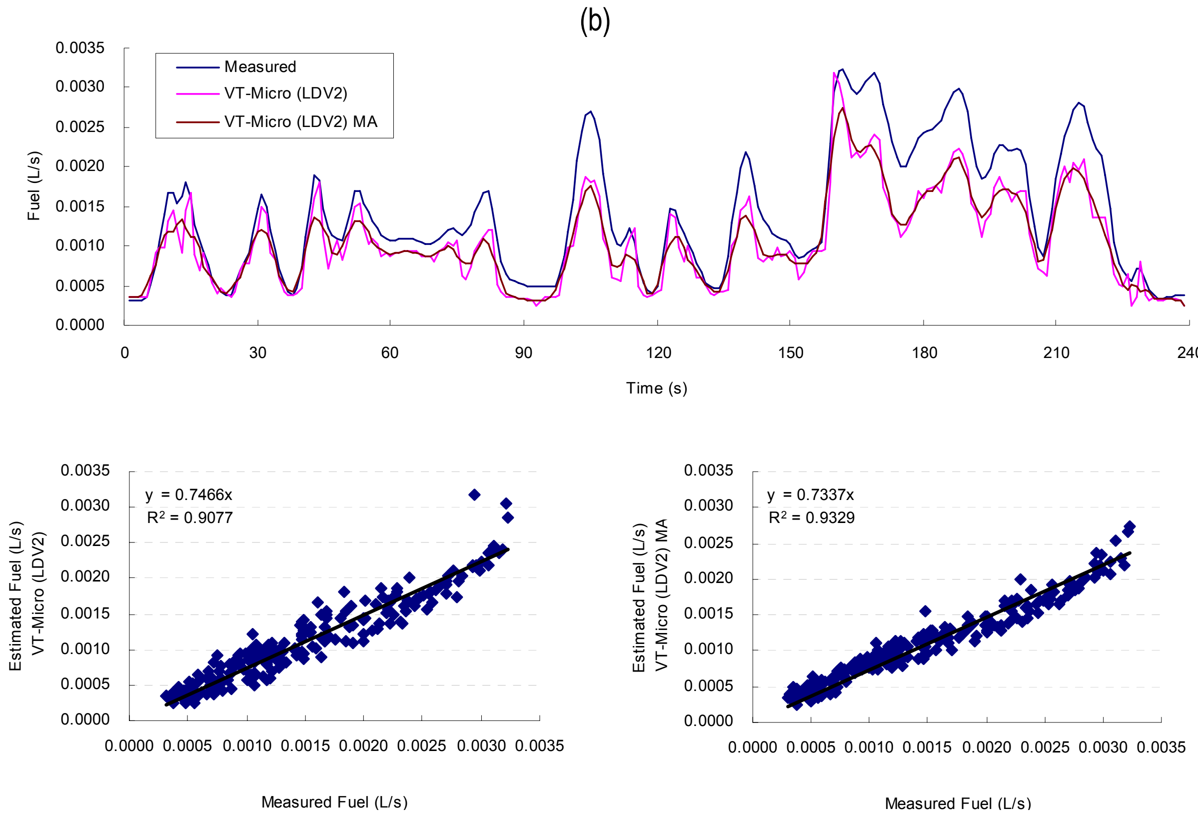


Figure 4.5: VT-Micro Estimated vs. In-laboratory Measured Fuel Consumption Rates

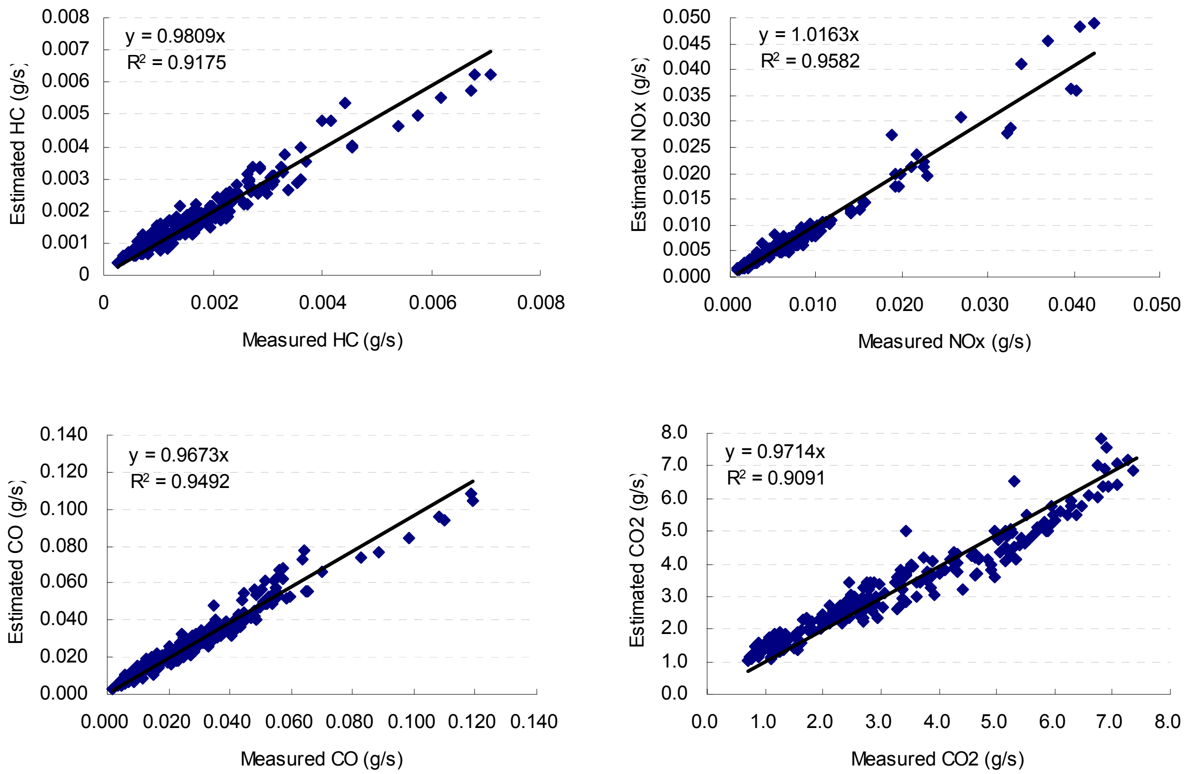


Figure 4.6: Estimated Emission Rates from Fuel Rates Estimated Using VT-Micro Model LDV5 vs. In-laboratory Measured Emission Rates

4.3.2 Different Vehicle Type Analysis

As was demonstrated in the previous section, both of the VT-Micro and PERE approaches provided reliable estimates of vehicle fuel consumption and mass emission estimates for the sample Honda vehicle. This section expands the analysis by considering different vehicle types including station wagons, full size vans, mini vans, pickup trucks, and sport utility vehicles, as summarized in Table 4.2.

The classification of the sample vehicles was achieved using two methods. The first method involved selecting the vehicle category based on the vehicle parameters and matching these parameters with the CART classifications that were demonstrated earlier in Table 4.1. The second approach categorized vehicles based on their fuel consumption rates by comparing each sample vehicle to the VT-Micro model vehicle classifications in terms of fuel consumption rates using the IM240 test cycle. The second approach was utilized because it provided better results in terms of systematic errors and degree of correlation.

Table 4.2 Specification of Tested Vehicles

Vehicle Type	Engine Size (L)	ETW* (lb)	Make	Model	Model Year	Number of Cylinders	Odometer (mi)	Tr.*	TRLHP*
Sedan	2.4	3500	Honda	Accord	1993	4	81,360	A	11.3
Station wagon	1.9	2750	Ford	Escort	1993	4	111,471	A	11.4
Full size	5	4000	Ford	E150 Econoline	1988	8	169,231	A	20
Minivan	3	4000	Mazda	MPV	1991	6	124,733	A	14.8
Pickup	1.6	2750	Geo	Tracker	1991	4	5,014	M	16
SUV	4	4500	Ford	Explorer 2-DR.	1993	6	127,928	A	16.5

*ETW: Equivalent Test Weight
*Tr.: Transmission Type (A:Auto, M: Manual)
*TRLHP: Track Road Load Horse Power

Using the second-by-second IM240 emission measurements for the five sample vehicles a comparison of the VT-Micro and PERE estimates was conducted, as summarized in Table 4.3. The results summarize the slope and R^2 of the regression line for each of the vehicle types. The results of the analysis demonstrate that both of the VT-Micro and PERE models provide reliable estimates of vehicle fuel consumption and emission rates, with low systematic errors and high degrees of correlation. It is hard to determine which model is superior than the other based on the results, although the VT-Micro models have slightly higher R^2 values. As can be seen in Table 4.3, the slope of the regression line ranges from 0.75 to 1.35 and 0.73 to 1.13 for the VT-Micro and PERE models, respectively. Alternatively, the R^2 ranges from 0.60 to 1.00 and 0.43 to 0.99, for the VT-Micro and PERE models, respectively.

Table 4.3 Slope and R^2 of Trend Line

	Vehicle Type	VT-Micro Model 1)					PERE 2)				
		HC	CO	NO_X	CO_2	Fuel	HC	CO	NO_X	CO_2	Fuel
Slope	Sedan	0.98	0.97	1.02	0.97	0.97	0.86	0.86	0.84	0.83	0.83
	Station Wagon	1.00	0.99	0.98	0.97	0.97	0.95	1.01	0.91	0.96	0.96
	Full Size Van	0.82	0.81	0.91	0.83	0.83	1.09	1.05	1.13	1.12	1.12
	Mini Van	0.85	0.85	0.84	0.85	0.85	0.89	0.86	0.85	0.87	0.87
	Pickup Truck	1.28	1.24	1.35	1.14	1.14	0.94	0.87	0.73	0.87	0.87
	SUV	0.78	0.81	0.75	0.76	0.76	1.03	0.96	0.91	0.91	0.91
R^2	Sedan	0.92	0.95	0.96	0.91	0.91	0.90	0.93	0.97	0.91	0.91
	Station Wagon	0.60	0.90	0.94	0.92	0.92	0.43	0.87	0.93	0.87	0.87
	Full Size Van	0.98	1.00	0.96	0.95	0.95	0.96	0.99	0.90	0.87	0.89
	Mini Van	0.99	0.99	0.99	0.97	0.97	0.93	0.93	0.94	0.89	0.89
	Pickup Truck	0.96	0.97	0.99	0.89	0.90	0.97	0.98	0.89	0.93	0.93
	SUV	0.97	0.97	0.98	0.92	0.92	0.97	0.97	0.97	0.89	0.89

1) VT-Micro Model means that HC, CO, NO_X, CO_2 emissions are estimated from the fuel rates that are estimated by using the VT-Micro models and smoothed (Moving average 5 seconds)
2) PERE means that HC, CO, NO_X, CO_2 emissions are estimated from the fuel rates that are estimated by using the PERE and smoothed (Moving average 5 seconds)

4.4 Screening High Emitting Vehicles

This section presents a new method for accurately identifying HEVs from RSD measurements. Both mass emission rates and HEV cut points must be calculated from the instantaneous measurements. As illustrated in the previous section, mass emission rates are calculated from RSD concentration measurements and fuel consumption rates predicted by VT-Micro. Then, second-by-second HEV thresholds are estimated using VT-Micro as a function of vehicle category, speed, acceleration, and appropriate scaling factors, whose derivation is described below. If the mass emission rate exceeds the HEV threshold, the vehicle is then considered to be a potential high emitter.

4.4.1 Emission Standards for High Emitting Vehicles

Quantitative criteria, or cut points, based on measured emission rates are desired to identify high emitting vehicles. The EPA *(1)* recommends a cutoff that is two times the certification emission standard for HC and NO_X emissions and three times the standard for CO emissions. These thresholds are developed for an entire cycle as opposed to second-by-second data. In addition, given that vehicle base emission rates differ from one vehicle to another, scaling factors are computed from the entire trip as

$$\text{Scale Factor} = \frac{\text{IM240 Standard}}{\text{LDV's IM240 Emissions}}. \qquad [4\text{-}18]$$

The second-by-second cut points are then computed as

$$\text{Cutpoint}_i = \text{Scale Factor} \times \text{LDV Emission Rate}_i . \qquad [4\text{-}19]$$

Where $Cutpoint_i$ is the cut-point at time instant *i*.

In computing the emission cut points, the IM240 emissions for the VT-Micro normal emitting vehicle classes, LDV1 through LDV5, and LDT1 and LDT2, are computed as the ratio of vehicle emission rates (Table 4.4) to the HEV thresholds (Table 4.5) to compute vehicle-class specific scale factors using Equation [4-18], as summarized in Table 4.6. The results of Table 4.6 clearly demonstrate that apart from LDV1, the required scale factors are much higher than what is recommended in the literature. Finally, the second-by-second emission cut points for the VT-Micro normal emitting vehicle classes are computed by multiplying the corresponding scale factors and the instantaneous emission rates. Consequently, a total of seven second-by-second emissions cut points are constructed; one for each vehicle class. Figure 4.7 illustrates the procedure of constructing the second-by-second emission cut points for LDV1.

An important aspect in deriving the cut points is determining the class of the vehicle in computing the corresponding cut point.

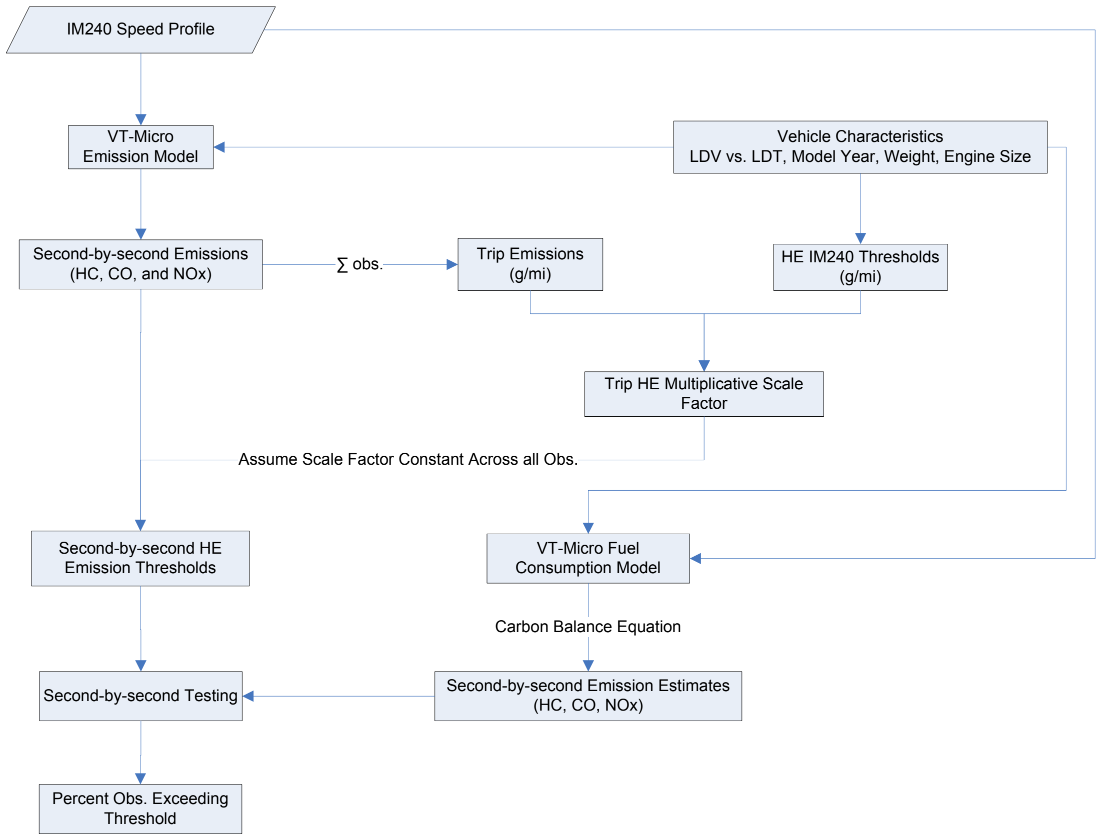


Figure 4.7 Flowchart for the Construction of the Second-by-second Emission Cut Points (LDV1)

Table 4.4 IM240 Emissions for Normal Emitting LDVs and LDTs using VT-Micro Model (grams/mile)

Category	HC	CO	NO_x
LDV 1	0.321	4.878	0.880
LDV 2	0.084	1.794	0.480
LDV 3	0.031	0.690	0.176
LDV 4	0.255	4.470	0.510
LDV 5	0.180	4.422	0.991
LDT 1	0.109	2.365	0.510
LDT 2	0.222	6.099	0.920

Table 4.5 IM240 Composite Emission Standards for LDVs and LDTs (grams/mile) ***(92)***

Category	Model Year	HC	CO	NO_x
LDV	1996+	0.6	10	1.5
	1983-1995	0.8	15	2
LDT (GVWR<6000)	1996+			
	(<= 3750)	0.6	10	1.5
	(>3750)	0.8	13	1.8
	1988-1995	1.6	40	2.5

Table 4.6 Vehicle Specific HEV Scale Factors

Category	HC	CO	NO_X
LDV 1	2.49	3.07	2.27
LDV 2	9.49	8.36	4.17
LDV 3	25.98	21.74	11.39
LDV 4	3.13	3.36	3.92
LDV 5	4.45	3.39	2.02
LDT 1	14.64	16.91	4.90
LDT 2	7.20	6.56	2.72

4.4.2 Screening High Emitting Vehicles

Having computed the HEV cut points, the next step was to validate the proposed procedure using the carbon balance equation in conjunction with the VT-Micro fuel consumption estimates for the screening of HEVs. Because an IM240 test includes second-by-second emission rates for HC, CO, and NO_X over 240 seconds (239 measurements), 239 tests are conducted. Using the proposed procedures for estimating mass emissions from emission concentrations, the estimated mass emissions were compared against the proposed HEV cut points and the percentage of observations that were below the HEV thresholds were recorded. The objective of this exercise was to quantify the efficiency of the proposed procedure in the screening of HEVs.

Figure 4.8 illustrates emission measurements and estimates for the Honda Accord sample vehicle that were presented earlier (Honda Accord, MY 1993, 2.4L engine) along with the proposed cut points. The sample vehicle is classified as a normal vehicle because it emits 0.22 g/mi of HC, 3.36 g/mi of CO, and 0.86 g/mi of NO_X over the entire IM240 test, which is less than the thresholds identified in Table 4.5. Consequently, it is anticipated that most of the second-by-second emission measurements should not exceed the proposed cut points. As can be seen in Figure 4.8, most emission measurements and estimates do not exceed the HEV cut points. However, there are a few measurements and estimates that do exceed the cut points, which imply that if a remote sensing test happened to catch this vehicle during these measurements, the vehicle would be erroneously identified as an HEV.

In validating the proposed method for screening HEVs, the percentage of correct identifications using the proposed approach are compared to direct measurement comparisons, as summarized in Table 4.7. The results are very encouraging demonstrating the use of the proposed procedure does not degrade the performance of the HEV screening procedure. For example, the Honda Accord (sedan) was correctly identified 100%, 97%, and 89% of the time as a normal emitting vehicle using in-laboratory measured emissions for HC, CO, NO_X emissions, respectively. Alternatively, 100%, 97%, and 88% of the observations, which are equivalent to 100%, 100%, and 99% relative to the results from the in-laboratory measured emissions, were correctly identified as normal in terms of HC, CO, NO_X emissions using the estimated emissions based on the proposed approach. The results of identification for other vehicle types that were described earlier in Table 4.2 are also shown in Table 4.7. As can be seen in Table 4.7, the correct identification of normal emitting vehicles is consistent with in-laboratory measured emissions. Therefore, it is clearly demonstrated that the proposed methods can be applicable for the screening HEVs and normal emitting vehicles.

Table 4.7 Correct Detection Rates of both Measured and Estimated Emissions

Category	HC			CO			NOx		
	Measured	Estimated		Measured	Estimated		Measured	Estimated	
		Absolute	Relative		Absolute	Relative		Absolute	Relative
Sedan	100%	100%	100%	97%	97%	100%	89%	88%	99%
Station Wagon	96%	93%	97%	92%	90%	98%	72%	70%	97%
Fullsize	94%	97%	104%	97%	98%	101%	73%	76%	105%
Minivan	100%	100%	100%	100%	100%	100%	88%	91%	103%
Pickup	98%	98%	100%	99%	99%	100%	97%	96%	99%
SUV	100%	100%	100%	99%	99%	100%	68%	82%	121%

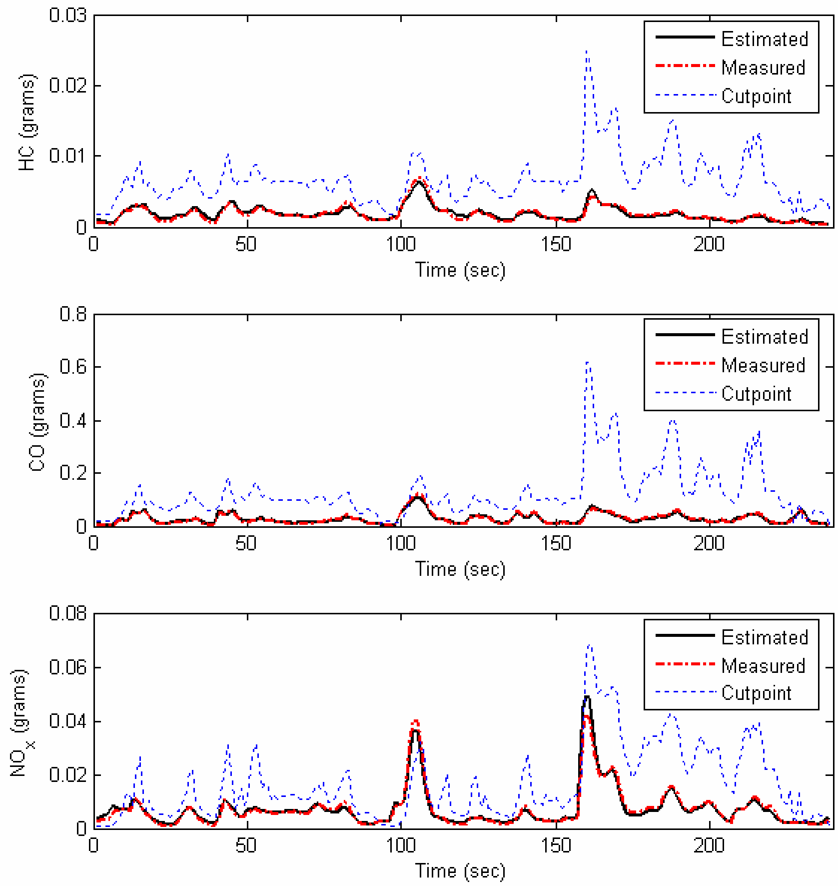


Figure 4.8 In-Laboratory Measured IM240 Emission and Estimated Emission

4.5 Conclusions

The study presents a new approach for estimating vehicle mass emissions from concentration emission measurements using the carbon balance equation in conjunction with the either the VT-Micro or PERE model fuel consumption rates. The study demonstrates that the proposed approach produces reliable mass emission estimates for different vehicle types including sedans, station wagons, full size vans, mini vans, pickup trucks, and SUVs. Finally, the study demonstrates that the proposed procedure can be used to enhance current state-of-the-art HEV screening procedures using RSD technology.

As is the case with any research effort, this study demonstrates the need for further research to identify the engine load conditions that provide optimum HEV screening and to develop instantaneous load-specific cut points for identifying HEVs. Since this study provides a procedure to convert concentration measurements into mass emissions per unit time at specific engine loads, HEV screening could be enhanced by identifying the engine loads that result in largest differences between normal vehicles and HEVs. Any screening procedure can produce erroneous vehicle screening depending on the vehicle speed and acceleration levels. Consequently, further research is required to identify the engine loads that are required to minimize false alarms (erroneous identification of normal vehicles as HEVs) and detection errors (erroneous identification of an HEV as a normal vehicle).

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Chapter 5: Derivation of Remote Sensing Cut Points for the Screening of High-Emitting Vehicles

Sangjun Park and Hesham Rakha, presented at the 87th Transportation Research Board Annual Meeting.

5.1 Introduction

There is no doubt that mobile-source emissions are a large contributor to air pollution. To achieve the U.S. National Ambient Air Quality Standards (NAAQS), state departments of environmental quality have been making a tremendous and continuous effort to reduce mobile-source emissions by identifying and repairing high-emitting (HE) vehicles. Remote sensing devices (RSDs), used to identify HE vehicles, are supplementary tools to enhance existing inspection and maintenance (I/M) programs. For example, the Virginia Department of Environmental Quality (DEQ) uses remote sensing (RS) to enhance the I/M program because the DEQ determined that RSDs are the only available technology to measure on-road vehicle emissions in a cost-effective manner. Specifically, RSDs are used to identify HE vehicles, very clean vehicles, and vehicles that are operated without an emission inspection although they are subject to it *(93, 94)*.

One concern of utilizing RSDs that researchers have identified is that the vehicle driving condition at the time of measurement is not known, although it is highly related to fuel consumption and emission rates. For instance, some vehicles running on a steep roadway grade have a high engine load, which commands the engine to operate in a fuel-rich manner and results in large increases in carbon monoxide (CO) emissions and volatile organic compounds (VOC) rates. Consequently, several researchers proposed a methodology to derive the engine load of a vehicle passing across the RSD with given tractive forces and resistance forces that are calculated from the information relating to roadway grades, vehicle specifications, vehicle speed, and acceleration *(4)*. The vehicle specific power (VSP) approach was proposed by Jimenez-Palacios, which is being used in a practical manner to avoid emission measurements under very low and/or high engine loads *(84)*. However, the state-of-practice of testing the compliance with on-road emission standards is actually to use a constant value insensitive to the vehicle driving condition at the time of measurement as an emission standard for a vehicle *(95, 96)*. Consequently, the objective of the study presented here is to construct on-road RS emission standards sensitive to vehicle speed and acceleration levels to enhance the effectiveness of RS.

This paper initially presents an overview of emission measurement techniques and the framework of the VT-Micro emission models and the Comprehensive Modal Emission Models (CMEMs) because the study uses these models to simulate normal-emitting and high-emitting vehicles. The following section details the proposed procedure for constructing remote sensing cut points sensitive to vehicle speed and acceleration levels. Subsequently, a comparison between the proposed cut points and the existing cut points is presented. In addition, sample tests utilizing the proposed remote sensing cut points are presented. Finally, the paper presents the conclusions of the study.

5.2 Background

This section presents a brief overview of emission measurement techniques focusing on IM240, acceleration simulation mode (ASM) because the emission standards for both the IM240 and ASM tests are used for the construction of remote sensing cut points in this study. Secondly, the background, technology, and issues associated with remote sensing are introduced to provide the basics of remote sensing and to derive the research motivation. Finally, two microscopic emissions models, the VT-Micro emission model and the CMEM, are introduced since the models are used to simulate normal-emitting and HE vehicles.

5.2.1 Measurement Techniques for Emission Tests

There are several emission measurement techniques in use such as the Federal Test Procedure (FTP), idle, IM240, ASM, remote sensing, and on-board diagnostics tests. Among these, either the IM240 or the ASM test is being utilized as a formal emission test for I/M programs across the United States.

IM240

The IM240 test directly measures the mass of exhaust emissions every second over a 240-second drive cycle while the test vehicle is being driven on a dynamometer following a pre-defined driving cycle. The driving cycle is equivalent to the first 240 s of the bag 2 phase of the FTP test, thus the vehicle is assumed to be fully warmed before the test *(4, 43)*. Instantaneous emission rates in grams of fuel are recorded and composite emission rates in grams per mile for phase 2 (from 49 to 239 s into the drive cycle) and the entire drive cycle are reported. Given the reported emission rates, the compliance to the corresponding IM240 emission standards is tested. The IM240 final standards include seven tables for light duty vehicles, high-altitude light duty vehicles, light duty trucks 1, high-altitude light duty trucks 1, light duty trucks 2, high-altitude light duty trucks 2, and heavy duty trucks. Each table includes standards in grams per mile for phase 2 and the entire test for hydrocarbons (HC), CO, and oxides of nitrogen (NO_X) for each model year classification *(92)*.

Acceleration Simulation Mode

The ASM test was developed by the California Bureau of Automotive Repair (BAR) to overcome the shortcomings that reside in the IM240 test. One shortcoming is a relatively-long test time of 240 s per vehicle. Another is the small number of centralized test stations available which, thus, causes significant queuing at the test facilities *(4, 50)*. The ASM test measures exhaust concentrations (from the vehicle that is driven) on a dynamometer under a pre-specified mode. The pre-specified mode is characterized by a speed and a vehicle load. Practically, the ASM 2525 test (25% of the maximum vehicle load encountered on the FTP at 25 mph) and the ASM5015 test (50% of the maximum vehicle load encountered on the FTP at 15 mph) are given to each vehicle *(4, 43)*. The ASM final standards consist of three lookup tables for HC, CO, and NO_X. The standards can be looked up using vehicle type, model year, and vehicle weight. The vehicle types include light duty vehicles, high-altitude light duty vehicles, light duty trucks 1, high-altitude light duty trucks 1, light duty trucks 2, and high-altitude light duty trucks 2 *(97)*.

5.2.2 Remote Sensing Emissions

The first version of remote sensing instrumentation applied in the field was developed in the late 1980's by researchers at the University of Denver, although the idea of remote sensing measurements of emissions was proposed elsewhere *(4, 80)*. The first attempt to develop an instrument that measures emissions was first made by Lockheed Missiles and Space Corporation, but it was not reported whether the device measured on-road emissions successfully. Later, it was demonstrated that the use of a gas filter correlation radiometer enables the measurement of CO plumes exhausted from passing cars. This system did not provide the parameters necessary to estimate emission rates from the measured plumes *(80)*.

RSDs use a technology for measuring the changes in the intensity of a light beam due to the interruption caused by a passing vehicle's exhaust plume. The first generation of RSDs used an infrared beam to measure concentrations of HC and CO. Some RSDs recently use an ultraviolet beam to measure NO *(4, 43)*. The most affordable reason to use RSDs is that they can measure on-road emissions from the in-use vehicle fleet. RSDs are typically installed at locations that do not incur high engine load conditions and are not a safety hazard to equipment, staff, and drivers at the same time. An installed RSD measures and records the concentration of HC, CO, carbon dioxide (CO_2) and NO_X emissions of a passing vehicle as well as its speed, acceleration, and license plate. Then the recorded data is checked to determine if it is valid and within the acceptable vehicle specific power (VSP) range, in order to increase the detection rate of HE vehicles (because it is difficult to identify HE vehicles under high or low VSP conditions). A comparison of the measured emissions to the RS cut points determines whether or not a vehicle is a high emitter. If a vehicle is identified as a high emitter, the vehicle is subjected to an official I/M program test such as the ASM or IM240 test for confirmation *(4, 98)*. Meanwhile, RS is also used to identify very clean vehicles in terms of exhaust emissions, which is referred to as white screening. In this application, if a vehicle is identified as a clean vehicle, the vehicle is exempted from a scheduled official emission test *(14, 99)*.

The literature describes several on-road remote sensing emission thresholds for HE vehicles. For example, the Oregon DEQ conducted an RSD study in 2003 that defined the dirty category threshold for HC, CO, and NO_X emissions standards as 220 parts per million (ppm), 1.0%, and 1,000 ppm, respectively *(95)*. The state of Illinois has established its own on-road RS emissions standards to include HC and CO emission thresholds for each model year classification *(96)*. These examples show that existing on-road remote sensing emission standards are not unified and are typically insensitive to vehicle speed and acceleration levels even though vehicle emissions are highly affected by engine loads.

5.2.3 VT-Micro Emissions Models

The VT-Micro emission models were developed from experimentation with numerous polynomial combinations of speed and acceleration levels. Specifically, linear, quadratic, cubic, and fourth degree combinations of speed and acceleration levels were tested using chassis dynamometer data collected at the Oak Ridge National Laboratory (ORNL). The final regression model included a combination of linear, quadratic, and cubic speed and acceleration terms because it provided the least number of terms with a relatively good fit to the original data (R^2 in excess of 0.92 for all measures of effectiveness [MOE]). The ORNL data consisted of nine normal-emitting vehicles including six light-duty automobiles and three light-duty trucks. These vehicles were selected in order to produce an average vehicle that was consistent with average vehicle sales in terms of engine displacement, vehicle curb weight, and vehicle type. The data collected at ORNL contained between 1,300 to 1,600 individual measurements for each vehicle and MOE combination depending on the vehicle's envelope of operation *(89)*.

This method has a significant advantage over emission data collected from a few driving cycles because it is impossible to cover the entire vehicle operational regime with only a few driving cycles. Typically, vehicle acceleration values ranged from −1.5 to 3.7 m/s^2 at increments of 0.3 m/s^2 (−5 to 12 ft/s^2 at 1-ft/s^2 increments). Vehicle speeds varied from 0 to 33.5 m/s (0 to 121 km/h or 0 to 110 ft/s) at increments of 0.3 m/s *(89)*.

Additionally, the VT-Micro model was expanded by including data from 60 light-duty vehicles (LDVs) and trucks (LDTs). Statistical clustering techniques were applied to group vehicles into homogenous categories using classification and regression tree (CART) algorithms. The 60 vehicles were classified into five LDV and two LDT categories *(61)*. In addition, HE vehicle emission models were constructed using second-by-second emission data. In constructing the models, HEVs are classified into four categories for modeling purposes. The employed HEV categorization was based on the CMEM categorization. The first type of HEVs has a chronically lean fuel-to-air ratio at moderate power or transient operation, which results in high emissions in NO. The second type has a chronically rich fuel-to-air ratio at moderate power, which results in high emissions in CO. The third type is high in HC and CO. The fourth type has a chronically or transiently poor catalyst performance, which results in high emissions in HC, CO, and NO. Each model for each category was constructed within the VT-Micro modeling framework. The HE vehicle model was found to estimate vehicle emissions with a margin of error of 10% when compared to in-laboratory bag measurements *(62)*.

5.2.4 Comprehensive Modal Emission Model

The CMEM was developed by the College of Engineering-Center for Environmental Research and Technology (CE-CERT) at the University of California-Riverside, as the result of the research sponsored by the National Cooperative Highway Research Program (NCHRP Project 25-11).

The CMEM is a modal emission and a physical, power-demand model based on a parameterized analytical representation of emissions production. It estimates second-by-second vehicle tailpipe emissions considering the vehicle's operating conditions, namely: variable soak time start, stoichiometric operation, enrichment and enleanment. It determines the vehicle's operating condition by comparing the vehicle power demand with previously-defined power demand thresholds. Given the operating condition, the fuel consumption rate is computed and then it is multiplied by an emission rate (grams of emissions per grams of fuel) to calculate engine emissions. Finally, the tail-pipe emissions are estimated by multiplying the engine emissions by the catalyst pass fraction.

In detail, the model has six modules: engine power demand, engine speed, fuel/air ratio, fuel-rates, engine-out emissions, and catalyst pass fraction. In terms of input parameters, they can be divided into two groups. One group contains operating variables such as road grade, accessory power, speed trace, soak time and specific humidity. The other group contains model parameters that include readily-available parameters, such as vehicle mass, idle speed of engine, and number of gear; and calibrated parameters related to fuel, engine-out emission, enleanment, enrichment, soak-time, cold-start and hot catalyst *(4)*.

5.3 Methodology for developing RS cut points

The methodology presented in this study to develop RS cut points for the screening of HE vehicles can be broadly divided into three sub-processes, as illustrated in Figure 5.1.

First, HE cut points in grams per second (g/s) were developed as a function of a vehicle's speed and acceleration levels using the VT-Micro emissions models and CMEMs for a representative LDV and LDT. Second, the HE cut points in grams per second were converted to concentration emissions cut points in parts per million using the carbon balance equation. Third, scale factors were computed using either ASM Equivalent Test Weight (ETW)- and model-year-based standards or engine-displacement-based standards. The following section describes the proposed procedures in more detail.

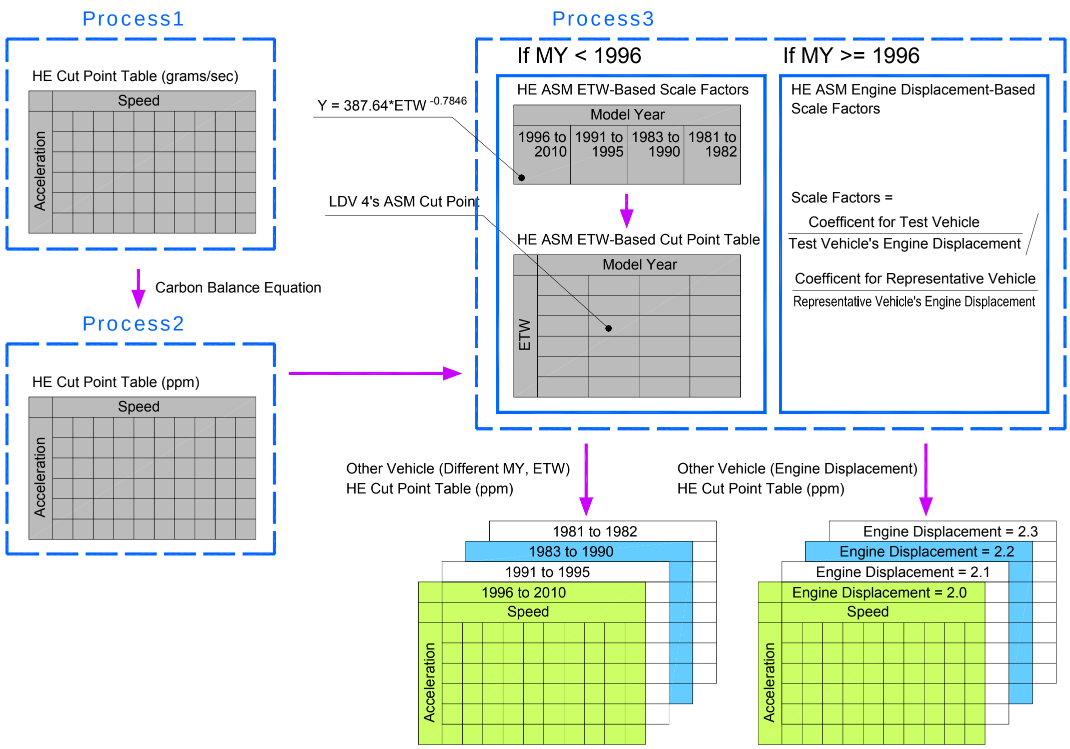

Figure 5.1 Schematic for RS cut point table.

5.3.1 Process 1: Developing HE Speed and Acceleration Cut Points

In developing HE grams per second cut points, the VT-Micro emissions models for LDV4 and LDT1 categories and the CMEMs for Category5 and Category17 were utilized to simulate normal-emitting vehicles. The VT-Micro LDV4 includes vehicle models of 1990 and greater, with an average weight of 2,460 lb. and an average engine displacement of 2.0 liters. Alternatively, the VT-Micro LDT1 class includes vehicle models of 1993 and greater, with an average weight of 3,761 lb. and an average engine displacement of 2.5 liters. For the unbiased comparison, the CMEM Category5 and Category17 were utilized because they are close to the VT-Micro LDV4 and LDT1 in terms of model year, respectively. Additionally, the CMEMs were calibrated using both the default parameters and the characteristics of VT-Micro LDV4 and LDT1.

First, LDV4, LDT1, Category5, and Category17's IM240 emissions in grams per mile were computed using the VT-Micro model and the CMEM, as illustrated in Figure 5.2. Second, the scale factors for LDV4, LDT1, Category5, and Category17 were calculated as the ratio of the IM240 threshold to the total drive cycle emission rate, as summarized in Figure 5.2. The literature details the IM240 standards *(92)*. Third, the emission tables for LDV4, LDT1, Category5, and Category17 vehicles were developed as a function of speed and acceleration levels. As can be seen in Table 5.2, the speed and acceleration were varied from 0 to 120 km/h and −1.7 to 2.8 m/s^2, respectively. Table 5.2 is the CO emission table for LDV4 and Category5. Finally, the HE cut point tables for LDV4, LDT1, Category5, and Category17 vehicles were calculated by multiplying the tables by the scale factors. A noteworthy point here is that other emissions models can be utilized for this purpose.

Table 5.1 Calculation of Scale Factors

Classification	HC (grams/mi)			CO (grams/mi)			NO (grams/mi)		
	IM240 Emissions	IM240 Standard	Scale Factor	IM240 Emissions	IM240 Standard	Scale Factor	IM240 Emissions	IM240 Standard	Scale Factor
LDV4	0.26	0.80	3.07	5.03	15.00	2.98	0.53	2.00	3.77
LDT1	0.12	1.60	13.81	2.67	40.00	14.98	0.53	2.50	4.70
Category5	0.14	0.80	5.79	2.92	15.00	5.13	0.25	2.00	8.05
Category17	0.05	1.60	34.08	0.79	40.00	50.84	0.18	2.50	13.52

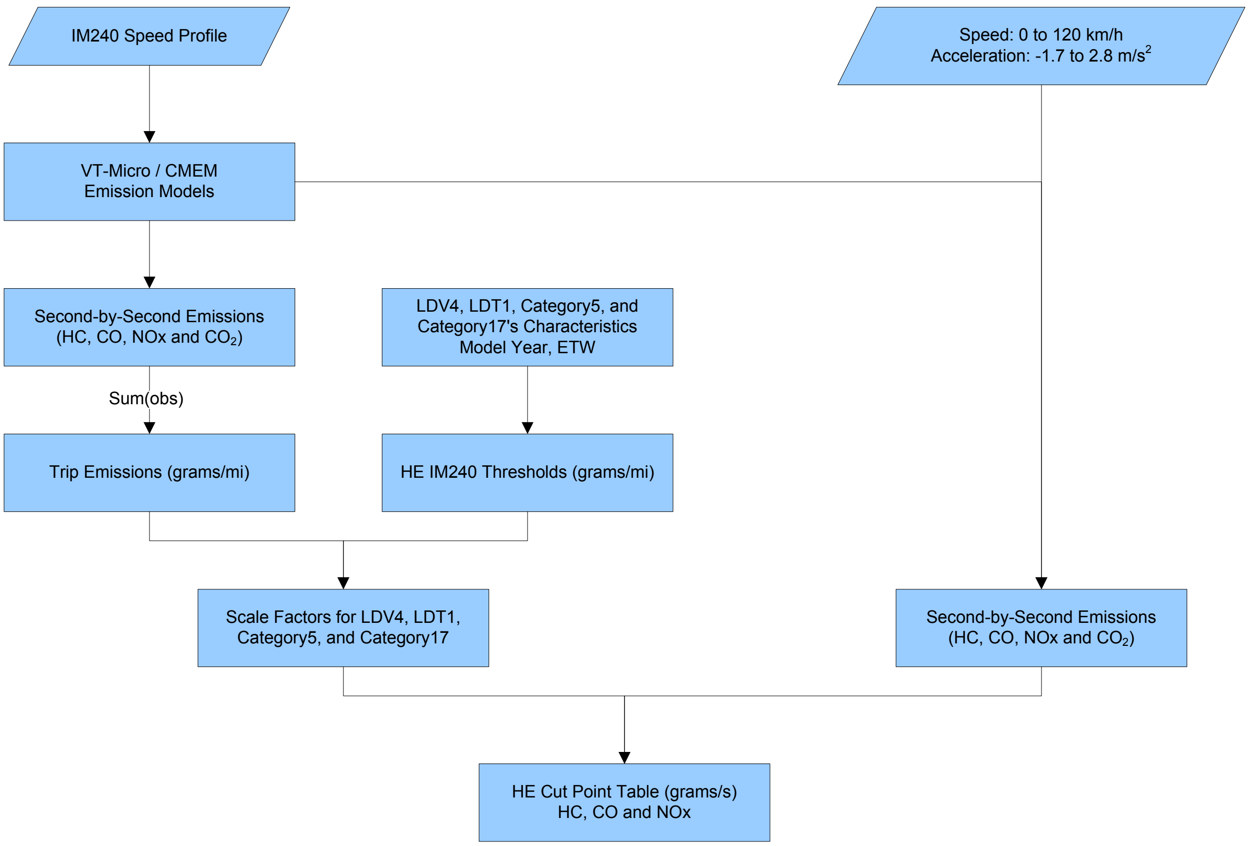

Figure 5.2 Flow chart of Process 1.

Table 5.2 CO Emission Rates (g/s) for VT-Micro LDV4 and CMEM Category5

		Speed (km/h)																								
		0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
(VT-Micro LDV4) Acceleration (m/s²)	2.8	0.03	0.03	0.04	0.06	0.12	0.25	0.53	1.03	1.76	2.60	3.26	3.52	3.30	2.78	2.16	1.60	1.18	0.89	0.70	0.58	0.51	0.46	0.42	0.37	0.31
	2.5	0.02	0.02	0.03	0.06	0.11	0.22	0.47	0.95	1.76	2.60	3.26	3.52	3.30	2.78	2.16	1.60	1.18	0.89	0.70	0.58	0.51	0.46	0.42	0.37	0.31
	2.2	0.01	0.02	0.03	0.05	0.09	0.17	0.35	0.70	1.31	2.26	3.26	3.52	3.30	2.78	2.16	1.60	1.18	0.89	0.70	0.58	0.51	0.46	0.42	0.37	0.31
	1.9	0.01	0.02	0.02	0.04	0.07	0.12	0.23	0.44	0.79	1.35	2.11	2.94	3.30	2.78	2.16	1.60	1.18	0.89	0.70	0.58	0.51	0.46	0.42	0.37	0.31
	1.6	0.01	0.01	0.02	0.03	0.05	0.09	0.15	0.25	0.42	0.69	1.06	1.51	1.97	2.31	2.16	1.60	1.18	0.89	0.70	0.58	0.51	0.46	0.42	0.37	0.31
	1.3	0.01	0.01	0.02	0.02	0.04	0.06	0.09	0.14	0.21	0.32	0.47	0.66	0.88	1.10	1.28	1.36	1.18	0.89	0.70	0.58	0.51	0.46	0.42	0.37	0.31
	1	0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.08	0.11	0.15	0.20	0.27	0.35	0.44	0.54	0.64	0.71	0.77	0.70	0.58	0.51	0.46	0.42	0.37	0.31
	0.7	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.06	0.07	0.09	0.11	0.14	0.17	0.20	0.25	0.29	0.35	0.42	0.50	0.51	0.46	0.42	0.37	0.31
	0.4	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.13	0.16	0.21	0.28	0.39	0.42	0.37	0.31
	0.1	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.05	0.06	0.08	0.11	0.17	0.28	0.31
	−0.2	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.07	0.11	0.19	0.34
	−0.5	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.06	0.09	0.14	0.25
	−0.8	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.05	0.08	0.13
	−1.1	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.06
	−1.4	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.04
	−1.7	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03
(CMEM Category5) Acceleration (m/s²)	2.8	0.00	0.75	0.81	0.96	1.14	0.42	0.71	0.99	1.34	1.62	5.10	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36
	2.5	0.00	0.63	0.69	0.82	0.10	0.12	0.19	0.47	0.78	1.32	5.10	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36
	2.2	0.00	0.52	0.57	0.68	0.08	0.10	0.12	0.15	0.35	1.04	4.20	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36
	1.9	0.00	0.43	0.46	0.05	0.07	0.08	0.10	0.13	0.16	0.81	2.04	3.64	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36
	1.6	0.00	0.33	0.36	0.04	0.05	0.07	0.08	0.07	0.09	0.11	1.15	1.83	2.40	3.00	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36
	1.3	0.00	0.21	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.11	0.21	0.80	1.62	1.76	1.46	1.04	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36
	1	0.00	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.05	0.05	0.06	0.10	0.12	0.15	0.40	0.88	1.41	1.92	2.63	3.67	0.38	5.36	5.36	5.36	5.36
	0.7	0.00	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.04	0.03	0.04	0.05	0.06	0.07	0.09	0.11	0.12	0.31	0.75	1.28	1.82	2.10	2.42	0.28	0.32
	0.4	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.04	0.05	0.06	0.05	0.06	0.08	0.09	0.10	0.12	0.26	0.53	0.89	1.40
	0.1	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.13
	−0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.07
	−0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02
	−0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	−1.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	−1.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	−1.7	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

5.3.2 Process 2: Converting to Concentration-Based Cut Points

Given the mass emissions of HC, CO, NO_x, and CO_2 from Process 1, the emission concentrations were computed by first estimating the mass emissions of N_2 through the use of the combustion equation, which can be cast as

$$CH_{1.9} + 1.48(O_2 + 3.76N_2) \rightarrow CO_2 + 0.95H_2O + 5.55N_2 \qquad [5\text{-}1]$$

where $CH_{1.9}$ represents gasoline; O_2 + 3.76 N_2 represents air composed of 21% O_2 and 79% N_2 (with argon and other non-oxygen components lumped with N_2); combustion is assumed to be complete with an equivalence ratio of 1; and formation of minor species such as NO and CO can be neglected relative to the amount of major species such as N_2 and CO_2 emitted in the exhaust.

Consequently, the mass ratio of N_2 to CO_2 can be computed as

$$\frac{5.55 \text{ mol N}_2}{1 \text{ mol CO}_2} \times \left(\frac{28 \text{ g N}_2}{\text{mol N}_2}\right) \times \left(\frac{\text{mol CO}_2}{44 \text{ g CO}_2}\right) = 3.53 \frac{\text{g N}_2}{\text{g CO}_2}. \qquad [5\text{-}2]$$

The N_2 emissions in grams per second are then computed as

$$N_2 = 3.53 \times CO_2. \qquad [5\text{-}3]$$

The volumetric concentrations of HC, CO, NO_x, and CO_2 can be computed as

$$HC_{ppm} = \frac{\frac{HC}{44}}{\frac{HC}{44} + \frac{CO}{28} + \frac{NO_x}{46} + \frac{CO_2}{44} + \frac{N_2}{28}} \times 1{,}000{,}000, \qquad [5\text{-}4]$$

$$CO_{ppm} = \frac{\frac{CO}{28}}{\frac{HC}{44} + \frac{CO}{28} + \frac{NO_x}{46} + \frac{CO_2}{44} + \frac{N_2}{28}} \times 1{,}000{,}000, \qquad [5\text{-}5]$$

$$NO_{x\_ppm} = \frac{\frac{NO_x}{46}}{\frac{HC}{44} + \frac{CO}{28} + \frac{NO_x}{46} + \frac{CO_2}{44} + \frac{N_2}{28}} \times 1{,}000{,}000, \text{ and} \qquad [5\text{-}6]$$

$$\%CO_2 = \frac{\frac{CO_2}{44}}{\frac{HC}{44} + \frac{CO}{28} + \frac{NO_x}{46} + \frac{CO_2}{44} + \frac{N_2}{28}} \times 100. \qquad [5\text{-}7]$$

5.3.3 Process 3: Computation of Scale Factors

The HE cut point tables as a function of vehicle speed and acceleration levels were computed assuming no differences across different vehicle model years. The next step was to adjust the HE cut points to reflect the fact that ASM standards vary depending on vehicle model year, ETW, and engine size. In the calculation of scale factors, either ASM ETW-based cut points or ASM engine-displacement-based cut points were used because the Virginia DEQ utilizes both cut points. Specifically, the ASM ETW-based cut points are used for emission tests for LDTs and model year 1995 or older LDVs. The ASM engine-displacement-based cut points are used for model year 1996 or newer LDVs. Therefore, both of the ASM standards are used to adjust the scale factors to account for vehicle model year and characteristics. The details of both calculations are presented in the following section.

ETW- and Model-Year-Based Scale Factor

First, the ASM ETW-based cut points for LDV4 and LDT1 were used as the base factor within the lookup table. Table 5.3 shows a portion of the ASM cut point lookup table. As can be seen in Table 5.3, since the ETW of LDV4 is 2,760 lbs., the ASM ETW-based cut points for LDV4 are 120 ppm (HC ASM 2525), 124 ppm (HC ASM 5015), 0.67% (CO ASM 2525), 0.70% (CO ASM 5015), 894 ppm (NO_X ASM 2525), and 989 ppm (NO_X ASM 5015).

Second, the ASM ETW-based scale factors were calculated by dividing the ASM ETW-based cut point table by the cut points for the LDV4 and LDT1 vehicles. An example of the calculation of the ASM ETW-based cut points is shown in Table 5.4. As can be seen in Table 5.4, the scale factors for ASM 2525 and ASM 5015 were averaged.

For the convenience of the calculation of the ASM ETW-based scale factors, regression models were constructed for each model year category. In developing the regression models, the scale factors were regressed against ETW. All regression models for LDVs and LDTs are summarized in Table 5.5. A noteworthy point here is that the fitted regression models can be used for the calculation of scale factors for CMEM Category5 and Category17, since the CMEMs for them are calibrated using the characteristics of VT-Micro LDV4 and LDT1.

Table 5.3 ASM Cut Point Lookup Table for Model Year 1991 to 1995 LDVs

ETW	HC (ppm) 2525	HC (ppm) 5015	CO (%) 2525	CO (%) 5015	NO (ppm) 2525	NO (ppm) 5015
1,750	176	183	1.00	1.03	1,369	1,516
1,875	167	173	0.95	0.97	1,289	1,428
2,000	159	164	0.89	0.92	1,217	1,347
2,125	150	156	0.85	0.88	1,150	1,273
2,250	143	149	0.81	0.83	1,089	1,205
2,375	137	141	0.77	0.79	1,034	1,144
2,500	131	136	0.74	0.76	983	1,087
2,625	125	130	0.70	0.73	936	1,035
2,750	120	124	0.67	0.70	894	989
2,760	120	124	0.67	0.70	894	989
2,875	115	119	0.65	0.67	855	945
3,000	111	115	0.62	0.65	820	907
⋮	⋮	⋮	⋮	⋮	⋮	⋮
7,125	59	61	0.33	0.33	381	419
7,250	59	61	0.33	0.33	381	419
7,375	59	61	0.33	0.33	381	419
7,500	59	61	0.33	0.33	381	419

Table 5.4 Calculation of the ASM ETW-Based Scale Factors for Model Year 1991 to 1995 LDVs

ETW	HC (ppm) 2525	HC (ppm) 5015	HC (ppm) Mean	CO (%) 2525	CO (%) 5015	CO (%) Mean	NO (ppm) 2525	NO (ppm) 5015	NO (ppm) Mean
1,750	1.47	1.48	1.47	1.49	1.47	1.48	1.53	1.53	1.53
1,875	1.39	1.40	1.39	1.42	1.39	1.40	1.44	1.44	1.44
2,000	1.33	1.32	1.32	1.33	1.31	1.32	1.36	1.36	1.36
2,125	1.25	1.26	1.25	1.27	1.26	1.26	1.29	1.29	1.29
2,250	1.19	1.20	1.20	1.21	1.19	1.20	1.22	1.22	1.22
2,375	1.14	1.14	1.14	1.15	1.13	1.14	1.16	1.16	1.16
2,500	1.09	1.10	1.09	1.10	1.09	1.10	1.10	1.10	1.10
2,625	1.04	1.05	1.05	1.04	1.04	1.04	1.05	1.05	1.05
2,750	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2,760	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2,875	0.96	0.96	0.96	0.97	0.96	0.96	0.96	0.96	0.96
3,000	0.93	0.93	0.93	0.93	0.93	0.93	0.92	0.92	0.92
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
7,125	0.49	0.49	0.49	0.49	0.47	0.48	0.43	0.42	0.42
7,250	0.49	0.49	0.49	0.49	0.47	0.48	0.43	0.42	0.42
7,375	0.49	0.49	0.49	0.49	0.47	0.48	0.43	0.42	0.42
7,500	0.49	0.49	0.49	0.49	0.47	0.48	0.43	0.42	0.42

Table 5.5 Regression Models for the ASM ETW-Based Scale Factors

	Model Year	Regression Model	R^2	P-value Model	P-value Coefficient Intercept	Linear	Quadratic
LDV							
HC	1996	$Y = 387.64*ETW^{-0.7846}$	0.9953	6.1E-54	4.7E-52	6.1E-54	
	1991 to 1995	$Y = 497.09*ETW^{-0.7835}$	0.9957	5.8E-55	6.8E-54	5.8E-55	
	1981 to 1990	$Y = 766.51*ETW^{-0.8181}$	0.9962	3.9E-56	1.5E-55	3.9E-56	
CO	1996	$Y = 468.3*ETW^{-0.8089}$	0.9969	3.6E-58	2.7E-56	3.6E-58	
	1991 to 1995	$Y = 573.79*ETW^{-0.8019}$	0.9956	1.4E-54	1.7E-53	1.4E-54	
	1983 to 1990	$Y = 870.71*ETW^{-0.8281}$	0.9964	1.3E-56	3.7E-56	1.3E-56	
	1981 to 1982	$Y = 2{,}498.1*ETW^{-0.8775}$	0.9971	6.6E-59	3.9E-60	6.6E-59	
NO_x	1996	$Y = 1{,}244.9*ETW^{-0.9283}$	0.9973	2.5E-59	1.2E-57	2.5E-59	
	1991 to 1995	$Y = 1{,}555.3*ETW^{-0.9282}$	0.9973	1.9E-59	2.3E-58	1.9E-59	
	1981 to 1990	$Y = 1{,}994.2*ETW^{-0.9404}$	0.9974	5.5E-60	2.7E-59	5.5E-60	
LDT							
HC	(ETW ≤ 3,750)						
	1996	$Y = 621.43*ETW^{-0.8589}$	0.9996	5.7E-27	1.3E-26	5.7E-27	
	1991 to 1995	$Y = 1{,}717.6*ETW^{-0.8979}$	0.9998	9.5E-29	4.5E-29	9.5E-29	
	1984 to 1990	$Y = 2{,}086.3*ETW^{-0.9093}$	0.9998	2.5E-29	9.6E-30	2.5E-29	
	1981 to 1983	$Y = 5{,}672.5*ETW^{-0.9619}$	0.9998	7.9E-29	1.1E-29	7.9E-29	
	(ETW > 3,750)						
	1996	$Y = 2E\text{-}08*ETW^2 – 0.0003*ETW + 1.4166$	0.9982	3.1E-39	2.2E-34	5.5E-26	2.2E-22
	1991 to 1995	$Y = 3E\text{-}08*ETW^2 – 0.0004*ETW + 2.2343$	0.9986	7.3E-41	1.8E-35	2.9E-27	1.6E-23
	1984 to 1990	$Y = 3E\text{-}08*ETW^2 – 0.0005*ETW + 2.5097$	0.9982	3.3E-39	8.2E-34	8.2E-26	3.6E-22
	1981 to 1983	$Y = 6E\text{-}08*ETW^2 – 0.0009*ETW + 4.6382$	0.9985	4.0E-40	2.3E-34	7.6E-27	3.1E-23
CO	(ETW ≤ 3,750)						
	1996	$Y = 446.28*ETW^{-0.8787}$	0.9996	1.3E-26	8.8E-26	1.3E-26	
	1991 to 1995	$Y = 2{,}319.3*ETW^{-0.9342}$	0.9998	1.2E-28	5.6E-29	1.2E-28	
	1984 to 1990	$Y = 2{,}891.3*ETW^{-0.9417}$	0.9997	2.6E-28	9.1E-29	2.6E-28	
	1981 to 1983	$Y = 4{,}395.4*ETW^{-0.9546}$	0.9998	1.4E-28	2.8E-29	1.4E-28	
	(ETW > 3,750)						
	1996	$Y = 1E\text{-}08*ETW^2 – 0.0002*ETW + 0.8661$	0.9973	1.3E-36	1.2E-31	2.6E-23	1.0E-19
	1991 to 1995	$Y = 3E\text{-}08*ETW^2 – 0.0004*ETW + 2.318$	0.9986	7.3E-41	2.7E-35	1.7E-27	7.4E-24
	1984 to 1990	$Y = 3E\text{-}08*ETW^2 – 0.0005*ETW + 2.7276$	0.9982	4.3E-39	1.7E-33	9.0E-26	3.8E-22
	1981 to 1983	$Y = 5E\text{-}08*ETW^2 – 0.0007*ETW + 3.7791$	0.9987	4.4E-41	2.2E-35	9.1E-28	3.9E-24
NO_x	(ETW ≤ 3,750)						
	1996	$Y = 1{,}781.3*ETW^{-0.9656}$	0.9998	1.2E-28	1.5E-28	1.2E-28	
	1991 to 1995	$Y = 3{,}159.4*ETW^{-0.9705}$	0.9996	6.4E-27	3.0E-27	6.4E-27	
	1988 to 1990	$Y = 3{,}650.5*ETW^{-0.9744}$	0.9994	9.8E-26	3.7E-26	9.8E-26	
	1981 to 1987	$Y = 3{,}883.9*ETW^{-0.8901}$	0.9948	1.5E-18	1.3E-19	1.5E-18	
	(ETW>3,750)						
	1996	$Y = 2E\text{-}08*ETW^2 – 0.0003*ETW + 1.7753$	0.9983	1.8E-39	9.2E-34	2.5E-26	9.2E-23
	1991 to 1995	$Y = 3E\text{-}08*ETW^2 – 0.0005*ETW + 2.4325$	0.9983	1.3E-39	7.9E-34	1.9E-26	6.9E-23
	1988 to 1990	$Y = 4E\text{-}08*ETW^2 – 0.0005*ETW + 2.7311$	0.9984	9.9E-40	6.6E-34	1.4E-26	5.3E-23
	1981 to 1987	$Y = 8E\text{-}08*ETW^2 – 0.0012*ETW + 5.8346$	0.9984	9.4E-40	9.7E-34	1.4E-26	5.1E-23

Engine-Displacement-Based Scale Factor

ASM engine-displacement-based scale factors are easily calculated as:

$$HC_{\text{Scale factor}} = \frac{HC_{\text{Coefficient,Test Vehicle}} / Disp_{\text{Test Vehicle}}}{HC_{\text{Coefficient, Representative Vehicle}} / Disp_{\text{Representative Vehicle}}}$$

$$CO_{\text{Scale factor}} = \frac{CO_{\text{Coefficient,Test Vehicle}} / Disp_{\text{Test Vehicle}}}{CO_{\text{Coefficient, Representative Vehicle}} / Disp_{\text{Representative Vehicle}}} . \quad [5\text{-}8]$$

$$NO_{\text{Scale factor}} = \frac{NO_{\text{Coefficient,Test Vehicle}} / Disp_{\text{Test Vehicle}}}{NO_{\text{Coefficient, Representative Vehicle}} / Disp_{\text{Representative Vehicle}}}$$

Where, *Disp* is engine displacement in liters; $HC_{coefficient}$, $CO_{coefficient}$ and $NO_{coefficient}$ is the coefficient for each type of emission, $HC_{scale\ factor}$, $NO_{scale\ factor}$ and $CO_{scale\ factor}$ is the scale factor for each emissions.

In each of the equations, the numerator is dividing the coefficient for a test vehicle by the engine displacement of it, while the denominator is dividing the coefficient for a representative vehicle by the engine displacement of it. As can be seen in the equations, the scale factors vary depending on engine displacement and emission coefficient rather than ETW. If the coefficient for the test vehicle is the same as that for the representative vehicle, the scale factor can be calculated by dividing the engine displacement of the representative vehicle by that of the vehicle to be tested.

Table 5.6 ASM Engine-Displacement-Based Cut Point Coefficient

Test Model	Start Year	End Year	HC	CO	NO
2525	1981	1982	275	1.30	3,600
2525	1983	1989	275	1.10	3,600
2525	1990	2020	275	1.10	3,600
5015	1981	1982	500	2.30	3,500
5015	1983	1989	500	1.60	3,500
5015	1990	2020	300	1.60	3,500

5.4 Comparison to the Current Standards

The Virginia DEQ developed RS cut point tables by multiplying RS cut point factors and ASM HE thresholds. These RS cut point tables are similar to the ASM HE thresholds and are insensitive to vehicle speed and acceleration levels. For example, the DEQ's RS cut points for LDV4 described in Table 5.7 (RS column) are computed by multiplying the RS cut-point factor of 4 and the average of the ETW-based cut points for ASM 2525 and ASM 5015 (sample calculation: RS for HC emission = (120+124)/2*4 = 488) or the average of the engine-displacement-based cut points.

For the illustration of the comparison to the current standards, the newly-constructed RS cut points for LDV4 that are within the valid VSP range are plotted along with the current standards as a function of vehicle speed and acceleration levels. Figure 5.3 clearly illustrates significant variations in the cut points for different speed/acceleration levels.

Table 5.7 Virginia DEQ's RS Cut Point for LDV4

	HC 2525 (ppm)	HC 5015 (ppm)	HC Mean (ppm)	RS Cut Point (ppm)	CO 2525 (%)	CO 5015 (%)	CO Mean (%)	RS Cut Point (%)	NO_X 2525 (ppm)	NO_X 5015 (ppm)	NO_X Mean (ppm)	RS Cut Point (ppm)
ETW-Based	120	124	122	488	0.67	0.70	0.69	2.74	894	989	941.5	3,766
Displacement-Based	150	137.5	143.8	575	0.8	0.55	0.675	2.7	1,750	1,800	1,775	7,100

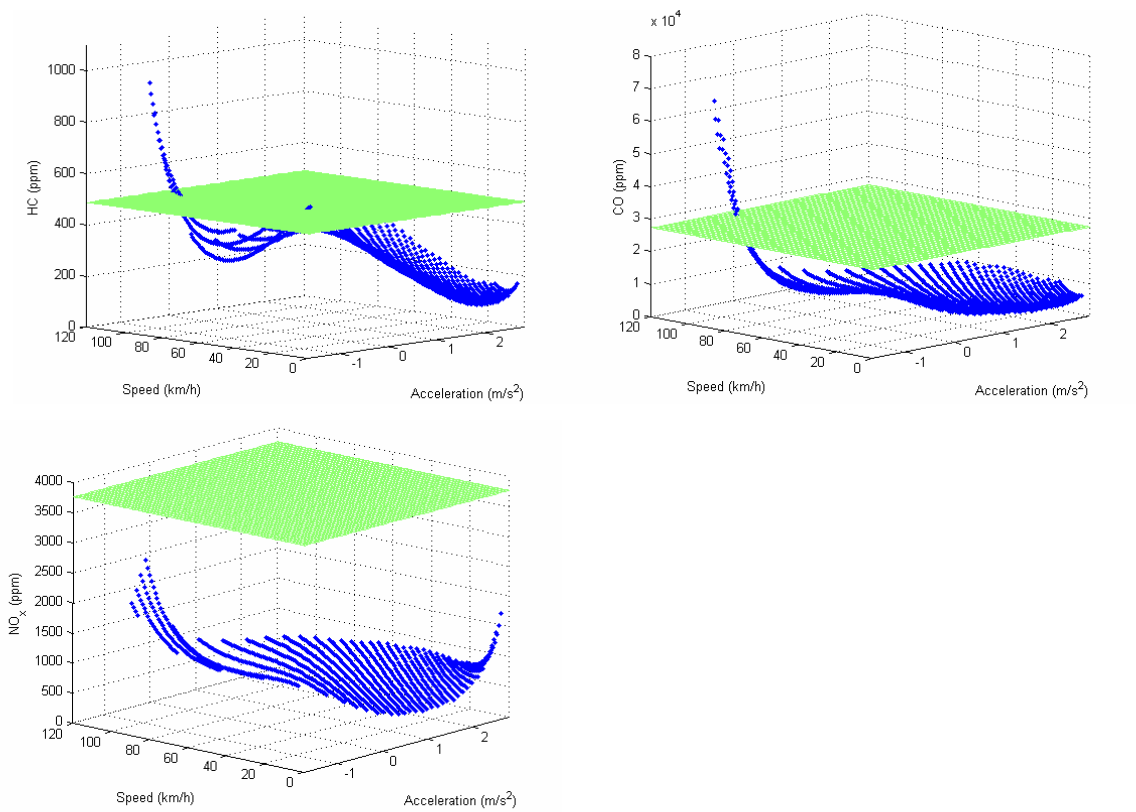

Figure 5.3 Comparison of DEQ's RS cut point and proposed RS cut point.

It should be noted that the DEQ's RS cut points are utilized when the VSP of LDVs and LDTs ranges between 3 to 15 kW/metric ton for model year 1968 to model year 1995 and from 3 to 22 kW/metric ton for model year 1996 and newer. The reason for using the given VSP ranges is that the Virginia DEQ is utilizing those ranges. The variation of VSP as a function of vehicle speed and acceleration levels is illustrated in Table 5.8.

The shaded cells show valid VSP speed and acceleration measurements for use with the current procedures.

Table 5.8 VSP as a Function of Speed and Acceleration Levels

Acceleration (m/s²)	Speed (km/h)																								
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
2.8	0	5	9	14	19	23	28	33	37	42	47	52	57	62	67	72	77	83	88	94	99	105	111	117	123
2.5	0	4	8	13	17	21	25	29	34	38	42	47	51	56	61	65	70	75	80	85	90	95	100	106	111
2.2	0	4	7	11	15	19	22	26	30	34	38	42	46	50	54	58	63	67	71	76	81	85	90	95	100
1.9	0	3	6	10	13	16	20	23	26	30	33	37	40	44	48	51	55	59	63	67	71	76	80	85	89
1.6	0	3	6	8	11	14	17	20	23	26	29	32	35	38	41	44	48	51	55	58	62	66	70	74	78
1.3	0	2	5	7	9	12	14	16	19	21	24	27	29	32	35	37	40	43	46	50	53	56	60	63	67
1	0	2	4	6	7	9	11	13	15	17	19	21	24	26	28	30	33	35	38	41	44	46	49	53	56
0.7	0	1	3	4	6	7	8	10	11	13	15	16	18	20	22	24	25	28	30	32	34	37	39	42	45
0.4	0	1	2	3	4	5	6	7	8	9	10	11	12	14	15	17	18	20	21	23	25	27	29	31	33
0.1	0	0	1	1	2	2	3	3	4	5	5	6	7	8	9	10	11	12	13	14	16	17	19	21	22
−0.2	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	3	3	4	5	5	6	7	9	10	11
−0.5	0	0	−1	−1	−2	−2	−3	−3	−3	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−3	−3	−2	−2	−1	0
−0.8	0	−1	−2	−3	−4	−5	−5	−6	−7	−8	−9	−9	−10	−10	−11	−11	−12	−12	−12	−12	−12	−12	−12	−12	−11
−1.1	0	−1	−3	−4	−6	−7	−8	−10	−11	−12	−13	−14	−15	−16	−17	−18	−19	−20	−20	−21	−21	−22	−22	−22	−22
−1.4	0	−2	−4	−6	−7	−9	−11	−13	−15	−16	−18	−19	−21	−22	−24	−25	−26	−28	−29	−30	−31	−32	−32	−33	−33
−1.7	0	−2	−5	−7	−9	−12	−14	−16	−18	−20	−22	−25	−27	−28	−30	−32	−34	−36	−37	−39	−40	−41	−42	−44	−44

5.5 Sample Tests

This section presents sample tests using the proposed RS cut points. For the test, the VT-Micro HE vehicle emission models were used to simulate HE vehicles' emissions as a function of speed and acceleration levels. As discussed in the overview of the VT-Micro emission models, four categories of high emitters were incorporated into the VT-Micro models: HE-1 has high NO_X emissions; HE-2 has high CO emissions; HE-3 has high HC and CO emissions; and HE-4 has high HC, CO, and NO_X emissions. In terms of average weight and model year, HE-1 through HE-4 has the average weight of 2698 lb., 3435 lb., 3091 lb., and 2783 lb. and the average model year of 89, 88, 95, and 91, respectively. In addition, the VT-Micro LDV models were used to simulate normal emitting vehicle emissions.

The instantaneous HC, CO, and NO_X emissions for high-emitting vehicles (HEV) and normal-emitting vehicles (NEV) were developed, varying the speed from 0 to 120 km/h in 1-km/h increments and the acceleration from −1.7 m/s^2 to 2.8 m/s^2 in 0.1-m/s^2 increments. Consequently, the number of the instantaneous emissions rates that were within the effective VSP range is 1,020. At the same time, the proposed RS cut points corresponding to the speed and acceleration levels were computed. Table 5.9 is the RS CO emission table in unit of percentage for HE-4. This table is calculated by multiplying the mass CO emission tables (Table 5.2) by each of the scale factors for LDV4 and Category5 (Table 5.1; 2.98 and 14.98). Then, the table is converted to concentration-based cut points and multiplied by the ETW- and MY-based scale factors ($0.91=573.79*3083^{-0.8019}$). In a practical point of view, once the RS cut point table is prepared, specific RS cut points at certain engine load conditions can be computed by interpolating two-dimensionally as a function of speed and acceleration levels.

Given the RS cut points and the HEV and NEV instantaneous emission rates, each instantaneous emission rate was compared to the corresponding RS cut point. For comparison purposes, the comparison to the current cut points was conducted as well. Table 5.10 presents the test results, i.e., the number of emission rates exceeding the cut points. The results demonstrate that the proposed RS cut points are more effective than the current RS cut points. Also, it is concluded that the approach is effective for HE-3 and HE-4 and requires further enhancements for HE-1 and HE-2 vehicles.

Table 5.9 CO Emission Standards (%) for HE-4 by VT-Micro LDV4 and CMEM Category5

Model	Acceleration (m/s²)	Speed (km/h) 0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
(VT-Micro LDV4) Acceleration (m/s²)	2.8	0.5	0.4	0.5	0.6	1.1	1.9	3.7	7.2	12.2	17.5	21.2	22.3	20.8	17.7	14.2	11.1	8.6	6.9	5.7	4.9	4.4	4.0	3.7	3.4	3.0
	2.5	0.4	0.4	0.4	0.6	1.1	2.0	3.7	7.0	12.2	17.5	21.2	22.3	20.8	17.7	14.2	11.1	8.6	6.9	5.7	4.9	4.4	4.0	3.7	3.4	3.0
	2.2	0.3	0.3	0.4	0.6	1.0	1.8	3.2	5.7	9.9	15.6	21.2	22.3	20.8	17.7	14.2	11.1	8.6	6.9	5.7	4.9	4.4	4.0	3.7	3.4	3.0
	1.9	0.3	0.3	0.4	0.6	0.9	1.4	2.4	4.1	6.6	10.3	14.7	19.2	20.8	17.7	14.2	11.1	8.6	6.9	5.7	4.9	4.4	4.0	3.7	3.4	3.0
	1.6	0.3	0.3	0.4	0.5	0.8	1.1	1.7	2.6	4.0	5.9	8.2	10.9	13.5	15.1	14.2	11.1	8.6	6.9	5.7	4.9	4.4	4.0	3.7	3.4	3.0
	1.3	0.3	0.4	0.4	0.5	0.7	0.9	1.2	1.7	2.3	3.2	4.2	5.5	6.9	8.2	9.2	9.6	8.6	6.9	5.7	4.9	4.4	4.0	3.7	3.4	3.0
	1	0.3	0.4	0.4	0.5	0.6	0.7	0.9	1.1	1.4	1.7	2.2	2.7	3.3	3.9	4.6	5.2	5.7	6.1	5.7	4.9	4.4	4.0	3.7	3.4	3.0
	0.7	0.4	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.1	1.2	1.4	1.6	1.9	2.2	2.5	2.9	3.3	3.8	4.3	4.4	4.0	3.7	3.4	3.0
	0.4	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.2	1.3	1.5	1.8	2.2	2.7	3.5	3.7	3.4	3.0
	0.1	0.3	0.4	0.5	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	1.1	1.4	1.9	2.8	3.0
	−0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.9	1.0	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.9	1.0	1.2	1.4	1.9	2.6	4.0
	−0.5	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.1	1.2	1.5	1.9	2.5	3.5	5.3
	−0.8	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	1.1	1.2	1.5	1.9	2.5	3.6	5.5
	−1.1	0.3	0.4	0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.9	1.0	1.2	1.5	1.9	2.6	3.7
	−1.4	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	1.0	1.2	1.4
	−1.7	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.8	0.8	0.8	0.8
(CMEM Category 5) Acceleration (m/s²)	2.8	0.3	15.2	15.8	17.2	18.8	6.4	9.7	12.3	15.0	16.3	37.7	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4
	2.5	0.3	13.9	14.5	15.9	1.8	1.9	2.9	6.3	9.3	14.0	37.7	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4
	2.2	0.3	12.7	13.2	14.5	1.6	1.8	2.0	2.2	4.5	12.0	31.8	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4
	1.9	0.3	11.4	11.9	1.4	1.5	1.7	1.8	2.0	2.2	10.0	18.9	28.6	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4
	1.6	0.3	10.1	10.5	1.2	1.4	1.5	1.7	1.6	1.7	1.9	12.6	17.3	20.5	22.6	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4
	1.3	0.3	7.4	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.7	1.9	3.1	10.3	18.6	15.3	11.3	7.1	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4
	1	0.3	0.8	0.8	0.9	1.1	1.0	1.1	1.2	1.3	1.3	1.5	1.8	2.0	2.2	5.1	10.2	14.8	18.1	22.6	28.9	3.2	38.4	38.4	38.4	38.4
	0.7	0.3	0.6	0.7	0.8	0.9	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.5	1.6	1.7	1.9	2.0	4.4	9.9	15.7	17.1	18.7	20.4	2.8	3.0
	0.4	0.3	0.5	0.5	0.6	0.7	0.6	0.7	0.8	0.9	0.8	0.9	1.1	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.8	2.0	3.5	6.6	10.4	15.3
	0.1	0.3	0.3	0.4	0.4	0.5	0.4	0.5	0.6	0.7	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.8	1.9	2.0
	−0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.4	1.5
	−0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.6	0.7	0.8	0.9
	−0.8	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	−1.1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	−1.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	−1.7	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Table 5.10 Sample Test Result: Number of Emissions Rates Exceeding the Cut Points

Classification		Current Cutpoint			VT Cutpoint			CMEM Cutpoint		
		HC	CO	NO_X	HC	CO	NO_X	HC	CO	NO_X
HEV	HE1	0 (0%)	0 (0%)	0 (0%)	245 (24%)	0 (0%)	588 (58%)	110 (11%)	0 (0%)	279 (27%)
	HE2	1 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	70 (7%)	4 (0%)	11 (1%)	0 (0%)
	HE3	961 (94%)	557 (55%)	0 (0%)	1016 (100%)	999 (98%)	0 (0%)	894 (88%)	857 (84%)	0 (0%)
	HE4	1020 (100%)	465 (46%)	0 (0%)	1020 (100%)	1003 (98%)	625 (61%)	1020 (100%)	860 (84%)	378 (37%)
NEV	LDV1	0 (0%)	0 (0%)	0 (0%)	129 (13%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	LDV2	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	LDV3	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	LDV4	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	7 (1%)	0 (0%)
	LDV5	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

*HEV: High-emitting vehicle   NEV: Normal-emitting vehicle

5.6 Conclusions

The study proposed a procedure for constructing on-road RS emissions standards sensitive to vehicle speed and acceleration levels. The proposed procedure is broadly divided into three sub-processes. In the first process, HE cut points in grams per second are developed as a function of a vehicle's speed and acceleration levels using the VT-Micro emissions models and the CMEMs. Subsequently, the HE cut points in grams per second are converted to concentration emissions cut points in parts per million using the carbon balance equation. Finally, the scale factors are computed using either ASM ETW- and model-year-based standards or engine-displacement-based standards.

The study demonstrated that the use of on-road RS cut points sensitive to speed and acceleration levels is required in order to enhance the effectiveness of RS. In addition, the study demonstrated that the proposed standards are effective for HE-3 and HE-4 and requires further enhancement for HE-1 and HE-2 vehicles. Consequently, further research is required to enhance the models within the proposed framework by minimizing the detection and false alarm rate.

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Chapter 6: Development of Fuel and Emission Models for High Speed Heavy Duty Trucks, Light Duty Trucks, and Light Duty Vehicles

Sangjun Park, Hesham Rakha, Mohamadreza Farzaneh, Josias Zietsman, and Doh-Won Lee, presented at the 87th Transportation Research Board Annual Meeting.

6.1 Introduction

Since mobile-source emissions are considered as one of the significant contributors to air pollution, the estimation of mobile-source emissions is critical, especially for on-road vehicles, in order to assess the impact of various transportation activities on the environment *(2)*. Accordingly, the EMPAC model for California and the MOBILE model for other states have been developed for the emission inventory assessment *(2, 3)*. Also, the Comprehensive Modal Emission Model (CMEM) and the VT-Micro fuel consumption and emission models are currently available to assess the impact of vehicle activities on energy use and exhaust emissions at the microscopic level; instantaneous fuel consumption rates and emissions rates at specific engine load conditions *(4, 5)*.

Although each of these vehicle emission models has been constructed using a different framework/structure, they are common in that they are developed based on a database of emissions and vehicle speed measurements. The EMFAC and MOBILE models were constructed from a database of vehicle emission rates at speeds of up to 65 mph *(3, 6)*. The CMEM and VT-Micro models were built from a set of emission rates at speeds up to 80 mph and 75 mph, respectively *(4, 5)*. This limitation of the models in the training data demonstrates the need to develop new vehicle fuel consumption and tailpipe-exhaust emission models for vehicle speeds that exceed 80 mph given that this is not uncommon on existing freeways. For example, some sections of I-10 in West Texas have the speed limit of 80 mph. Additionally, the state of Texas has a plan to construct high speed corridor systems, whose design criteria for speed is up to 100 mph in or near nonattainment areas. Thus, there is a need for the development of new models. Consequently, the objective of this study is to develop new models for high-speed heavy duty vehicles, light duty trucks, and light duty vehicles.

In terms of the paper layout, initially the data collection procedures are presented, which includes the description of the equipment used to measure vehicle instantaneous emission rates together with a description of the test facility where the vehicles ran, the specifications of the test vehicles, and a description of the drive cycles that were used for vehicle testing. Secondly, the details of the model construction are described including the VT-Micro model framework. Subsequently, the model validation exercise is presented with an illustration of the various model parameters. Finally, the study conclusions are presented together with recommendations for further research.

6.2 Data Collection Procedures

For the collection of vehicle tailpipe emissions under real world conditions, a total of nine vehicles were tested using a series of drive cycles from March 4 to 12, 2007 at the Pecos Research and Testing Center (RTC). For the measurement of emissions, two portable emissions measurement system (PEMS) units were utilized. In this section, the data collection procedure is presented, including the specification of the equipment and vehicles, the features of the test track, and the tested drive cycles.

6.2.1 Emissions Measurement Equipment

In this study, two PEMS units were utilized to measure instantaneous emission rates of the test vehicles, as shown in Figure 6.1. While the traditional chassis dynamometer tests incur higher costs per test and require a test facility to conduct the tests, PEMS units allow for the testing of vehicles at a relatively lower cost and can be easily conducted by a small group of individuals. Additionally, the tests under real world conditions using PEMS enable researchers to obtain more realistic data that reflect real-life driving. For example, it is possible to test heavy duty vehicles easily without removing the vehicle engine, as is the case for engine dynamometer tests *(100)*.

One of the PEMS used in the study is a "SEMTECH-DS" unit manufactured by Sensors, Inc.; it consists of two parts, emission analyzers and an exhaust flow meter (EFM). The emission analyzer continuously records instantaneous exhaust emission rates (including hydrocarbon [HC], nitric oxide [NO], nitrogen dioxide [NO_2], carbon monoxide [CO], and carbon dioxide[CO_2]) and its optional communications and GPS modules keep track of fuel consumption rates, engine speed, and ground speed. For the measurement of vehicle emissions, Flame Ionization Detection (FID), Non-Dispersive InfraRed (NDIR), and Non-Dispersive UltraViolet (NDUV) sensors are included inside the unit. The EFM is directly connected to the tailpipe of the vehicle and measures the volumetric flow rates directly, as shown in Figure 6.1 *(101)*.

Another PEMS is the "OEM-2100 Montana System" manufactured by Clean Air Technologies International, Inc. (CATI). It is lighter and easier to be carried than the "SEMTECH-DS" unit, and reports the concentrations of HC, CO, $CO_{2,}$ nitrogen oxides (NO_x), and particulate matter (PM). One critical difference from "SEMTECH-DS" is that the Montana system computes exhaust volumetric flow rates based on intake air mass flow and engine operating parameters (which are collected from an on-board diagnostics connector or sensor array system) with the characteristics of fuel specified by users. For this study, the Montana system was only used to gather PM data *(102)*.

In order to achieve the accuracy, the Montana system was calibrated by CATI, Inc. before conducting the tests and the SEMTECH-DS unit was calibrated and audited in the field at least twice daily with the National Institute of Standards and Technology (NIST) traceable calibration gases.

(a) (b) (c)

Figure 6.1 Test equipment and installed flow meter.

6.2.2 Specification of Test Vehicles and Site

A total of nine vehicles were utilized for testing including three semi-trucks, three pick-up trucks and three passenger cars as described in Table 6.1. As can be seen, the model years of all the vehicles were newer than 2000, except for the Nissan Altima which was a 1996 model.

These vehicles were tested at the Pecos RTC, which has nine distinct test tracks inside its 5800-acre complex located in Pecos, Texas. The vehicles were driven at pre-defined drive cycles on the high-speed test track, which is a 9-mile and 3-lane circular track. The track is designed for the tested vehicles to speed of up to 200 mph.

Table 6.1 Summary of Test Vehicle Characteristics

Vehicle Type	Fuel Type	Make	Model/Engine	Transmission Type	Model Year	Curb Weight (lb.)	Engine Size (L)
Semi-Truck 1	Diesel	International	Cummins 870	Manual	2006	75000 (Gross Weight)	15
Semi-Truck 2	Diesel	International	Detroit	Manual	2002	75000 (Gross Weight)	12.7
Semi-Truck 3	Diesel	International	CAT C15	Automatic	2001	75000 (Gross Weight)	15
Pick-up Truck 1	Diesel	Chevrolet	Silverado 2500 HD	Automatic	2007	4588	6.6 (V8)
Pick-up Truck 2	Diesel	Ford	F-250	Automatic	2006	6395	6 (V8)
Pick-up Truck 3	Diesel	Dodge	RAM-2500 SLT	Automatic	2002	5509	5.9 (L6)
Passenger Car 1	Gasoline	Nissan	Altima	Automatic	1996	2853	2.4 (L4)
Passenger Car 2	Gasoline	Jeep	Liberty	Automatic	2007	4011	3.7 (V6)
Passenger Car 3	Gasoline	Ford	Mustang	Automatic	2006	3613	4 (V6)

** For semi-trucks, the gross weight of each truck is approximately set to 75000 lb. by adding loads*

6.2.3 Drive Cycle Description

In order to provide full coverage of vehicle speed and the acceleration level envelope, a total of four different drive cycles were developed and utilized as part of the experiment, as illustrated in Figure 6.2. The first drive cycle (referred to as the STEP cycle) was designed to collect sample data when the vehicle was cruising at different speed levels. In the STEP drive cycle the driver was directed to accelerate to different speed levels at increments of 16 km/h (10 mph) up to a speed of 144 km/h (90 mph) while maintaining a constant speed for 20 s at each speed level. In the case of pick-up trucks and cars, the final speed was 160 km/h (100 mph) instead of 144 km/h (90 mph). The other three drive cycles were developed to collect sample data when the vehicles were accelerating. Three levels of acceleration were considered: aggressive, normal, and mild. The second drive cycle involved vehicle acceleration at an aggressive rate up to its maximum speed and then decelerating mildly (referred to as FAST cycle). The third drive cycle involved vehicles accelerating at a typical acceleration level that was driver dependent and then decelerating at a typical rate (referred to as NORMAL cycle). Finally, the fourth drive cycle involved accelerating at a mild level and decelerating the vehicle at the highest possible deceleration rate (referred to as SLOW cycle). Individual vehicles were tested at least four times on each of the four drive cycles. Fuel consumption rates, tailpipe emission rates, and other parameters such as the vehicle engine speed and ground speed were assembled. Noteworthy is the fact that the drive cycles varied in duration due to variability in the driver behavior and the vehicle characteristics.

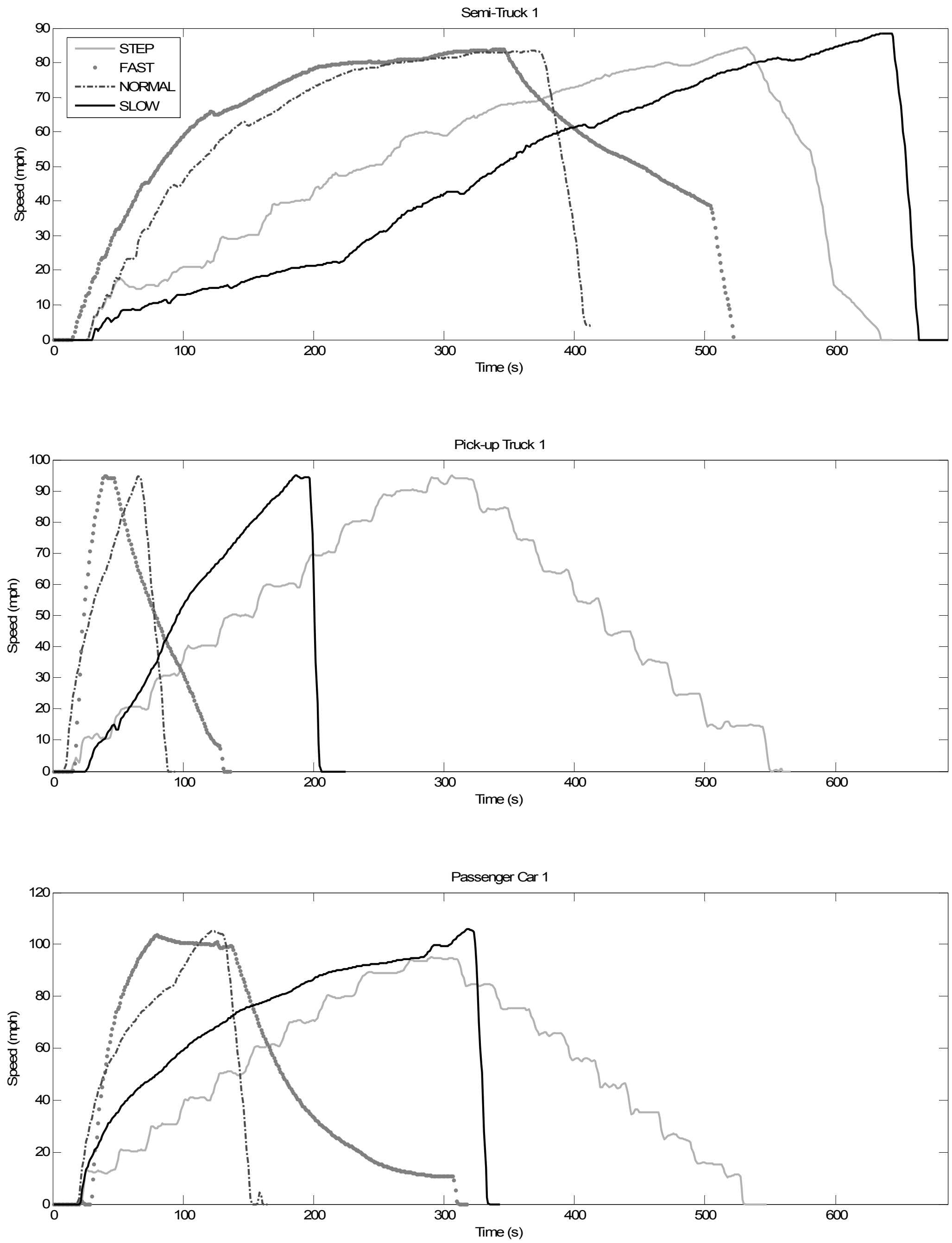

Figure 6.2 Drive cycle speed profile.

6.3 Construction of Models

This section describes the procedures that were utilized to develop the fuel consumption and emission models for the test vehicles.

6.3.1 Speed and Acceleration Coverage

Since the modeling framework requires vehicle speed and acceleration levels as key input variables, a first step was to investigate the data coverage adequacy. This characterization identifies the boundary confines of the constructed models and provides knowledge of each vehicle's kinetic characteristics. For the emissions estimation, the extrapolation of emission rates is not recommended due to the nature of the non-linear function of speed and acceleration levels. Once the speed and acceleration levels exceed the pre-determined boundary condition, its corresponding boundary values are used as the input parameters.

As can be seen in Figure 6.3, all semi-trucks accelerated to a final speed of 144 km/h (90 mph) at acceleration levels that varied between -3 m/s^2 (-9.8 ft/s^2) and 1 m/s^2 (3.3 ft/s^2). All semi-trucks were unable to attain their desired final speed of 160 km/h (100 mph) even though the drivers attempted to accelerate to that speed. The figure demonstrates the lower vehicle dynamics aspects of the semi-trucks in comparison to the pickup-trucks and passenger cars. The figure also demonstrates a reduction in the vehicle acceleration rates as their speeds increased (positive accelerations) regardless of the type of vehicles, as clearly seen in Figure 6.3. For the pick-up trucks and passenger cars, the vehicles' speeds increased up to 160 km/h (100 mph) and the accelerations ranged from -7 m/s^2 (-23.0 ft/s^2) to 4 m/s^2 (13.1 ft/s^2). Although the range of accelerations for the pick-up trucks and passenger cars was wider than that of the semi-trucks, some regions in the speed-acceleration domain did not include sufficient data samples. As clearly seen in the sub-figures for the pick-up trucks and passenger cars, the number of accelerations less than -3 m/s^2 (-9.8 ft/s^2) was insufficient to fit the models in these regions.

6.3.2 Model Framework

In this study, the VT-Micro modeling framework was utilized to construct the models from the field-gathered emission measurements because various modeling frameworks, which consisted of a combination of speed and acceleration terms, were tried in the course of constructing the new models. The VT-Micro modeling framework was found appropriate although the data were measured by the PEMS at high speeds. Additionally, the reliable estimates from the models supported the fact that the modeling structure is effective.

The VT-Micro emission models were developed from experimentation with numerous polynomial combinations of speed and acceleration levels. Specifically, linear, quadratic, cubic, and fourth degree combinations of speed and acceleration levels were tested using chassis dynamometer data collected at the Oak Ridge National Laboratory (ORNL). The final regression model included a combination of linear, quadratic, and cubic speed and acceleration terms because it provided the least number of terms with a relatively good fit to the original data (R^2 in excess of 0.92 for all measures of effectiveness [MOE]). The ORNL data consisted of nine normal-emitting vehicles including six light-duty automobiles and three light-duty trucks. These vehicles were selected in order to produce an average vehicle that was consistent with average vehicle sales in terms of engine displacement, vehicle curb weight, and vehicle type. The data collected at ORNL contained between 1,300 to 1,600 individual measurements for each vehicle and MOE combination depending on the vehicle's envelope of operation *(89)*.

This method has a significant advantage over emission data collected from a few driving cycles because it is difficult to cover the entire vehicle operational regime with only a few driving cycles. Typically, vehicle acceleration values ranged from −1.5 to 3.7 m/s^2 at increments of 0.3 m/s^2 (−5 to 12 ft/s^2 at 1-ft/s^2 increments). Vehicle speeds varied from 0 to 33.5 m/s (0 to 121 km/h or 0 to 110 ft/s) at in increments of 0.3 m/s *(89)*.

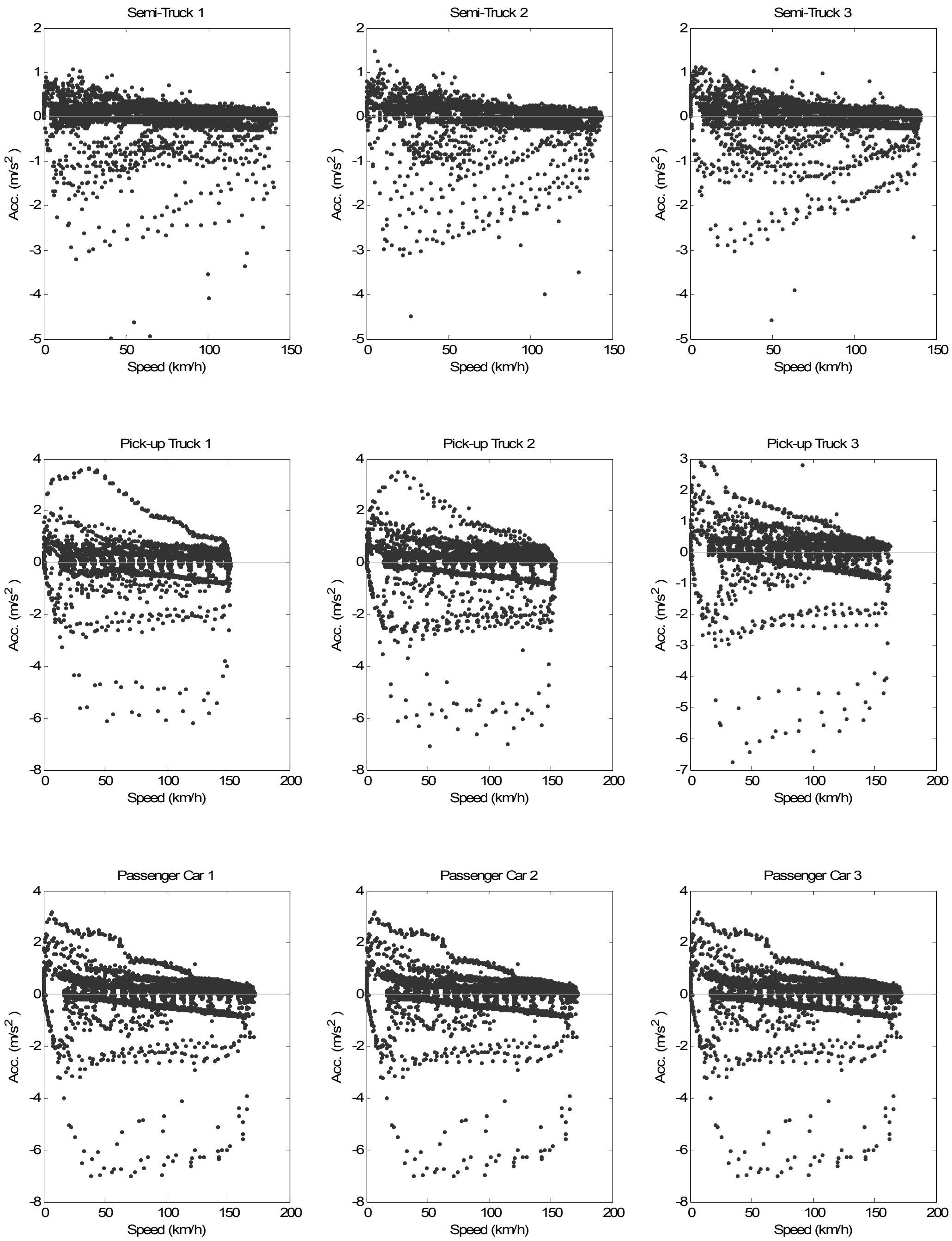

Figure 6.3 Data coverage in speed/acceleration domain.

The model had the problem of overestimating HC and CO emissions especially for high acceleration levels. Since this problem arose from the fact that the sensitivity of the dependent variables to the positive acceleration levels is significantly different from that for the negative acceleration levels, a two-regime model for positive and negative acceleration regimes was developed as demonstrated in Equation [6-1] *(5, 89)*.

$$\ln(MOE_e) = \begin{cases} \sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}^{e} \times s^{i} \times a^{j}) & \text{for } a \geq 0 \\ \sum_{i=0}^{3}\sum_{j=0}^{3}(M_{i,j}^{e} \times s^{i} \times a^{j}) & \text{for } a < 0 \end{cases} \quad [6\text{-}1]$$

where:

MOE_e	Instantaneous fuel consumption or emission rate (ml/s or mg/s)
$L^e_{i,j}$	Model regression coefficient for MOE "e" at speed power "*i*" and acceleration power "*j*" for positive accelerations
$M^e_{i,j}$	Model regression coefficient for MOE "e" at speed power "*i*" and acceleration power "*j*" for negative accelerations
S	Instantaneous speed (km/h)
A	Instantaneous acceleration (km/h/s)

Additionally, the VT-Micro model was expanded by including data from 60 light-duty vehicles (LDVs) and trucks (LDTs). Statistical clustering techniques were applied to group vehicles into homogenous categories using classification and regression tree (CART) algorithms. The 60 vehicles were classified into five LDV and two LDT categories *(61)*. In addition, high emitting vehicle (HEV) emission models were constructed using second-by-second emission data. In constructing the models, HEVs are classified into four categories for modeling purposes. The employed HEV categorization was based on the CMEM categorization. The first type of HEVs has a chronically lean fuel-to-air ratio at moderate power or transient operation, which results in high emissions in NO. The second type has a chronically rich fuel-to-air ratio at moderate power, which results in high emissions in CO. The third type is high in HC and CO. The fourth type has a chronically or transiently poor catalyst performance, which results in high emissions in HC, CO, and NO. Each model for each category was constructed within the VT-Micro modeling framework. The HE vehicle model was found to estimate vehicle emissions with a margin of error of 10% when compared to in-laboratory bag measurements *(62)*. Furthermore, all the models were incorporated into the INTEGRATION software, which made it possible to evaluate the environmental impacts of operational level transportation projects *(103)*.

6.3.3 Model Construction

This section describes the procedures that were applied to develop the fuel consumption and emission models. Initially, the instantaneous fuel consumption and emission rates were aligned with their corresponding speed and acceleration levels to adjust for any temporal lags in the data. This time lag results from different response times of the analyzers and mechanical delays within the vehicle engine and exhaust system *(84)*. The data alignment was achieved by minimizing the sum of squared error between the estimated emissions considering the instantaneous speed and acceleration levels and the observed emission rates.

After the data were aligned, invalid records such as void cells were removed from the data set. Subsequently, the data were categorized into user-defined speed and acceleration bins, as illustrated in Table 6.2. For the categorization, the speed and acceleration bin size was set at 5 km/h and 0.3 m/s^2, respectively. The median fuel consumption, HC, CO, CO_2, NO, NO_2, NO_x, and PM emission rates were computed for each speed-acceleration bin. The median was utilized because it is a more robust central tendency measure in comparison to the mean and thus is minimally influenced by outlier data. Data for NO_2 emissions for passenger car 2 and passenger car 3 were not available because most of the measurements were invalid. Similarly, PM data were not available for the passenger car 1 and passenger car 3 because PM emission magnitude was very small and within the PEMS margin of error.

Table 6.2 Data Speed and Acceleration Distribution (Semi-Truck 1)

Speed	Acceleration (m/s^2)																		
	-2.90	-2.60	-2.30	-2.00	-1.70	-1.40	-1.10	-0.85	-0.65	-0.45	-0.30	-0.20	-0.10	0.00	0.10	0.20	0.30	0.45	0.65
0 km/h	0	0	0	0	0	0	0	0	2	4	0	5	2	558	15	6	6	15	12
5 km/h	0	0	0	0	1	2	2	3	6	2	0	5	3	12	32	6	5	3	19
10 km/h	0	0	0	1	0	3	6	0	2	1	0	9	8	21	42	19	13	22	3
15 km/h	0	1	1	1	0	4	3	2	2	0	0	8	19	75	66	12	22	17	5
20 km/h	1	0	0	0	3	2	2	1	1	1	0	9	25	37	52	13	17	15	9
25 km/h	1	1	0	0	3	2	3	1	2	1	0	8	37	51	64	17	4	13	11
30 km/h	1	0	0	0	2	2	4	4	3	0	0	0	33	41	54	13	17	16	8
35 km/h	0	1	0	1	1	1	4	0	6	0	0	0	37	72	67	18	8	17	4
40 km/h	1	0	0	0	0	3	5	5	2	2	0	0	20	3	22	22	6	31	1
45 km/h	0	1	1	0	0	2	5	5	4	1	0	2	21	15	47	18	3	29	1
50 km/h	1	0	1	0	0	1	5	4	2	0	0	1	39	55	75	23	29	8	0
55 km/h	0	1	0	0	0	0	9	5	3	0	0	0	31	0	26	20	34	9	0
60 km/h	0	1	1	0	0	0	3	5	11	2	1	0	29	4	17	22	38	11	0
65 km/h	0	0	0	0	0	0	1	2	8	5	2	1	51	66	51	16	43	3	0
70 km/h	0	1	2	0	0	0	1	2	6	4	1	10	73	35	84	40	26	0	0
75 km/h	0	0	0	1	0	0	2	2	10	1	0	8	54	11	58	41	32	0	0
80 km/h	0	1	0	2	0	0	1	3	7	2	1	13	42	57	80	42	20	0	0
85 km/h	0	0	0	1	0	1	0	5	4	2	1	18	60	30	50	75	6	0	0
90 km/h	0	0	2	1	1	0	1	3	2	0	1	23	55	7	64	70	5	0	0
95 km/h	0	0	1	0	1	0	1	6	0	0	5	35	35	71	130	46	0	0	0
100 km/h	0	1	0	1	0	0	3	0	2	4	3	24	55	52	166	32	0	0	0
105 km/h	0	0	2	1	1	0	2	1	3	2	1	26	53	41	226	12	0	0	0
110 km/h	0	0	0	0	1	0	1	3	4	2	1	39	18	67	236	9	1	0	0
115 km/h	0	0	1	1	2	0	1	1	4	2	1	51	9	43	237	4	2	0	0
120 km/h	0	0	1	1	1	1	2	2	3	5	3	36	17	53	225	9	0	0	0
125 km/h	0	0	0	0	0	1	1	2	1	5	7	38	1	138	270	1	0	0	0
130 km/h	0	0	0	1	2	1	3	1	1	5	16	26	11	470	274	0	0	0	0
135 km/h	0	0	0	0	1	2	2	3	1	2	10	23	28	575	193	0	0	0	0
140 km/h	0	0	0	0	0	0	2	0	3	3	0	5	11	485	52	0	0	0	0
145 km/h	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The models for the negative and positive acceleration regimes were calibrated independently and the boundary conditions were set before the application of the models to avoid unreasonable estimates due to extrapolation. However, the first version of the model resulted in significant fluctuations in the model estimates, as illustrated in Figure 6.4. One of the reasons for such oscillations was a discontinuity between the negative and positive regime models at the zero acceleration level. Consequently, several techniques were introduced to improve the models. Firstly, the independent and dependent variables were smoothed using an Epanechnikov kernel (EK) smoothing procedure considering a bandwidth of two. Kernel smoothing methods use weight sequences to determine the underlying trend of a series of observations. In these methods, each observation around a given data point is assigned a weight relative to its position to the data point in question *(104, 105)*. These weights are then used to compute a weighted average representing the underlying trend. EK smoothing methods use the parabolic density function defined by Equations [6-2] and [6-3] to assign weights to observations around a given data point x.

$$K(z) = \begin{cases} 0.75\ (1\text{-}z^2) & \text{if } |z| \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad [6\text{-}2]$$

$$z = \frac{t - t_{i\Delta t}}{\Delta t} \quad [6\text{-}3]$$

where:

K(z) = Kernel density function,

t = Data point at which the underlying trend is estimated,

$t\text{-}t_{i\Delta t}$ = Relative position of data point i in relation to data point under consideration,

Δt = Bandwidth of density function.

In this model, the bandwidth parameter Δt controls the width of the density function and, thus, how many observations surrounding a data point *t* will be included in the trend line estimation. As a result, the selection of a larger bandwidth parameter typically results in more smoothing, as more data points are used to compute the underlying trend, while the selection of a smaller bandwidth results in less smoothing. For this study, the impacts of assigning values of 0, 1, 2, 3 and 4 to the bandwidth parameter Δt were analyzed before determining that a value of 3 produced the best overall results.

Secondly, a variable acceleration bin size was implemented considering a bin size of 0.1 m/s^2 for acceleration levels of -0.3 m/s^2 to +0.3 m/s^2 and a bin size of 0.3 m/s^2 elsewhere because of the larger number of data observations in the -0.3 m/s^2 to +0.3 m/s^2 region, as demonstrated in Table 6.2. In addition, the independent variables that fell into the zero acceleration bin were included while calibrating the models for each regime. Finally, the coefficients for the linear, quadratic, and cubic speed terms considering a zero acceleration level were fixed to equal the positive regime coefficients in order to ensure that no major discontinuities were present in the model. As can be seen in Figure 6.4, the final version of the model produced a better fit to the data and less model fluctuations when compared to the first model. In addition, Figure 6.5 shows that the estimates of fuel consumption for each of the nine vehicles against the measured fuel consumption rates at three different acceleration levels; -0.2 m/s^2, 0 m/s^2, and 0.2 m/s^2. The figure clearly demonstrates a good fit to the data. However, the fuel consumption rates for the semi-trucks, including both the model estimates and field measurements, at the speeds greater than 100 km/h at the acceleration level of 0.2m/s^2 are different from those for the pick-up trucks and passenger cars with a significant dip in the emission rates. This appears to be attributed to the effect of gear shifts. Figure 6.6 shows the fuel consumption rates for the semi-truck2 at an acceleration level of 0.2m/s^2. As can be clear seen in the figure, the effect of gear shifts is evident in the green area highlighted area. In addition, the lack of the field data in the red area also is one of the factors causing problems given that we computed the mean value in conducting our regression.

In terms of the adjusted R^2 of the various models, the models for the pick-up trucks and passenger cars had generally higher R^2 values than those for the semi-trucks, as summarized in Table 6.3. Noteworthy is the fact that some of the models showed poor fits due to voids in the data. For example, a total of 6606 instantaneous emission rates were measured for passenger car 3 for all emissions except NO_2, with only 31% of the data available (2048 measurements). That resulted in a lower adjusted R^2 value than other models. The reason that all the negative regime models had lower adjusted-R^2 values was that they were forced to utilize the coefficients of the linear, quadratic, cubic speed and zero accelerations for the positive regime models.

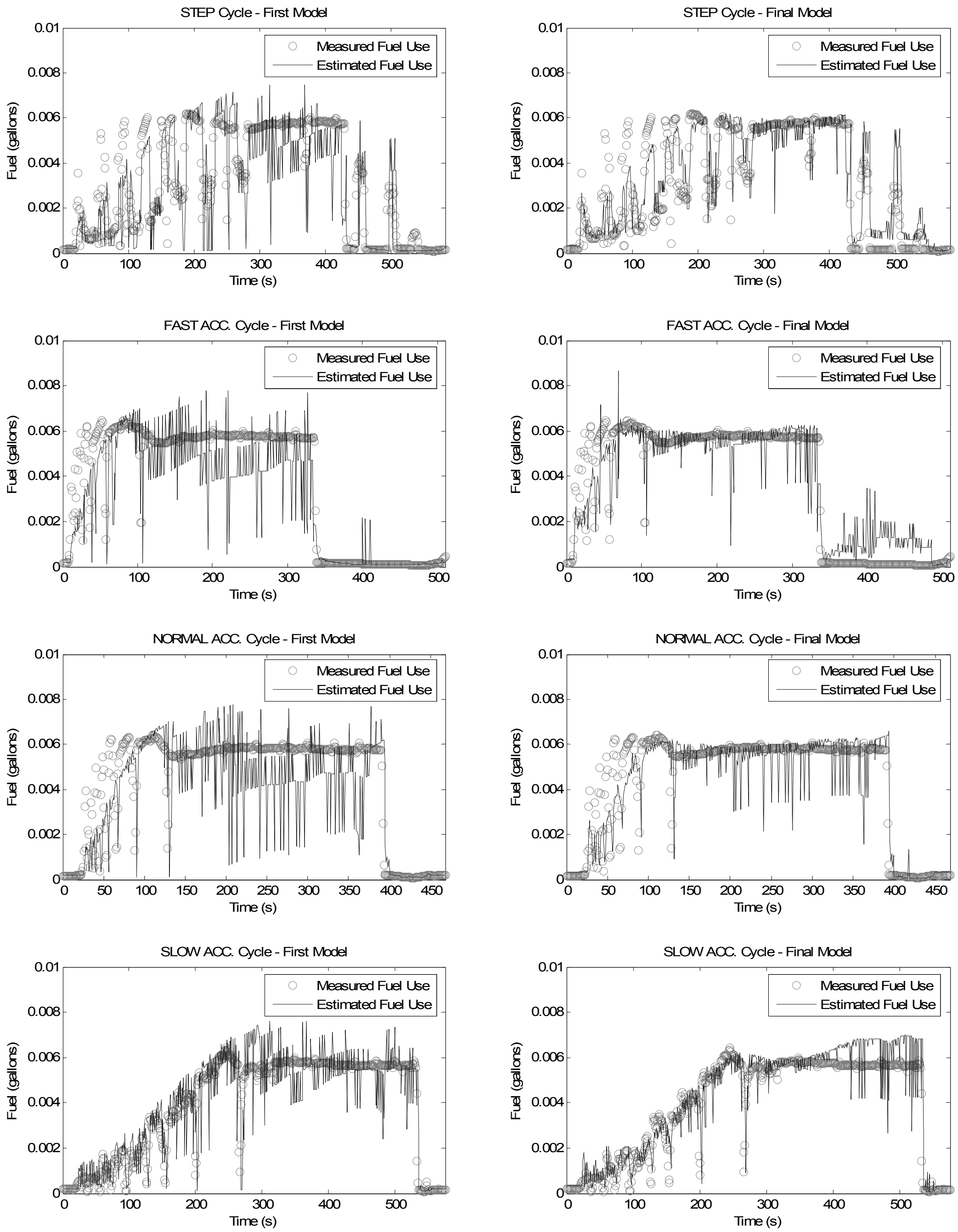

Figure 6.4 First model vs. final model (semi-truck 1).

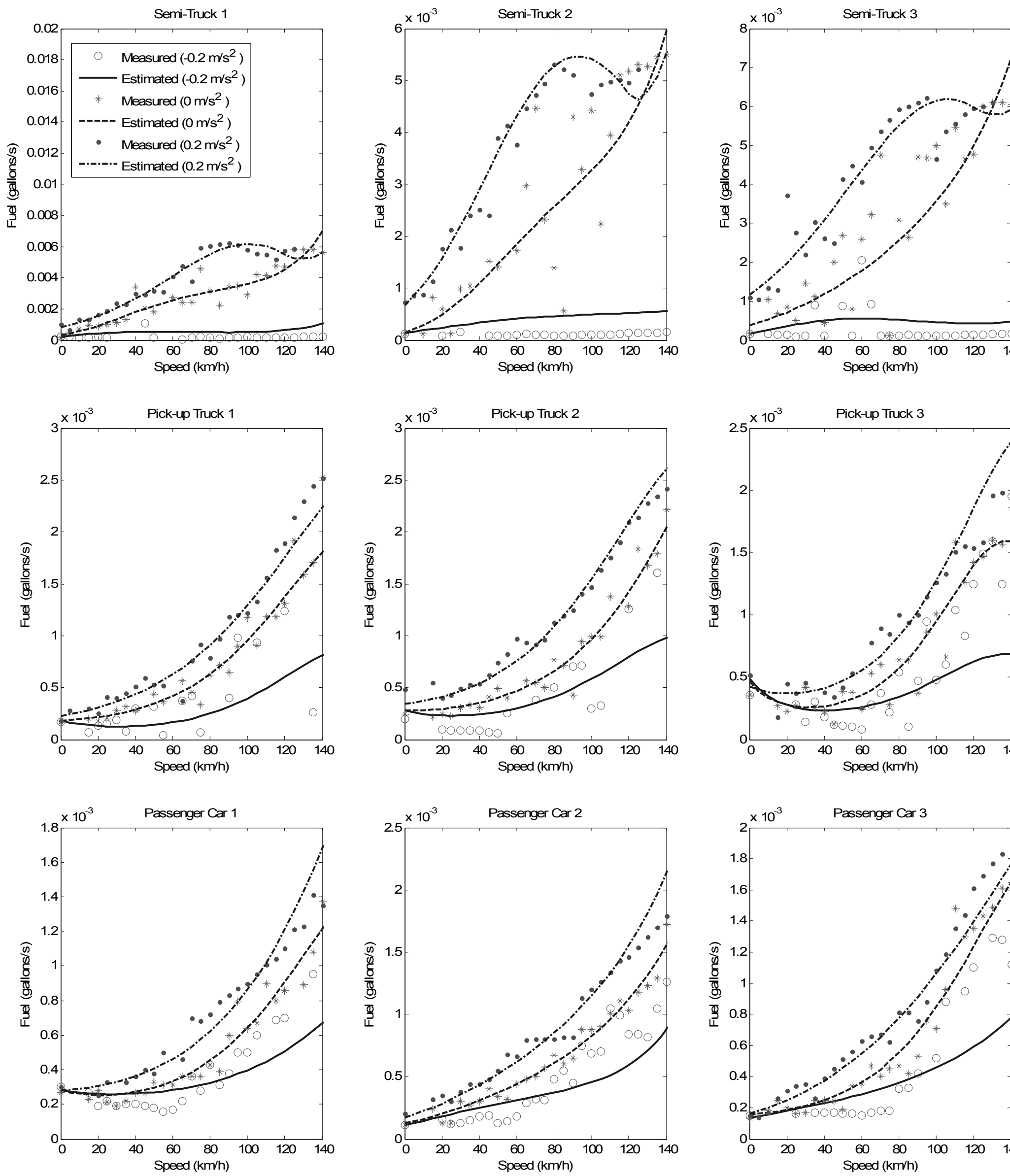

Figure 6.5 Model estimation (fuel consumption).

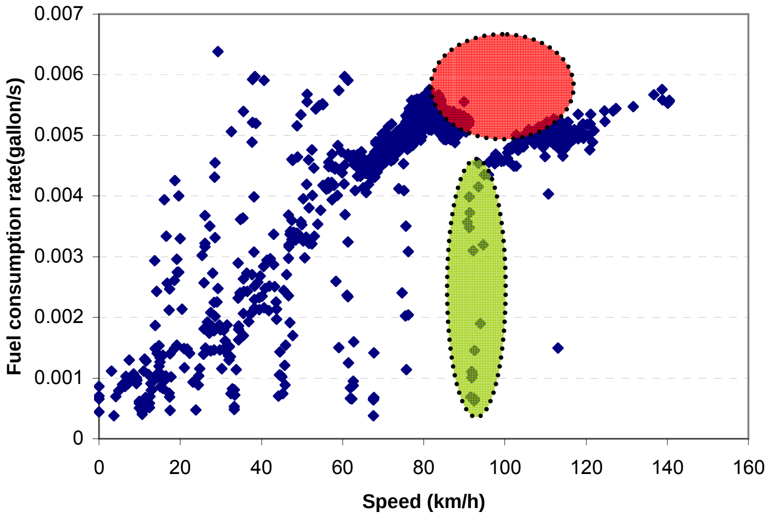

Figure 6.6 Fuel consumption field measurements for semi-truck2 at acceleration of 0.2 m/s^2

Table 6.3 Model Adjusted R^2

Classification		Fuel	CO_2	CO	NO	NO_2	NO_X	HC	PM
ST 1	Positive	0.8819	0.8823	0.5956	0.6588	0.5903	0.6560	0.5815	0.7832
	Negative	0.4004	0.3781	0.3446	0.5235	0.2907	0.2064	0.5939	0.5607
ST 2	Positive	0.8090	0.8111	0.4218	0.8474	0.5823	0.8454	0.4022	0.7836
	Negative	0.1219	-0.0252	-0.0139	0.1061	0.2208	0.0434	0.2637	0.3373
ST 3	Positive	0.6869	0.5329	0.3152	0.6766	0.5245	0.6849	0.4325	0.5196
	Negative	0.2076	0.0420	0.0160	0.1394	0.1868	0.0848	0.5679	0.1595
PT 1	Positive	0.9413	0.9415	0.8300	0.9103	0.4728	0.9127	0.8657	0.9105
	Negative	0.6435	0.5514	0.5896	0.4977	0.6720	0.5021	0.7136	0.5731
PT 2	Positive	0.9025	0.9029	0.6101	0.8849	0.6596	0.8870	0.5258	0.8536
	Negative	0.4675	0.4295	0.4485	0.3807	0.2732	0.3415	0.4828	0.6452
PT 3	Positive	0.8728	0.8738	0.5166	0.8015	0.5956	0.8065	0.5150	0.8832
	Negative	0.6567	0.6746	0.5762	0.7268	0.7089	0.7438	0.7100	0.6578
PC 1	Positive	0.9618	0.9644	0.8637	0.8329	0.5885	0.8330	0.8849	NA
	Negative	0.7271	0.7263	0.7059	0.7694	0.5854	0.7695	0.6829	NA
PC 2	Positive	0.9675	0.9661	0.8733	0.8984	NA	0.8984	0.8599	0.9695
	Negative	0.5724	0.5729	0.8143	0.7045	NA	0.7036	0.7950	0.7995
PC 3	Positive	0.9482	0.9452	0.9117	0.8112	NA	0.8111	0.8832	NA
	Negative	0.4169	0.4190	0.5835	0.7657	NA	0.7477	0.6719	NA

ST: Semi-Truck PT: Pick-up Truck PC: Passenger Car

6. 4 Model Validation

Following the model development, the models were validated in three different ways. First, the instantaneous model estimates were compared to the instantaneous measurements. Second, the differences in aggregated fuel consumption and emission rates were compared for the various drive cycles. Finally, the relative variability in aggregated trip fuel consumption and emission rates for each of the drive cycles was compared. Noteworthy is the fact that the training data was unfortunately used for the validation due to the lack of previous studies on high speed vehicle emission measurement.

First, a comparison between instantaneous model estimates and field measurements was achieved by constructing scatter plots and fitting regression models to the data, as illustrated in Figure 6.7. A regression line with a slope of 1.0 demonstrates a perfect fit between the estimated and field observed data, while a slope of less than 1.0 demonstrates that the models tend to underestimate the dependent variable. In addition, the adjusted R^2 of the line shows the degree of correlation between the two datasets. As can be shown in Figure 6.7, the slope and adjusted R^2 of the lines varied from 0.89 to 1.00 and 0.94 to 0.98, respectively. Consequently, the fuel consumption models produced a maximum error of 11% and provided a high degree of correlation to the field data. Specifically, the models for the pick-up trucks and passenger cars tended to underestimate the vehicle fuel consumption rates. In the case of the other models, the CO_2, NO_2, HC, and PM models generally produced fewer errors and high degrees of correlation when compared to other NO and NO_x, as summarized in Table 6.4. The NO and NO_x models for passenger car 3 produce larger differences with a trend line slope of 0.14 and an adjusted R^2 of 0.33.

Second, the aggregated fuel consumption and emission rates were validated, as summarized in Table 6.5. The differences in the aggregated fuel use and emissions varied depending on the type of vehicle. For example, the models for semi-truck 1 over-estimate the mass fuel consumption and emission rates slightly. Alternatively, the models for the pick-up trucks and passenger cars tend to underestimate the dependent variables. Generally, the differences in fuel use and CO_2 emissions were less than those for other dependent variables; the differences in fuel use and CO_2 emissions varied from -6% to +4% and -7% to +4%, respectively. On the other hand, one or two models for each of the semi-trucks and pick-up trucks produced errors that were greater than ±10%. However, all CO, NO, NO_x and HC models for the passenger cars underestimated the dependent variables with errors greater than -10%. As previously discussed, the NO and NO_x models for passenger car 3 produced a maximum error of -53%.

Finally, the aggregated fuel consumption and emission rates for each of the drive cycles were plotted as a function of drive cycle sequence, as illustrated in Figure 6.8. The figure clearly demonstrates a good match between the model estimates and field observed data.

In conclusion, the fuel consumption, CO, CO_2, HC, and PM models appear to be consistent with the field observations. However, the NO, NO_x models for the passenger car 3 require further enhancement.

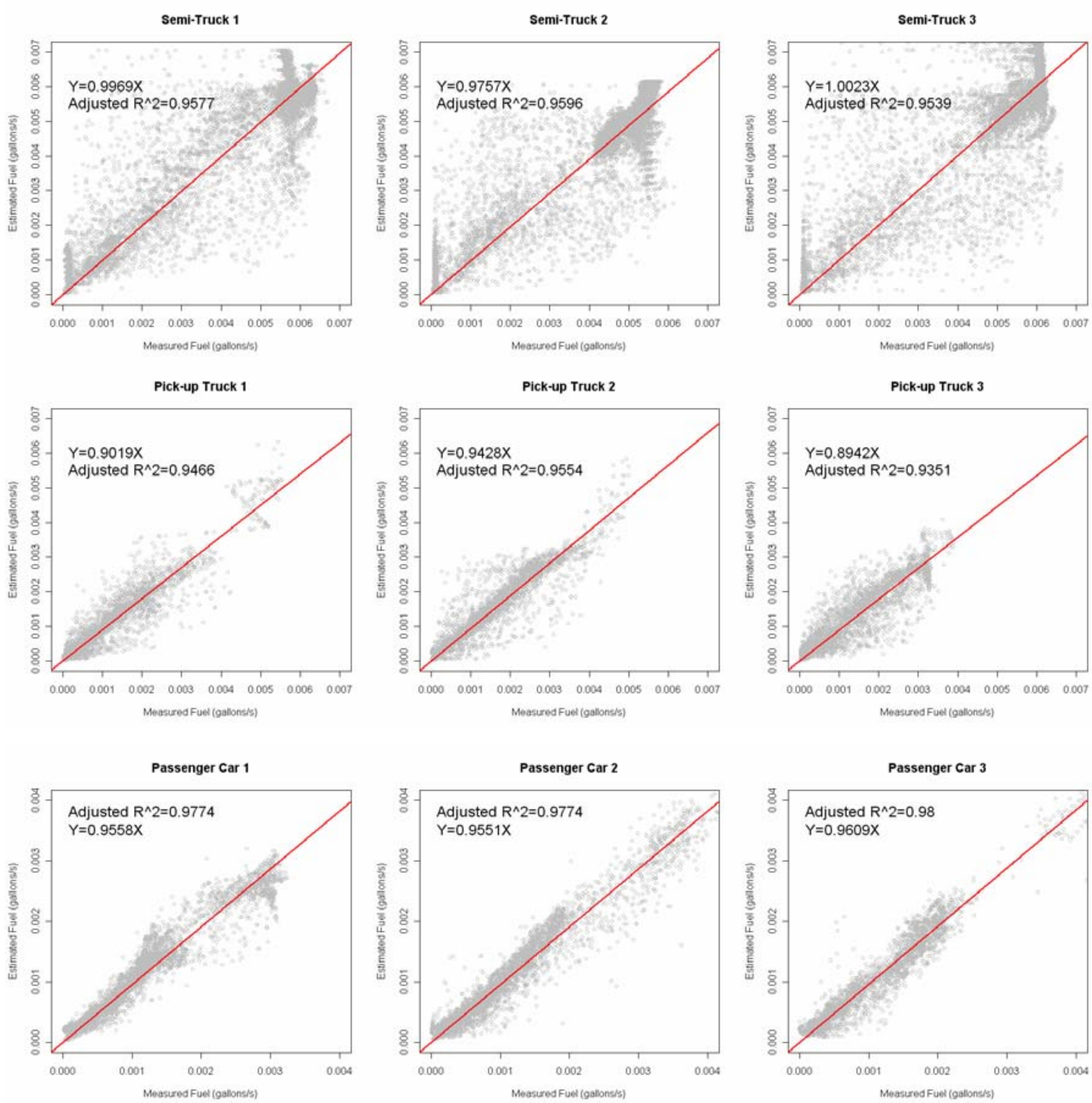

Figure 6.7 Measurements vs. estimates (fuel consumption).

Table 6.4 Slope and Adjusted R^2 of Trend Line of Measurements vs. Estimates

Classification		Fuel	CO_2	CO	NO	NO_2	NO_X	HC	PM
ST 1	Slope	0.9969	0.9876	0.9311	0.9403	0.9673	0.9572	0.7041	0.9772
	Adj. R^2	0.9577	0.9572	0.9268	0.8989	0.9322	0.9075	0.7191	0.9282
ST 2	Slope	0.9757	0.9716	0.4944	0.9504	0.9463	0.9522	0.7295	0.8752
	Adj. R^2	0.9596	0.9576	0.5619	0.9612	0.9576	0.9630	0.7668	0.8859
ST 3	Slope	1.0023	1.0208	0.4352	1.0041	1.1028	1.0153	0.8786	0.7597
	Adj. R^2	0.9539	0.9440	0.5294	0.9516	0.9372	0.9524	0.8843	0.8412
PT 1	Slope	0.9019	0.8949	0.8121	0.8945	0.7076	0.8895	0.8814	0.8794
	Adj. R^2	0.9466	0.9454	0.8123	0.9421	0.7883	0.9438	0.9305	0.9215
PT 2	Slope	0.9428	0.9427	0.6639	0.9152	0.7526	0.9194	0.4410	0.8477
	Adj. R^2	0.9554	0.9561	0.7100	0.9404	0.7555	0.9421	0.5862	0.8829
PT 3	Slope	0.8942	0.8801	0.4101	0.8840	0.8670	0.8957	0.7419	0.7876
	Adj. R^2	0.9351	0.9322	0.4842	0.9350	0.8956	0.9378	0.8147	0.8975
PC 1	Slope	0.9558	0.9956	0.7102	0.6532	0.7605	0.6535	0.7591	NA
	Adj. R^2	0.9774	0.9879	0.6823	0.7681	0.8059	0.7689	0.8934	NA
PC 2	Slope	0.9551	0.9549	0.6972	0.6350	NA	0.6471	0.6231	0.8419
	Adj. R^2	0.9774	0.9761	0.4583	0.7217	NA	0.7215	0.7770	0.8949
PC 3	Slope	0.9609	0.9580	0.8569	0.1427	NA	0.1425	0.7029	NA
	Adj. R^2	0.9800	0.9799	0.8080	0.3266	NA	0.3276	0.7974	NA

Table 6.5 Difference between Aggregated Measurements and Model Estimates

	ST 1			ST 2			ST 3		
	Measured	Estimated	Diff.	Measured	Estimated	Diff.	Measured	Estimated	Diff.
Fuel	31.9	33.3	4%	31.4	32.0	2%	33.0	34.2	4%
CO_2	327509.0	335787.5	3%	323046.5	324475.4	0%	338323.0	353466.8	4%
CO	365.8	371.2	1%	519.7	467.0	-10%	591.0	497.8	-16%
NO	1129.8	1140.4	1%	3362.2	3282.7	-2%	2856.4	2957.3	4%
NO_2	88.0	92.5	5%	105.5	105.9	0%	72.5	81.0	12%
NO_X	1217.8	1259.2	3%	3467.7	3411.5	-2%	2928.8	3071.0	5%
HC	65.3	65.2	0%	38.1	36.5	-4%	47.4	45.7	-4%
PM	30.3	31.3	3%	24.7	24.4	-1%	23.5	21.4	-9%
	PT 1			PT 2			PT 3		
	Measured	Estimated	Diff.	Measured	Estimated	Diff.	Measured	Estimated	Diff.
Fuel	4.2	3.9	-6%	5.9	5.9	-1%	5.2	4.9	-5%
CO_2	42666.0	39494.1	-7%	60877.3	59948.5	-2%	52962.4	49207.6	-7%
CO	59.2	54.7	-8%	103.7	98.0	-5%	90.0	78.7	-13%
NO	225.9	210.2	-7%	295.2	286.4	-3%	401.6	378.0	-6%
NO_2	4.1	3.6	-13%	11.0	10.2	-8%	29.6	28.6	-3%
NO_X	230.0	214.1	-7%	306.3	298.3	-3%	431.2	409.5	-5%
HC	11.7	11.2	-4%	25.6	19.5	-24%	11.3	10.3	-9%
PM	2.9	2.8	-5%	2.7	2.5	-8%	4.6	4.1	-11%
	PC 1			PC 2			PC 3		
	Measured	Estimated	Diff.	Measured	Estimated	Diff.	Measured	Estimated	Diff.
Fuel	5.8	5.7	-1%	5.1	5.0	-2%	3.9	3.9	-2%
CO_2	42703.1	43326.8	1%	42668.4	41707.2	-2%	33969.2	33253.9	-2%
CO	4357.0	3087.0	-29%	2033.3	1442.5	-29%	720.4	620.1	-14%
NO	165.3	140.6	-15%	7.0	5.7	-18%	2.2	1.0	-53%
NO_2	0.2	0.2	-7%	NA	NA	NA	NA	NA	NA
NO_X	164.7	140.1	-15%	7.0	5.8	-17%	2.2	1.0	-53%
HC	36.2	29.4	-19%	22.7	15.8	-30%	6.5	5.2	-20%
PM	NA	NA	NA	0.789413	0.7448	-6%	NA	NA	NA

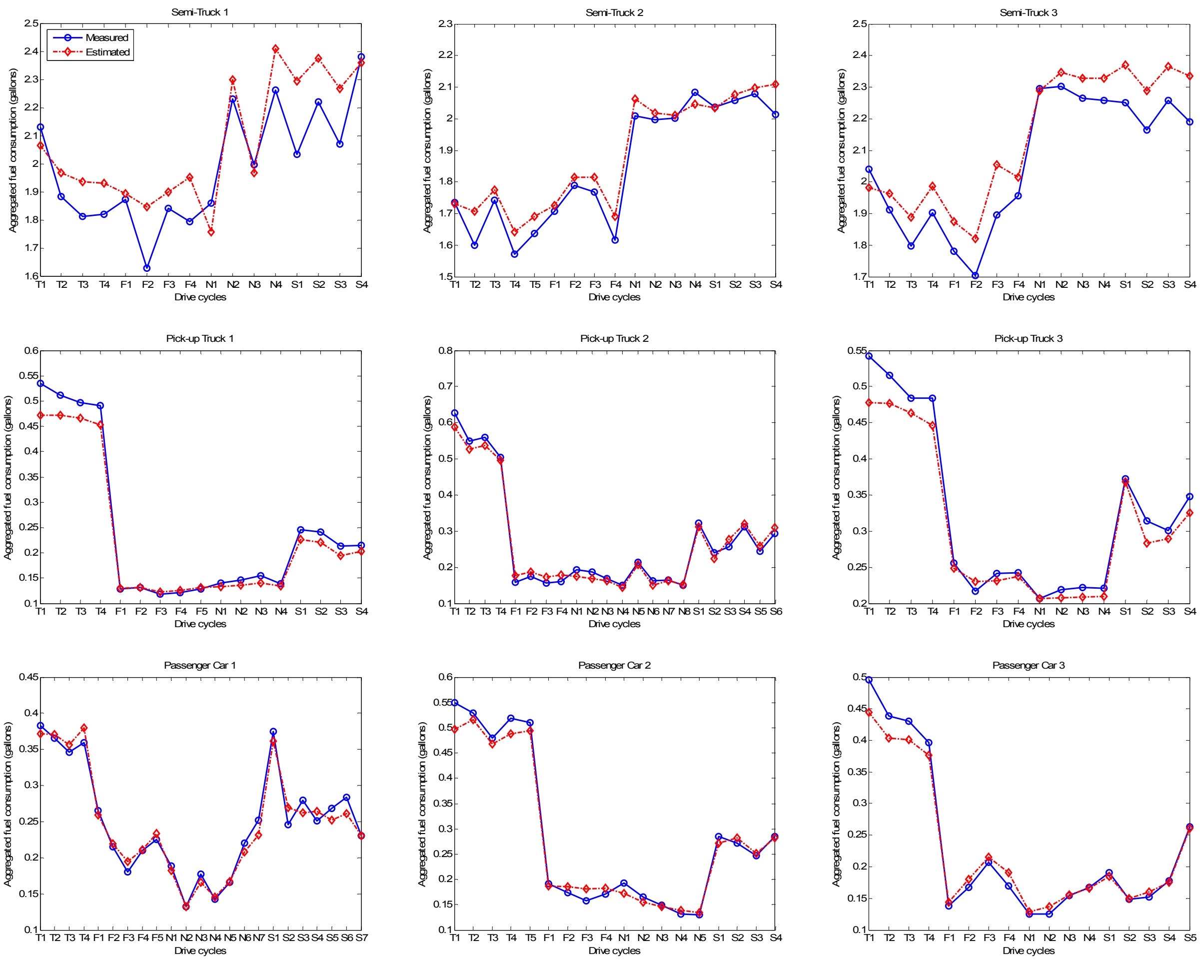

Figure 6.8 Aggregate model validation.

Table 6.6 Fuel Consumption Model Coefficients

Classification		ST1	ST2	ST3	PT1	PT2	PT3	PC1	PC2	PC3
Positive Regime	C	-8.0832	-8.8394	-7.8782	-8.6005	-8.1924	-7.6787	-8.1668	-8.9966	-8.7563
	S	0.06749	0.07175	0.03508	0.004	-0.0004	-0.0397	-0.0114	0.02721	0.00399
	S^2	-0.0007	-0.0006	-0.0002	0.00022	0.00019	0.00077	0.00029	-0.0001	0.00022
	S^3	2.7E-06	2.1E-06	6.8E-07	-9E-07	-6E-07	-3E-06	-1E-06	4.4E-07	-9E-07
	A	1.78757	3.0349	2.53992	0.25138	0.32659	-0.1784	-0.0786	0.47102	-0.0337
	AS	-0.0819	-0.032	-0.0286	0.01747	0.0093	0.04041	0.02286	0.0013	0.03033
	AS^2	0.00171	0.00037	0.00052	-0.0002	-1E-05	-0.0006	-0.0003	-1E-05	-0.0004
	AS^3	-9E-06	-2E-06	-3E-06	8.6E-07	-4E-07	2.5E-06	1.1E-06	4.8E-08	1.4E-06
	A^2	-0.6387	-1.4484	-1.6134	0.04939	-0.02	0.10482	0.07634	-0.035	0.07593
	A^2S	0.05713	0.00063	0.03682	-0.0056	-0.0014	-0.0095	-0.0067	-0.0007	-0.0064
	A^2S^2	-0.0014	4.1E-05	-0.0007	8E-05	-2E-05	0.00017	0.00011	8.6E-06	8.6E-05
	A^2S^3	6.9E-06	-6E-07	4E-06	-3E-07	1.8E-07	-8E-07	-4E-07	-5E-08	-3E-07
	A^3	0.12008	0.26257	0.33998	-0.0031	0.00316	-0.007	-0.0058	0.00129	-0.0044
	A^3S	-0.0185	-0.0012	-0.0134	0.00028	-0.0001	0.00063	0.0005	3.3E-05	0.0003
	A^3S^2	0.00049	3E-05	0.00027	-3E-06	5.1E-06	-1E-05	-8E-06	-2E-07	-3E-06
	A^3S^3	-2E-06	3E-08	-1E-06	6.8E-09	-2E-08	5.7E-08	2.1E-08	4E-09	2.3E-09
Negative Regime	C	-8.0832	-8.8394	-7.8782	-8.6005	-8.1924	-7.6787	-8.1668	-8.9966	-8.7563
	S	0.06749	0.07175	0.03508	0.004	-0.0004	-0.0397	-0.0114	0.02721	0.00399
	S^2	-0.0007	-0.0006	-0.0002	0.00022	0.00019	0.00077	0.00029	-0.0001	0.00022
	S^3	2.7E-06	2.1E-06	6.8E-07	-9E-07	-6E-07	-3E-06	-1E-06	4.4E-07	-9E-07
	A	0.45125	-0.0673	1.4115	-0.0377	0.00107	-0.0954	0.00809	0.17601	0.21255
	AS	0.04493	0.07197	-0.0267	0.05362	0.02371	0.00205	-0.0076	-0.0036	-0.0158
	AS^2	-0.0001	-0.0006	0.00074	-0.0006	-0.0003	0.00018	0.00027	0.00023	0.0004
	AS^3	-3E-07	2.4E-06	-3E-06	1.9E-06	1.3E-06	-9E-07	-1E-06	-1E-06	-2E-06
	A^2	0.10594	-0.1322	0.38385	-0.0171	0.00574	-0.0224	-0.0028	0.03369	0.02067
	A^2S	0.00741	0.02105	-0.0122	0.01398	0.00291	0.00147	-0.0004	-0.001	-0.0021
	A^2S^2	9.6E-06	-0.0002	0.00025	-0.0002	-5E-05	-4E-06	2E-05	2.9E-05	5.2E-05
	A^2S^3	-2E-07	9.2E-07	-7E-07	5.6E-07	2.2E-07	5.2E-09	-9E-08	-1E-07	-2E-07
	A^3	0.00805	-0.0148	0.0248	-0.0017	0.0004	-0.0007	-0.0002	0.00097	0.00023
	A^3S	0.00029	0.00162	-0.0008	0.00095	8.1E-05	6E-05	-3E-06	-3E-05	-5E-05
	A^3S^2	2.9E-06	-2E-05	1.4E-05	-1E-05	-2E-06	-5E-07	3.6E-07	6.4E-07	1.5E-06
	A^3S^3	-2E-08	8.9E-08	-7E-09	3.7E-08	7.5E-09	2.2E-09	-2E-09	-3E-09	-6E-09

C: Constant *S: Speed Term* *A: Acceleration Term*

6.5 Example Model Illustrations

In order to demonstrate the effectiveness of the developed models, the model together with the CMEM and VT-Micro models were applied to sample high speed drive cycles. Three models were considered, namely: the models for passenger car 1, the CMEM model for category 11, and LDV3 VT-Micro model. The CMEM category 11 and VT-Micro LDV3 were selected because the model years were relatively newer than those of other light-duty vehicles incorporated in the CMEM and VT-Micro models. In running the CMEM model, the default parameters for category 11 were used except those for engine displacement, vehicle mass, and number of gears. The objective of using the three models was to compare the alternative models to conduct environmental studies involving high speed vehicles rather than to assess the models' overall performance. Thus, it is unreasonable to judge which model is superior based on this illustration.

The STEP high speed drive cycle was utilized to compare the model estimates to field measurements. The STEP drive cycle involves traveling at speeds of up to 150 km/h (93 mph), as can be shown in Figure 6.9. The instantaneous model estimates of fuel consumption, HC, CO, and NO_x emissions produced by the CMEM, VT-Micro, and PC-1 models (passenger car 1) were plotted as a function of time. According to the results, the CMEM model over-estimates the vehicle fuel consumption and emission rates, while the VT-Micro model tends to underestimate these rates. Specifically, prediction errors range from +2413 to -10%, -80 to -32%, and -50 to +3%, for the CMEM, VT-Micro and PC-1 models, respectively. The most important factor is whether the models were sensitive to high speeds. As can be clearly seen in Figure 6.9, the newly constructed models for passenger car 1 produced different estimates that were sensitive to high speeds, while the CMEM and VT-Micro models produced identical estimates at high speeds and/or high engine load conditions. This is because the CMEM and VT-Micro models are set to use boundary conditions when the engine load condition of the vehicle exceeds the boundary.

In conclusion, the figure clearly demonstrates that the newly constructed models are more suitable for the evaluation of the environmental impact of high speed vehicles.

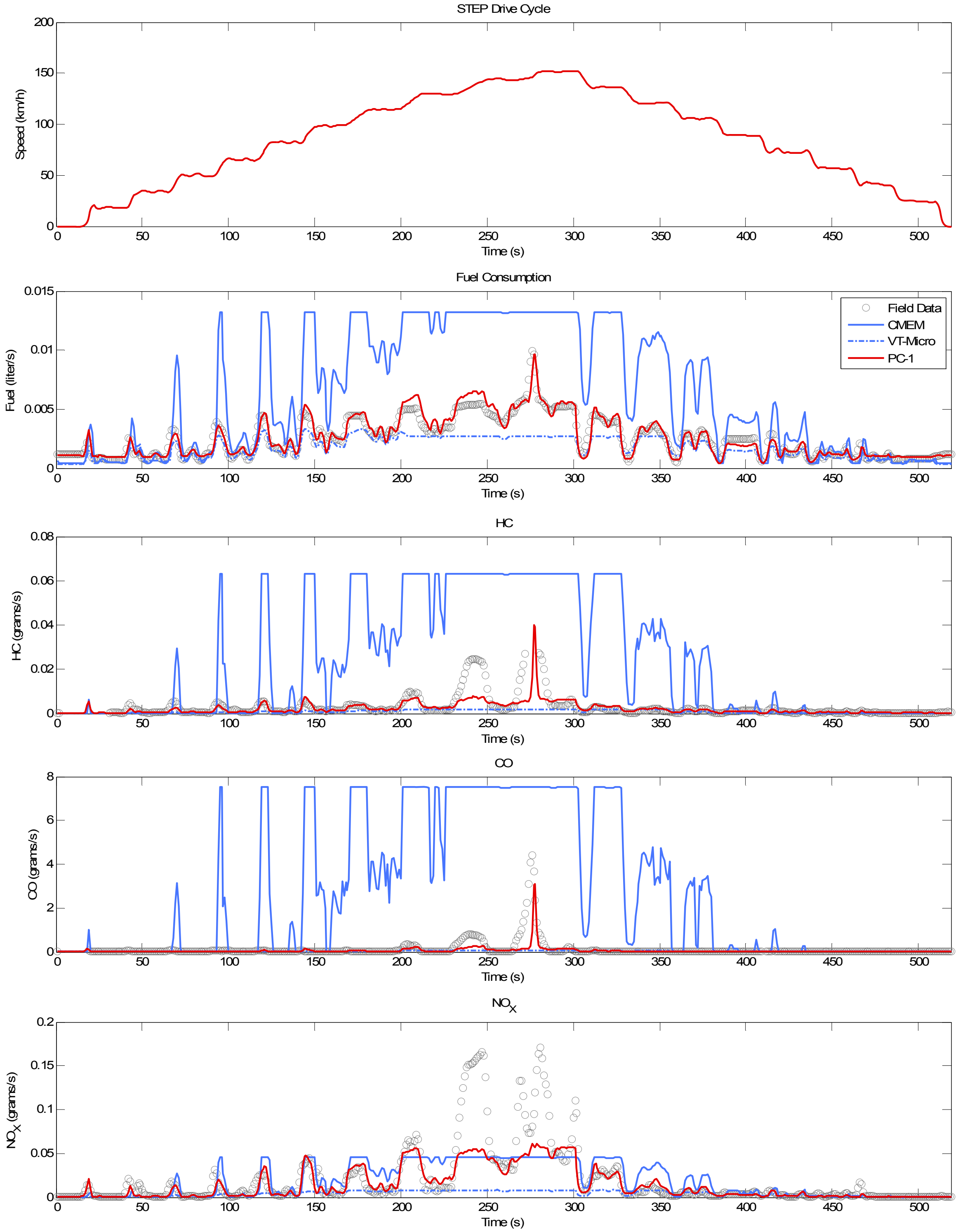

Figure 6.9 Instantaneous model comparison.

6.6 Conclusions

The research effort gathered field data and developed models for the estimation of fuel consumption, CO_2, CO, NO, NO_2, NO_x, HC, and PM emissions at high speeds. A total of nine vehicles including three semi-trucks, three pick-up trucks, and three passenger cars were tested on a nine-mile test track in Pecos, Texas.

The fuel consumption and emission rates were measured using two portable emissions measurement systems. Models were developed using these data producing minimum errors for fuel consumption, CO_2, NO_2, HC, and PM emissions. Alternatively, the NO and NO_x emission models produced the highest errors with a least degree of correlation. The study demonstrated that the newly constructed models overcome the shortcomings of the state-of-practice models and can be utilized to evaluate the environmental impacts of high speed driving.

In conclusion, the new models constructed in this study are expected to be utilized for conducting sensitivity studies involving high speed vehicles since the current state-of-practice models do not provide reliable estimates for high speeds. Additionally, the study demonstrates that PEMS can be practically utilized to measure vehicle emissions in the field even when the test vehicles are running at high speeds. Finally, the VT-Micro modeling structure can be utilized for constructing new models for high speed vehicles.

Future research is required to quantify the impact of high speed vehicles on the environment using the newly constructed models in conjunction with traffic simulation software. In this sense, the inclusion of these models in traffic simulation software is needed.

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Chapter 7: Conclusions and Recommendations for Further Research

7.1 Dissertation Conclusions

The dissertation extended the state-of-the-art analysis of high emitting vehicles by quantifying their environmental impact at a network-level as opposed to temporal and spatial confined studies that are reported in the literature. The literature reports that 7% to 12% of HEVs account for somewhere between 41% to 63% of the total CO emissions, and 10% are responsible for 47% to 65% of HC emissions, and 10% are responsible for 32% of NO_x emissions. These studies, however, are based on spot measurements and do not necessarily reflect network-wide impacts. Consequently, the research presented in this chapter extends the state-of-knowledge by quantifying HEV contributions on a network level. The study uses microscopic vehicle emission models (CMEM and VT-Micro model) along with pre-defined drive cycles (under the assumption that the composite HEV and VT-LDV3 represent HEVs and NEVs, respectively) in addition to the simulation of two transportation networks (freeway and arterial) to quantify the contributions of HEVs. The study demonstrates that HEVs are responsible for 67% to 87% of HC emissions, 51% to 78% of CO emissions, and 32% to 62% of the NO_X emissions for HEV percentages ranging from 5% to 20%. Additionally, the traffic simulation results demonstrate that 10% of the HEVs are responsible for 50% to 66% of the I-81 HC and 59% to 78% of the Columbia Pike HC emissions, 35% to 67% of the I-81 CO and 38% to 69% of the Columbia Pike CO emissions, and 35% to 44% of the I-81 NO_X and 35% to 60% of the Columbia Pike NO_X emissions depending on the percentage of the normal-emitting LDTs to the total NEVs. HEV emission contributions to total HC and CO emissions appear to be consistent with what is reported in the literature. However, the contribution of NO_X emissions is greater than what is reported in the literature. The study demonstrates that the contribution of HEVs to the total vehicle emissions is dependent on the type of roadway facility (arterials vs. highways), the background normal vehicle composition, and the composition of HEVs. Consequently, these results are network and roadway specific. Finally, considering that emission control technologies in new vehicles are advancing, the contribution of HEVs will increase given that the background emission contribution will decrease.

Given that HEVs are responsible for a large portion of on-road vehicle emissions, the dissertation proposed some solutions to screen HEVs and repair or retire them early. First, a new approach was proposed for estimating vehicle mass emissions from concentration remote sensing emission measurements using the carbon balance equation in conjunction with either the VT-Micro or PERE model fuel consumption rates for the enhancement of current state-of-the-art HEV screening procedures using RSD technology. Also, it was demonstrated that the proposed approach produces reliable mass emission estimates for different vehicle types including sedans, station wagons, full size vans, mini vans, pickup trucks, and SUVs. Second, a procedure was proposed for constructing on-road RS emissions standards sensitive to vehicle speed and acceleration levels. The proposed procedure is broadly divided into three sub-processes. In the first process, HE cut points in grams per second are developed as a function of a vehicle's speed and acceleration levels using the VT-Micro and CMEM emission models. Subsequently, the HE cut points in grams per second are converted to concentration emissions cut points in parts per million using the carbon balance equation. Finally, the scale factors are computed using either ASM ETW- and model-year-based standards or engine-displacement-based standards. Given the RS emissions standards, the study demonstrated that the use of on-road RS cut points sensitive to speed and acceleration levels is required in order to enhance the effectiveness of RS.

Finally, the dissertation conducted a study to develop fuel consumption and emissions models for high-speed vehicles to overcome the shortcomings of state-of-practice models. The research effort gathered field data and developed models for the estimation of fuel consumption, CO_2, CO, NO, NO_2, NOx, HC, and PM emissions at high speeds. A total of nine vehicles including three semi-trucks, three pick-up trucks, and three passenger cars were tested on a nine-mile test track in Pecos, Texas. The fuel consumption and emission rates were measured using two portable emission measurement systems.

Models were developed using these data producing minimum errors for fuel consumption, CO_2, NO_2, HC, and PM emissions. Alternatively, the NO and NO_x emission models produced the highest errors with a least degree of correlation. Given the models, the study demonstrated that the newly constructed models overcome the shortcomings of the state-of-practice models and can be utilized to evaluate the environmental impacts of high speed driving.

In conclusion, the dissertation demonstrated that the detection of high-emitting vehicles should have the priority in emissions control strategies. In other words, it has been shown that high-emitting vehicles emit much higher air pollution of interest when compared to normal-emitting vehicles. In order to suggest a solution to identify the high-emitting vehicles, the dissertation proposed two different methodologies that can be used to enhance the currently-used high-emitting vehicle detection procedures using remote sensing devices. Finally, the fuel consumption and emissions models for high speed vehicles were developed. The new models are expected to be utilized for conducting sensitivity studies involving high speed vehicles since the current state-of-practice models do not provide reliable estimates for high vehicle speeds.

7.2 Recommendations for Further Research

In the last few years, scientific consensus has strengthened around the fact that the emission of greenhouse gases (GHGs) into the atmosphere is contributing to changes in the earth's climate. While uncertainty remains over the pace and dimensions of the change, a consensus around the need for action has grown among the public and elected officials. In part, this shift has been accelerated by concern over energy security and rising fuel prices. The new political landscape has led many cities, states, and regions to institute policies aimed at reducing GHG emissions. These policies and emerging initiatives have significant implications for the transportation planning process.

About 28% of the United States' GHG emissions are from transportation sources. Carbon dioxide emissions from personal vehicles and trucks account for 82% of these emissions and have grown by 28% since 1990. Unlike conventional air pollutants, carbon dioxide emissions are directly tied to the amount of fuel consumed and its carbon intensity. Therefore, emissions reductions can be achieved by increasing the use of low-carbon fuels, improving fuel economy, or reducing total vehicle miles–often called the three legged stool. (A fourth leg is congestion reduction, at certain optimal speeds). These same factors are related to our use of imported oil, so actions taken to reduce GHG emissions may actually produce benefits in both policy areas.

The climatic risks of additional emissions associated with capacity projects must be balanced against the mobility, safety, and economic needs of a community or region. Consequently, the impact of high speed vehicles to energy uses and vehicle emissions needs to be quantified in future research efforts, because vehicle speed is one of the critical factors affecting fuel consumption and emission rates. Furthermore, speed limits can be used to achieve desirable environmental goals. Consequently, the impacts of high speed vehicles need to be quantified microscopically in a network level using the microscopic traffic simulation software and the newly-developed fuel consumption and emission models.

Further research is also required to develop route guidance systems that minimize vehicle fuel consumption levels by considering the levels of congestion on the roadway facilities, the speed limits of the facilities, and the roadway grades.

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Appendix A – Matlab codes

1. Matlab code for VT-Micro models

```
%fuel (Liter/second)
%HC (grams/second)
%CO (grams/second)
%NOx (grams/second)
%CO2 (grams/second)
%
% Vehicle Type T=1:ORNL 2:LDV1 3:LDV2 4:LDV3 5:LDV4 6:LDV5
%                   7:LDT1 8:LDT2 9:HE1 10:HE2 11:HE3 12:HE4

function [fuel, hc, co, nox, co2]=VTM(V,A,T)

if T==1
   load VTM_COEF_ORNL.txt;
   COEF = VTM_COEF_ORNL;
   clear VTM_COEF_ORNL;
elseif T==2 %LDV1
   load VTM_COEF_LDV1.txt;
   COEF = VTM_COEF_LDV1;
   clear VTM_COEF_LDV1;
elseif T==3 %LDV2
   load VTM_COEF_LDV2.txt;
   COEF = VTM_COEF_LDV2;
   clear VTM_COEF_LDV2;
elseif T==4 %LDV3
   load VTM_COEF_LDV3.txt;
   COEF = VTM_COEF_LDV3;
   clear VTM_COEF_LDV3;
elseif T==5 %LDV4
   load VTM_COEF_LDV4.txt;
   COEF = VTM_COEF_LDV4;
   clear VTM_COEF_LDV4;
elseif T==6 %LDV5
   load VTM_COEF_LDV5.txt;
   COEF = VTM_COEF_LDV5;
   clear VTM_COEF_LDV5;
elseif T==7 %LDT1
   load VTM_COEF_LDT1.txt;
   COEF = VTM_COEF_LDT1;
   clear VTM_COEF_LDT1;
elseif T==8 %LDT2
   load VTM_COEF_LDT2.txt;
   COEF = VTM_COEF_LDT2;
   clear VTM_COEF_LDT2;
elseif T==9
   load VTM_COEF_HE1.txt;
   COEF = VTM_COEF_HE1;
   clear VTM_COEF_HE1;
elseif T==10
   load VTM_COEF_HE2.txt;
```

```
   COEF = VTM_COEF_HE2;
   clear VTM_COEF_HE2;
elseif T==11
   load VTM_COEF_HE3.txt;
   COEF = VTM_COEF_HE3;
   clear VTM_COEF_HE3;
elseif T==12
   load VTM_COEF_HE4.txt;
   COEF = VTM_COEF_HE4;
   clear VTM_COEF_HE4;
end



for i=1:length(A)

%Boundary condition check
if T == 1
   if V(i) > 121
      V(i)= 121;
   end

   if A(i)>0
      if V(i)< 30
         if A(i) <= 10
            Aadj = A(i);
         else
            Aadj = 10;
         end
      elseif V(i) >= 30
         if A(i) <= (-V(i)/9+10+10/3)
            Aadj = A(i);
         else
            Aadj = (-V(i)/9+10+10/3);
         end
      end
   else
      if A(i) >= (-5.4)
         Aadj =A(i);
      elseif A(i) < (-5.4)
         Aadj = (-5.4);
      end
   end

else
            if V(i) > 120
                        V(i) = 120;
   end

   if A(i) >0
      if A(i) > (10-0.0714*V(i))
         Aadj = (10-0.0714*V(i));
      else
```

```
            Aadj = A(i);
        end
    else
        if A(i) < -4
            Aadj = -4;
        else
            Aadj = A(i);
        end
    end
end

if (Aadj > 0 | Aadj == 0)
    fuel(i) = exp(COEF(1,1)+COEF(1,2).*V(i)+COEF(1,3).*V(i).^2+COEF(1,4).*V(i).^3 + ...
        (COEF(1,5)+COEF(1,6).*V(i)+COEF(1,7).*V(i).^2+COEF(1,8).*V(i).^3).*Aadj + ...
        (COEF(1,9)+COEF(1,10).*V(i)+COEF(1,11).*V(i).^2+COEF(1,12).*V(i).^3).*Aadj.^2 + ...
        (COEF(1,13)+COEF(1,14).*V(i)+COEF(1,15).*V(i).^2+COEF(1,16).*V(i).^3).*Aadj.^3);
    hc(i)                           =                           0.001*exp(COEF(2,1)+COEF(2,2).*V(i)+COEF(2,3).*V(i).^2+COEF(2,4).*V(i).^3
+(COEF(2,5)+COEF(2,6).*V(i)+COEF(2,7).*V(i).^2+COEF(2,8).*V(i).^3).*Aadj
+(COEF(2,9)+COEF(2,10).*V(i)+COEF(2,11).*V(i).^2+COEF(2,12).*V(i).^3).*Aadj.^2
+(COEF(2,13)+COEF(2,14).*V(i)+COEF(2,15).*V(i).^2+COEF(2,16).*V(i).^3).*Aadj.^3);
    co(i)                           =                           0.001*exp(COEF(3,1)+COEF(3,2).*V(i)+COEF(3,3).*V(i).^2+COEF(3,4).*V(i).^3
+(COEF(3,5)+COEF(3,6).*V(i)+COEF(3,7).*V(i).^2+COEF(3,8).*V(i).^3).*Aadj
+(COEF(3,9)+COEF(3,10).*V(i)+COEF(3,11).*V(i).^2+COEF(3,12).*V(i).^3).*Aadj.^2
+(COEF(3,13)+COEF(3,14).*V(i)+COEF(3,15).*V(i).^2+COEF(3,16).*V(i).^3).*Aadj.^3);
    nox(i)=                                                     0.001*exp(COEF(4,1)+COEF(4,2).*V(i)+COEF(4,3).*V(i).^2+COEF(4,4).*V(i).^3
+(COEF(4,5)+COEF(4,6).*V(i)+COEF(4,7).*V(i).^2+COEF(4,8).*V(i).^3).*Aadj
+(COEF(4,9)+COEF(4,10).*V(i)+COEF(4,11).*V(i).^2+COEF(4,12).*V(i).^3).*Aadj.^2
+(COEF(4,13)+COEF(4,14).*V(i)+COEF(4,15).*V(i).^2+COEF(4,16).*V(i).^3).*Aadj.^3);
    co2(i)=                                                     0.001*exp(COEF(5,1)+COEF(5,2).*V(i)+COEF(5,3).*V(i).^2+COEF(5,4).*V(i).^3
+(COEF(5,5)+COEF(5,6).*V(i)+COEF(5,7).*V(i).^2+COEF(5,8).*V(i).^3).*Aadj
+(COEF(5,9)+COEF(5,10).*V(i)+COEF(5,11).*V(i).^2+COEF(5,12).*V(i).^3).*Aadj.^2
+(COEF(5,13)+COEF(5,14).*V(i)+COEF(5,15).*V(i).^2+COEF(5,16).*V(i).^3).*Aadj.^3);
else
    fuel(i) = exp(COEF(6,1)+COEF(6,2).*V(i)+COEF(6,3).*V(i).^2+COEF(6,4).*V(i).^3+ ...
        (COEF(6,5)+COEF(6,6).*V(i)+COEF(6,7).*V(i).^2+COEF(6,8).*V(i).^3)*Aadj+ ...
        (COEF(6,9)+COEF(6,10).*V(i)+COEF(6,11).*V(i).^2+COEF(6,12).*V(i).^3)*Aadj.^2+ ...
        (COEF(6,13)+COEF(6,14).*V(i)+COEF(6,15).*V(i).^2+COEF(6,16).*V(i).^3)*Aadj.^3);
    hc(i)                           =                           0.001*exp(COEF(7,1)+COEF(7,2).*V(i)+COEF(7,3).*V(i).^2+COEF(7,4).*V(i).^3
+(COEF(7,5)+COEF(7,6).*V(i)+COEF(7,7).*V(i).^2+COEF(7,8).*V(i).^3).*Aadj
+(COEF(7,9)+COEF(7,10).*V(i)+COEF(7,11).*V(i).^2+COEF(7,12).*V(i).^3).*Aadj.^2
+(COEF(7,13)+COEF(7,14).*V(i)+COEF(7,15).*V(i).^2+COEF(7,16).*V(i).^3).*Aadj.^3);
    co(i)                           =                           0.001*exp(COEF(8,1)+COEF(8,2).*V(i)+COEF(8,3).*V(i).^2+COEF(8,4).*V(i).^3
+(COEF(8,5)+COEF(8,6).*V(i)+COEF(8,7).*V(i).^2+COEF(8,8).*V(i).^3).*Aadj
+(COEF(8,9)+COEF(8,10).*V(i)+COEF(8,11).*V(i).^2+COEF(8,12).*V(i).^3).*Aadj.^2
+(COEF(8,13)+COEF(8,14).*V(i)+COEF(8,15).*V(i).^2+COEF(8,16).*V(i).^3).*Aadj.^3);
    nox(i)=                                                     0.001*exp(COEF(9,1)+COEF(9,2).*V(i)+COEF(9,3).*V(i).^2+COEF(9,4).*V(i).^3
+(COEF(9,5)+COEF(9,6).*V(i)+COEF(9,7).*V(i).^2+COEF(9,8).*V(i).^3).*Aadj
+(COEF(9,9)+COEF(9,10).*V(i)+COEF(9,11).*V(i).^2+COEF(9,12).*V(i).^3).*Aadj.^2
+(COEF(9,13)+COEF(9,14).*V(i)+COEF(9,15).*V(i).^2+COEF(9,16).*V(i).^3).*Aadj.^3);
    co2(i)=                                              0.001*exp(COEF(10,1)+COEF(10,2).*V(i)+COEF(10,3).*V(i).^2+COEF(10,4).*V(i).^3
+(COEF(10,5)+COEF(10,6).*V(i)+COEF(10,7).*V(i).^2+COEF(10,8).*V(i).^3).*Aadj
+(COEF(10,9)+COEF(10,10).*V(i)+COEF(10,11).*V(i).^2+COEF(10,12).*V(i).^3).*Aadj.^2
+(COEF(10,13)+COEF(10,14).*V(i)+COEF(10,15).*V(i).^2+COEF(10,16).*V(i).^3).*Aadj.^3);
```

```
end
end

fuel = fuel'; hc=hc'; co=co'; nox=nox'; co2=co2';
```

2. Matlab code for remote sensing standards

```
%RS_Cutpoint function
%speed: mph, acceleration: mph/s, Vehicletype: true=LDV, false=LDT,
%ETW: lbs, MY: #### (ex:1996)
%HC, CO, NO cut point: ppm

function [HC_Cutpoint,CO_Cutpoint,NO_Cutpoint]=RS_Cutpoint(speed,acceleration,VehicleType,ETW,MY);

ScaleFactor_LDV=[3.13 3.36 3.92];
ScaleFactor_LDT=[14.64 16.91 4.9];
%Procedure: VSP effect or not?
   VSP_Min = 3;
if MY < 1996
   VSP_Max = 15;
else
   VSP_Max = 22;
end

VSP = 0.22.*speed.*acceleration+0.0954*speed+0.0000272*speed.^3;

if (VSP < VSP_Min) || (VSP > VSP_Max)
   HC_Cutpoint = NaN;
   CO_Cutpoint = NaN;
   NO_Cutpoint = NaN;
else
% Process 1 - HE mass emission cut point
   if VehicleType %if vehicletype = LDV
      [fuel,HC_Mass,CO_Mass,NO_Mass,CO2_Mass] = VTM(speed*1.6,acceleration*1.6,5);
      HC_Multiplied = HC_Mass * ScaleFactor_LDV(1);
      CO_Multiplied = CO_Mass * ScaleFactor_LDV(2);
      NO_Multiplied = NO_Mass * ScaleFactor_LDV(3);
   else
      [fuel,HC_Mass,CO_Mass,NO_Mass,CO2_Mass] = VTM(speed*1.6,acceleration*1.6,7);
      HC_Multiplied = HC_Mass * ScaleFactor_LDT(1);
      CO_Multiplied = CO_Mass * ScaleFactor_LDT(2);
      NO_Multiplied = NO_Mass * ScaleFactor_LDT(3);
   end
   N2_Mass = 3.49 * CO2_Mass;
% Process 2 - HE concentration emission cut point
   Denominator = HC_Mass/44 + CO_Mass/28 + NO_Mass/46 + CO2_Mass/44 + N2_Mass/28;

   HC_PPM = (HC_Multiplied/44)./Denominator*1000000;
   CO_PPM = (CO_Multiplied/28)./Denominator*1000000;
   NO_PPM = (NO_Multiplied/46)./Denominator*1000000;

% Process 3 - Calculate ASM ETW-based scale factors
   if VehicleType %if vehicletype = LDV
      if MY >= 1996
         HC_ASM_Scale_Factor = 387.64*ETW.^(-0.7846);
         CO_ASM_Scale_Factor = 468.3*ETW.^(-0.8089);
         NO_ASM_Scale_Factor = 1244.9*ETW.^(-0.9283);
      elseif MY >= 1991 && MY <=1995
         HC_ASM_Scale_Factor = 497.09*ETW.^(-0.7835);
```

```
        CO_ASM_Scale_Factor = 573.79*ETW.^(-0.8019);
        NO_ASM_Scale_Factor = 1555.3*ETW.^(-0.9282);
    elseif MY >= 1983 && MY <=1990
        HC_ASM_Scale_Factor = 766.51*ETW.^(-0.8181);
        CO_ASM_Scale_Factor = 870.71*ETW.^(-0.8281);
        NO_ASM_Scale_Factor = 1994.2*ETW.^(-0.9404);
    elseif MY >= 1981 && MY <=1982
        HC_ASM_Scale_Factor = 766.51*ETW.^(-0.8181);
        CO_ASM_Scale_Factor = 2498.1*ETW.^(-0.8775);
        NO_ASM_Scale_Factor = 1994.2*ETW.^(-0.9404);
    end
else
    if ETW <=3750
        if MY >= 1996
            HC_ASM_Scale_Factor = 621.43*ETW.^(-0.8589);
            CO_ASM_Scale_Factor = 446.28*ETW.^(-0.8787);
        elseif MY >= 1991 && MY <=1995
            HC_ASM_Scale_Factor = 1717.60*ETW.^(-0.8979);
            CO_ASM_Scale_Factor = 2319.30*ETW.^(-0.9342);
        elseif MY >= 1984 && MY <=1990
            HC_ASM_Scale_Factor = 2086.3*ETW.^(-0.9093);
            CO_ASM_Scale_Factor = 2891.3*ETW.^(-0.9417);
        elseif MY >= 1981 && MY <=1983
            HC_ASM_Scale_Factor = 5672.5*ETW.^(-0.9619);
            CO_ASM_Scale_Factor = 4395.4*ETW.^(-0.9546);
        end

        if MY >=1996
            NO_ASM_Scale_Factor = 1781.3*ETW.^(-0.9656);
        elseif MY >= 1991 && MY <= 1995
            NO_ASM_Scale_Factor = 3159.4*ETW.^(-0.9705);
        elseif MY >= 1988 && MY <= 1990
            NO_ASM_Scale_Factor = 3650.5*ETW.^(-0.9744);
        elseif MY >= 1981 && MY <= 1987
            NO_ASM_Scale_Factor = 3883.9*ETW.^(-0.8901);
        end
    else
        if MY >= 1996
            HC_ASM_Scale_Factor = 2E-08*ETW.^2-0.0003*ETW+1.4166;
            CO_ASM_Scale_Factor = 1E-08*ETW.^2-0.0002*ETW+0.8661;
        elseif MY >= 1991 && MY <=1995
            HC_ASM_Scale_Factor = 3E-08*ETW.^2-0.0004*ETW+2.2343;
            CO_ASM_Scale_Factor = 3E-08*ETW.^2-0.0004*ETW+2.3180;
        elseif MY >= 1984 && MY <=1990
            HC_ASM_Scale_Factor = 3E-08*ETW.^2-0.0005*ETW+2.5097;
            CO_ASM_Scale_Factor = 3E-08*ETW.^2-0.0005*ETW+2.7276;
        elseif MY >= 1981 && MY <=1983
            HC_ASM_Scale_Factor = 6E-08*ETW.^2-0.0009*ETW+4.6382;
            CO_ASM_Scale_Factor = 5E-08*ETW.^2-0.0007*ETW+3.7791;
        end

        if MY >=1996
            NO_ASM_Scale_Factor = 2E-08*ETW.^2-0.0003*ETW+1.7753;
```

```
        elseif MY >= 1991 && MY <= 1995
          NO_ASM_Scale_Factor = 3E-08*ETW.^2-0.0005*ETW+2.4325;
        elseif MY >= 1988 && MY <= 1990
          NO_ASM_Scale_Factor = 4E-08*ETW.^2-0.0005*ETW+2.7311;
        elseif MY >= 1981 && MY <= 1987
          NO_ASM_Scale_Factor = 8E-08*ETW.^2-0.0012*ETW+5.8346;
        end
      end
    end


    HC_Cutpoint = HC_PPM .* HC_ASM_Scale_Factor;
    CO_Cutpoint = CO_PPM .* CO_ASM_Scale_Factor;
    NO_Cutpoint = NO_PPM .* NO_ASM_Scale_Factor;

End
```

3. Matlab code for summarizing simulation result

```
%Produce two matrix having total / average statistics from a Integration summary file
%Input: filename of the INTEGRATION summary file
%Output: Total Statistics & Average Statistics
%                    Veh_1  Veh_2  Veh_3  Veh_4 Veh_5 Total
%1 vehicle trips
%2 person trips
%3 vehicle-km
%4 person-km
%5 vehicle-stops
%6 vehicle-secs
%7 person-secs
%8 total delay
%9 stopped delay
%10 accel/decel delay
%11 accel-noise
%12 fuel (l)
%13 HC (g)
%14 CO (g)
%15 NOx (g)
%16 CO2 (g)
%17 PM (g)
%18 crashes*10e-6
%19 injury crashes
%20 fatal crashes
%21 no damage
%22 minor damage
%23 moderate damage
%24 dollars of toll

function [Stat_Total,Stat_Average] = MySummary(Myfilename)

Mycell = cell(52,1);
fid = fopen(Myfilename);
i=1;
while 1
    Mycell{i,1} = fgetl(fid);
    if ~ischar(Mycell{i,1}),   break,   end
    i=i+1;
end
fclose(fid);
clear i
for i=1:24
    Stat_Total(i,1)=str2num(Mycell{i+2,1}(4:17));
    Stat_Total(i,2)=str2num(Mycell{i+2,1}(18:31));
    Stat_Total(i,3)=str2num(Mycell{i+2,1}(32:45));
    Stat_Total(i,4)=str2num(Mycell{i+2,1}(46:59));
    Stat_Total(i,5)=str2num(Mycell{i+2,1}(60:73));
    Stat_Total(i,6)=str2num(Mycell{i+2,1}(74:87));

    Stat_Average(i,1)=str2num(Mycell{i+28,1}(4:17));
    Stat_Average(i,2)=str2num(Mycell{i+28,1}(18:31));
```

```
    Stat_Average(i,3)=str2num(Mycell{i+28,1}(32:45));
    Stat_Average(i,4)=str2num(Mycell{i+28,1}(46:59));
    Stat_Average(i,5)=str2num(Mycell{i+28,1}(60:73));
    Stat_Average(i,6)=str2num(Mycell{i+28,1}(74:87));

end
```

Appendix B – R file for regression analysis for constructing the models for high-speed vehicles

```
#Load a csv file ---------------------------------------------------------------------------------------------------------------------------------
PosFuel <- read.csv("PosFuel.csv")
PosCO2 <- read.csv("PosCO2.csv")
PosCO <- read.csv("PosCO.csv")
PosNO <- read.csv("PosNO.csv")
PosNO2 <- read.csv("PosNO2.csv")
PosNOX <- read.csv("PosNOX.csv")
PosHC <- read.csv("PosHC.csv")
PosPM <- read.csv("PosPM.csv")

NegFuel <- read.csv("NegFuel.csv")
NegCO2 <- read.csv("NegCO2.csv")
NegCO <- read.csv("NegCO.csv")
NegNO <- read.csv("NegNO.csv")
NegNO2 <- read.csv("NegNO2.csv")
NegNOX <- read.csv("NegNOX.csv")
NegHC <- read.csv("NegHC.csv")
NegPM <- read.csv("NegPM.csv")

#Do regression -----------------------------------------------------------------------------------------------------------------------------------

PosCO2.summary  <- summary(PosCO2.reg  <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,PosCO2))
PosCO.summary   <- summary(PosCO.reg   <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,PosCO))
PosNO.summary   <- summary(PosNO.reg   <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,PosNO))
PosNO2.summary  <- summary(PosNO2.reg  <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,PosNO2))
PosNOX.summary  <- summary(PosNOX.reg  <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,PosNOX))
PosHC.summary   <- summary(PosHC.reg   <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,PosHC))
PosPM.summary   <- summary(PosPM.reg   <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,PosPM))

NegFuel.summary <- summary(NegFuel.reg <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,NegFuel))
NegCO2.summary  <- summary(NegCO2.reg  <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,NegCO2))
NegCO.summary   <- summary(NegCO.reg   <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,NegCO))
NegNO.summary   <- summary(NegNO.reg   <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,NegNO))
NegNO2.summary  <- summary(NegNO2.reg  <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,NegNO2))
NegNOX.summary  <- summary(NegNOX.reg  <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                        + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,NegNOX))
```

```
NegHC.summary   <- summary(NegHC.reg   <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                                + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,NegHC))
NegPM.summary   <- summary(NegPM.reg   <- lm(LN_MOE ~ S + S2 + S3 + A + AS + AS2 + AS3
                                                + A2 + A2S + A2S2 + A2S3 + A3 + A3S + A3S2 + A3S3,NegPM))


#Summary Table for models - $R-squared $Adj-R $F-value $P-value ------------------------------------------------------------------------------

#R-squred
PosRsquare <- c(PosFuel.summary$r.squared,PosCO2.summary$r.squared,PosCO.summary$r.squared,
                PosNO.summary$r.squared,PosNO2.summary$r.squared,PosNOX.summary$r.squared,
                PosHC.summary$r.squared,PosPM.summary$r.squared)
NegRsquare <- c(NegFuel.summary$r.squared,NegCO2.summary$r.squared,NegCO.summary$r.squared,
                NegNO.summary$r.squared,NegNO2.summary$r.squared,NegNOX.summary$r.squared,
                NegHC.summary$r.squared,NegPM.summary$r.squared)

#AdjRsqured
PosAdjRsquare <- c(PosFuel.summary$adj.r.squared,PosCO2.summary$adj.r.squared,PosCO.summary$adj.r.squared,
                   PosNO.summary$adj.r.squared,PosNO2.summary$adj.r.squared,PosNOX.summary$adj.r.squared,
                   PosHC.summary$adj.r.squared,PosPM.summary$adj.r.squared)
NegAdjRsquare <- c(NegFuel.summary$adj.r.squared,NegCO2.summary$adj.r.squared,NegCO.summary$adj.r.squared,
                   NegNO.summary$adj.r.squared,NegNO2.summary$adj.r.squared,NegNOX.summary$adj.r.squared,
                   NegHC.summary$adj.r.squared,NegPM.summary$adj.r.squared)

#F-value
PosF_Value <- c(PosFuel.summary$f[1],,PosCO2.summary$f[1],PosCO.summary$f[1],PosNO.summary$f[1],
                PosNO2.summary$f[1],PosNOX.summary$f[1],PosHC.summary$f[1],PosPM.summary$f[1])
NegF_Value <- c(NegFuel.summary$f[1],,NegCO2.summary$f[1],NegCO.summary$f[1],NegNO.summary$f[1],
                NegNO2.summary$f[1],NegNOX.summary$f[1],NegHC.summary$f[1],NegPM.summary$f[1])

#P-value
PosP_Value <- c(1-pf(PosFuel.summary$f[1],PosFuel.summary$f[2],PosFuel.summary$f[3]),
          1-pf(PosCO2.summary$f[1],PosCO2.summary$f[2],PosCO2.summary$f[3]),
          1-pf(PosCO.summary$f[1],PosCO.summary$f[2],PosCO.summary$f[3]),
          1-pf(PosNO.summary$f[1],PosNO.summary$f[2],PosNO.summary$f[3]),
          1-pf(PosNO2.summary$f[1],PosNO2.summary$f[2],PosNO2.summary$f[3]),
          1-pf(PosNOX.summary$f[1],PosNOX.summary$f[2],PosNOX.summary$f[3]),
          1-pf(PosHC.summary$f[1],PosHC.summary$f[2],PosHC.summary$f[3]),
          1-pf(PosPM.summary$f[1],PosPM.summary$f[2],PosPM.summary$f[3]))
NegP_Value <- c(1-pf(NegFuel.summary$f[1],NegFuel.summary$f[2],NegFuel.summary$f[3]),
          1-pf(NegCO2.summary$f[1],NegCO2.summary$f[2],NegCO2.summary$f[3]),
          1-pf(NegCO.summary$f[1],NegCO.summary$f[2],NegCO.summary$f[3]),
          1-pf(NegNO.summary$f[1],NegNO.summary$f[2],NegNO.summary$f[3]),
          1-pf(NegNO2.summary$f[1],NegNO2.summary$f[2],NegNO2.summary$f[3]),
          1-pf(NegNOX.summary$f[1],NegNOX.summary$f[2],NegNOX.summary$f[3]),
          1-pf(NegHC.summary$f[1],NegHC.summary$f[2],NegHC.summary$f[3]),
          1-pf(NegPM.summary$f[1],NegPM.summary$f[2],NegPM.summary$f[3]))

SummaryTable.model <- cbind(PosRsquare,NegRsquare,PosAdjRsquare,NegAdjRsquare,
                PosF_Value,NegF_Value,PosP_Value,NegP_Value)
rownames(SummaryTable.model) <- c('Fuel','CO2','CO','NO','NO2','NOx','HC','PM')
```

```
#Summary Table for coefficients ------------------------------------------------------------------------------------------------------------------------------
FuelCoef <- rbind(PosFuel.summary$coef[,1],PosFuel.summary$coef[,4],
                NegFuel.summary$coef[,1],NegFuel.summary$coef[,4])
CO2Coef <- rbind(PosCO2.summary$coef[,1],PosCO2.summary$coef[,4],
                NegCO2.summary$coef[,1],NegCO2.summary$coef[,4])
COCoef <- rbind(PosCO.summary$coef[,1],PosCO.summary$coef[,4],
               NegCO.summary$coef[,1],NegCO.summary$coef[,4])
NOCoef <- rbind(PosNO.summary$coef[,1],PosNO.summary$coef[,4],
               NegNO.summary$coef[,1],NegNO.summary$coef[,4])
NO2Coef <- rbind(PosNO2.summary$coef[,1],PosNO2.summary$coef[,4],
               NegNO2.summary$coef[,1],NegNO2.summary$coef[,4])
NOXCoef <- rbind(PosNOX.summary$coef[,1],PosNOX.summary$coef[,4],
               NegNOX.summary$coef[,1],NegNOX.summary$coef[,4])
HCCoef <- rbind(PosHC.summary$coef[,1],PosHC.summary$coef[,4],
               NegHC.summary$coef[,1],NegHC.summary$coef[,4])
PMCoef <- rbind(PosPM.summary$coef[,1],PosPM.summary$coef[,4],
               NegPM.summary$coef[,1],NegPM.summary$coef[,4])

SummaryTable.coef <-rbind(FuelCoef,CO2Coef,COCoef,NOCoef,NO2Coef,NOXCoef,HCCoef,PMCoef)

SummaryTable <- list(SummaryTable.model,SummaryTable.coef)

MyCoefficients <-rbind(PosFuel.summary$coef[,1],PosCO2.summary$coef[,1],
                    PosCO.summary$coef[,1],PosNO.summary$coef[,1],
                    PosNO2.summary$coef[,1],PosNOX.summary$coef[,1],
                    PosHC.summary$coef[,1],PosPM.summary$coef[,1],
                    NegFuel.summary$coef[,1],NegCO2.summary$coef[,1],
                    NegCO.summary$coef[,1],NegNO.summary$coef[,1],
                    NegNO2.summary$coef[,1],NegNOX.summary$coef[,1],
                    NegHC.summary$coef[,1],NegPM.summary$coef[,1])

write.table(SummaryTable.model,file="SummaryModel.csv",sep=",",col.names=NA,qmethod="double")
write.table(SummaryTable.coef,file="SummaryCoef.csv",sep=",",col.names=NA,qmethod="double")
write.table(MyCoefficients,file="MyCoef.csv",sep=",",col.names=NA,qmethod="double")
```

Appendix C – The coefficients for the models for high speed vehicles

1. Semi-truck 1

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-8.08E+00	6.75E-02	-6.98E-04	2.68E-06	1.79E+00	-8.19E-02	1.71E-03	-8.70E-06	-6.39E-01	5.71E-02	-1.44E-03	6.89E-06	1.20E-01	-1.85E-02	4.91E-04	-2.19E-06
	CO_2	1.16E+00	6.76E-02	-7.01E-04	2.69E-06	1.79E+00	-8.18E-02	1.70E-03	-8.69E-06	-6.38E-01	5.70E-02	-1.43E-03	6.86E-06	1.20E-01	-1.84E-02	4.88E-04	-2.17E-06
	CO	-4.17E+00	3.21E-02	-3.79E-04	1.60E-06	1.03E+00	-5.74E-02	1.08E-03	-5.49E-06	-3.43E-01	3.90E-02	-9.65E-04	5.89E-06	8.14E-02	-1.50E-02	4.15E-04	-2.78E-06
	NO	-3.79E+00	7.56E-02	-1.02E-03	4.34E-06	2.16E+00	-1.39E-01	2.36E-03	-1.08E-05	-1.07E+00	9.70E-02	-1.99E-03	9.88E-06	2.11E-01	-2.45E-02	5.31E-04	-2.29E-06
	NO_2	-5.33E+00	4.99E-02	-8.28E-04	3.83E-06	7.95E-01	-7.38E-02	1.59E-03	-8.04E-06	-3.35E-01	5.11E-02	-1.20E-03	6.28E-06	8.77E-02	-1.62E-02	4.13E-04	-2.35E-06
	NO_x	-3.58E+00	7.10E-02	-9.71E-04	4.18E-06	1.95E+00	-1.29E-01	2.23E-03	-1.03E-05	-9.59E-01	9.13E-02	-1.91E-03	9.61E-06	1.91E-01	-2.37E-02	5.24E-04	-2.34E-06
	HC	-5.56E+00	5.16E-02	-8.42E-04	3.78E-06	1.10E+00	-8.69E-02	1.73E-03	-8.29E-06	-3.90E-01	4.86E-02	-1.16E-03	5.05E-06	8.71E-02	-1.38E-02	3.49E-04	-1.15E-06
	PM	-7.54E+00	4.83E-02	-5.71E-04	2.57E-06	1.59E+00	-8.88E-02	1.84E-03	-9.40E-06	-4.90E-01	6.11E-02	-1.42E-03	7.09E-06	8.68E-02	-1.71E-02	4.20E-04	-2.05E-06
Negative	Fuel	-8.08E+00	6.75E-02	-6.98E-04	2.68E-06	4.51E-01	4.49E-02	-1.35E-04	-3.47E-07	1.06E-01	7.41E-03	9.59E-06	-1.92E-07	8.05E-03	2.86E-04	2.88E-06	-1.55E-08
	CO_2	1.16E+00	6.76E-02	-7.01E-04	2.69E-06	6.43E-01	6.03E-03	1.10E-03	-7.06E-06	1.43E-01	-1.24E-03	2.95E-04	-1.74E-06	1.04E-02	-2.30E-04	1.97E-05	-1.03E-07
	CO	-4.17E+00	3.21E-02	-3.79E-04	1.60E-06	3.21E-01	2.10E-02	4.73E-05	-1.04E-06	7.58E-02	2.49E-03	5.40E-05	-4.16E-07	6.05E-03	1.95E-05	5.45E-06	-3.22E-08
	NO	-3.79E+00	7.56E-02	-1.02E-03	4.34E-06	1.57E+00	7.31E-03	6.23E-04	-3.88E-06	3.39E-01	2.56E-03	9.81E-05	-5.11E-07	2.05E-02	1.69E-04	3.48E-06	-3.97E-09
	NO_2	-5.33E+00	4.99E-02	-8.28E-04	3.83E-06	9.92E-01	6.89E-03	2.51E-04	-2.05E-06	2.63E-01	-5.94E-03	1.92E-04	-1.04E-06	2.03E-02	-7.30E-04	1.77E-05	-8.50E-08
	NO_x	-3.58E+00	7.10E-02	-9.71E-04	4.18E-06	1.31E+00	2.12E-02	4.09E-04	-3.30E-06	2.96E-01	3.28E-03	1.23E-04	-8.23E-07	1.97E-02	3.09E-05	9.76E-06	-5.05E-08
	HC	-5.56E+00	5.16E-02	-8.42E-04	3.78E-06	4.76E-01	5.63E-02	-8.50E-04	3.32E-06	1.21E-01	9.52E-03	-1.29E-04	4.49E-07	9.63E-03	3.69E-04	-3.77E-06	8.44E-09
	PM	-7.54E+00	4.83E-02	-5.71E-04	2.57E-06	4.32E-01	3.05E-02	-5.75E-05	-8.29E-07	9.04E-02	5.56E-03	5.64E-06	-2.35E-07	6.37E-03	2.29E-04	1.95E-06	-1.82E-08

C: Constant, S: Speed, A: Acceleration

2. Semi-truck 2

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-8.84E+00	7.17E-02	-6.14E-04	2.08E-06	3.03E+00	-3.20E-02	3.67E-04	-1.92E-06	-1.45E+00	6.34E-04	4.11E-05	-5.94E-07	2.63E-01	-1.23E-03	2.97E-05	2.96E-08
	CO_2	4.14E-01	7.10E-02	-6.03E-04	2.04E-06	2.94E+00	-2.64E-02	2.89E-04	-1.59E-06	-1.36E+00	-4.38E-03	1.12E-04	-9.10E-07	2.42E-01	3.46E-05	9.37E-06	1.52E-07
	CO	-4.57E+00	6.63E-02	-7.16E-04	2.37E-06	1.29E+00	-2.80E-02	2.66E-04	-6.31E-07	-3.06E-01	2.96E-02	-7.63E-04	2.33E-06	6.56E-02	-5.57E-03	-3.69E-05	2.97E-06
	NO	-3.59E+00	2.80E-02	4.79E-05	-6.49E-07	2.13E+00	-1.34E-02	2.52E-04	-2.07E-06	-1.05E+00	-7.35E-03	1.62E-05	1.45E-06	2.15E-01	-2.93E-03	2.06E-04	-2.72E-06
	NO_2	-6.07E+00	3.64E-02	-3.23E-04	1.21E-06	1.37E+00	-1.61E-02	2.35E-04	-1.33E-06	-4.64E-01	1.91E-03	-1.31E-04	7.36E-07	6.51E-02	-2.46E-04	1.46E-05	3.43E-07
	NO_x	-3.50E+00	2.86E-02	2.43E-05	-5.29E-07	2.09E+00	-1.54E-02	2.95E-04	-2.25E-06	-1.02E+00	-4.94E-03	-3.63E-05	1.59E-06	2.10E-01	-3.18E-03	2.03E-04	-2.55E-06
	HC	-6.24E+00	4.41E-02	-7.07E-04	3.20E-06	1.03E+00	-5.59E-02	9.71E-04	-4.52E-06	-5.91E-01	4.36E-02	-8.60E-04	4.14E-06	1.48E-01	-1.26E-02	2.83E-04	-1.50E-06
	PM	-9.31E+00	8.63E-02	-8.19E-04	2.88E-06	2.98E+00	-3.54E-02	3.02E-04	-1.21E-06	-1.31E+00	2.93E-02	-3.66E-04	-3.62E-07	2.36E-01	-5.73E-03	-6.63E-05	2.73E-06
Negative	Fuel	-8.84E+00	7.17E-02	-6.14E-04	2.08E-06	-6.73E-02	7.20E-02	-6.36E-04	2.36E-06	-1.32E-01	2.10E-02	-2.15E-04	9.16E-07	-1.48E-02	1.62E-03	-1.87E-05	8.86E-08
	CO_2	4.14E-01	7.10E-02	-6.03E-04	2.04E-06	-1.49E-01	6.78E-02	-9.76E-05	-8.35E-07	-1.92E-01	2.24E-02	-1.07E-04	2.15E-07	-2.09E-02	1.85E-03	-1.42E-05	5.90E-08
	CO	-4.57E+00	6.63E-02	-7.16E-04	2.37E-06	-4.09E-01	7.69E-02	-6.71E-04	1.81E-06	-2.61E-01	2.67E-02	-2.73E-04	9.03E-07	-2.28E-02	2.06E-03	-2.30E-05	8.64E-08
	NO	-3.59E+00	2.80E-02	4.79E-05	-6.49E-07	-6.50E-02	2.40E-02	1.05E-03	-6.69E-06	-1.68E-01	1.21E-02	1.58E-04	-1.08E-06	-2.00E-02	1.24E-03	1.09E-06	-9.79E-09
	NO_2	-6.07E+00	3.64E-02	-3.23E-04	1.21E-06	6.47E-01	3.46E-02	-3.09E-04	1.06E-06	5.07E-02	1.04E-02	-1.08E-04	4.57E-07	-6.77E-04	7.92E-04	-9.19E-06	4.44E-08
	NO_x	-3.50E+00	2.86E-02	2.43E-05	-5.29E-07	-1.94E-01	5.00E-02	2.93E-04	-2.74E-06	-1.80E-01	1.72E-02	-1.28E-05	-1.93E-07	-1.93E-02	1.46E-03	-7.65E-06	3.29E-08
	HC	-6.24E+00	4.41E-02	-7.07E-04	3.20E-06	3.59E-01	4.02E-02	-6.01E-04	2.30E-06	3.32E-02	1.01E-02	-1.30E-04	4.39E-07	-1.06E-05	6.54E-04	-7.48E-06	2.17E-08
	PM	-9.31E+00	8.63E-02	-8.19E-04	2.88E-06	7.54E-02	2.10E-02	1.15E-04	-1.18E-06	-5.12E-02	1.07E-02	-6.27E-05	1.25E-07	-6.38E-03	9.50E-04	-8.62E-06	3.25E-08

C: Constant, S: Speed, A: Acceleration

3. Semi-truck 3

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-7.88E+00	3.51E-02	-1.94E-04	6.76E-07	2.54E+00	-2.86E-02	5.19E-04	-3.42E-06	-1.61E+00	3.68E-02	-7.17E-04	3.99E-06	3.40E-01	-1.34E-02	2.70E-04	-1.47E-06
	CO_2	1.44E+00	3.09E-02	-2.09E-04	1.00E-06	2.35E+00	-2.13E-02	6.73E-04	-4.92E-06	-1.50E+00	3.43E-02	-9.11E-04	5.41E-06	3.20E-01	-1.32E-02	3.18E-04	-1.71E-06
	CO	-4.09E+00	4.50E-02	-4.81E-04	1.66E-06	2.95E+00	-4.62E-02	5.38E-04	-2.83E-06	-2.00E+00	8.18E-02	-1.93E-03	1.08E-05	4.69E-01	-3.00E-02	6.78E-04	-2.96E-06
	NO	-3.40E+00	-1.71E-03	4.62E-04	-2.17E-06	1.98E+00	-1.70E-02	6.31E-04	-4.74E-06	-1.10E+00	2.81E-02	-7.77E-04	4.93E-06	2.19E-01	-1.29E-02	3.51E-04	-2.44E-06
	NO_2	-6.07E+00	3.25E-02	-5.00E-04	2.72E-06	1.68E+00	-6.59E-02	1.39E-03	-7.45E-06	-1.04E+00	5.26E-02	-1.25E-03	6.78E-06	2.09E-01	-1.34E-02	3.27E-04	-1.65E-06
	NO_X	-3.30E+00	-1.53E-03	4.43E-04	-2.07E-06	1.91E+00	-1.76E-02	6.34E-04	-4.69E-06	-1.07E+00	2.82E-02	-7.66E-04	4.81E-06	2.13E-01	-1.27E-02	3.41E-04	-2.35E-06
	HC	-5.89E+00	3.96E-02	-7.48E-04	3.78E-06	6.55E-01	-2.98E-02	3.65E-04	-1.42E-06	-5.08E-01	2.53E-02	-3.43E-04	1.34E-06	1.22E-01	-5.33E-03	9.74E-06	7.09E-07
	PM	-7.65E+00	6.67E-02	-8.72E-04	3.59E-06	3.01E+00	-8.54E-02	9.97E-04	-4.19E-06	-1.82E+00	7.46E-02	-9.78E-04	4.30E-06	3.72E-01	-1.87E-02	2.19E-04	-6.82E-07
Negative	Fuel	-7.88E+00	3.51E-02	-1.94E-04	6.76E-07	1.41E+00	-2.67E-02	7.42E-04	-2.66E-06	3.84E-01	-1.22E-02	2.50E-04	-6.97E-07	2.48E-02	-8.31E-04	1.41E-05	-7.30E-09
	CO_2	1.44E+00	3.09E-02	-2.09E-04	1.00E-06	1.71E+00	-5.91E-02	1.66E-03	-7.20E-06	4.72E-01	-2.15E-02	5.16E-04	-1.99E-06	3.14E-02	-1.48E-03	3.18E-05	-8.43E-08
	CO	-4.09E+00	4.50E-02	-4.81E-04	1.66E-06	1.49E+00	-4.28E-02	8.80E-04	-3.74E-06	3.45E-01	-1.16E-02	2.31E-04	-8.69E-07	2.09E-02	-6.46E-04	1.14E-05	-2.39E-08
	NO	-3.40E+00	-1.71E-03	4.62E-04	-2.17E-06	8.90E-01	-5.32E-02	1.96E-03	-9.44E-06	2.82E-01	-1.91E-02	5.76E-04	-2.48E-06	2.02E-02	-1.38E-03	3.68E-05	-1.21E-07
	NO_2	-6.07E+00	3.25E-02	-5.00E-04	2.72E-06	1.55E+00	-2.84E-02	5.43E-04	-2.14E-06	3.99E-01	-1.27E-02	2.43E-04	-9.39E-07	2.74E-02	-1.05E-03	1.94E-05	-6.49E-08
	NO_X	-3.30E+00	-1.53E-03	4.43E-04	-2.07E-06	8.39E-01	-3.82E-02	1.55E-03	-7.42E-06	2.66E-01	-1.50E-02	4.63E-04	-1.94E-06	1.91E-02	-1.11E-03	2.97E-05	-8.96E-08
	HC	-5.89E+00	3.96E-02	-7.48E-04	3.78E-06	7.71E-01	-2.77E-03	-3.35E-04	2.48E-06	1.61E-01	9.11E-05	-9.53E-05	6.64E-07	8.35E-03	1.40E-04	-8.52E-06	5.33E-08
	PM	-7.65E+00	6.67E-02	-8.72E-04	3.59E-06	1.18E+00	-3.82E-02	8.06E-04	-3.55E-06	2.69E-01	-9.97E-03	2.03E-04	-8.01E-07	1.59E-02	-5.36E-04	1.00E-05	-2.55E-08

C: Constant, S: Speed, A: Acceleration

4. Passenger car 1

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-8.17E+00	-1.14E-02	2.94E-04	-9.90E-07	-7.86E-02	2.29E-02	-2.94E-04	1.12E-06	7.63E-02	-6.72E-03	1.07E-04	-4.36E-07	-5.84E-03	4.97E-04	-7.58E-06	2.07E-08
	CO_2	9.03E-01	-1.27E-02	3.16E-04	-1.08E-06	-2.80E-02	1.84E-02	-1.67E-04	3.64E-07	4.76E-02	-3.81E-03	3.70E-05	-9.81E-08	-3.25E-03	2.13E-04	-1.52E-06	-4.54E-09
	CO	-6.55E+00	5.35E-02	-5.88E-04	2.81E-06	1.94E+00	-4.07E-02	1.76E-04	6.44E-07	-2.57E-01	-3.72E-03	2.38E-04	-1.11E-06	1.44E-02	5.43E-04	-1.39E-05	-1.89E-08
	NO	-6.92E+00	-2.72E-02	5.83E-04	-1.51E-06	5.74E-01	8.76E-03	2.44E-04	-2.07E-06	-3.43E-02	5.49E-04	-8.54E-05	5.16E-07	3.28E-03	-2.96E-04	1.15E-05	-8.36E-08
	NO_2	-1.02E+01	-3.15E-02	6.61E-04	-2.53E-06	1.54E-01	4.05E-02	-3.34E-04	-4.95E-07	-1.89E-01	-5.67E-03	-2.22E-04	3.09E-06	3.23E-02	-1.07E-03	1.14E-04	-1.14E-06
	NO_X	-6.92E+00	-2.64E-02	5.73E-04	-1.48E-06	5.78E-01	8.12E-03	2.49E-04	-2.08E-06	-3.56E-02	6.75E-04	-8.59E-05	5.15E-07	3.36E-03	-3.04E-04	1.15E-05	-8.37E-08
	HC	-8.30E+00	2.54E-02	-1.83E-04	1.02E-06	6.56E-02	3.42E-02	-5.49E-04	2.22E-06	1.42E-01	-1.52E-02	2.51E-04	-7.00E-07	-9.50E-03	1.01E-03	-1.10E-05	-4.47E-08
	PM	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Negative	Fuel	-8.17E+00	-1.14E-02	2.94E-04	-9.90E-07	8.09E-03	-7.64E-03	2.66E-04	-1.19E-06	-2.77E-03	-4.34E-04	1.97E-05	-8.77E-08	-1.90E-04	-2.88E-06	3.59E-07	-1.57E-09
	CO_2	9.03E-01	-1.27E-02	3.16E-04	-1.08E-06	-1.26E-03	-7.58E-03	2.64E-04	-1.18E-06	-3.12E-03	-4.76E-04	2.04E-05	-9.03E-08	-2.01E-04	-4.46E-06	3.88E-07	-1.70E-09
	CO	-6.55E+00	5.35E-02	-5.88E-04	2.81E-06	2.93E-01	1.21E-02	-1.28E-04	4.28E-07	4.74E-02	1.05E-03	-1.63E-05	6.98E-08	1.76E-03	1.70E-05	-4.30E-07	2.17E-09
	NO	-6.92E+00	-2.72E-02	5.83E-04	-1.51E-06	4.17E-01	-1.62E-02	2.64E-04	-8.70E-07	6.58E-02	-2.09E-03	2.72E-05	-7.94E-08	1.88E-03	-5.48E-05	6.25E-07	-1.48E-09
	NO_2	-1.02E+01	-3.15E-02	6.61E-04	-2.53E-06	3.50E-01	-4.56E-02	1.02E-03	-4.82E-06	1.65E-01	-1.98E-02	4.15E-04	-1.85E-06	1.55E-02	-1.88E-03	3.77E-05	-1.37E-07
	NO_X	-6.92E+00	-2.64E-02	5.73E-04	-1.48E-06	4.10E-01	-1.61E-02	2.65E-04	-8.75E-07	6.46E-02	-2.08E-03	2.73E-05	-8.02E-08	1.84E-03	-5.41E-05	6.24E-07	-1.48E-09
	HC	-8.30E+00	2.54E-02	-1.83E-04	1.02E-06	-9.84E-03	1.05E-02	-3.09E-05	-1.03E-07	1.47E-02	3.85E-04	4.06E-06	-3.43E-08	6.02E-04	9.61E-09	1.91E-07	-1.11E-09
	PM	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

C: Constant, S: Speed, A: Acceleration

5. Passenger car 2

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-9.00E+00	2.72E-02	-1.26E-04	4.37E-07	4.71E-01	1.30E-03	-1.42E-05	4.77E-08	-3.50E-02	-6.96E-04	8.56E-06	-4.91E-08	1.29E-03	3.34E-05	-2.27E-07	3.95E-09
	CO_2	1.23E-01	2.44E-02	-7.23E-05	1.74E-07	4.59E-01	2.23E-03	-1.81E-05	-1.21E-08	-3.55E-02	-5.96E-04	2.82E-06	-1.14E-09	1.54E-03	3.37E-07	9.87E-07	-7.29E-09
	CO	-8.11E+00	4.75E-02	-6.08E-04	3.68E-06	1.20E+00	-1.95E-02	-1.23E-04	2.06E-06	-1.61E-01	-1.97E-03	2.16E-04	-1.41E-06	8.22E-03	2.94E-04	-1.97E-05	1.44E-07
	NO	-9.34E+00	4.96E-03	1.04E-05	6.18E-07	1.32E-01	4.59E-03	2.96E-04	-1.77E-06	5.95E-02	-9.20E-05	-6.58E-05	2.41E-07	-3.88E-03	2.52E-05	2.96E-06	-2.96E-09
	NO_2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	NO_X	-9.34E+00	4.95E-03	1.05E-05	6.17E-07	1.32E-01	4.53E-03	2.97E-04	-1.77E-06	5.92E-02	-5.02E-05	-6.64E-05	2.43E-07	-3.86E-03	2.25E-05	2.99E-06	-2.96E-09
	HC	-9.47E+00	7.88E-03	-1.71E-04	1.87E-06	6.86E-01	-1.39E-03	5.49E-05	1.41E-08	-7.17E-02	-1.34E-04	1.34E-05	-1.42E-07	1.83E-03	2.01E-04	-7.19E-06	6.86E-08
	PM	-1.17E+01	3.16E-02	-2.65E-04	1.43E-06	5.35E-01	-8.09E-03	1.64E-04	-7.34E-07	-3.88E-02	-4.74E-04	1.83E-05	-4.83E-08	2.48E-03	8.12E-06	7.07E-07	-1.97E-08
Negative	Fuel	-9.00E+00	2.72E-02	-1.26E-04	4.37E-07	1.76E-01	-3.64E-03	2.26E-04	-1.18E-06	3.37E-02	-1.04E-03	2.86E-05	-1.30E-07	9.67E-04	-2.80E-05	6.43E-07	-2.62E-09
	CO_2	1.23E-01	2.44E-02	-7.23E-05	1.74E-07	1.76E-01	-4.15E-03	2.35E-04	-1.22E-06	3.18E-02	-9.99E-04	2.82E-05	-1.29E-07	9.13E-04	-2.62E-05	6.21E-07	-2.54E-09
	CO	-8.11E+00	4.75E-02	-6.08E-04	3.68E-06	3.82E-01	9.26E-03	-1.60E-04	6.05E-07	1.43E-01	-2.20E-03	2.07E-05	-6.91E-08	5.37E-03	-1.17E-04	1.17E-06	-3.71E-09
	NO	-9.34E+00	4.96E-03	1.04E-05	6.18E-07	1.68E-01	1.55E-02	-2.73E-04	1.21E-06	4.92E-02	1.39E-03	-3.10E-05	1.43E-07	2.50E-03	6.55E-07	-4.85E-07	2.80E-09
	NO_2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	NO_X	-9.34E+00	4.95E-03	1.05E-05	6.17E-07	1.68E-01	1.55E-02	-2.73E-04	1.21E-06	4.92E-02	1.39E-03	-3.10E-05	1.43E-07	2.50E-03	6.49E-07	-4.85E-07	2.80E-09
	HC	-9.47E+00	7.88E-03	-1.71E-04	1.87E-06	6.06E-01	9.64E-04	-1.14E-04	5.86E-07	1.55E-01	-2.01E-03	8.18E-06	-4.17E-09	6.25E-03	-1.24E-04	9.37E-07	-2.41E-09
	PM	-1.17E+01	3.16E-02	-2.65E-04	1.43E-06	7.84E-02	1.57E-02	-2.20E-04	8.82E-07	4.27E-02	8.95E-04	-1.75E-05	7.86E-08	2.12E-03	-8.41E-06	-1.67E-07	1.24E-09

C: Constant, S: Speed, A: Acceleration

6. Passenger car 3

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-8.76E+00	3.99E-03	2.21E-04	-9.23E-07	-3.37E-02	3.03E-02	-4.10E-04	1.39E-06	7.59E-02	-6.45E-03	8.58E-05	-2.58E-07	-4.39E-03	3.05E-04	-3.40E-06	2.26E-09
	CO_2	3.40E-01	2.43E-03	2.44E-04	-1.01E-06	-2.82E-02	3.15E-02	-4.15E-04	1.40E-06	7.41E-02	-6.68E-03	8.59E-05	-2.78E-07	-4.43E-03	3.26E-04	-3.75E-06	7.71E-09
	CO	-8.81E+00	1.01E-01	-1.15E-03	4.50E-06	4.64E-01	-2.75E-03	-2.28E-04	1.20E-06	1.44E-01	-7.26E-03	1.83E-04	-3.96E-07	-7.73E-03	3.20E-04	-4.28E-06	-6.39E-08
	NO	-1.12E+01	3.28E-03	3.75E-04	-1.57E-06	5.10E-01	-1.12E-02	1.35E-04	-3.74E-07	-4.56E-02	3.63E-03	-3.02E-05	2.56E-08	1.91E-03	-2.01E-04	1.33E-06	-4.00E-09
	NO_2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	NO_x	-1.12E+01	3.28E-03	3.75E-04	-1.57E-06	5.10E-01	-1.12E-02	1.35E-04	-3.74E-07	-4.56E-02	3.63E-03	-3.02E-05	2.54E-08	1.91E-03	-2.01E-04	1.32E-06	-3.97E-09
	HC	-9.55E+00	-1.87E-02	1.89E-04	1.83E-07	-2.27E-01	3.58E-02	-3.19E-04	6.35E-07	1.34E-01	-5.91E-03	5.28E-05	1.05E-07	-6.51E-03	1.79E-04	1.03E-06	-4.50E-08
	PM	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Negative	Fuel	-8.76E+00	3.99E-03	2.21E-04	-9.23E-07	2.13E-01	-1.58E-02	4.04E-04	-1.74E-06	2.07E-02	-2.08E-03	5.20E-05	-2.18E-07	2.34E-04	-5.33E-05	1.49E-06	-6.24E-09
	CO_2	3.40E-01	2.43E-03	2.44E-04	-1.01E-06	2.10E-01	-1.60E-02	4.04E-04	-1.73E-06	1.98E-02	-2.07E-03	5.15E-05	-2.15E-07	1.92E-04	-5.22E-05	1.46E-06	-6.09E-09
	CO	-8.81E+00	1.01E-01	-1.15E-03	4.50E-06	-4.03E-01	3.18E-02	-2.57E-04	5.35E-07	-2.58E-02	3.03E-03	-1.15E-05	-3.41E-08	1.49E-04	6.46E-05	1.85E-07	-3.51E-09
	NO	-1.12E+01	3.28E-03	3.75E-04	-1.57E-06	-1.69E-01	6.20E-03	-8.47E-05	4.81E-07	-4.08E-02	1.94E-03	-3.42E-05	1.64E-07	-1.78E-03	9.07E-05	-1.57E-06	7.15E-09
	NO_2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	NO_x	-1.12E+01	3.28E-03	3.75E-04	-1.57E-06	-2.07E-01	7.53E-03	-1.03E-04	5.53E-07	-4.28E-02	1.96E-03	-3.58E-05	1.73E-07	-1.87E-03	9.06E-05	-1.63E-06	7.58E-09
	HC	-9.55E+00	-1.87E-02	1.89E-04	1.83E-07	3.69E-01	-7.59E-04	6.61E-05	-3.54E-07	8.28E-02	-6.80E-04	1.92E-05	-9.88E-08	3.90E-03	-5.74E-05	1.09E-06	-5.01E-09
	PM	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

C: Constant, S: Speed, A: Acceleration

7. Pickup truck 1

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-8.60E+00	4.00E-03	2.16E-04	-9.13E-07	2.51E-01	1.75E-02	-2.43E-04	8.56E-07	4.94E-02	-5.63E-03	8.04E-05	-2.96E-07	-3.15E-03	2.76E-04	-3.44E-06	6.84E-09
	CO_2	6.41E-01	4.05E-03	2.15E-04	-9.08E-07	2.52E-01	1.74E-02	-2.41E-04	8.50E-07	4.88E-02	-5.59E-03	7.98E-05	-2.94E-07	-3.11E-03	2.74E-04	-3.42E-06	6.81E-09
	CO	-5.25E+00	2.26E-02	-2.24E-04	1.04E-06	-9.56E-02	1.57E-02	-3.02E-04	1.21E-06	1.46E-01	-9.39E-03	1.60E-04	-5.76E-07	-7.59E-03	4.69E-04	-6.37E-06	5.79E-10
	NO	-4.59E+00	4.37E-02	-3.10E-04	6.57E-07	6.78E-01	-7.94E-03	4.64E-05	-1.50E-07	-5.96E-02	-1.53E-03	2.86E-05	-5.52E-08	3.72E-03	2.49E-05	4.34E-07	-1.22E-08
	NO_2	-8.71E+00	7.12E-02	-7.66E-04	2.68E-06	6.40E-01	-3.50E-02	3.12E-04	-9.65E-07	-1.10E-01	3.76E-03	-7.25E-06	7.82E-08	7.58E-03	-2.55E-04	2.83E-06	-3.26E-08
	NO_x	-4.57E+00	4.43E-02	-3.21E-04	7.06E-07	6.72E-01	-8.26E-03	5.15E-05	-1.73E-07	-5.86E-02	-1.48E-03	2.78E-05	-5.13E-08	3.66E-03	2.35E-05	4.56E-07	-1.24E-08
	HC	-6.84E+00	7.07E-03	7.04E-05	-2.34E-07	-5.09E-02	1.70E-02	-3.11E-04	1.22E-06	7.33E-02	-5.72E-03	1.01E-04	-3.56E-07	-3.70E-03	2.75E-04	-4.05E-06	2.52E-09
	PM	-7.77E+00	-8.05E-03	1.91E-04	-6.39E-07	4.84E-02	1.29E-02	-2.46E-04	1.18E-06	6.13E-02	-5.70E-03	1.07E-04	-4.75E-07	-2.68E-03	2.77E-04	-4.72E-06	1.26E-08
Negative	Fuel	-8.60E+00	4.00E-03	2.16E-04	-9.13E-07	-3.77E-02	5.36E-02	-5.77E-04	1.85E-06	-1.71E-02	1.40E-02	-1.68E-04	5.55E-07	-1.65E-03	9.55E-04	-1.14E-05	3.66E-08
	CO_2	6.41E-01	4.05E-03	2.15E-04	-9.08E-07	-1.71E-02	4.54E-02	-3.09E-04	4.26E-07	-3.20E-02	1.40E-02	-1.35E-04	3.35E-07	-2.34E-03	9.71E-04	-9.49E-06	2.27E-08
	CO	-5.25E+00	2.26E-02	-2.24E-04	1.04E-06	-2.27E-01	3.39E-02	-2.77E-04	6.96E-07	-5.13E-02	7.80E-03	-6.46E-05	1.41E-07	-1.61E-03	4.77E-04	-3.34E-06	3.81E-09
	NO	-4.59E+00	4.37E-02	-3.10E-04	6.57E-07	-2.51E-01	7.72E-02	-7.93E-04	2.20E-06	-9.81E-02	2.15E-02	-2.50E-04	7.73E-07	-7.36E-03	1.48E-03	-1.73E-05	5.28E-08
	NO_2	-8.71E+00	7.12E-02	-7.66E-04	2.68E-06	6.68E-01	4.10E-02	-6.89E-04	2.63E-06	1.71E-01	1.42E-02	-2.42E-04	9.19E-07	1.27E-02	1.26E-03	-2.07E-05	7.70E-08
	NO_x	-4.57E+00	4.43E-02	-3.21E-04	7.06E-07	-2.52E-01	7.85E-02	-8.43E-04	2.46E-06	-9.50E-02	2.16E-02	-2.60E-04	8.28E-07	-7.10E-03	1.49E-03	-1.79E-05	5.62E-08
	HC	-6.84E+00	7.07E-03	7.04E-05	-2.34E-07	9.62E-02	8.03E-03	2.06E-05	-3.44E-07	5.96E-03	3.25E-03	-1.98E-05	1.97E-08	1.44E-03	2.23E-04	-1.36E-06	8.63E-10
	PM	-7.77E+00	-8.05E-03	1.91E-04	-6.39E-07	1.35E-01	2.85E-02	-3.45E-04	1.18E-06	4.07E-02	7.61E-03	-1.05E-04	3.88E-07	2.28E-03	5.55E-04	-7.54E-06	2.70E-08

C: Constant, S: Speed, A: Acceleration

8. Pickup truck 2

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-8.19E+00	-4.48E-04	1.89E-04	-6.00E-07	3.27E-01	9.30E-03	-1.21E-05	-3.50E-07	-2.00E-02	-1.43E-03	-2.10E-05	1.75E-07	3.16E-03	-1.04E-04	5.05E-06	-2.32E-08
	CO_2	1.04E+00	-6.81E-04	1.94E-04	-6.21E-07	3.29E-01	9.38E-03	-1.36E-05	-3.44E-07	-2.06E-02	-1.42E-03	-2.10E-05	1.75E-07	3.20E-03	-1.04E-04	5.04E-06	-2.31E-08
	CO	-4.17E+00	2.29E-02	-4.15E-04	1.97E-06	-1.91E-02	-7.59E-04	1.85E-05	-1.82E-07	4.16E-02	-2.93E-03	4.12E-05	-2.96E-08	2.42E-03	-1.26E-04	5.16E-06	-5.68E-08
	NO	-4.03E+00	3.27E-03	1.12E-04	-3.94E-07	4.29E-01	3.00E-04	8.40E-05	-5.62E-07	-4.36E-02	-3.45E-04	-2.81E-05	1.60E-07	4.71E-03	-1.60E-04	5.41E-06	-2.34E-08
	NO_2	-7.60E+00	2.85E-03	9.12E-05	-3.59E-08	6.15E-01	2.07E-02	-2.56E-04	4.97E-07	-1.08E-01	-3.09E-03	2.23E-05	8.61E-08	9.86E-03	-1.28E-04	5.36E-06	-4.06E-08
	NO_x	-3.94E+00	9.10E-04	1.40E-04	-4.84E-07	4.20E-01	2.15E-03	5.59E-05	-4.65E-07	-4.63E-02	-5.55E-04	-2.48E-05	1.54E-07	5.09E-03	-1.62E-04	5.53E-06	-2.49E-08
	HC	-6.33E+00	1.30E-02	-1.91E-04	1.09E-06	4.55E-02	8.81E-03	4.24E-05	-6.47E-07	4.19E-02	-2.42E-03	-1.40E-05	1.73E-07	-1.90E-03	5.55E-05	2.68E-06	-1.56E-08
	PM	-9.01E+00	-3.45E-03	1.58E-04	-2.04E-07	3.59E-01	1.20E-02	-7.54E-06	-4.59E-07	-4.56E-02	-1.63E-03	-2.37E-05	2.34E-07	8.07E-03	-2.80E-04	9.24E-06	-4.96E-08
Negative	Fuel	-8.19E+00	-4.48E-04	1.89E-04	-6.00E-07	1.07E-03	2.37E-02	-2.91E-04	1.27E-06	5.74E-03	2.91E-03	-4.71E-05	2.21E-07	3.95E-04	8.10E-05	-1.51E-06	7.50E-09
	CO_2	1.04E+00	-6.81E-04	1.94E-04	-6.21E-07	3.70E-02	1.96E-02	-2.47E-04	1.24E-06	-8.52E-04	3.17E-03	-5.54E-05	2.80E-07	-8.70E-05	1.07E-04	-2.07E-06	1.07E-08
	CO	-4.17E+00	2.29E-02	-4.15E-04	1.97E-06	3.43E-02	2.07E-02	-3.18E-04	1.44E-06	-1.78E-02	2.43E-03	-3.97E-05	1.88E-07	-9.50E-04	7.95E-05	-1.32E-06	6.36E-09
	NO	-4.03E+00	3.27E-03	1.12E-04	-3.94E-07	-4.95E-02	8.47E-03	2.86E-05	-1.95E-07	-1.96E-02	2.24E-03	-2.49E-05	1.10E-07	-8.20E-04	8.79E-05	-1.24E-06	5.80E-09
	NO_2	-7.60E+00	2.85E-03	9.12E-05	-3.59E-08	6.56E-02	9.60E-03	-1.42E-04	7.42E-07	5.95E-03	1.00E-03	-1.62E-05	9.02E-08	-4.09E-05	3.87E-05	-6.35E-07	3.53E-09
	NO_x	-3.94E+00	9.10E-04	1.40E-04	-4.84E-07	-2.26E-03	6.72E-03	5.02E-05	-2.82E-07	-1.15E-02	1.83E-03	-1.87E-05	8.38E-08	-5.64E-04	7.35E-05	-1.01E-06	4.81E-09
	HC	-6.33E+00	1.30E-02	-1.91E-04	1.09E-06	2.28E-01	2.59E-03	-4.95E-05	2.32E-07	2.97E-02	-3.21E-04	2.17E-06	-2.97E-09	1.10E-03	-2.22E-05	2.21E-07	-6.43E-10
	PM	-9.01E+00	-3.45E-03	1.58E-04	-2.04E-07	1.36E-01	1.37E-02	-2.38E-04	1.10E-06	2.31E-02	1.71E-03	-3.68E-05	1.78E-07	1.01E-03	4.36E-05	-1.12E-06	5.72E-09

C: Constant, S: Speed, A: Acceleration

9. Pickup truck 3

		C	S	S^2	S^3	A	AS	AS^2	AS^3	A^2	A^2S	A^2S^2	A^2S^3	A^3	A^3S	A^3S^2	A^3S^3
Positive	Fuel	-7.68E+00	-3.97E-02	7.73E-04	-3.05E-06	-1.78E-01	4.04E-02	-6.00E-04	2.54E-06	1.05E-01	-9.48E-03	1.67E-04	-8.06E-07	-7.01E-03	6.28E-04	-1.22E-05	5.70E-08
	CO_2	1.55E+00	-3.97E-02	7.73E-04	-3.05E-06	-1.77E-01	4.03E-02	-5.99E-04	2.53E-06	1.04E-01	-9.43E-03	1.66E-04	-8.04E-07	-6.97E-03	6.26E-04	-1.22E-05	5.74E-08
	CO	-4.19E+00	-2.08E-02	4.22E-04	-1.82E-06	-3.31E-01	2.56E-02	-4.60E-04	2.06E-06	1.42E-01	-8.85E-03	1.53E-04	-5.64E-07	-5.01E-03	2.73E-04	-1.22E-06	-4.01E-08
	NO	-2.77E+00	-2.09E-02	4.05E-04	-1.66E-06	-6.67E-02	2.36E-02	-3.84E-04	1.76E-06	6.73E-02	-7.21E-03	1.36E-04	-6.67E-07	-5.19E-03	5.41E-04	-1.01E-05	4.42E-08
	NO_2	-5.28E+00	-8.78E-03	2.61E-04	-1.30E-06	-4.66E-01	2.90E-02	-4.56E-04	2.00E-06	1.65E-01	-9.09E-03	1.54E-04	-6.55E-07	-1.13E-02	6.68E-04	-1.08E-05	3.46E-08
	NO_x	-2.69E+00	-1.98E-02	3.91E-04	-1.62E-06	-9.28E-02	2.34E-02	-3.82E-04	1.76E-06	7.26E-02	-7.18E-03	1.35E-04	-6.61E-07	-5.46E-03	5.35E-04	-9.98E-06	4.32E-08
	HC	-5.99E+00	-1.36E-02	2.23E-04	-8.87E-07	-2.70E-01	2.16E-02	-3.36E-04	1.13E-06	1.02E-01	-5.79E-03	6.88E-05	1.81E-08	-5.29E-03	2.51E-04	1.54E-06	-6.52E-08
	PM	-8.04E+00	-2.36E-02	4.29E-04	-1.32E-06	-8.58E-02	2.17E-02	-2.94E-04	1.04E-06	8.28E-02	-5.99E-03	1.03E-04	-2.86E-07	-3.62E-03	2.83E-04	-2.07E-06	-4.01E-08
Negative	Fuel	-7.68E+00	-3.97E-02	7.73E-04	-3.05E-06	-9.54E-02	2.05E-03	1.79E-04	-8.92E-07	-2.24E-02	1.47E-03	-3.77E-06	5.21E-09	-7.41E-04	6.01E-05	-5.16E-07	2.23E-09
	CO_2	1.55E+00	-3.97E-02	7.73E-04	-3.05E-06	1.99E-02	-1.10E-02	4.23E-04	-1.86E-06	-2.09E-02	5.48E-04	1.62E-05	-7.46E-08	-1.07E-03	5.24E-05	-2.15E-07	1.08E-09
	CO	-4.19E+00	-2.08E-02	4.22E-04	-1.82E-06	4.44E-02	-5.90E-03	1.96E-04	-8.78E-07	-7.11E-03	8.39E-06	8.22E-06	-3.65E-08	-3.39E-04	9.99E-06	9.21E-09	7.81E-11
	NO	-2.77E+00	-2.09E-02	4.05E-04	-1.66E-06	2.96E-02	-1.31E-02	4.81E-04	-2.16E-06	-2.46E-02	6.25E-04	1.96E-05	-9.79E-08	-1.21E-03	6.00E-05	-2.00E-07	7.42E-10
	NO_2	-5.28E+00	-8.78E-03	2.61E-04	-1.30E-06	-2.82E-01	4.90E-03	1.85E-04	-1.13E-06	-7.13E-02	1.23E-03	3.20E-06	-3.27E-08	-3.07E-03	6.90E-05	-4.83E-07	1.89E-09
	NO_x	-2.69E+00	-1.98E-02	3.91E-04	-1.62E-06	-8.41E-03	-1.00E-02	4.28E-04	-1.97E-06	-2.91E-02	9.20E-04	1.42E-05	-7.96E-08	-1.31E-03	6.60E-05	-3.16E-07	1.07E-09
	HC	-5.99E+00	-1.36E-02	2.23E-04	-8.87E-07	5.83E-02	-7.71E-03	1.88E-04	-8.40E-07	-1.54E-03	-2.98E-04	1.01E-05	-4.88E-08	7.32E-05	-6.71E-06	1.99E-07	-9.49E-10
	PM	-8.04E+00	-2.36E-02	4.29E-04	-1.32E-06	1.23E-01	-3.93E-03	1.31E-04	-5.80E-07	1.51E-02	8.64E-05	3.18E-06	-1.46E-08	6.57E-04	3.24E-06	-2.65E-08	2.87E-10

C: Constant, S: Speed, A: Acceleration