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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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)*.

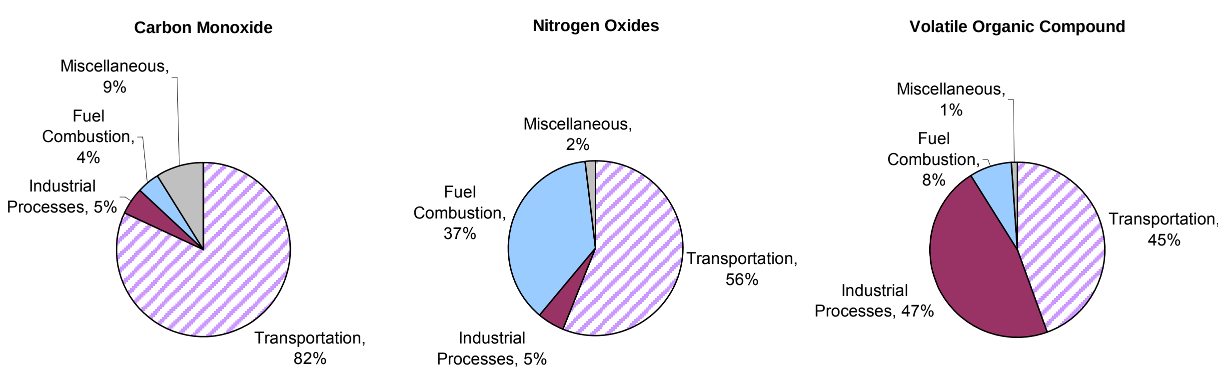

Figure 2.1 Emissions Contributions by source category, 2002

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 realworld 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.

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

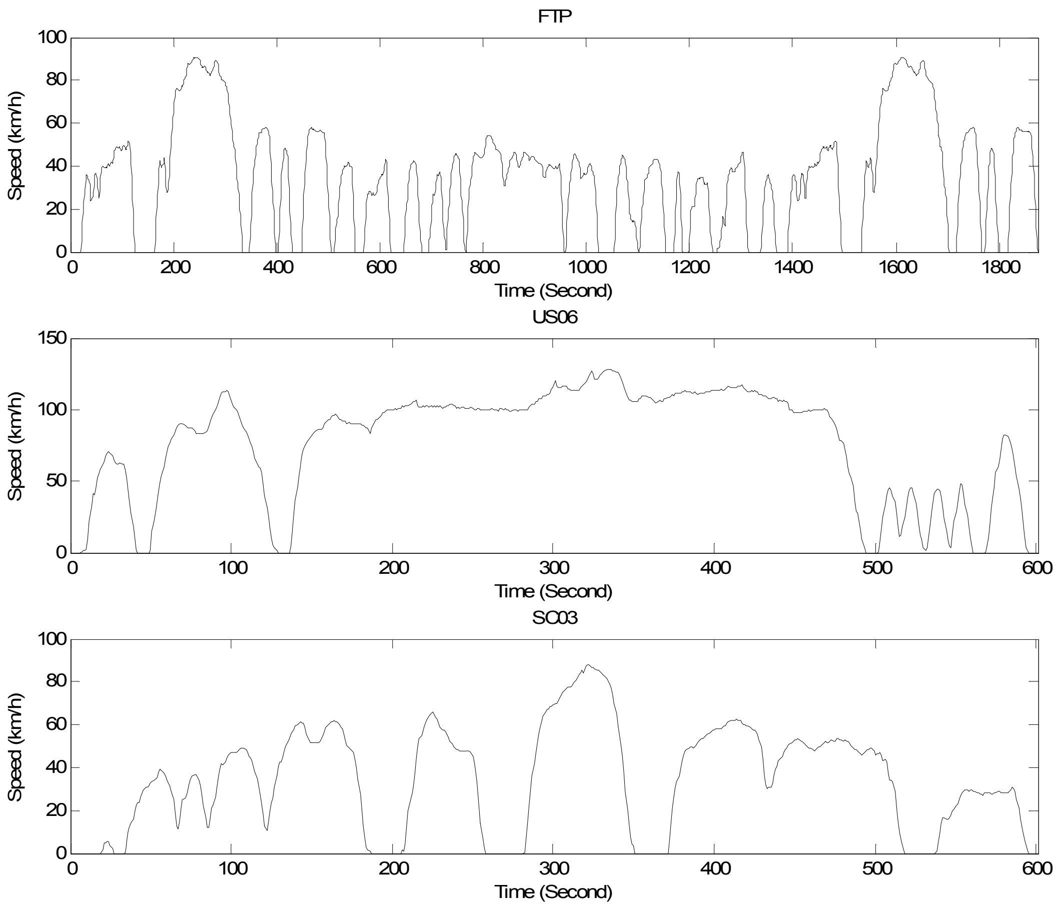

Figure 2.2 FTP, US06, and SC03

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)*.

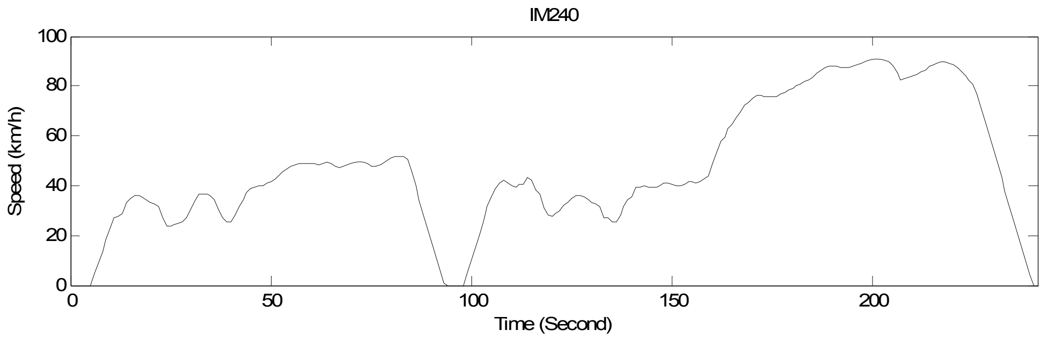

Figure 2.3 IM240

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.

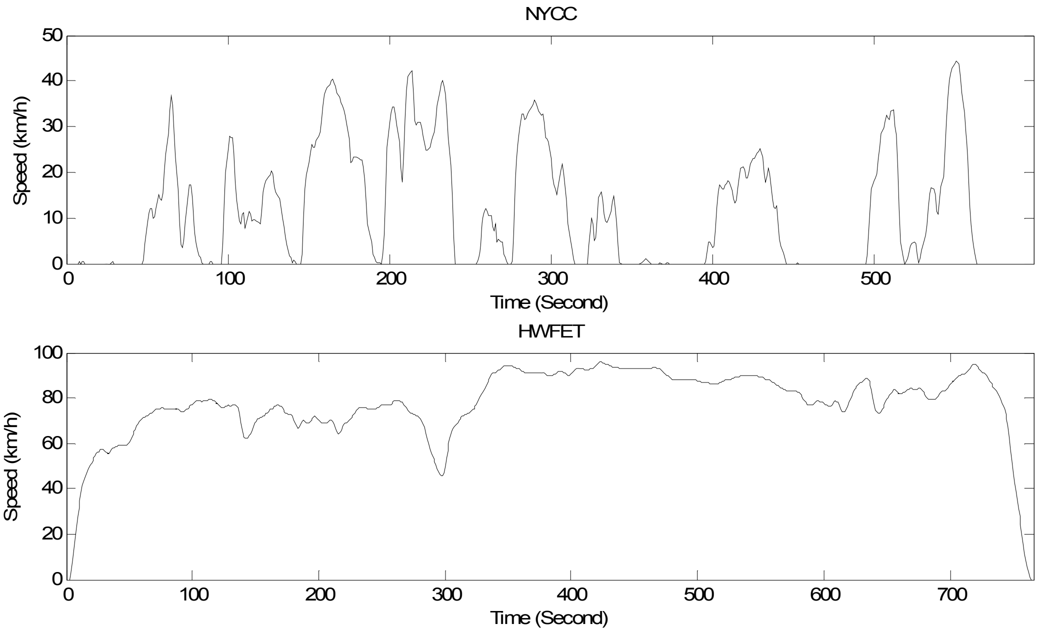

Figure 2.4 NYCC and HWFET

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)*.

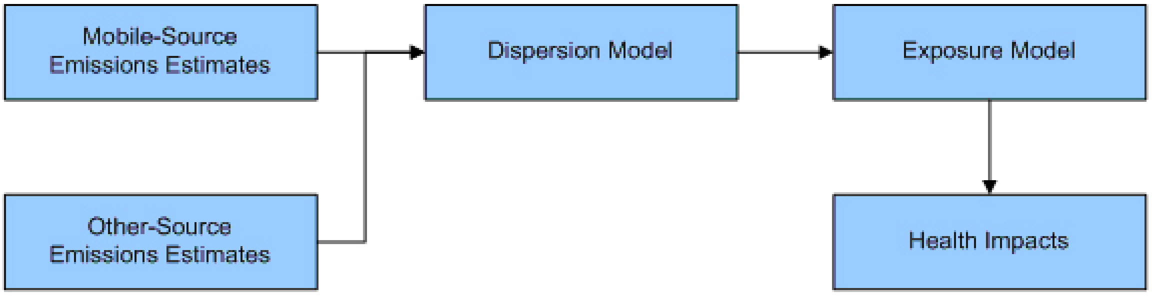

Figure 2.5 Health Impacts Estimates

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.

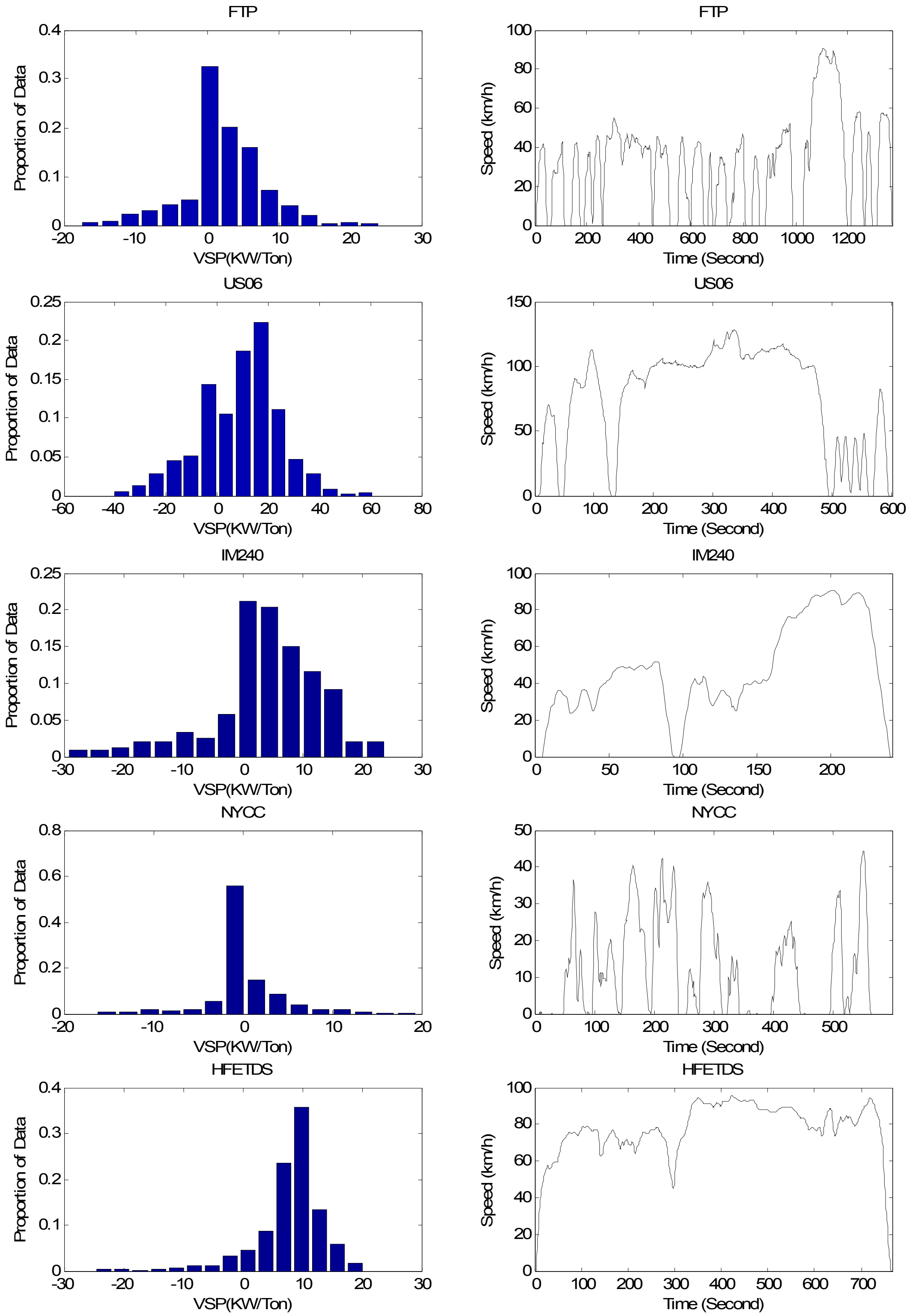

Figure 3.1 Pre-defined drive cycles.

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

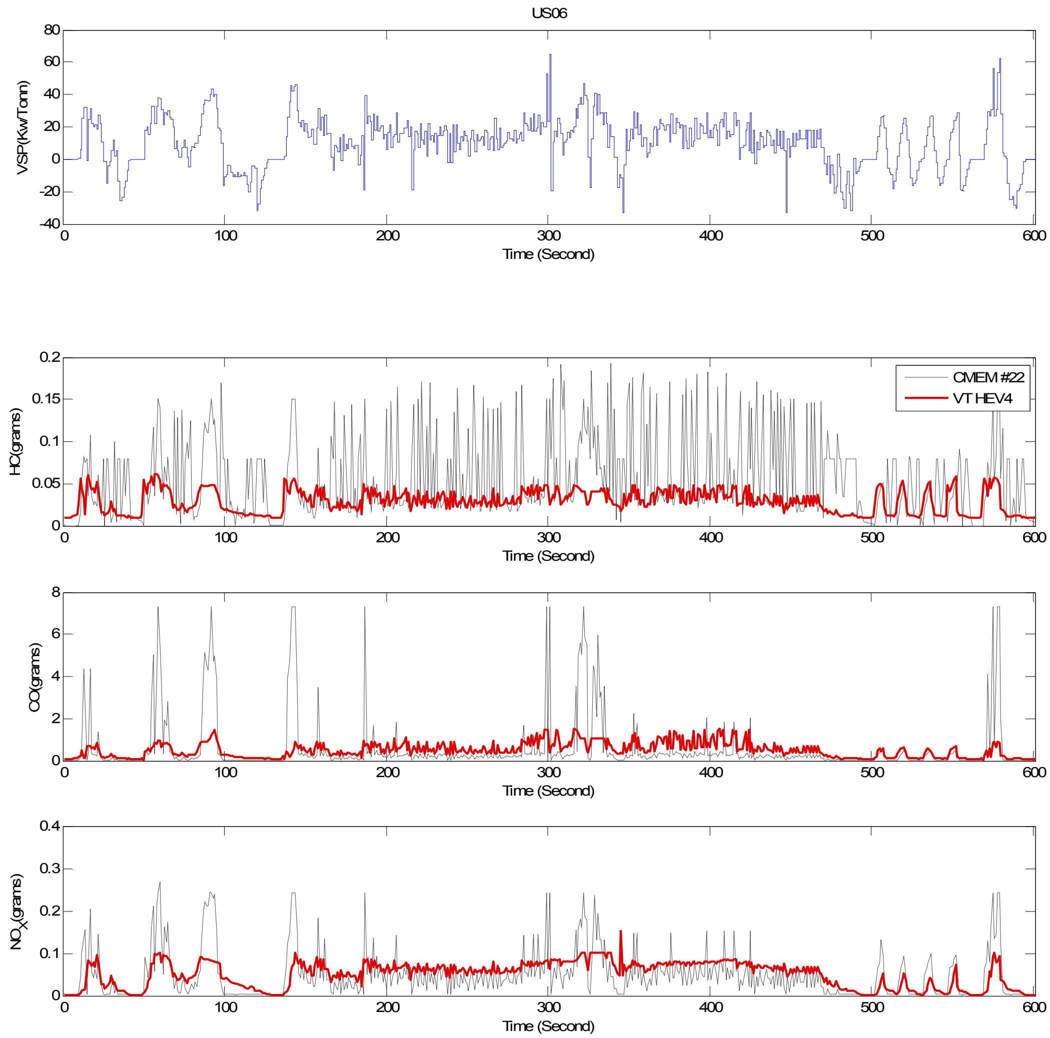

Figure 3.2 Second-by-second US06 emission rates for CMEM-22 and VT-HEV4.