

**QUANTIFYING THE IMPACT OF TRAFFIC-RELATED AND  
DRIVER-RELATED FACTORS ON VEHICLE FUEL  
CONSUMPTION AND EMISSIONS**

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# QUANTIFYING THE IMPACT OF TRAFFIC-RELATED AND DRIVER-RELATED FACTORS ON VEHICLE FUEL CONSUMPTION AND EMISSIONS

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## ABSTRACT

The transportation sector is the dominant source of U.S. fuel consumption and emissions. Specifically, highway travel accounts for nearly 75 percent of total transportation energy use and slightly more than 33 percent of national emissions of EPA's six Criteria pollutants. Enactment of the Clean Air Act Amendment of 1990 (CAAA) and the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) have changed the ways that most states and local governments deal with transportation problems. Transportation planning is geared to improve air quality as well as mobility. It is required that each transportation activity be analyzed in advance using the most recent mobile emission estimate model to ensure not to violate the Conformity Regulation.

Several types of energy and emission models have been developed to capture the impact of a number of factors on vehicle fuel consumption and emissions. Specifically, the current state-of-practice in emission modeling (i.e. Mobile5 and EMFAC7) uses the average speed as a single explanatory variable. However, up to date there has not been a systematic attempt to quantify the impact of various travel and driver-related factors on vehicle fuel consumption and emissions.

This thesis first systematically quantifies the impact of various travel-related and driver-related factors on vehicle fuel consumption and emissions. The analysis indicates that vehicle fuel consumption and emission rates increase considerably as the number of vehicle stops increases especially at high cruise speed. However, vehicle fuel consumption is more sensitive to the cruise speed level than to vehicle stops. The aggressiveness of a vehicle stop, which represents a vehicle's acceleration and deceleration level, does have an impact on vehicle fuel consumption and emissions. Specifically, the HC and CO emission rates are highly sensitive to the level of acceleration when compared to cruise speed in the range of 0 to 120 km/h. The impact of the deceleration level on all MOEs is relatively small. At high speeds the introduction of vehicle stops that involve extremely mild acceleration levels can actually reduce vehicle emission rates. Consequently, the thesis demonstrated that the use of average speed as a sole explanatory variable is inadequate for estimating vehicle fuel consumption and emissions, and the addition of speed variability as an explanatory variable results in better models.

Second, the thesis identifies a number of critical variables as potential explanatory variables for estimating vehicle fuel consumption and emission rates. These explanatory variables include the average speed, the speed variance, the number of vehicle stops, the acceleration noise associated with positive acceleration and negative acceleration noise, the kinetic energy, and the power exerted. Statistical models are developed using these critical variables. The statistical models predict the vehicle fuel consumption rate and emission rates of HC, CO, and NO<sub>x</sub> (per unit of distance) within an accuracy of 88%-96% when compared to instantaneous microscopic models (Ahn and Rakha, 1999), and predict emission rates of HC, CO, and NO<sub>x</sub> within 95 percentile confidence limits of chassis dynamometer tests conducted by EPA.

Comparing with the current state-of-practice, the proposed statistical models provide better estimates for vehicle fuel consumption and emissions because speed variances about the average speed along a trip are considered in these models. On the other hand, the statistical models only require several aggregate trip variables as input while generating reasonable estimates that are consistent with microscopic model estimates. Therefore, these models could be used with transportation planning models for conformity analysis.

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## CHAPTER 1 : INTRODUCTION

The enactment of the Clean Air Act Amendment of 1990 (CAAA) and the introduction of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) have changed the ways that most states and local governments deal with transportation problems. Specifically, the CAAA has geared transportation planning towards improving air quality in addition to what it was previously geared to, mobility.

The transportation sector is the dominant source of U.S. fuel consumption and emissions. Specifically, transportation accounts for nearly two-thirds of the petroleum consumed in the United States, and the highway vehicle accounts for nearly three-fourths of total transportation energy use (NRC, 1995). Reduction in fuel consumption will lead to reduction in carbon dioxide emissions, thus reducing the contribution of motor vehicles to the production of greenhouse gases. Moreover, by reducing the total amount of gasoline consumed, hydrocarbon emissions could be reduced from the entire fuel cycle.

Mobile source emissions contribute significantly to the air pollution problem in the United States. Out of six principal pollutants defined by EPA, three pollutants, which are hydrocarbon, carbon monoxide, and nitrogen oxides, are discussed in this thesis.

Carbon Monoxide (CO) is a colorless, odorless and at high levels, a poisonous gas, resulting from incomplete combustion of motor fuels. It is a component of motor vehicle exhaust. Nationwide, 79 percent of carbon monoxide (CO) emissions come from transportation sources, with 60 percent resulting from highway motor vehicles (EPA, 1996), as illustrated in Figure 1-1. High concentrations of CO generally occur in areas with heavy traffic congestion. In cities, as much as 95 percent of all CO emissions may come from automobile exhaust.

Oxides of Nitrogen (NO<sub>x</sub>) emissions consist of a mixture of NO and NO<sub>2</sub>, which are formed by high-temperature chemical processes during the combustion of fossil fuels (Horowitz, 1982 and NRC, 1991). NO<sub>x</sub> is one of the ground-level Ozone precursors and has received significant

attention from the scientific and regulatory communities as result of the depletion of the Ozone layer. Transportation sources account for 51 percent of  $\text{NO}_x$  emissions, with 31 percent from highway motor vehicles (EPA, 1996), as illustrated in Figure 1-1.

Hydrocarbon (HC) emissions result from the unburned portion of the fuel that escapes through the exhaust system and/or the vehicle fuel storage and the delivery system. It is one of components of volatile organic compounds (VOCs), which are the other ground-level Ozone precursors. The Transportation sector contributes 41 percent of the total VOC emissions, with 29 percent from highway motor vehicles (EPA, 1996), as illustrated in Figure 1-1.

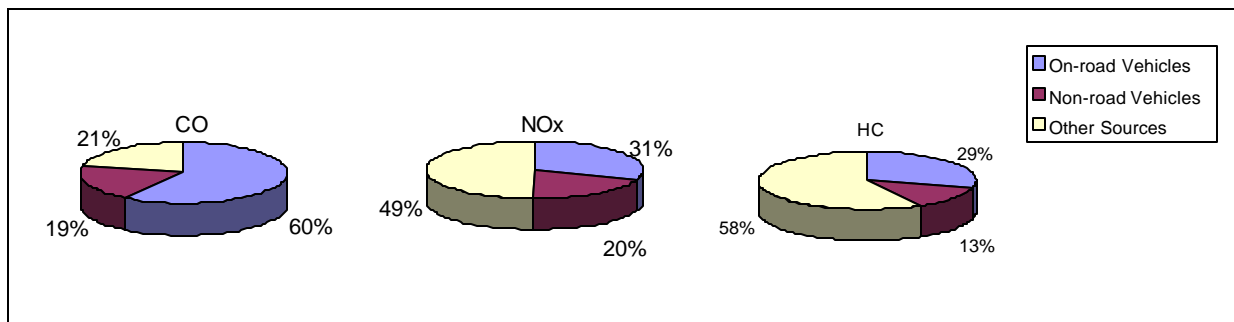


Figure 1-1. Contributions of Sources to Emissions in US (1996)

Between 1970 and 1997, the population in US increased by 31 percent, with an increase in vehicle miles traveled by 127 percent. At the same time, total emissions of the six principal air pollutants decreased by 31 percent. However, in 1997 there were still approximately 107 million people nationwide who lived in counties with monitored air quality levels above at least one of the National Ambient Air Quality Standards (NAAQS), and as of September 1997, 158 areas in the US are still designated as non-attainment areas.

## 1.1 Problem Definition

HC, CO and  $\text{NO}_x$  are three primary pollutants associated with motor vehicles. These emissions can be linked to two different emission producing processes, including the fuel combustion process and the evaporation process, as illustrated in Figure 1-2. Furthermore, vehicle emissions can be linked to two motor vehicle systems, which are the exhaust system and the fuel storage and delivery system, as illustrated in Figure 1-2. Exhaust emissions are products of the

combustion of fossil fuel leaving the engine through the tailpipe system, which include all three pollutants, while evaporative emissions consist of only HC emissions, which escape from the fueling system. For gasoline vehicles, exhaust emissions are formed in a two-stage process. First, emissions originate in the vehicle engine as a result of the fuel combustion, which are commonly termed as engine-out emissions. Second, emissions are reduced by passing through a catalytic converter, resulting in what is commonly known as tail pipe or exhaust emissions. For diesel-powered vehicles, the process of producing exhaust emissions is simpler, because there is presently no after-treatment (i.e., catalytic converter).

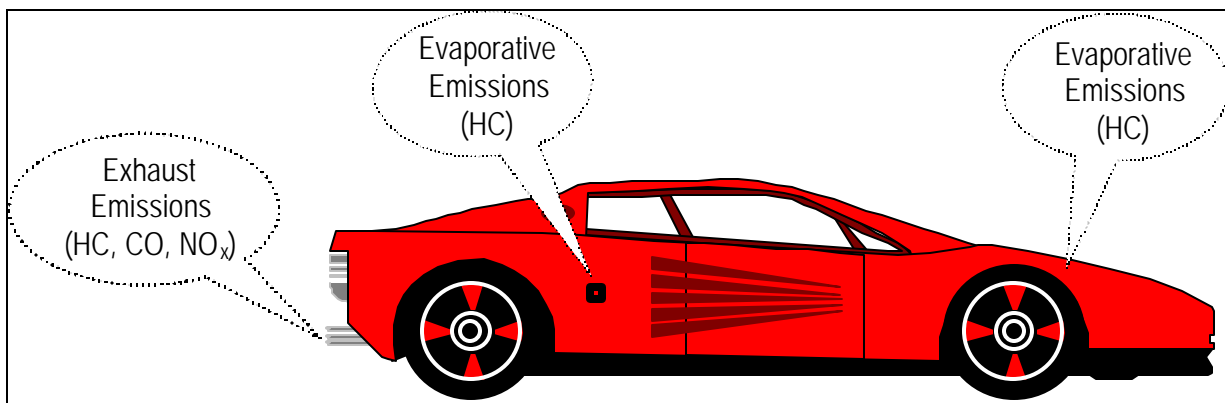


Figure 1-2. Motor Vehicle Emissions

The air/fuel (A/F) ratio, which is controlled by the carburetor or fuel injection system, is the most important factor affecting the efficiency of the catalytic converter and thus the exhaust emissions. CO and HC emissions are highest under fuel enrichment conditions, and NO<sub>x</sub> is highest under fuel enleanment conditions. Fuel-rich operations occur during cold-start conditions (when the vehicle has been turned off for some time and the catalytic converter is cold) and under heavy engine loads (e.g., during rapid accelerations, on steep grades, or at high speeds) (TRB, 1995). Fuel-lean operations typically occur with sharp deceleration or load reduction events, and sometimes during long decelerations. In addition, malfunction in the catalytic converter may result in high emissions. Vehicles with such malfunctions are termed as high emitter vehicles.

The current state-of-practice in estimating vehicle emissions is based on the vehicle's average speed, however, research has demonstrated that the use of average speed alone is insufficient in

estimating vehicle emissions. For example, although the environmental Protection Agency (EPA) MOBILE5 model would indicate that a slowing of traffic typically increases emissions, empirical research indicates the opposite in many cases (EPA, 1993). For example, research in Germany has shown that the greater the speed of a vehicle in built-up areas, the higher is the incidence of acceleration, deceleration, and braking, all of which increase air pollution (Newman and Kenworth, 1992). The research indicated that traffic calming reduced idle times by 15 percent and gasoline use by 12 percent. The slower and calmer style of driving was found to reduce CO emissions by up to 17 percent, VOC emissions by up to 22 percent, and NO<sub>x</sub> emissions by up to 48 percent, depending on the gear engaged and the driver's aggressiveness. The findings in Germany are consistent with statistical energy and emission models that were developed as part of the Metropolitan Model Deployment Initiative (MMDI) evaluation, as illustrated in Figure 1-3 (Ahn *et al.*, 1999 and Rakha *et al.*, 1999). Specifically, Figure 1-3 illustrates that while both the instantaneous speed and acceleration significantly impact vehicle emissions, vehicle acceleration become a more dominant factor on HC and CO emissions, especially at high speeds. The high emissions that are produced while the vehicle is accelerating is attributed to an operating design that allows vehicles to operate with a richer fuel/air mixture in order to prevent engine knock and damage to the catalytic converter. In addition, the catalytic converter is overridden, thereby producing high levels of emissions (TRB, 1995).

Apparently, different speed-acceleration profiles may result in the same average trip speed. However, higher load conditions will occur in a trip with higher accelerations even though the average trip speed is the same. Studies have found that during moderate to heavy loads on the engine, the vehicle operates under fuel enrichment conditions, resulting in CO emissions that exceed 2,500 times normal stoichiometric operation and HC emissions that exceed 40 times normal stoichiometric operation (Barth *et al.*, 1999).

Besides that, the current models (MOBILE5 and EMFAC) offer little help for evaluating operational improvements that are more microscopic in nature, such as the impact of ramp metering, signal coordination, and many improvements through the implementation of ITS strategies because these models do not capture vehicle-to-vehicle nor vehicle-to-control interactions that are necessary for the evaluation of such systems.

In addition, studies using the current state-of-practice models (MOBILE5 and EMFAC) indicate a high level of uncertainty in estimating emission rates. For example, the 95 percent confidence interval for CO emissions associated with an increase in average speed from 31 km/h (FTP city cycle average speed) to 63 km/h (close to fuel economy cycle average speed (77 km/h)) is in the range of a 10 percent increase to a 75 percent decrease in CO emissions (TRB, 1995).

Based on these findings, others (TRB, 1995) have concluded that “the current models do not reflect important explanatory variables that can significantly affect emission levels, such as the incidence of sharp accelerations at lower and moderate speeds.” However, up to this date there has not been a systematic attempt to quantify the impacts of different explanatory variables on vehicle fuel consumption and emission rates. These explanatory variables include the average speed, the number of vehicle stops, the total power consumed, and the energy consumed.

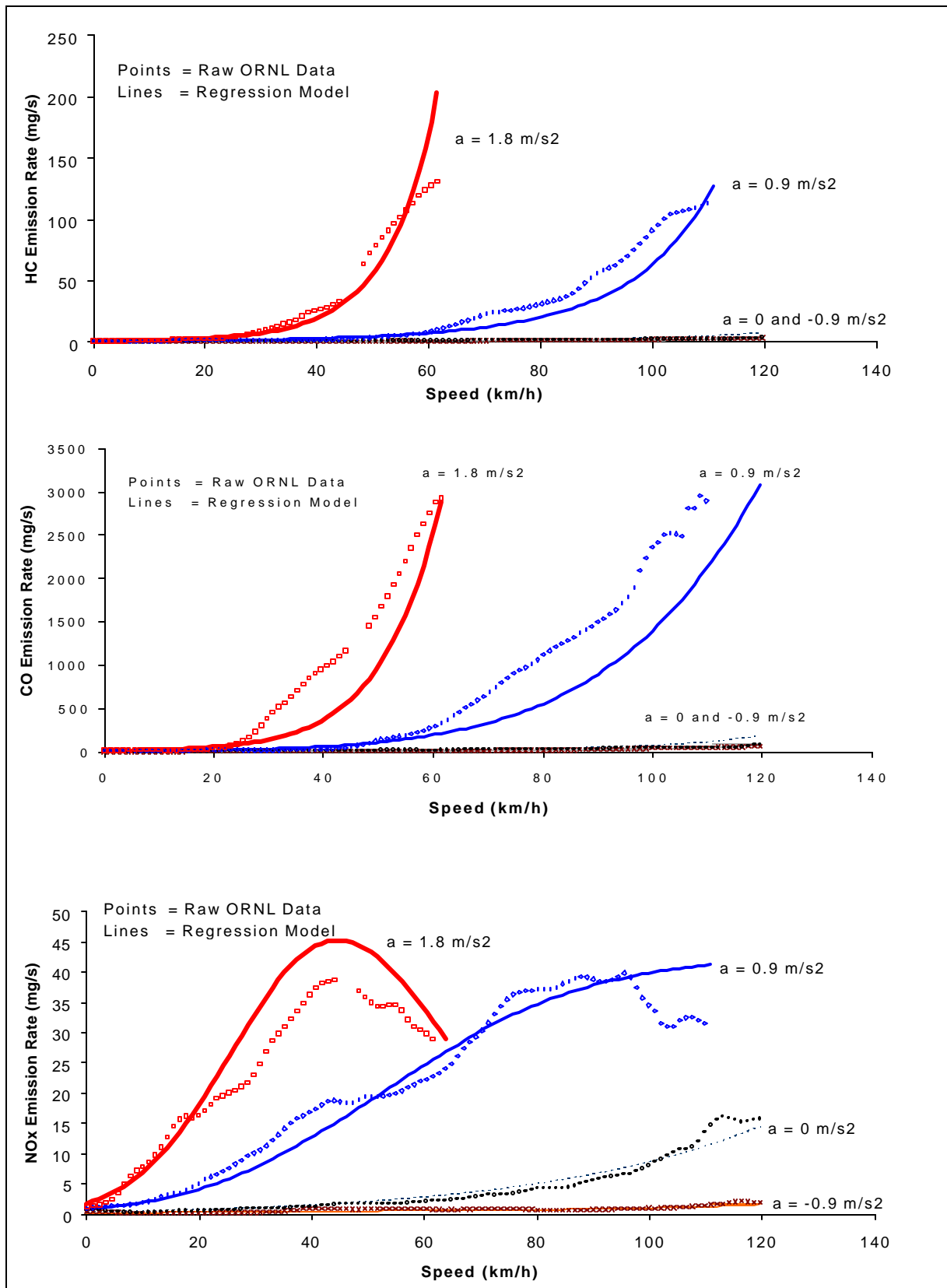


Figure 1-3. Variations of Emissions as a Function of Vehicle's Speed and Acceleration (Ahn et al., 1999)

## **1.2 Thesis Objectives**

The objectives of this thesis are three-fold. First, the thesis not only systematically quantifies the impact of various travel-related and drive-related factors on vehicle fuel consumption and emissions, but also systematically demonstrates that the use of average speed alone for estimating vehicle fuel consumption and emissions is inadequate. Second, the thesis identifies explanatory trip variables for the estimation of vehicle fuel consumption and emissions. The variables considered are the average speed, the speed variability, the number of vehicle stops, the level of deceleration, the level of acceleration, the kinetic energy, and the power exerted by the vehicle. Third, the thesis develops statistical models that compute the vehicle fuel consumption and emissions based on the explanatory variables that are defined in the second step. While the ideal approach to estimate vehicle fuel consumption and emission rates would be based on instantaneous speed and acceleration levels, however, these data require a second-by-second speed profile of the vehicle. The proposed aggregate models could be utilized if the second-by-second data are not readily available.

## **1.3 Research Approach**

The current state-of-practice in conformity analysis is to compute the average speed using a transportation-planning tool similar to TRANPLAN, MINUTP, or EMME/2. Vehicle emissions are then computed using standard tools (MOBILE5 or EMFAC) based on the average speed and total Vehicle Miles Traveled (VMT). However, researchers have realized that average speed alone is not sufficient to accurately quantify environmental impacts (TRB, 1995). Unfortunately, the level of error associated with computing emissions based solely on the average speed has not been systematically quantified. This study not only quantifies the impact of speed variability on fuel consumption and emissions, but also establishes relationships between speed variability and fuel consumption and emission estimates.

As illustrated in Figure 1-4, the research approach is to initially construct trips in order to systematically isolate the impact of different factors on vehicle fuel consumption and emission rates. Three drive cycle sets are constructed. The first is a constant speed drive cycle set, which

serves as a base case. The second set includes trips that involve a single stop, in order to establish the extra fuel consumption and emissions that are associated with a stop. In constructing this set, field data collected in Phoenix (Arizona) are analyzed to identify the typical driver acceleration and deceleration levels. Using these typical acceleration or deceleration levels, a number of artificial trips are generated by varying the deceleration level, the acceleration level, and the speed variability. The third set of trips includes typical drive cycles, which include the FTP city cycle, the New York City cycle and/or the US06 cycle. These cycles were modified by applying scale factors in order to quantify the impact of speed variability on vehicle fuel consumption and emissions. For each trip, fuel consumption and emission rates are computed using the microscopic fuel consumption and emission models, which were developed as part of the Metropolitan Model Deployment Initiative (MMDI) evaluation (Ahn *et al.*, 1999 and Rakha *et al.*, 1999). The impacts of different potential explanatory variables (e.g. average speed, speed variability, level of deceleration, and the level of acceleration) on each MOE are then compared and quantified.

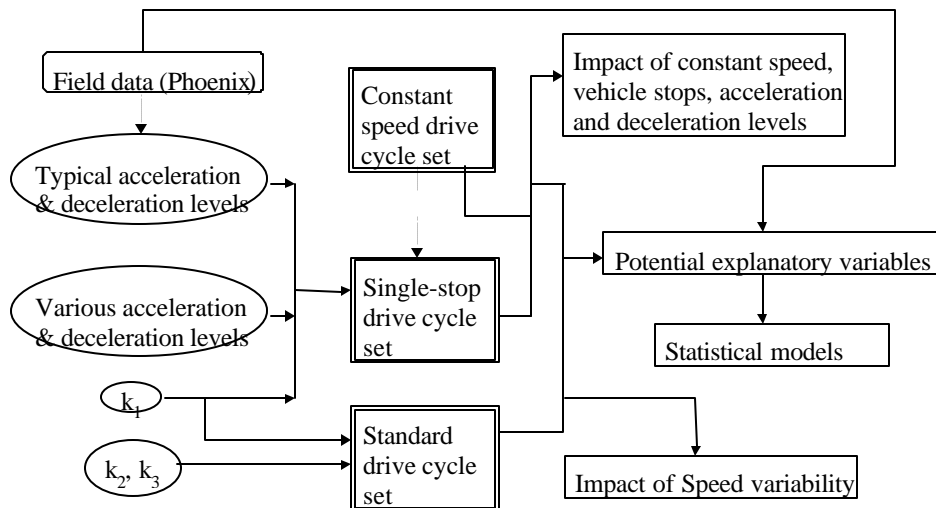


Figure 1-4. Flow Chart of Research Approach

Next, the critical trip variables are identified based upon the constructed trip sets. Using these critical trip variables statistical models are developed and then validated against dynamometer collected data that were gathered by the Environmental Protection Agency (EPA) in order to demonstrate the adequacy of the models.

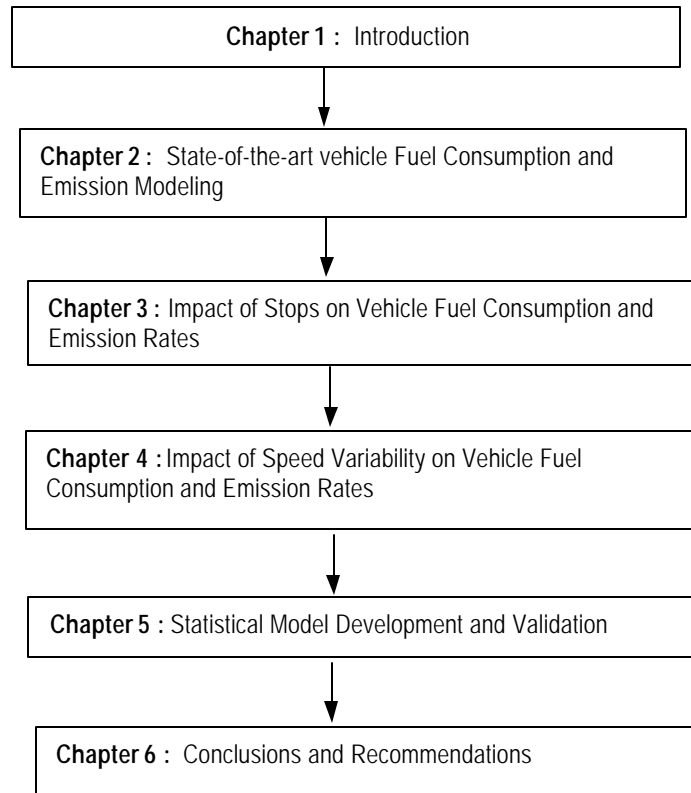
## **1.4 Thesis Layout**

The thesis consists of five chapters, as illustrated in Figure 1-5. Chapter 2 provides an overview of the state-of-the-art in vehicle fuel consumption and emissions modeling. This chapter demonstrates the current state-of-practice together with enhancements that are required to advance the current state-of-art.

Chapter 3 and Chapter 4 not only systematically quantify the impact of various travel-related and driver-related factors on vehicle fuel consumption and emissions, but also systematically demonstrate the inadequacy of average speed as a sole explanatory variable. Specifically, Chapter 3 quantifies the impact of vehicle cruise speed and vehicle stop and their associated levels of acceleration and deceleration on vehicle fuel consumption and emissions. Chapter 4 extends the analysis that was conducted in Chapter 3 by quantifying the impact of speed variability on vehicle fuel consumption and emissions.

In Chapter 5, statistical models for fuel consumption and emission estimates are developed using aggregate trip variables identified as potential explanatory variables in the study. The chapter describes the development of these models and the statistical tests of these models.

Finally, a summary of the findings and recommendations for future research are made in Chapter 6.



*Figure 1-5. Flow Chart of Thesis Layout*

## **CHAPTER 2 : STATE-OF-THE-ART VEHICLE ENERGY AND EMISSION MODELING**

The EPA vehicle emission control program has achieved considerable success in reducing carbon monoxide, oxides of nitrogen and hydrocarbon emissions. Cars coming off today's production lines typically emit 90 percent less carbon monoxide, 70 percent less oxides of nitrogen and 80 to 90 percent less hydrocarbons over their lifetimes than their uncontrolled counterparts of the 1960s (EPA, 1993). However, transportation sources still account for about 45 percent of nationwide pollutants defined by EPA, and highway vehicles, contribute slightly more than one-third of the nationwide emissions of EPA's six criteria pollutants (NRC 1995). In addition, nearly two-thirds of the petroleum in the United States are consumed by the transportation sector, of which 75 percent are as a result from highway travel (NRC, 1995).

A first step in reducing the impact of the transportation sector on the environment is to predict the amount of fuel consumed and pollutants emitted from motor vehicles based on representative travel characteristics, the physical nature of highways and others. Several models for estimating vehicle fuel consumption and emissions have been developed and are reviewed in this chapter. The objective of the chapter is to provide the reader with a background of the current state-of-art and current state-of-practice in vehicle fuel consumption and emission modeling.

### **2.1 Background**

#### ***2.1.1 Vehicle Fuel Consumption***

Petroleum used in the United States is highly dependent on imported oil. Moreover, the U.S. fleet of gasoline-powered automobiles and light trucks contributes about one-fifth of the total U.S. carbon dioxide (CO<sub>2</sub>) emissions (NRC 1995), which is the principle greenhouse gas. Improvements in vehicle fuel efficiency can reduce the extent of the Nation's dependence on foreign oil. Even though the impact of fuel economy improvements on the emissions of other

pollutants is still unclear, total volatile organic compound (VOC) emissions are likely to be lower due to reduced demand for fuel.

### ***2.1.2 Vehicle Emissions and Conformity Analysis***

According to a NRC report (1995), highway vehicles account for slightly more than one-third of nationwide emissions of EPA's six criteria pollutants. The three primary pollutants associated with motor vehicles are hydrocarbon, carbon monoxide and oxides of nitrogen.

Since 1968, when the first emission controls were installed on motor vehicles and since 1974, when the first motor vehicle emissions inspection and maintenance (I/M) programs were instituted, significant emission reductions have been achieved. However, the benefits associated with these emission reductions have been increasingly eroded by the substantial growth in vehicle usage and Vehicle Miles of Travel (VMT).

The 1977 Clean Air Act Amendment (CAAA) was a first attempt at regulating and reducing vehicle emissions. Specifically, the CAAA established the National Ambient Air Quality Standards (NAAQS) to achieve its goal. Following the 1977 CAAA, the 1990 CAAA was initiated in an attempt to balance the nation's mobility and air quality requirements.

Specifically, the 1990 CAAA established criteria for attaining and maintaining the NAAQS by defining geographic regions within the US that do not meet the NAAQS as being classified as nonattainment areas. Depending on the severity of the air quality problem, these nonattainment areas are classified as marginal, moderate, serious, severe and/or extreme nonattainment areas. Officials in each nonattainment area are required to take specific actions within a set time frame in order to reduce emissions and attain the NAAQS. The time frame varies with the severity of the problems, and the actions become more numerous and more stringent as the air quality gets worse.

To help ensure attainment of mandates, the 1990 CAAA strengthens existing conformity requirements. Conformity is a determination made by Metropolitan Planning Organizations

(MPOs) and DOTs that transportation plans, programs, and projects in non-attainment areas meet the "purpose" of the State Implementation Plan (SIP) for attaining the NAAQS. Under the new conformity, MPOs and U.S. DOTs have an affirmative responsibility to ensure that the transportation activities will not create new NAAQS violations, increase the frequency or severity of existing NAAQS violations, or delay timely attainment of the NAAQS.

Conformity regulations require that MPOs in nonattainment and maintenance areas use the most recent mobile source emission estimate models to show that (a) all federal funded and "regional significant projects" including nonfederal projects, in regional Transportation Improvement Programs (TIPs) and plans, will not lead to emissions higher than those in the 1990 baseline year; and (b) by embarking on these projects, emissions will be lower than the no-build scenario. Once TIPs are approved by EPA, the conformity test becomes less demanding.

Conformity determinations are to be made no less than every 3 years or whenever changes are made to plans, programs, and/or projects. Certain events, such as SIP revisions that establish or revise a transportation-related emission budget, or add or delete Transportation Control Measurements (TCMs) will also trigger a new conformity determination. MPOs must reconcile emission estimates from transportation plans and TIPs with those contained in the motor vehicle emission budgets in the SIPs, conduct periodic testing to determine whether actual emissions are consistent with estimates, and if not, remedial action must be taken.

If a transportation plan, program, or project does not meet conformity requirements, transportation officials must modify the plan, program, or project to offset the negative emission impacts, or work with the appropriate state agency to modify the SIP to offset the plan, program, or project emissions. If any of the above actions is not accomplished, the plan, program, or project cannot advance. Failure to create and implement a SIP to meet the CAAA requirements will result in such sanctions enforced as withholding Federal Highway Funding, or withholding grants for air pollution planning, or two-to-one emission offsets for major stationary sources.

Following the CAAA of 1990, the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) gave state and local governments the tools to adapt their plans to meet the

requirements of the CAAA. The ISTEA complements the CAAA by providing funding and flexibility to use it in ways that will help improve air quality through development of a balanced, environmentally sound, intermodal transportation program.

It should be noted that under the CAAA of 1990, as of September 1997, 158 areas are still designated as nonattainment areas with approximately 107 million people nationwide living in counties which fail to meet the primary national air quality standards (National Air Quality: Status and Trends, 1997).

## **2.2 Estimation of Vehicle Fuel Consumption**

### ***2.2.1 Factors Affecting Vehicle Fuel Consumption***

The primary factors affecting fuel economy can be classified into four categories (NRC, 1995), which are travel-related factors, driver-related factors, highway-related factors, and vehicle-related factors. These factors are discussed in further detail in the following sub-sections.

#### **2.2.1.1 Travel-Related Factors**

Travel-related factors, as the name suggests, include factors that relate to traffic conditions. These factors include average speed, number of vehicle stops, cruise-type driving conditions and/or free-flow conditions. These factors have significant impacts on vehicle fuel consumption. For example, it has been shown that a 15 percent reduction in average speed in built-up areas may reduce fuel consumption by 20 to 25 percent (Baker, 1994). Furthermore, six times more gasoline is required for a vehicle to start from a complete stop than it does if the vehicle doesn't come to a complete stop (Baker, 1994).

### **2.2.1.2 Driver-Related Factors**

Driver-related factors relate to how the driver accelerates, brakes or shifts gear. Aggressive acceleration and braking both result in greater fuel consumption than cruise-type driving. For example, in congested urban areas, an aggressive driving is estimated to increase vehicle fuel consumption by up to 10 percent (NRC, 1995). Even with the same average speed and a standard transmission, fuel consumption between drivers can vary by up to 20 percent due to differences in gear shifting, as more gas is consumed at lower gears. Traffic control devices, like various signal timing plans during a day and traffic smoothing strategies, like capacity addition, can influence both traffic conditions and driver behaviors, thus alleviating driving aggressiveness and congestion, which contributes to a reduction in fuel consumption.

### **2.2.1.3 Highway-Related Factors**

Highway-related factors include road grade, and road roughness. These factors can lead to a great variation in fuel consumption. For example, the Ontario Ministry of Transportation (1992) concluded that driving on a gravel road increased a vehicle's fuel consumption by 35 percent when compared to a smooth road, and 15 percent when compared to patched asphalt. In addition more fuel is required to drive up a steep grade and along a highly winding road versus a straight road. However, the additional fuel consumption related to those factors requires quantification.

### **2.2.1.4 Vehicle-Related Factors**

Vehicle-related include all factors that are related to a vehicle's operation and maintenance and other factors that are neither travel, driver, or highway-related, like for example weather conditions. It is well known that good maintenance of a vehicle can help curb its fuel consumption increase with the vehicle's age and utilization. In addition, auxiliary equipment as air conditioning, power accessories and automatic transmission will significantly increase the use of fuel. Vehicles consume additional fuel as a result of being idle. For example, based on the duration of a vehicle soak time, it can operate in cold-start, hot-start or hot stabilized mode. Generally, a vehicle needs more fuel during the cold-start mode to warm up the engine and to

ensure that all components are in operation. Other vehicle characteristics like weight and size also affect fuel consumption. For example, light and small vehicles typically consume less fuel than heavy and large vehicles. In addition, the weather conditions, like temperature, moisture, and wind, can have a significant influence on fuel consumption. In Europe for example, vehicle fuel consumption is thought to be 15 to 20 percent worse in winter than in summer (Baker, 1994).

### ***2.2.2 State-of-the-art Models for Estimating Vehicle Fuel Consumption***

Many models have been proposed by researchers to estimate vehicle fuel consumption rates. These models can be grouped into three main categories: (1) Instantaneous models, also termed microscopic models, that relate fuel consumption to the time history of driving patterns and road gradient; (2) Modal models that estimate each portion of total fuel consumption associated with each operating condition along an entire trip; and (3) Average-speed models that estimate fuel consumption based on the average trip speed. These models are described in further detail in the following sub-sections.

#### **2.2.2.1 Instantaneous Fuel Consumption Models**

Instantaneous fuel consumption models compute a vehicle's fuel consumption based on instantaneous measurements of explanatory variables. Examples of explanatory variables include the vehicle speed, the roadway gradient, and the vehicle's power. The instantaneous fuel consumption models are ideal for the evaluation of the energy impacts that are associated with operational-level traffic improvement projects because they are sensitive to vehicle-to-vehicle and vehicle-to-control interactions.

The most common of these fuel consumption models uses the vehicle's instantaneous power as an explanatory variable based on the principle of conservation of energy. The Total fuel consumed by a vehicle is an input source of energy that is transformed into kinetic energy for the movement of the vehicle and required to overcome the internal energy that results from friction or resistance. These models attempt to determine the proportion of the total input energy required

to meet the vehicle's steady-state speed drag and inertial power requirements for vehicle acceleration.

The original power-based model was developed by Post *et al.* (1984) where it computed aggregate fuel consumption estimates for on-road driving within 2 percent of the actual measured fuel usage for an individual vehicle. The instantaneous fuel consumption-power relationship is expressed as Equation 2-1.

$$\begin{aligned} FC &= \mathbf{a} + \mathbf{b}P & P > 0 \\ &= \mathbf{a} & P \leq 0 \end{aligned} \tag{2-1}$$

Where:

FC = Instantaneous Fuel Consumption rate (ml/s)

**a** = Idle Fuel Consumption Rate (ml/s)

**b** = An Average Efficiency Factor (ml/s/kw)

P = Instantaneous Total Power (kw)

The coefficients **a** and **b** vary for each vehicle as the vehicle's condition and state of tune alters. The zero power fuel consumption rate (**a**) strongly correlates with engine capacity and could be expressed as a linear function of engine capacity for spark ignition vehicles. The fuel consumption rate per power generated (**b**) is a measure of the efficiency with which a vehicle produces each additional power. The model can be applied to any traffic situation provided on-road power demand is known. The instantaneous power demand is a function of a vehicle's mass, drag, speed, acceleration and road gradient.

The Australian Road Research Board extended the original power-based model to produce more accurate estimates of fuel consumption in different driving modes based on vehicle speed and road geometry data (Alcelik, 1989). Equation 2-2 is the general form of the fuel consumption model.

$$FC = \mathbf{a} + \mathbf{b}_c P_c + \mathbf{b}_a P_a \tag{2-2}$$

Where:

- $\mathbf{b}_c, \mathbf{b}_a$  = Efficiency parameters applicable to constant-speed, and acceleration modes of driving;  
 $P_c$  = Total drag power during constant-speed driving;  
 $P_a$  = Total inertia drag power

Unlike the original power-based model, this model predicts vehicle fuel consumption in different driving modes by applying different efficiency parameters to overcome the inadequacy as a result of use of an average efficient factor for all driving modes.

Another power-based model developed by An and Ross (1993) expresses the fuel consumption of a vehicle in terms of a few vehicle characteristics and summary characteristics of any trip, as illustrated in Equation 2-3.

$$Fuel = \left[ \mathbf{a}_{f.pwr} (1 - t_c - t_D) \left( \frac{v_{gear}}{\bar{v}} \right) + \mathbf{a}_{f.idle} \frac{(t_c + t_D)}{\bar{v}} \right] + (\mathbf{a}_{tire} + \mathbf{a}_{air} \mathbf{l} v_r^2 + \mathbf{a}_{brake} \mathbf{b} v_p^2 n + \frac{\mathbf{a}_{acc}}{\bar{v}}) \quad (2-3)$$

Where:

- Fuel = Fuel consumption per unit distance;  
 $\bar{v}$  = Overall average speed;  
 $v_r$  = Average running speed;  
 $v_p$  = Average peak speed (root-mean-square of subcycle peak speeds);  
 $n$  = Number of stops per mile (or major slowdowns);  
 $v_{gear}$  = Average vehicle speed in gear used in neighborhood of  $v_r$ , times the gear ratio relative to that in top gear;  
 $\mathbf{l}$  = Average of cubed running speed divided by the cube of the average running speed;  
 $\mathbf{b}$  = Fraction of vehicle kinetic energy absorbed by brakes;  
 $t_c, t_D$  = Fraction of time braking and stopped, respectively;  
 $\mathbf{a}_{f.pwr}, \mathbf{a}_{f.idle}$  = Generalized engine friction in powered operation and idle operation, respectively;  
 $\mathbf{a}_{tire}$  = Coefficient related to tire rolling resistance;  
 $\mathbf{a}_{air}$  = Coefficient related to air resistance;  
 $\mathbf{a}_{brake}$  = Coefficient related to brakes;

$a_{acc}$  = Coefficient related to vehicle accessories.

Ahn *et al.* (1999) and Rakha *et al.* (1999) developed a microscopic fuel consumption model based on second-by-second speed/acceleration data and fuel consumption and emission measurements that were collected by the Oak Ridge Laboratory Lab (ORNL) for eight light-duty vehicles and light-duty trucks. A composite vehicle was derived as a typical average vehicle by taking average fuel consumption and emission rates for all eight vehicles at various speeds and accelerations.

The test vehicles used by the ORNL are representative of a typical 1995 U.S. Internal Combustion Engine light-duty vehicle. The average engine size for the test vehicles was 3.3 liters, the average number of cylinders was 5.8, and the average curb weight was 1497 kg (3300 lbs). The vehicles were tested on-road and on a chassis dynamometer as a function of vehicle speed and acceleration. The data for fuel consumption and emissions of HC, CO and NO<sub>x</sub> were measured thereon. Each test recorded 1,300-1,600 data points on the second-by-second basis. Typically, data collected include speeds varying from 0 to 120 km/h (110 ft/s) at the increments of 1.1 km/h (1 ft/s), and acceleration ranging from -1.5 m/s<sup>2</sup> to 3.7 m/s<sup>2</sup> (-5 to 12 ft/s) at increments of 0.3 m/s<sup>2</sup> (1 ft/s<sup>2</sup>). The ORNL data didn't include high emitter vehicles and only tested vehicles under hot-stabilized conditions.

It should be noted that the raw data collected at ORNL represent a unique vehicle performance characteristic. For example, high power-to-weight ratio vehicles have better acceleration performance at high speeds than their low power-to-weight ratio counterparts (Ahn *et al.*, 1999). This inherent speed-acceleration performance is incorporated in the microscopic models and shown in Figure 2-1 for a hypothetical composite vehicle. The linear relationship between speed and acceleration illustrates that acceleration at a certain speed cannot exceed the boundary constrained by a vehicle physical kinematics.

Equation 2-4 shows the general format of the model. The log-transformed data are applied in the model to preclude any negative value of fuel consumption.

$$\log(Fuel) = \sum_{i=1}^3 \sum_{j=1}^3 (k_{i,j} * s^i * a^j) \quad (2-4)$$

Where:

*Fuel* = Fuel consumption (l/s)

*k* = Model regression coefficients

*s* = Vehicle instantaneous speed (m/s)

*a* = Vehicle instantaneous acceleration (m/s<sup>2</sup>)

*i* = Power to speed (i.e. *s*, *s*<sup>2</sup>, *s*<sup>3</sup>)

*j* = Power to acceleration (i.e. *a*, *a*<sup>2</sup>, *a*<sup>3</sup>)

The model estimates vehicle fuel consumption to within 2.5 percent of actual measured values. The model has been incorporated within INTEGRATION, a microscopic traffic simulation model to further demonstrate its application to traffic engineering and management studies.

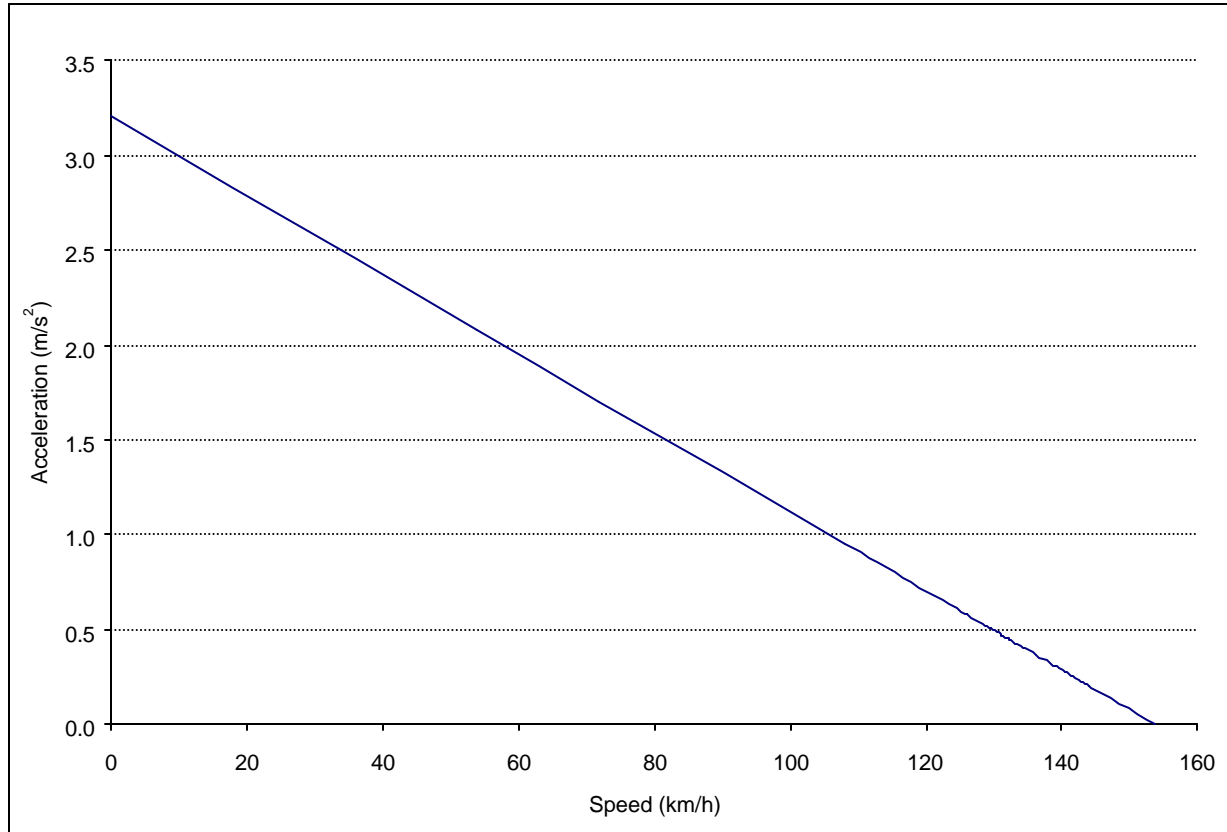


Figure 2-1. Speed and Acceleration Envelop for a Composite Vehicle (Ahn et al., 1999)

### 2.2.2.2 Drive Modal Fuel Consumption Models

Areas of application of drive modal fuel consumption models are similar to those of instantaneous models. Specifically, these models are applied to the evaluation of the energy impacts associated with operational-level traffic improvement projects.

Drive modal fuel consumption models attempt to capture the fuel consumption associated with different vehicle operating conditions in a typical trip. These models are based on the assumption that each driving mode of a vehicle, e.g. cruising, acceleration/deceleration, and idling, is independent of one another and the total fuel consumed in a trip is simply equal to the sum of the fuel used for each driving mode. Unlike the instantaneous models, the drive modal models require a number of explanatory variables, including the vehicle's cruise speed (or the initial or terminal speed of each driving mode), number of vehicle stops (complete stops, effective stops, first time stops, subsequent stops), stopped time, and/or total delay along a trip.

The advantage of these models is their simplicity, generality, and conceptual clarity, as well as the direct relationship to existing traffic modeling techniques (Richardson *et al.*, 1981). However, because the "average" coefficients, which account for the "average maneuver" taken by drivers, are implicit in the mode, these models are unable to capture any differences that result from differing driver characteristics, or any differences that result from travel conditions that differ from the "average travel condition."

An attempt to overcome these limitations was made by Baker (1994) who employed a simple acceleration/deceleration-speed relationship to capture the differences in driver behaviors, as illustrated in Figure 2-2. The basic models were derived from data collected using a TravTek vehicle in Orlando, Florida. The models developed predict fuel consumption rates as a function of vehicle's speed during idle, cruise and stop/go modes of driving. Using the acceleration/deceleration-speed relationship, a more microscopic speed profile for a vehicle can be defined and then used to compute time spent during each mode (i.e. cruise, deceleration, and acceleration mode). The fuel consumed along an entire trip is apportioned to the acceleration and deceleration phases of the speed profile by the following approaches:

- (1) During travel at constant speed, only cruise fuel is calculated;
- (2) During periods of deceleration, only the idle fuel is computed;
- (3) During periods of acceleration, first, cruise fuel at average speed  $v$  and the additional fuel that is consumed while completing a full stop/go cycle (decelerate from  $v_2$  to  $v_1$ , then acceleration from  $v_1$  to  $v_2$ ) are computed. Second, the time required to complete a corresponding speed drop from  $v_2$  to  $v_1$  during deceleration is calculated based on the defined acceleration/deceleration-speed relationship. Third, this time is multiplied by the cruise rate at average speed  $v$ , minus the idle rate, to generate a net volume of fuel. Fourth, the summation of these three volumes of fuel is attributed to the acceleration phase.

Again, This model suffers from the general limitations of modal models in that it assumes that two drivers who drive at the same speed will have the same acceleration/deceleration characteristics and is unable to capture differences that arise from different travel conditions.

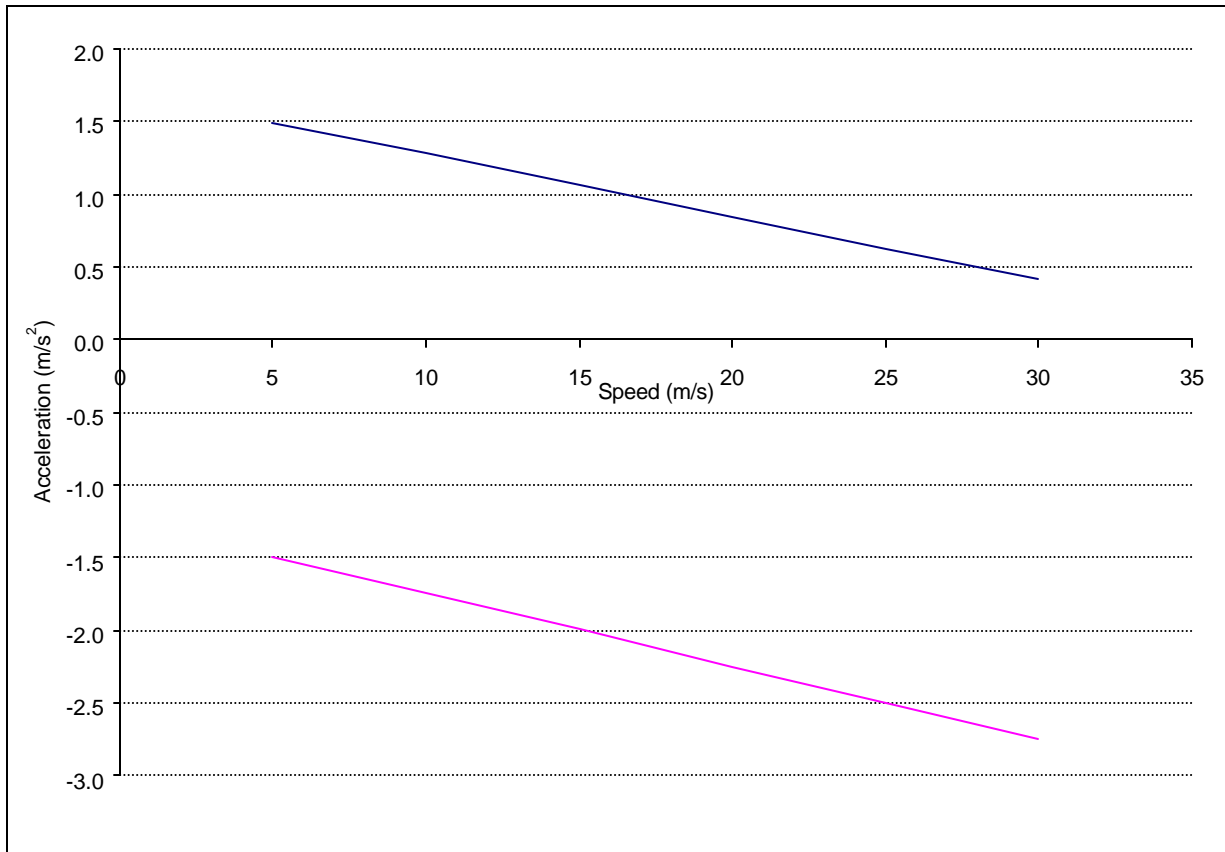


Figure 2-2. Acceleration Rates vs. Speed (Baker, 1994)

Dion *et al.* (1999, 2000) developed a mesoscopic model that estimates average vehicle fuel consumption based on an average speed, an average number of vehicle stops per unit distance, and an average stop duration for eight light duty gasoline vehicles under hot-stabilized conditions. Similar to the modal models, the model estimates separately fuel consumption rates per unit distance during each mode of operation of a vehicle (deceleration, idling, acceleration, and cruising) using relationships derived from a microscopic fuel consumption model (Ahn and Rakha *et al.*, 1999). As illustrated in Figure 2-3, first, the model (Parsing Module) constructs a typical drive cycle for a specific vehicle based on a given average speed, an average number of vehicle stops per unit distance, and an average stop duration. Second, the model (Amount of Travel by Mode Module) computes the most likely proportion of time that the vehicle spends cruising, decelerating, stopped, and acceleration during this typical drive. Then, the fuel consumption and emissions associated with each mode of operation are calculated by multiplying the corresponding time with the fuel consumption and emission rates per unit of time derived from the microscopic model for each mode. As an output, the total fuel consumed and

pollutants emitted for each mode over the typical drive cycle are summed, then normalized to compute average rates on a per kilometer basis.

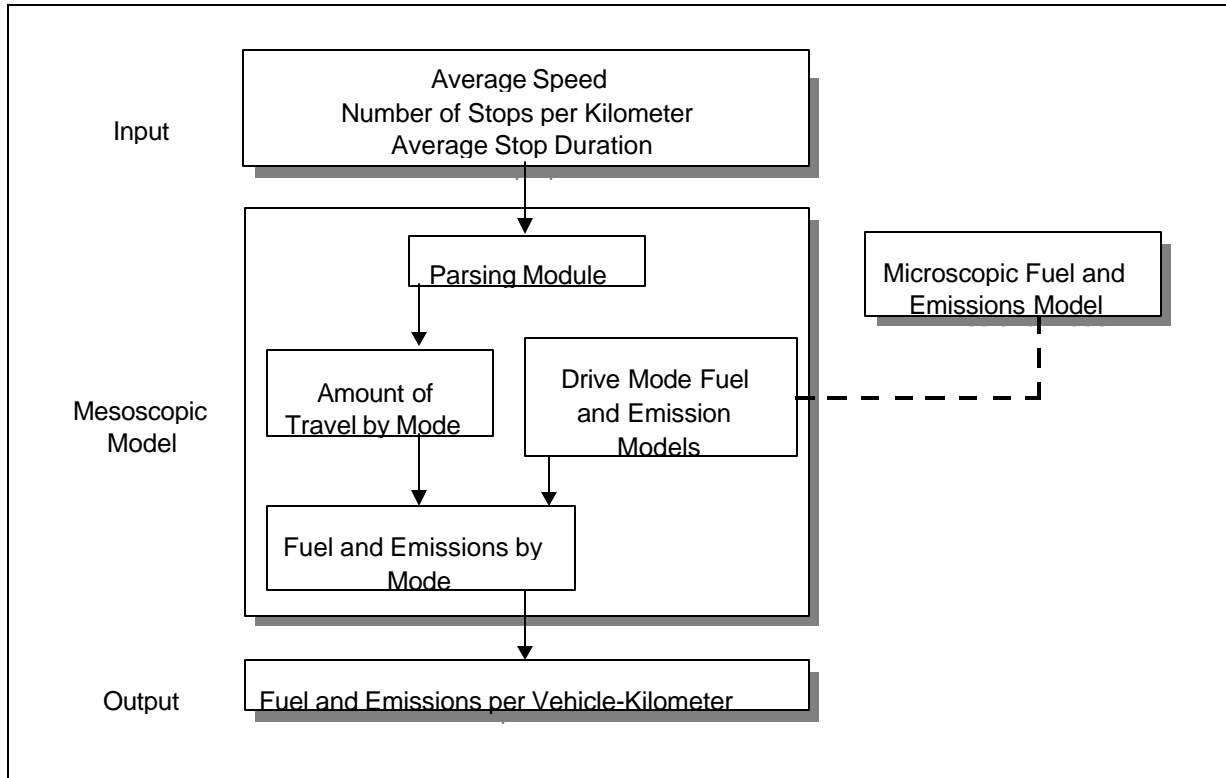


Figure 2-3. Flow of Information within Mesoscopic Fuel Consumption and Emission Model (Dion et al., 1999 and 2000)

Applications of the model to the EPA urban and highway drive cycles indicate its ability to predict fuel consumption rates that are consistent with the rates predicted by the microscopic model, as well as published EPA fuel consumption rates, as illustrated in Figure 2-4.

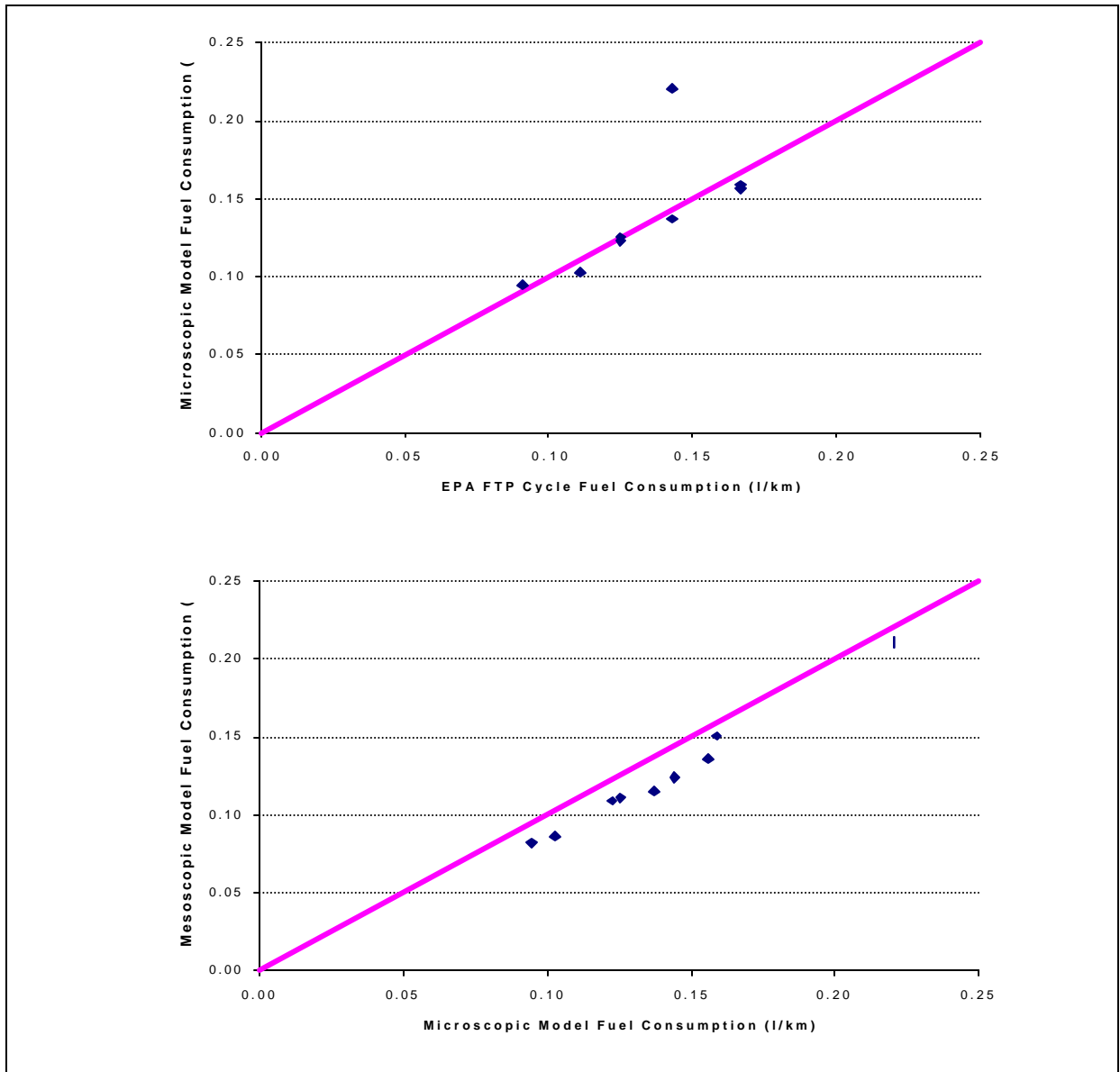


Figure 2-4. Mesoscopic and Microscopic Fuel Consumption for EPA Urban Drive Cycle (Dion et al., 2000)

### 2.2.2.3 Fuel Consumption Models Based on Average Speed

Average speed fuel consumption models relate fuel consumption to trip time, or the reciprocal of average trip speed (Evans and Herman, 1978), as illustrated in Equation 2-5. These models are suitable for estimating the total fuel consumption in large urban traffic systems and for assessing the impact of transportation management schemes that likely have impacts on average speeds and the level of travel demand.

$$Fuel = k_1 + k_2 \bar{t} = k_1 + \frac{k_2}{\bar{v}} \quad (2-5)$$

Where:

$Fuel$  = Fuel consumption per unit distance;

$\bar{t}$  = Average trip time per unit distance;

$\bar{v}$  = Average trip speed;

$k_1, k_2$  = Constants

Average speed models can be applied when the average speed ranges between 10 and 50 km/h, however these models have limited application at very low speeds and at high speeds where the aerodynamic drag becomes a dominant factor and thus the fuel consumption can not be explained solely by the average speed.

Lam (1985) developed a second-degree statistical model for estimating vehicle fuel consumption based on a vehicle's average speed. The Model was developed using high speed and uniform speed driving cycles. Lam proposed two models. The first of these models relates a vehicle's fuel consumption to the average trip speed, engine size and vehicle mass for urban driving, as expressed in Equation 2-6. The second model computes the fuel consumption using the same explanatory variables, except that the model is valid for rural driving conditions, as expressed in Equation 2-7.

$$Fuel = w(cE^d)(1 + \frac{u}{v}) + wL \quad (2-6)$$

$$Fuel = w(cE^d) + Bv^2 + wL \quad (2-7)$$

Where:

$Fuel$  = Fuel consumption per unit distance;

$E$  = Engine displacement in cubic centimeters;

$v$  = Average speed;

$L$  = Payload;

$w, c, d, B$  = Constants.

## **2.3 Estimation of Vehicle Emissions**

### ***2.3.1 Factors Affecting Vehicle Emissions***

The primary factors effecting vehicle emissions fall into the same categories as those affecting fuel consumption. However, the impacts of these factors on emissions are not well understood compared with fuel consumption. Theoretically, vehicle emissions are expected to decrease with the reduction in the volume of fuel consumed. These factors are discussed in more details in this section.

#### **2.3.1.1 Travel-Related Factors**

Travel-Related Factors include vehicle operating modes, speeds, and accelerations. The operating mode of a vehicle is important because exhaust emissions vary significantly with the different operating modes. As was discussed earlier, vehicle exhaust emissions are a primary source of motor vehicle emissions, besides evaporative emissions from the fueling system. The amount of emissions produced by a vehicle is a function of the number of trips and the trip length.

The nature of a trip can be characterized by the percentage of time that a vehicle spends in different operating modes. Three operating modes are considered in computing exhaust emissions, including the cold start, hot start, and hot stabilized modes. The difference between a cold start and a hot start mode is the duration of time that the engine is turned off before being restarted. When a vehicle is not affected by its start mode, it is in a hot stabilized mode. Emission rates of HC, CO and NO<sub>x</sub> are higher during cold start than during hot start and are lowest during hot stabilized operation. Differences in vehicle emissions between operating modes are caused primarily by two factors, namely: fuel/air ratio and the emission control equipment. In cold start mode, the catalytic emission control system is not fully functional until it reaches its operating temperature and more fuel can be provided to get satisfactory performance, therefore a vehicle

emits the highest HC and CO emissions and elevated NO<sub>x</sub> emission during this mode of operation.

Evaporative emissions include running losses, which occur when a vehicle operates in a hot stabilized mode; hot soak emissions, which result from fuel evaporation when an engine is still hot at the end of a trip; diurnal emissions, which result from the fuel evaporating from the gasoline tank due to the fluctuation of ambient temperature; resting losses from vapor permeating or liquid leaking; refueling losses and crankcase emissions due to defective positive crankcase ventilation valves.

Vehicle speed, acceleration, and load on the engine also have significant impact on emissions. According to estimates from the state-of-practice emission models, HC and CO emissions are highest at low-speeds, as illustrated in Figure 2-5. These emissions decrease to their minimum rates at intermediate speeds, then rise again at high speeds to levels lower than those at lower speeds. NO<sub>x</sub> emissions indicate a different trend, they rise from the lowest at a low-speed to the highest at high speeds (NRC, 1995). The smoothness and consistency of vehicle speed, which can be explained by acceleration and heavily affected by traffic conditions and driving behavior, contribute to more emissions and are not considered by the current models (MOBILE5 and EMFAC7F). Sharp acceleration at a high speed and heavy load on the engine will require more fuel to feed into the engine, thus, generate more HC and CO emissions, there is little effect on NO<sub>x</sub> emissions.

### **2.3.1.2 Driver-Related Factors**

Driver Behaviors vary greatly with different personalities and traffic conditions. For example, aggressive drives may exert sharp accelerations more frequently than their less aggressive counterparts in congested conditions. As mentioned above, sharp accelerations impose heavy loads on the engine and thus result in high emission levels.

### **2.3.1.3 Highway-Related Factors**

Highway-Related Factors are related to the physical nature of highways. These factors include geometric characteristics of a highway, including the grade, the existence of ramps and signals, and the roughness of a pavement surface. Research (Rakha *et al.*, 1999) has shown that the level of traffic signal coordination can result in up to 50 percent reduction in emissions when only through-traffic along a single direction was modeled.

### **2.3.1.4 Vehicle-Related and Other Factors**

Vehicle-Related and Other Factors also influence vehicle emission levels. It is well known that vehicle emissions levels relate to vehicle characteristics such as vehicle age, vehicle mileage, vehicle maintenance condition, vehicle weight, vehicle size, and engine power, etc. Older model vehicles usually produce more emissions than a newer vehicle fleet. For example, 1990-model vehicles emit CO at only one-third the rate of 1975-model vehicles (NRC, 1995). Generally, heavier and larger vehicles emit more pollutants than lighter and smaller vehicles.

The type of fuel used also has a significant impact on emission levels. Specifically, unleaded fuel has effectively eliminated lead as a pollutant from transportation sources. The use of reformulated and oxygenated fuel with the introduction of clean fuels programs will also help reduce vehicle emission levels.

Enhanced vehicle Inspection and Maintenance programs required by CAAA in nonattainment areas also have a positive influence on vehicle emissions.

Vehicle emission levels vary with the ambient temperature. At colder temperatures, a longer time is required to warm up the engine and the emission control systems, thus increasing the cold start emissions. At higher temperatures, evaporative emissions will increase due to the increased fuel-evaporating rate.

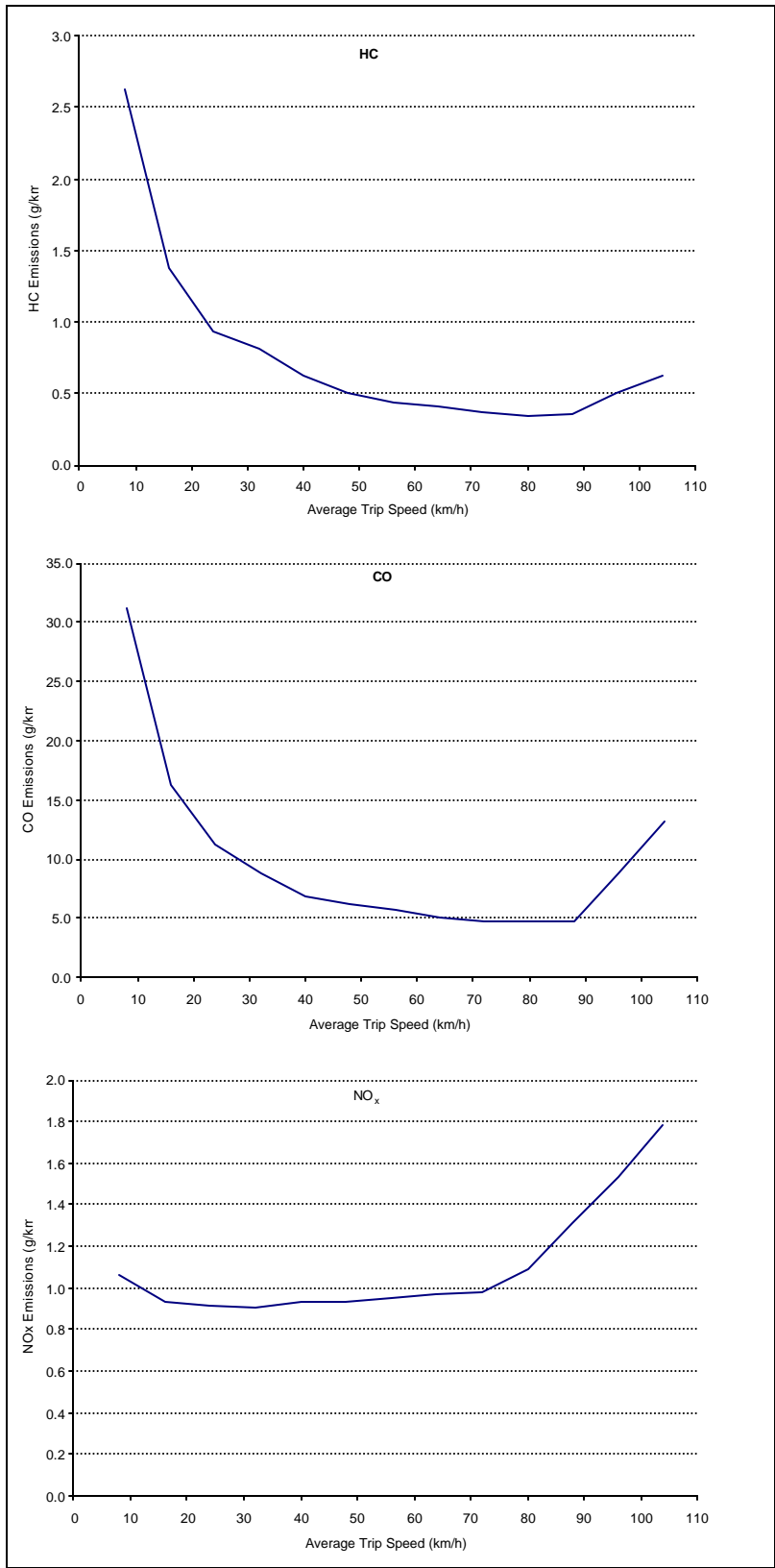


Figure 2-5. Trends of Emission Rates with Average Trip Speeds Estimated by MOBILE5a (NRC, 1995)

### ***2.3.2 State-of-the-art Vehicle Emission Models***

Most models that estimate vehicle emissions can also be fit into the same three categories as fuel consumption models, namely: (1) emission models based on average speed, such as MOBILE and EMFAC7; (2) emission models based on different vehicle modes of operation, i.e. modal emission models; and (3) emission models based on second-by-second vehicle speed profile, i.e. microscopic emission models. In addition to these three categories, a fourth category of models estimates vehicle emissions based on the fuel consumption rates along a trip. These models are termed fuel based emission models.

#### **2.3.2.1 State-of-Practice Emission Models**

The U.S. Environmental Protection Agency (EPA) only permits two models, the EPA's MOBILE model and the California Air Resources Board (CARB)'s EMFAC model, to be used in vehicle emission estimates for conformity analysis. The EMFAC model is used only in California, while all other states use the MOBILE model.

##### *Model Logic*

Both models produce composite emission factors associated with each pollutant in the model for each vehicle classification. The current version of the MOBILE model in use is the MOBILE5a, which develops composite emission factors for the three pollutants: hydrocarbons, carbon monoxide, and oxides of nitrogen. The current version of the EMFAC model in use is EMFAC7F, which produces composite emission factors for four pollutants, including total organic gases, carbon monoxide, oxides of nitrogen, and particulate matter. Each emission rate from both models is a function of the vehicle average speed, the vehicle's technology, the vehicle's age, the ambient temperature, fuel parameters, and the vehicle's operating mode (NRC, 1995).

Both models are composed of five primary components, including base emission rates, fleet characteristics, local conditions (e.g. correction factors considering the impact of temperature, operating mode and speed), fuel characteristics, and the inspection and maintenance program.

Specifically, the fleet average emission factor for a vehicle class, calendar year, pollutant, and emission producing process can be described using Equation 2-8.

$$EF_{i,j,k} = \sum_{m=1}^n F\_VMT_{i,m} * (BER_{i,j,k,m} * CF_{i,j,k,m...}) \quad (2-8)$$

Where:

$EF_{i,j,k}$  = Fleet-average emission factor for calendar year  $i$ , pollutant  $j$ , and emission producing process  $k$  (e.g. exhaust, evaporative);

$F\_VMT_{i,m}$  = Fractional VMT attributed to model year  $m$  for a calendar year  $i$  ( $n=25$  in MOBILE5, the sum of  $F\_VMT_{i,m}$  over all model years  $m$  is unity);

$BER_{i,j,k,m}$  = Base emission rate for a calendar year  $i$ , pollutant  $j$ , process  $k$ , and model year  $m$ ;

$CF_{i,j,k,m...}$  = Correction factor(s) (e.g. temperature, speed) for a calendar year  $i$ , pollutant  $j$ , process  $k$ , and model year  $m$ , etc.

The base emission rates are derived from testing data on the Federal Test Procedure (FTP) drive cycle, created in the 1960s on Los Angeles freeways and surface arterials to represent urban driving conditions. The drive cycle is composed of a cold-start phase, a hot-stabilized phase, and a hot-start phase. The speed profiles for the cold-start and hot-start phase are identical, as illustrated in Figure 2-6. The MOBILE model spreads the emissions from vehicle starts over the entire trip so that only a single emission factor in grams per mile is provided to account for both start related emissions and stabilized exhaust emissions, as expressed in Equation 2-9. Therefore, the base emission rates in MOBILE are based on the average speed of 31.6 km/h (19.6 mph), which is the average speed for an entire FTP cycle.

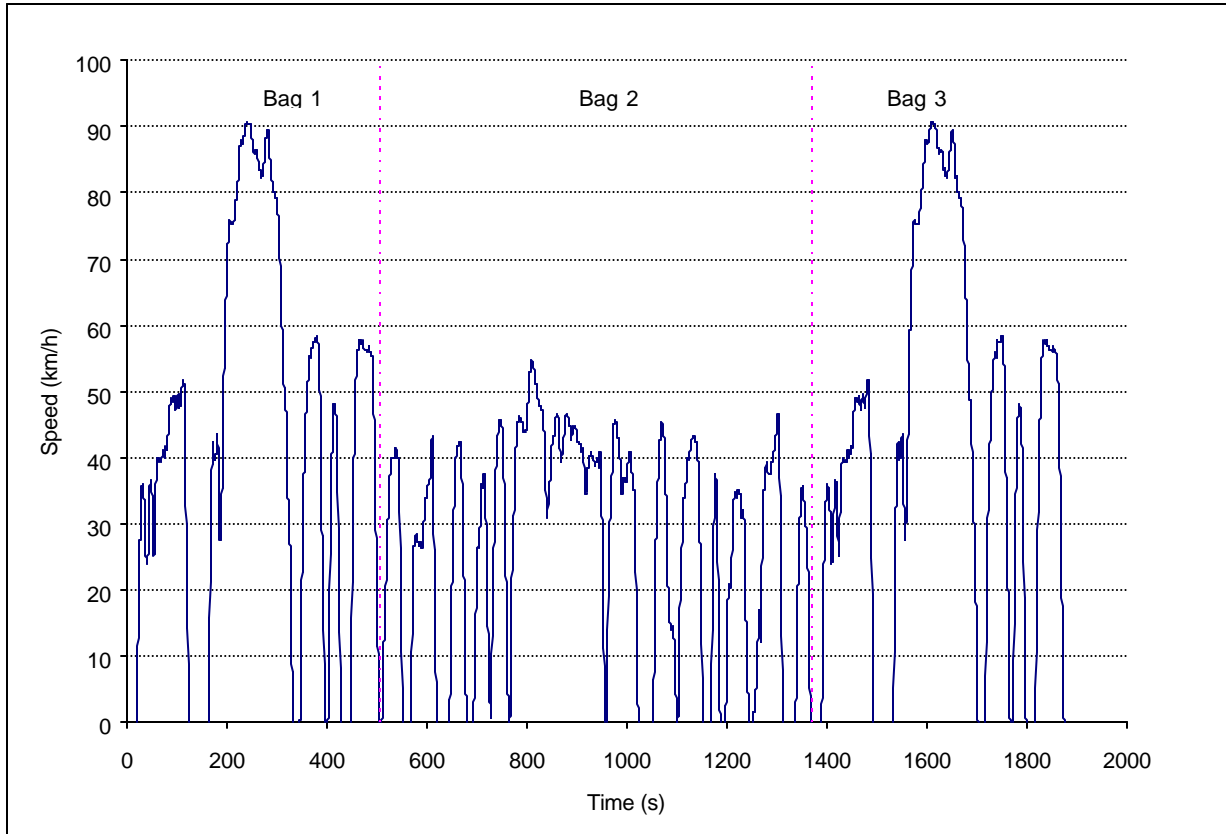


Figure 2-6. The FTP City Cycle

$$BER = \frac{3.59 * (0.43 * \text{cold start} + 0.57 * \text{hot start}) + 3.91 * \text{hot - stabilized}}{7.5} \quad (2-9)$$

$$= 0.206 * \text{cold start} + 0.273 * \text{hot start} + 0.521 * \text{hot - stabilized}$$

Where:

*Cold start* = Emissions during a cold start portion, Bag 1;

*Hot start* = Emissions during a hot start portion, Bag 3;

*Hot-stabilized* = Emissions during a hot-stabilized portion, Bag 2;

3.59 = The distance over the Bag 1/Bag 3 in miles;

3.91 = The distance over the Bag 2 in miles;

7.5 = The distance over the Bag 1/Bag 3 plus the Bag 2 in miles;

0.43 = EPA assumes that 43 percent of all vehicle starts are cold starts;

0.57 = EPA assumes that 57 percent of all vehicle starts are hot starts.

While, EMFAC7G produces separate emission factors for cold starts, hot starts, and hot-stabilized conditions. The start related emission factors represent emission increments to base

hot-stabilized emission rates. Thus, basic emission rates for EMFAC7G are based on an average speed of 25.6 km/h (16 mph), which is the average speed for the hot-stabilized phase.

Base emission rates are then converted into episodic emission factors through a series of correction factors including the average trip speed, operating mode, and temperature to represent conditions that differ from the FTP standard test. It should be noted that the speed correction factors are developed from several other driving cycles to adjust emission rates for vehicles travelling at average speeds other than the FTP baseline speed. The range of permissible average speeds in MOBILE5a is 4 km/p to 104 km/h (2.5 mph to 65 mph).

The fleet characteristic component accounts for factors relating to fleet characteristics as vehicle age distribution, the rate of mileage accumulation within each vehicle class, and the mix of travel experienced by the vehicle classes in a specific community. National average values of fleet characteristics are utilized by MOBILE as default values.

#### *b. Model Shortcoming*

The MOBILE and EMFAC models suffer from a number of shortcomings, as discussed below.

First, the standard FTP drive cycle, which MOBILE and EMFAC are derived from, was established over two decades ago to simulate the operation of a typical in-use urban vehicle. However, it did not include vehicle operation that consists of speeds in excess of 91.2 km/h (57 mph) and acceleration rates above 5.3 km/h/s (3.3 mph/s), which are common events in today's traffic operation. For example, an analysis of data from vehicles driven in the Baltimore found that approximately 18 percent of the trips was composed of higher speeds and sharper accelerations than those represented in the FTP cycle (NRC, 1995).

Second, the base emission rates developed in the MOBILE and EMFAC models are solely based on average vehicle speeds. However, it is well known that two vehicle trips with the same average speed can have different speed profiles consisting of dramatically different modal characteristics (speed-acceleration combinations), and thus different emissions results.

Third, speed correction factors (SCFs) have been incorporated in the models to adjust emission rates for average speeds that differ from that of the FTP cycle. However, the SCFs are derived from a limited set of transient tests (non steady-speed tests), and based on the assumption that averages in the skewed distribution representing the range of emissions at measured speeds can be validly combined to yield emissions factors for the non-measured average speeds (Barth *et al.*, 1999). At a given speed, vehicle emissions may vary significantly with other factors, for example, the occurrence of a high acceleration. Thus, variations about a given average speed will greatly affect vehicle emission levels associated with this average speed. Running a limited set of tests and scaling them to construct the SCF curves may not accurately reflect the real-world driving conditions.

Forth, due to the inherent "average" nature in the models, they offer little help for evaluating traffic operational improvements that are more microscale in nature. Therefore, the MOBILE and EMFAC models are insufficient to assess the impacts that result from the applications of intelligent transportation system technologies, transportation control devices, and other traffic flow improvement strategies.

### **2.3.2.2 MOBILE6**

MOBILE6 is the successive version of MOBILE5 and was released in 2000 (incomplete). MOBILE6 incorporates updated base emission rates, off-cycle ("real world") driving patterns and emissions, separation of start and running emissions, improved correction factors, and updated fleet information (EPA, 1999).

MOBILE6 is being developed to account for the impacts of driving behaviors not represented by the FTP cycle, the impacts of newer vehicles being certified using the Supplemental FTP (SFTP), and the impacts of air conditioning on emissions. Inclusion of off-cycle driving patterns in MOBILE6, which include vehicle operations at higher speeds and higher acceleration rates, will result in a significant increase for all pollutants in comparison with MOBILE5 estimates.

Four facility types are considered in the MOBILE6 model, namely: freeways, arterial/collectors, local roadways, and freeway ramps. Base emission factors can be adjusted, based on vehicle testing over a series of facility cycles, for different facility types, different average speeds (only for arterials and freeway), and the level of driver aggressiveness. Area-wide emission factors for each pollutants and vehicle type can be calculated as a weighted sum of the four facility-specific emission factors.

Unlike single average emission factors for a trip, MOBILE6 produces emission factors for the start portion and the running portion of the trip. Running emission factors continue to be represented in terms of grams per mile, and are based only on hot stabilized operating conditions. Start emissions account for the additional emissions that result from a vehicle start. The previous distinction between "cold starts" and "hot starts" is replaced by the distribution of soak time preceding engine restarts, and these start emissions can then be allocated to specific locations within an area and specific times of day.

By employing a daily minimum and maximum temperature or the distribution of temperature over a 24-hour period, MOBILE6 is able to provide both daily average emission factors similar to MOBILE5 and hourly emission factors for each hour of the day.

In addition to the previously indicated enhancements, MOBILE6 incorporates other enhancements, including: an update of fuel effects on emissions, a use of diurnal evaporative emissions based on real-time diurnal testing, an update of hot soak evaporative emission factors, an update of heavy-duty engine emission conversion factors, an update fleet characterization data, and a provision of distinct emission factor calculations for a wider range of vehicle categories, etc.

MOBILE6 overcomes some shortcomings in the MOBILE5 model to a certain extent, for example, it considers vehicle operations with higher speeds and higher accelerations to reflect real-world conditions more accurately than before. The model also includes the application of different driving cycle correction factors associated with facility types. In addition, MOBILE6 provides the ability to allocate emissions spatially and temporally. However, it is still unclear

whether MOBILE6 will give users better results in terms of efficiency and cost when compared to MOBILE5, because more efforts are required to collect input data. It should be noted, however that MOBILE6 still uses the average speed as the sole explanatory variable for estimating vehicle emissions.

### **2.3.2.3 Modal Emission Estimate Models**

Modal emission estimate models attempt to establish the relationship between vehicle emissions and vehicle operating modes (i.e. cruise, acceleration, deceleration and idling).

#### *a. Georgia Tech Models*

For the past five years, the Georgia Tech Research Partnership has been developing a GIS (geographic information system)-based modal emission model (Bachman *et al.*, 1996; Wolf *et al.*, 1998; Fomunung *et al.*, 1999), named MEASURE (Mobile Emissions Assessment System for Urban and Regional Evaluation). Two different modal approaches developed at the Georgia Tech are included in the model to predict vehicle emissions during hot-stabilized conditions as a function of the conditions under which the vehicles are operating. One is an aggregate modal model based on statistical analysis of historical laboratory data and the other is a load-based prediction module based upon analysis of instrumented vehicle data (Fomunung *et al.*, 1999).

The aggregate modal model within the MEASURE model is derived from laboratory data collected by the EPA and CARB using standardized test cycles and alternative driving cycles. It predicts emissions from light-duty vehicles as a function of vehicle's operating mode (including cruise, acceleration, deceleration, idle and the power demand conditions that lead to enrichment), taking into account the interaction between vehicle technology characteristics and vehicle operating modes. The Emission rates are estimated based on theoretical engine-emission relationships, which are dependent on both modal and vehicle technology variables. Modal activities are derived from aggregate measures of a vehicle speed and acceleration profile, and include average speed, acceleration rates, deceleration rates, idle times, and surrogates for the power demand imposed on an engine (speed \*acceleration). Vehicle technology variables

include the fuel metering system, the catalytic converter type, the availability of supplemental air injection, and the transmission speed (Fomunung *et al.*, 1999).

The algorithms of the model are presented below. First, the model estimates the ratio of vehicle emission rate per unit time driven on a given cycle (or equivalently across a specified speed/acceleration matrix) to the emission rate obtained from the FTP Bag 2. The equations for computing the ratios for HC, CO and NO<sub>x</sub> emissions are tabulated in Table 2-1. Second, the emission rate for each pollutant is computed using Equation 2-10.

$$MOE_i = R_i * A_{iBag2} \quad (2-10)$$

Where:

$MOE_i$  = Emission rate of  $i$  ( $i$  represents HC, CO or NO<sub>x</sub>), g/sec;

$R_i$  = Ratio for emission  $i$  (calculated as equations shown in Table 2-1);

$A_{iBag2}$  = The observed FTP Bag 2 rate for emission  $i$  for a given vehicle.

#### *b. University of California, Riverside Models*

The University of California, Riverside (Barth *et al.*, 1996; An *et al.*, 1997) developed modal emission models for light-duty cars and trucks based on data collected from 300 in-use vehicles tested under a variety of laboratory drive cycles. The model is based on a simple parameterized physical approach that breaks the entire emission process into components corresponding to the physical phenomena associated with vehicle operation and emission production. The model consists of six modules that predict engine power, engine speed, air-to-fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction, as indicated by the rectangular boxes in Figure 2-7. The model as a whole only requires two groups of inputs, which are operating variables (i.e. speed, acceleration, vehicle mass, and road grade) and model parameters. The model then outputs tailpipe emissions and fuel consumption.

Four vehicle-operating conditions are considered in the model, as indicated in Figure 2-7 by the oval boxes: cold start operation, stoichiometric operation, high-power enrichment operation, and enleanment operation. Hot-stabilized vehicle operation includes conditions b through d. The

model determines the condition in which a vehicle is operating at a given moment by comparing the vehicle power demand with predefined power demand thresholds. But the model does not inherently determine when a cold start occurs, rather, the user should specify any cold start. However, the model is able to determine when the operating condition switches from cold start to stoichiometric operation.

Table 2-1. Equations for Estimating Ratios for HC, CO, and NO<sub>x</sub> Emissions

<b>Log(R<sub>CO</sub>)</b> =0.0809+0.002*SPD+0.0461*ACC_3+0.0165*IPS_60-0.0283*ips45sar2+0.3778*ips90tran1-0.0055*tran3idle+0.1345*tran5km1+0.3966*finj3sar3-0.0887*cat3tran1-0.2636*sar3tran4-0.4818flagco	
Variables	Description
SPD	Average speed of the driving cycle in mph
ACC_3	Proportion of the driving cycle on acceleration greater than 3mph/sec
IPS_X	Proportion of the driving cycle on inertial power surrogate (IPS) (speed*acceleration) greater than X mph <sup>2</sup> /sec. IPS_60 implies IPS greater than 60 mph <sup>2</sup> /sec.
ips45sar2	Interaction between IPS_45 and a vehicle with no air injection
ips90tran1	Interaction variable for a vehicle with automatic transmission on IPS_90
cat3idle	Interaction variable for a 3-speed manual transmission at idle
Tran5km1	Interaction variable for a 5-speed manual transmission vehicle with mileage<=25 k miles
Finj3sar3	Interaction variable for a vehicle that has throttle body fuel injection and pump air injection
cat3tran1	Interaction variable for a vehicle with automatic transmission and TWC
Sar3tran4	Interaction variable for a vehicle with 4-speed manual transmission and pump air injection
flagco	Flag used to tag a high emitting vehicle under CO emissions
<b>Log(R<sub>HC</sub>)</b> =0.0451-0.6707*my79-0.1356*my82+0.0019*SPD+0.2021*finj2tran4+0.1795*cat2sar1+0.1651*cat3sar2-0.1189*sar3tran1+0.5646*sar1tran5+0.0004*cid-0.2581*sar3km1-0.0169*finj2km3-0.5144*flaghc-0.0129*acc1finj2-0.1626*acc3cat2-0.3891*ips90sar3+0.03078dps8finj2	
Variables	Description
my79	Model year<79
my82	79<Model year<82
finj2tran4	Interaction variable for a 4-speed manual transmission vehicle with a carburetor
cat2sar1	Variable for a pre 1981 model year vehicle with 'oxidation only' catalyst and of unspecified air injection type
cat3sar1	Variable for a pre 1981 model year vehicle with a TWC and of unspecified air injection type
cat3sar2	Variable for a vehicle with TWC and no air injection
sar3tran1	Automatic transmission vehicle with pump air injection
sar1tran5	A pre 1981 model year, 5-speed manual transmission vehicle of unspecified air injection type
cid	Cubic inch displacement
sar3km1	A vehicle with pump air injection and mileage<=25k miles
finj2km3	A vehicle with pump air injection and 50k<mileage<=100k miles
flaghc	High emitting vehicle flag under HC emission
acc1finj2	A carburetor-equipped vehicle operating with acceleration greater than 1 mph/sec
acc3cat2	An 'oxidation only' catalyst vehicle on ACC_3
ips90sar3	A vehicle with air pump on IPS_90
dps8finj2	Proportion of drag power surrogate (DPS) (speed <sup>2</sup> *acceleration) greater than 8 mph <sup>3</sup> /sec
<b>Log(R<sub>NOx</sub>)</b> =-0.5864+0.0225*SPD+0.3424*IPS_120+0.6329*ACC_6+0.0247*DEC_2+0.0083*finj2km1+0.0028finj2km2-0.0021*cat2km3+0.0026*cat3km2+0.0003*cat3km3-0.0085*finj1km3flagnox-0.0068*finj3km3flagno	
Variables	Description
ACC_6	Proportion of acceleration >6 mph/sec
DEC_2	Proportion of deceleration >2 mph/sec
finj2km1	A carburetor equipped vehicle with mileage<25k miles
finj2km2	A carburetor equipped vehicle with 25k<mileage<=50k miles
cat2km2	An 'oxidation only' catalyst vehicle with 50k<mileage<=100 miles
cat3km2	A TWC vehicle with 25k<mileage<=50k mileage
cat3km3	A TWC vehicle with 50k<mileage<=100k mileage
Finj1km3f lagnox	Second order interaction variable for a high emitting vehicle with port fuel injection and 50k<mileage<=100 miles
Finj3km3f lagnox	Second order interaction variable for a high emitting vehicle with throttle body fuel injection and 50k<mileage<=100 miles

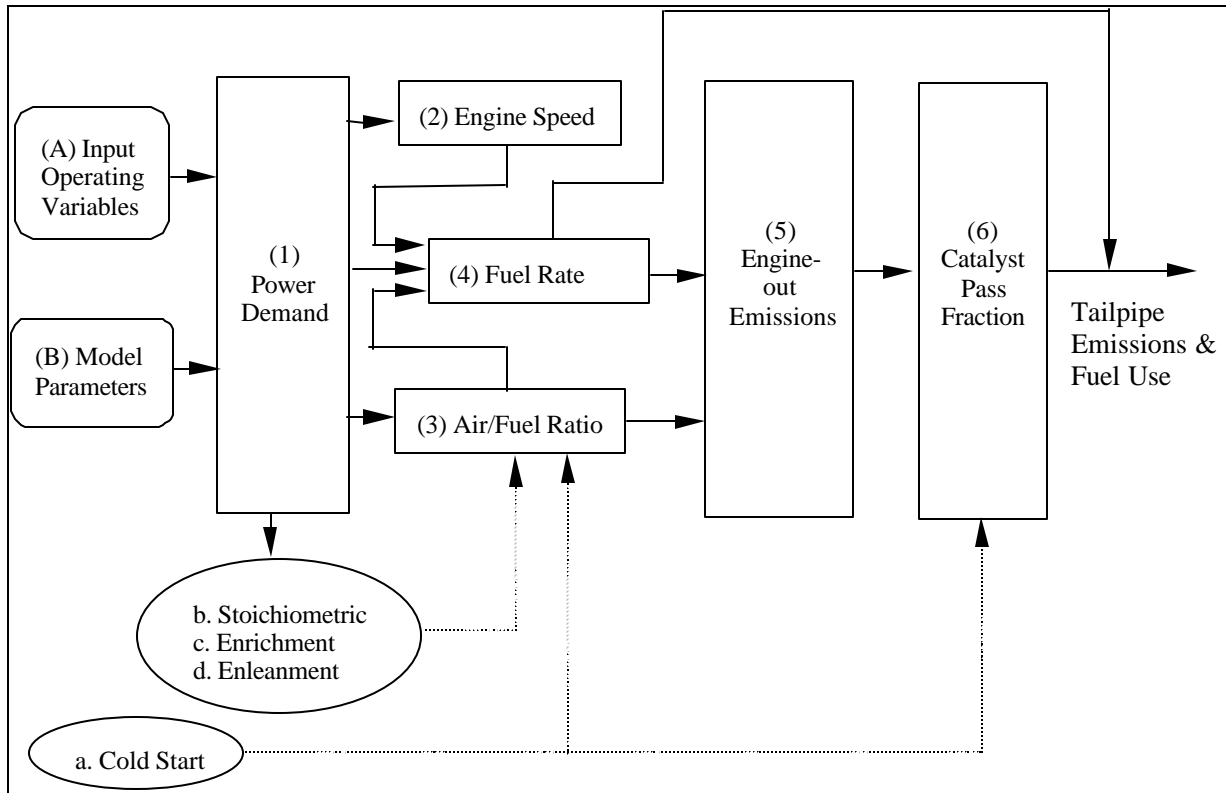


Figure 2-7. Modal Emissions Model Architecture (An et al., 1997)

The vehicle power demand is determined as a function of operating variables (i.e. vehicle acceleration and speed), specific vehicle parameters (e.g. vehicle mass, transmission efficiency, effects of accessories), and road conditions (i.e. the road gradient). The engine speed is determined by vehicle speed, gear shift schedule, and power demand. The air/fuel ratio is determined as a function of the power demand and is modeled separately in each of the four operating conditions. The fuel rate is calculated as a function of the power demand, engine speed, and air/fuel ratio. Engine-out emissions are estimated solely as a function of the fuel rate and air/fuel ratio, given a vehicle's characteristics. The catalyst pass fractions defined as the ratio of tailpipe emissions to engine-out emissions should be modeled separately for hot-stabilized operating conditions and cold start conditions. Under hot-stabilized operating conditions, the catalyst pass fractions are assumed to be a function of engine-out emission rates and air/fuel ratios alone. As a result, vehicle tailpipe emissions can be modeled as the product of fuel consumption, engine-out emissions, and catalyst pass fraction, as expressed in Equation 2-11.

$$Emission_{tailpipe} = FR * g_{engine\_out} * CPF \quad (2-11)$$

Where:

$Emission_{tailpipe}$  = Tailpipe emission in grams/sec;

$FR$  = Fuel-use rate in grams/sec;

$g_{engine\_out}$  = Grams of engine-out emissions per gram of fuel consumed;

$CPF$  = The catalyst pass fraction, defined as the ratio of tailpipe emissions to engine-out emissions

### c. Virginia Tech Models

Using the methodology that was describe for the modal fuel consumption models, Dion *et al.* (1999, 2000) developed modal emission models for light duty gasoline vehicles under hot-stabilized conditions. These models require as input the average trip speed, the number of vehicle stops, and the duration of stopped delay. As indicated in Table 2-2, the emission rates that were predicted by the model for the EPA urban and highway drive cycles are consistent with the rates estimated by the microscopic model that was used to develop the model, as well as rates predicted by MOBILE5a,

Table 2-2. MOBILE5, Mesoscopic and Microscopic Emissions Comparison (Dion *et al.*, 2000)

Model		FTP City Cycle			Highway Cycle		
		HC (g/km)	CO (g/km)	NO <sub>x</sub> (g/km)	HC (g/km)	CO (g/km)	NO <sub>x</sub> (g/km)
Mobile5		0.096	1.930	0.249	0.045	0.643	0.269
Microscopic Model	Minimum	0.054	0.444	0.130	0.048	0.410	0.095
	Composite	0.140	1.714	0.308	0.114	2.006	0.274
	Maximum	0.368	8.582	0.492	0.332	9.125	0.455
Mesoscopic Model	Minimum	0.035	0.173	0.125	0.046	0.372	0.093
	Composite	0.116	1.578	0.235	0.107	2.047	0.262
	Maximum	0.321	6.843	0.418	0.346	9.432	0.468

#### 2.3.2.4 Instantaneous Emission Models

Ahn *et al.* and Rakha *et al.* (1999) also developed microscopic vehicle emission models using the methodology and data that were described in the development of microscopic fuel consumption model. The general form of equation for these emission models is the same as Equation 2-4, except that the dependent variable is the emission rate rather than the fuel consumption rate. The

data description and Equation 2-4 can be found in the section 2.2.2.1. The models estimate emissions to within 3-33 percent of actual instantaneous measurements with correlation coefficients ranging from 0.94 to 0.99. As illustrated in Figure 1-2, the models follow closely the trends of each emission observed in the ORNL data. Furthermore, it is indicated in Figure 1-2 that HC and CO emissions are sensitive to vehicle speed and acceleration levels in a non-linear fashion, and are highly dependent on the vehicle 's level of acceleration, especially at high speeds.

### 2.3.2.5 Fuel-Based Emission Models

A fuel-based methodology for calculating motor vehicle emission inventories was developed by Singer and Harley (1999). In this method, emission factors were normalized against fuel consumption rates and expressed as grams of emissions per gallon of gasoline burned. Using a carbon balance, emission factor for pollutant "p" can be computed using Equation 2-12.

$$E_p = \left( \frac{[p]}{[CO_2] + [CO] + [HC]} \right) * \frac{w_c \mathbf{r}_f M_p}{12} \quad (2-12)$$

Where:

$E_p$  = Emission rate of pollutant p in unit of grams per gallon of fuel consumed;

[p] = Exhaust concentration of pollutant p;

$w_c$  = Carbon weight fraction of the fuel;

$\mathbf{r}_f$  = Fuel density;

$M_p$  = Molecular weight of p

In this model, the vehicle activity is measured by the fuel consumed rather than by the miles traveled. Average emission factors for each subgroup of vehicles are weighted by the fraction of total fuel used by each vehicle subgroup to obtain an overall fleet-average emission factor. A major advantage of this approach is that fuel-based emission factors vary much less than travel-based emission factors as drive mode changes. The authors suggest that fuel-based emission factors be calculated from on-road emission measurements such as those from remote sensors

and that precise fuel use data be obtained from state tax records. However, these data are difficult to attain and do require fairly expensive data collection technology.

## **2.4 Summary of Findings**

A review of the current state-of-the-art in vehicle energy and emission modeling demonstrates considerable research efforts in this arena. These research efforts have resulted in the development of several types of energy and emission models, including macroscopic, mesoscopic, and microscopic models.

These models attempt to capture the impact of a number of factors on vehicle emissions, including travel-related, driver-related, highway-related, and vehicle-related factors. While the macroscopic models attempt to capture all factors, they use average speed as the sole explanatory variable of travel and drive-related factors. Mesoscopic models, on the other hand, assume an average driver behavior in estimating vehicle emissions. Alternatively, microscopic models attempt to capture instantaneous changes in travel and driver-related factors in estimating emissions.

While the literature provides significant information on the various modeling approaches, it does demonstrate a void in terms of quantifying the impact of the above mentioned assumptions on the accuracy of these models. The objective of this research effort is to systematically quantify the impact of travel and driver-related factors on vehicle fuel consumption and emission levels.

## **CHAPTER 3 : IMPACT OF STOPS ON VEHICLE FUEL CONSUMPTION AND EMISSION RATES**

As was demonstrated in Chapter 2, there is a need to systematically quantify the impact of various traffic-related and driver-related factors on vehicle fuel consumption and emission rates. Consequently, this chapter quantifies the impact of vehicle stops on vehicle fuel consumption and emission rates. Given that a vehicle stop involves a deceleration from a cruising speed followed by a subsequent acceleration back to the cruising speed, this chapter investigates the impact of different levels of deceleration and acceleration on vehicle fuel consumption and emissions.

In addressing these objectives, this chapter first quantifies the impact of different levels of cruise speed on vehicle fuel consumption and emission rates in order to establish a base case for the subsequent analysis of vehicle stops. In quantifying the impact of vehicle stops on fuel consumption and emission rates, typical deceleration and acceleration rates are first established using second-by-second speed measurements that were collected using floating cars driven along a signalized arterial in Phoenix. These typical acceleration and deceleration levels are then utilized to construct simple single-stop drive cycles for purposes of this study. In conducting this study vehicle fuel consumption and emissions are computed based on instantaneous speed measurements using microscopic fuel consumption and emission models that were described in Chapter 2 (Ahn *et al.*, 1999). These models are representative of a typical average vehicle in the United States.

### **3.1 Impact of Cruise Speed on Vehicle Fuel Consumption and Emissions**

A first step in characterizing the impact of various traffic and driver-related factors on vehicle fuel consumption and emissions is to characterize the impact of different levels of cruise speed on these MOEs. In conducting this analysis, a sequence of constant speed trips is executed over a 4.5-km section. Vehicle fuel consumption and emissions are estimated for the entire trip using microscopic fuel consumption and emission models.

The analysis demonstrates that the fuel consumption rate per unit distance exhibits a convex function, as illustrated in Figure 3-1. Specifically, the fuel consumption rate is highest for low speeds and decreases as the cruise speed increases achieving its minimum at a speed of approximately 80 km/h before increasing again. The function also demonstrates that vehicle fuel consumption is highest for low cruise speeds. Similarly, the HC emission rates follow a convex function, however, the emission rates are highest for high cruise speeds, as illustrated in Figure 3-2. Specifically, the minimum HC emission rate of 0.08 g/km is attained at a speed of 55 km/h with the highest emission rate occurring at a cruise speed of 120 km/h. Figure 3-3 and Figure 3-4 illustrate similar trends in variation of vehicle CO and NO<sub>x</sub> emissions, respectively. Specifically, both minimum emission rates are achieved at a cruise speed of 20 km/h with maximum rates achieved at a cruise speed of 120 km/h.

In conclusion, the analysis indicates that the fuel consumption rate varies from a minimum of 0.09 l/km to a maximum of 0.25 l/km as a function of a vehicle's cruise speed. This variation constitutes a difference in the range of 300 percent. Similarly, the HC emission rate ranges from 0.08 g/km to 0.25 g/km while the CO emission rate varies considerably from a rate of 1.2 g/km to a rate of 5.9 g/km, as illustrated in Figure 3-3. This variation in CO constitutes a difference in the range of 600 percent. Finally, the NO<sub>x</sub> emission rate varies in the range of 0.13 g/km to 0.44 g/km, which corresponds to a variation in the range of 350 percent.

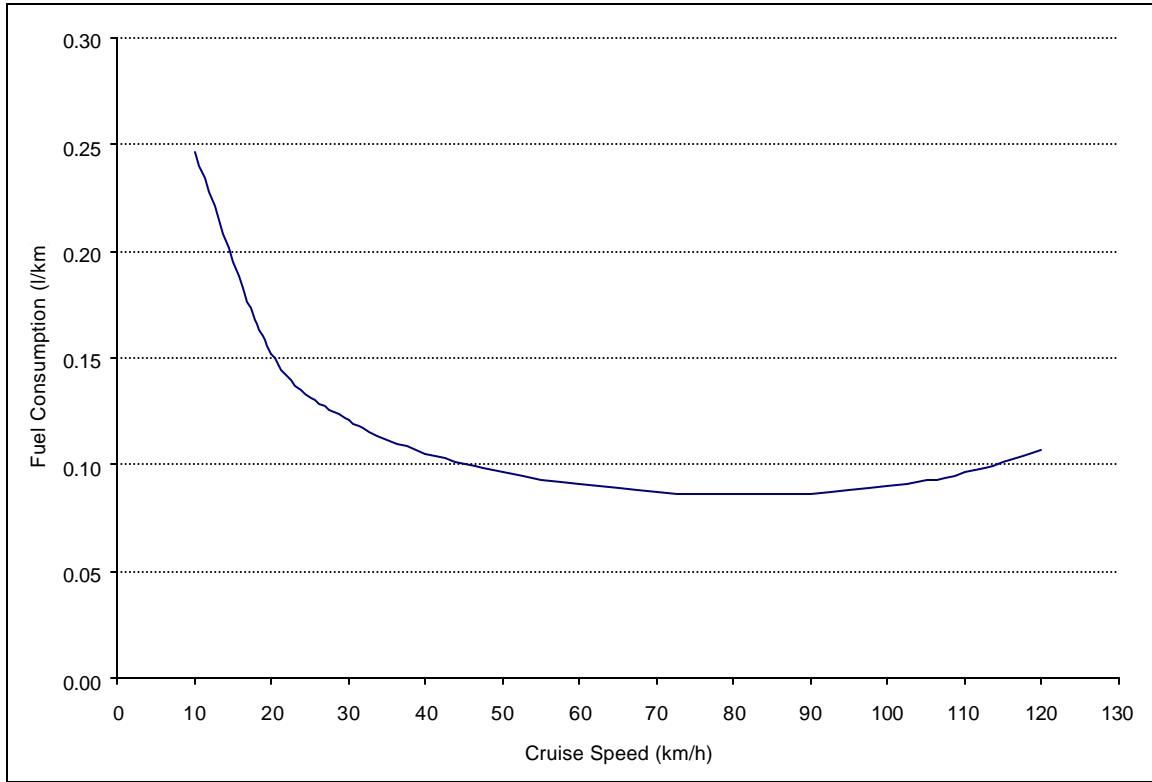


Figure 3-1. Variation in Vehicle Fuel Consumption Rates as a Function of Cruise Speed

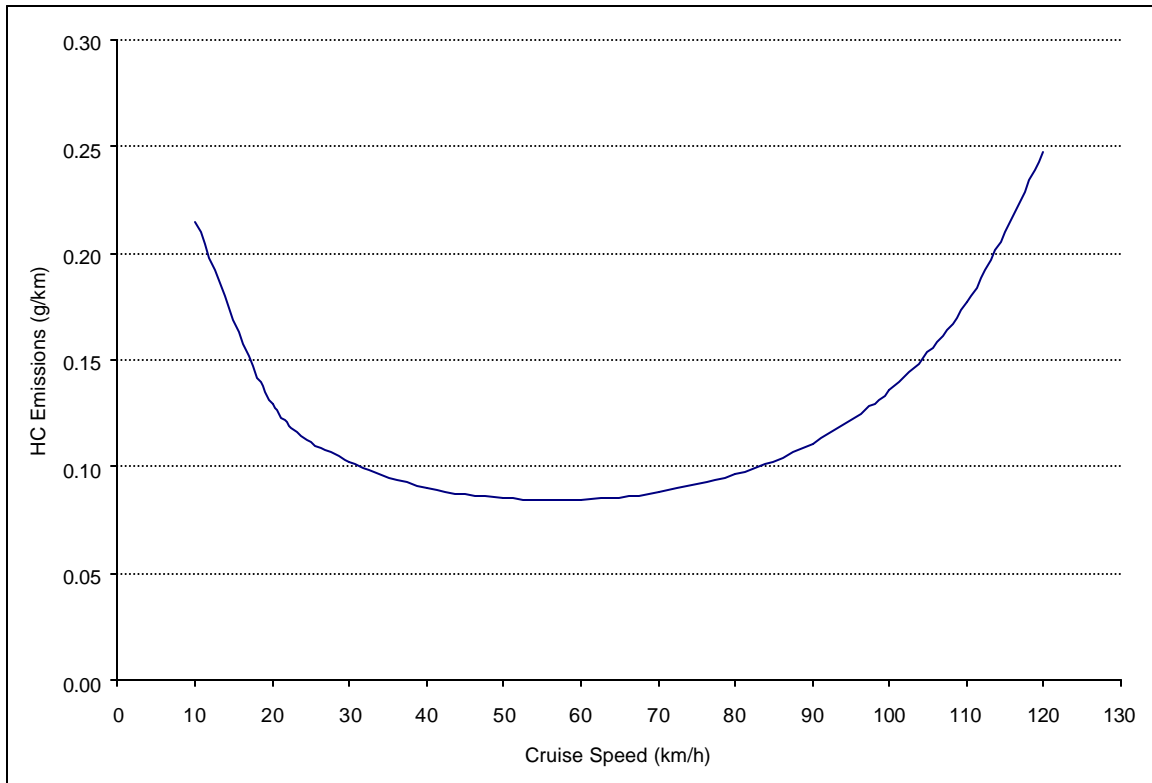


Figure 3-2. Variation in Vehicle HC Emission Rate as a Function of Cruise Speed

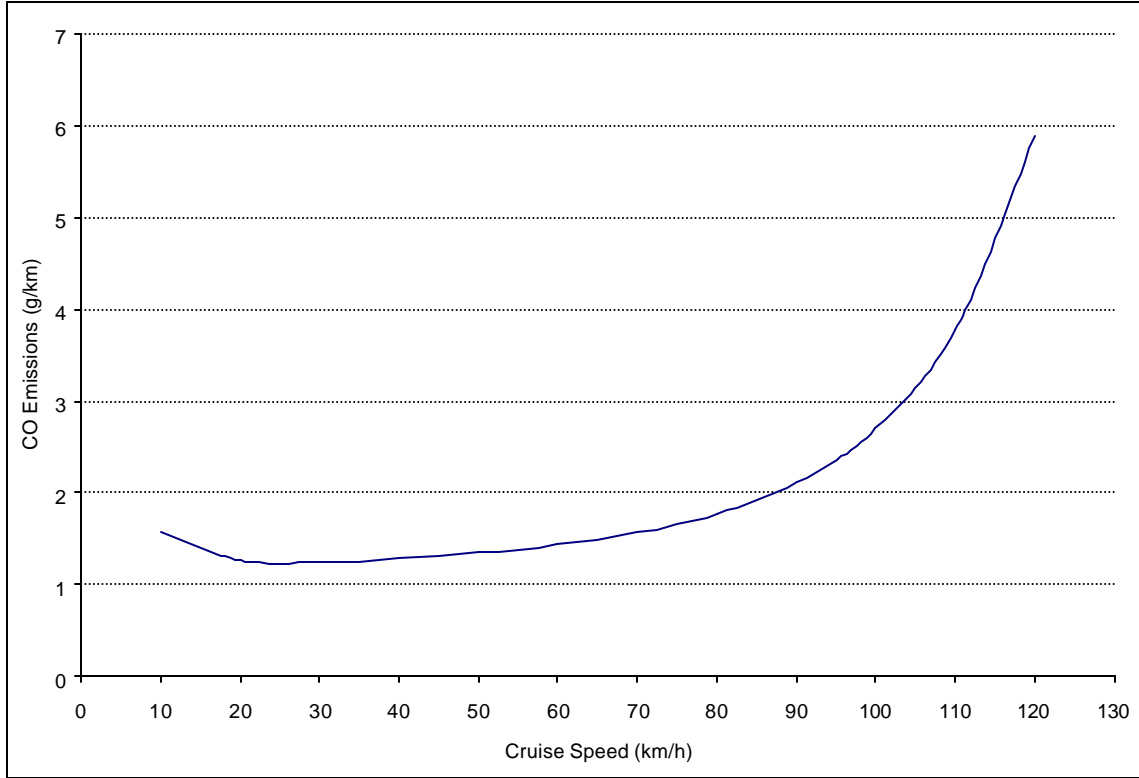


Figure 3-3. Variation in Vehicle CO Emission Rate as a Function of Cruise Speed

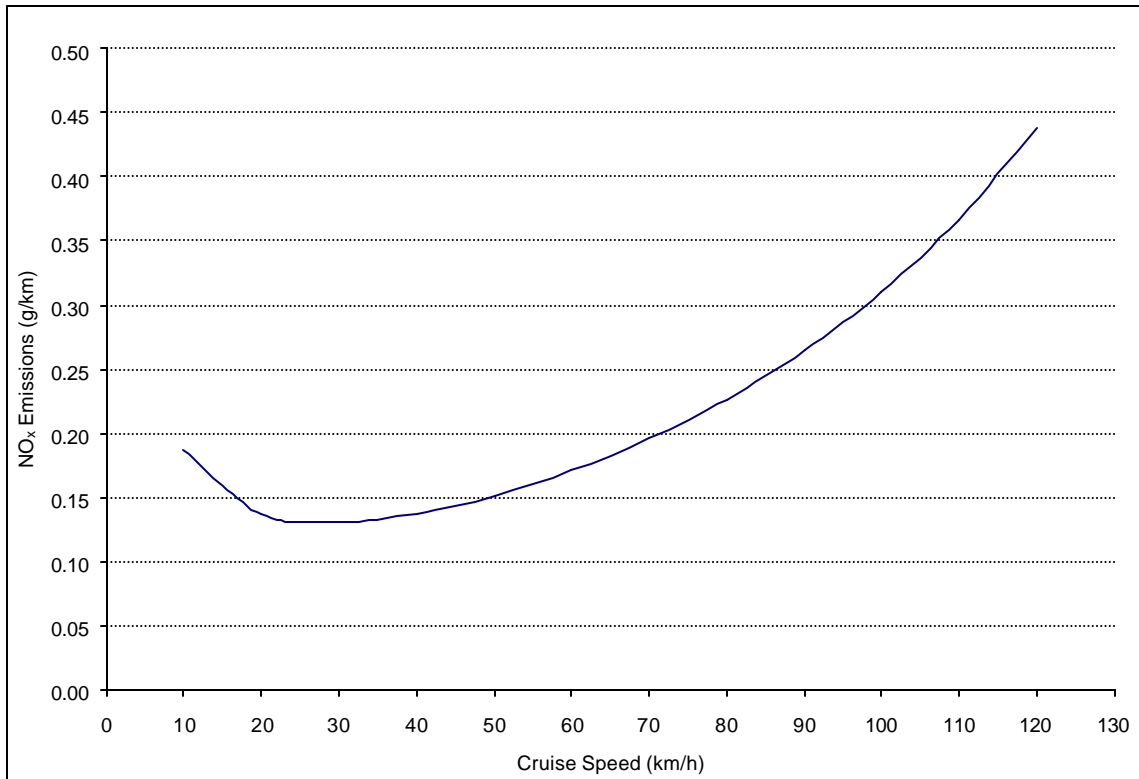


Figure 3-4. Variation in Vehicle NO<sub>x</sub> Emission Rate as a Function of Cruise Speed

## 3.2 Characterization of Typical Vehicle Acceleration and Deceleration Behavior

In order to quantify the impact of vehicle stops on fuel consumption and emission rates, a number of simplistic single-stop drive cycles were constructed. A first step in developing these drive cycles is to characterize typical vehicle acceleration and deceleration behaviors. This characterization ensures consistency between these hypothetical drive cycles and field observations.

The acceleration/deceleration characterization utilized data that were collected along a signalized arterial corridor in Phoenix using GPS-equipped vehicles (Rakha *et al.*, 2000). These vehicles were driven along the study corridor for three days (Tuesday through Thursday) before and after changes were made to the signal timings along the corridor during the AM peak (7am-8am), the off-peak (11am-1pm), and the PM peak (4pm-6pm). A total of 301 trips was recorded over the 9.6-kilometer study section. The GPS unit measured the vehicle's location, its heading, and its speed every second. Subsequently, acceleration was computed based on the second-by-second speed measurements. Because of errors in the speed measurements, the acceleration estimates resulted in occasional unrealistic observations, which exceeded the maximum feasible acceleration that a vehicle can attain at a specific speed (Rakha *et al.*, 1999). Consequently, a robust form of acceleration smoothing was applied to the acceleration estimates, which in turn resulted in more realistic speed estimates (Rakha *et al.*, 2000).

The distribution of speed and acceleration estimates for the entire 301 trips are summarized in Table 3-1. As demonstrated in Table 3-1, the majority of observations experienced longitudinal accelerations that ranged from  $-0.25 \text{ m/s}^2$  to  $+0.25 \text{ m/s}^2$  ( $0 \text{ m/s}^2$  acceleration bin). Furthermore, the table demonstrates a maximum feasible acceleration in the  $1.5 \text{ m/s}^2$  bin and a minimum deceleration in the  $-2.5 \text{ m/s}^2$  bin. Assuming a constant vehicle power it can be demonstrated that the maximum feasible acceleration decreases as a function of the vehicle's speed. Consequently, acceleration levels are quoted as a fraction of the maximum feasible acceleration for the remainder of the thesis. The GPS data indicates that acceleration levels ranged from 0 up to 60 percent of the maximum feasible acceleration level, as illustrated in Figure 3-5. Deceleration

levels were found to range of 0 to  $-3 \text{ m/s}^2$  with the majority of observations in the range from 0 to  $-0.5 \text{ m/s}^2$ . Using the GPS data, the mean acceleration rate was estimated to be 19 percent of the maximum feasible acceleration and the mean deceleration rate was computed to be  $-0.52 \text{ m/s}^2$ , as summarized in Table 3-2. Consequently, in constructing the single-stop drive cycles an acceleration rate of 20 percent the maximum feasible acceleration rate and a deceleration rate of  $-0.5 \text{ m/s}^2$  were utilized.

Table 3-1. Speed/Acceleration Distribution for GPS Arterial Data

a. Number of Observations												
		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration ( $\text{m/s}^2$ )	-3.0											
	-2.5	40	159	240	278	228	168	63	3			1179
	-2.0	72	209	322	362	294	186	56	10			1511
	-1.5	291	655	765	775	737	509	182	29			3943
	-1.0	1108	828	780	828	1090	1209	703	138	3		6687
	-0.5	2887	775	650	925	1844	4383	6224	1736	72		19496
	0.0	24218	689	782	1426	3434	12819	31216	8831	226	1	83642
	0.5	2281	320	554	1319	2704	5284	5063	958	18		18501
	1.0	501	282	745	1677	2257	1628	610				7700
	1.5	1841	2093	1688								5622
2.0												
Total		33239	6010	6526	8357	12704	26186	44117	11768	322	2	149231
b. Percentage of Total Observations												
		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration ( $\text{m/s}^2$ )	-3.0											
	-2.5	0.03	0.11	0.16	0.19	0.15	0.11	0.04	0.00			0.80
	-2.0	0.05	0.14	0.22	0.24	0.20	0.12	0.04	0.01			1.02
	-1.5	0.19	0.44	0.51	0.52	0.49	0.34	0.12	0.02			2.65
	-1.0	0.74	0.55	0.52	0.55	0.73	0.81	0.47	0.09	0.00		4.49
	-0.5	1.93	0.52	0.44	0.62	1.24	2.94	4.17	1.16	0.05		13.07
	0.0	16.23	0.46	0.52	0.96	2.30	8.59	20.92	5.92	0.15	0.00	56.05
	0.5	1.53	0.21	0.37	0.88	1.81	3.54	3.39	0.64	0.01		12.40
	1.0	0.34	0.19	0.50	1.12	1.51	1.09	0.41				5.16
	1.5	1.23	1.40	1.13								3.77
2.0												
Total		22.28	4.03	4.38	5.09	8.44	17.55	29.57	7.85	0.22	0.01	100.00

Table 3-2. Summary of the Acceleration and Deceleration GPS Data

a. Acceleration Distribution										
	Proportion of Maximum Feasible Acceleration									
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
No. of Observations	28462	14597	6431	3484	7468	4668	0	0	0	0
% of Total Observations	0.44	0.22	0.10	0.05	0.11	0.07	0.00	0.00	0.00	0.00
Cumulative Percentage	0.44	0.66	0.76	0.81	0.93	1.00	1.00	1.00	1.00	1.00
Mean Value ( $a_{max}$ )	<b>0.19</b>									

b. Deceleration Distribution						
	Deceleration ( $m/s^2$ )					
	-2.75	-2.25	-1.75	-1.25	-0.75	-0.25
No. of Observations	840	866	2618	5232	9780	46935
% of Total Observations	0.01	0.01	0.04	0.08	0.15	0.71
Cumulative Percentage	0.01	0.03	0.07	0.14	0.29	1.00
Mean Value ( $m/s^2$ )	<b>-0.52</b>					

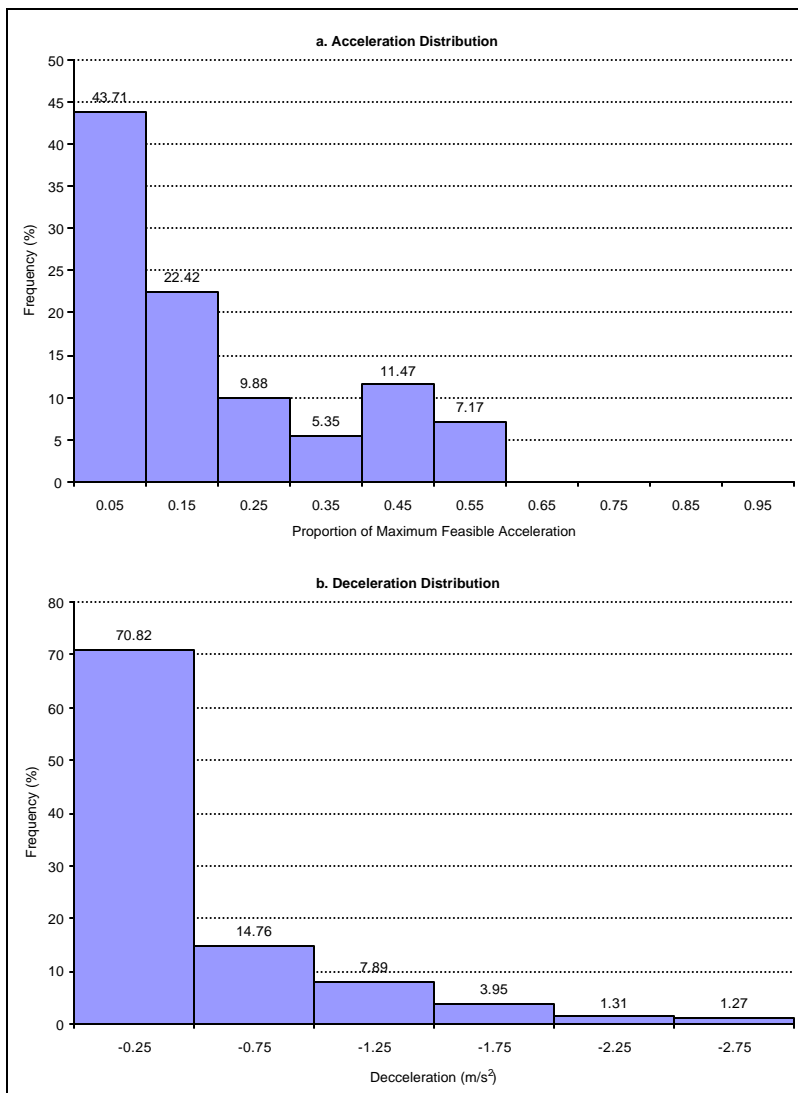


Figure 3-5. Acceleration and Deceleration Distribution for GPS Arterial Data

### 3.3 Impact of Full Stops on Vehicle Fuel Consumption and Emissions

In quantifying the impact of vehicle stops on fuel consumption and emission rates, a single stop is introduced into the sequence of constant speed trips. An acceleration rate of 20 percent the maximum feasible acceleration ( $0.2a_{max}$ ) and a deceleration rate of  $-0.5 \text{ m/s}^2$  are utilized in constructing these vehicle stops. The speed profiles as a function of time and distance for the constructed drive cycles are illustrated in Figure 3-6 and Figure 3-7, respectively.

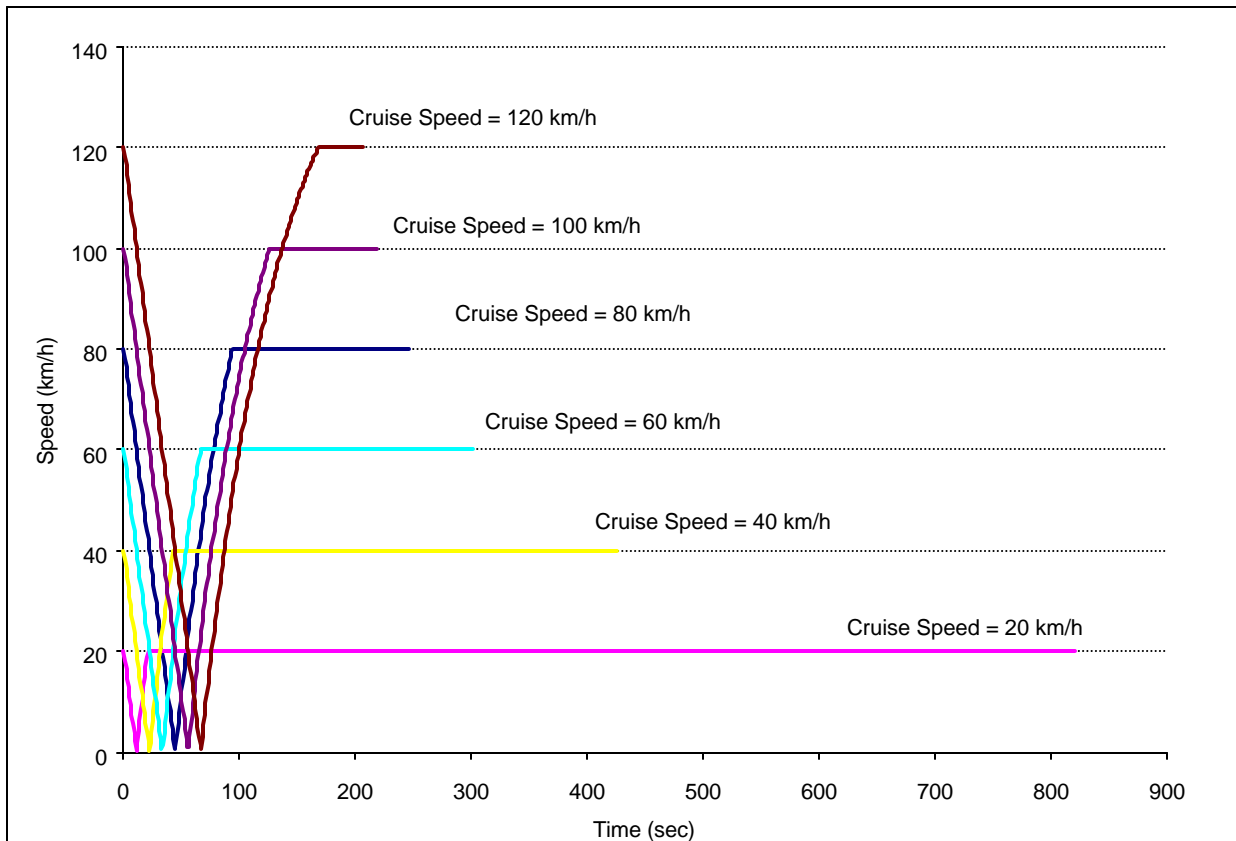


Figure 3-6. Temporal Speed Profile for Single-Stop Drive Cycle Set (Deceleration level =  $-0.5 \text{ m/s}^2$ , Acceleration level =  $0.2a_{max}$ .)

The impact of vehicle stops on fuel consumption is found to be minor, as illustrated in Figure 3-8 and Figure 3-9. Specifically, the variation in vehicle fuel consumption as a function of a vehicle's cruise speed is significantly larger than that associated with a single stop. It should be noted, however, that the acceleration rate from the stop is assumed to be 20 percent of the maximum feasible acceleration rate. Future analyses will investigate the impact of more aggressive driving

behavior on vehicle fuel consumption and emissions. Noteworthy is the fact that the introduction of a stop reduces the trip average speed, as illustrated in Figure 3-8.

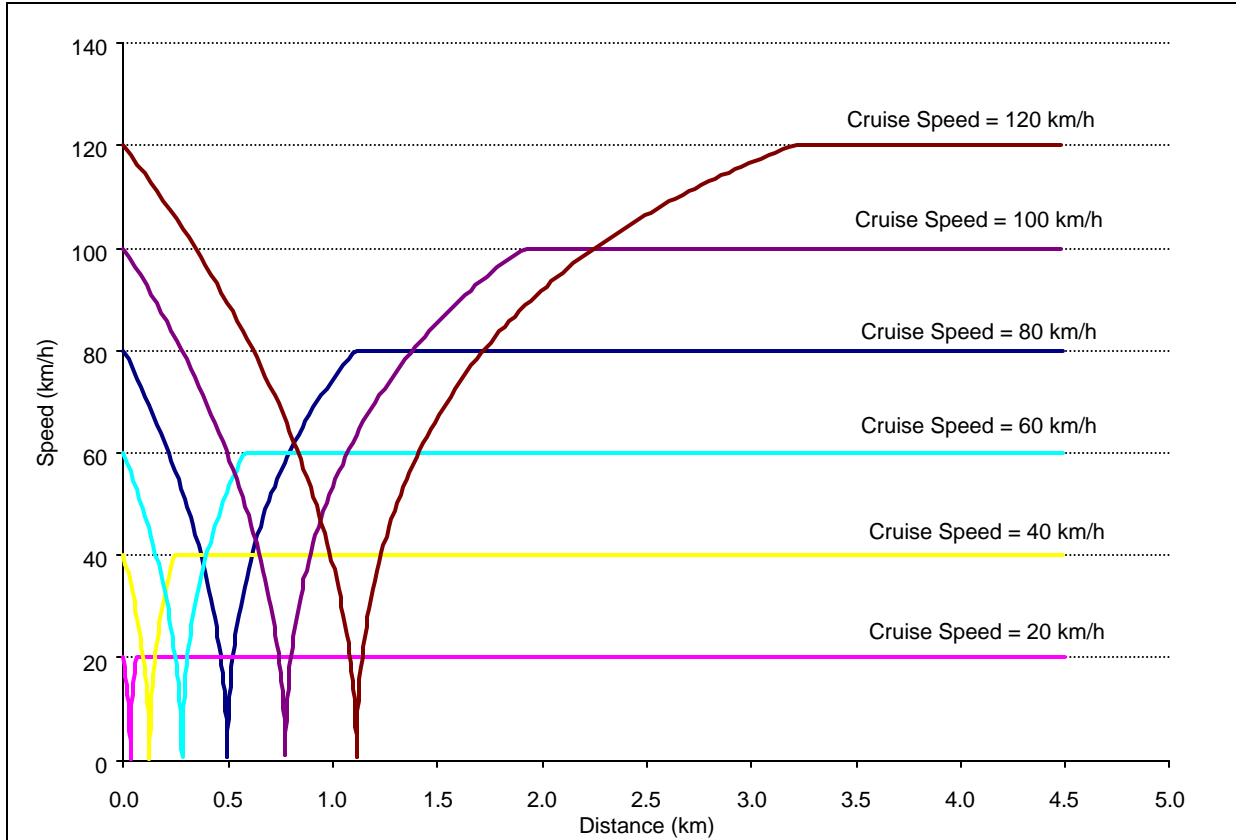


Figure 3-7. Spatial Speed Profile for Single Stop Drive Cycle Set (Deceleration level =  $-0.5 \text{ m/s}^2$ , Acceleration level =  $0.2a_{max}$ )

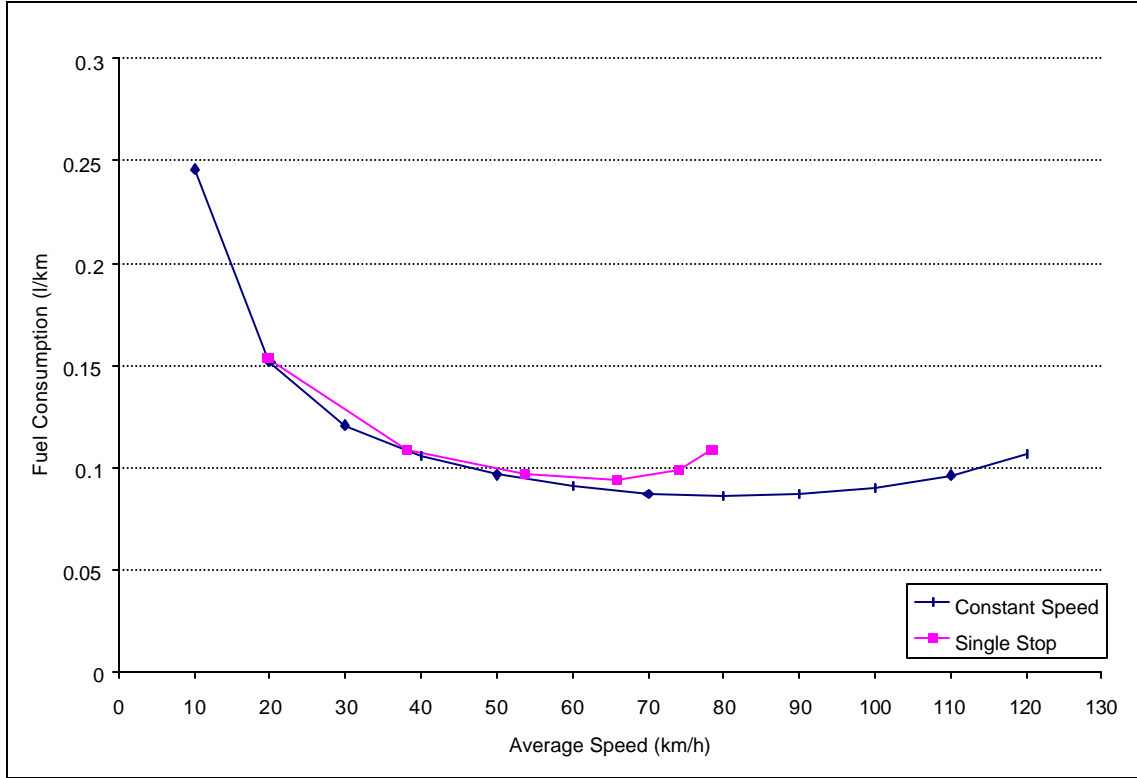


Figure 3-8. Impact of Single Vehicle Stop on Fuel Consumption Rate as a Function of Average Speed

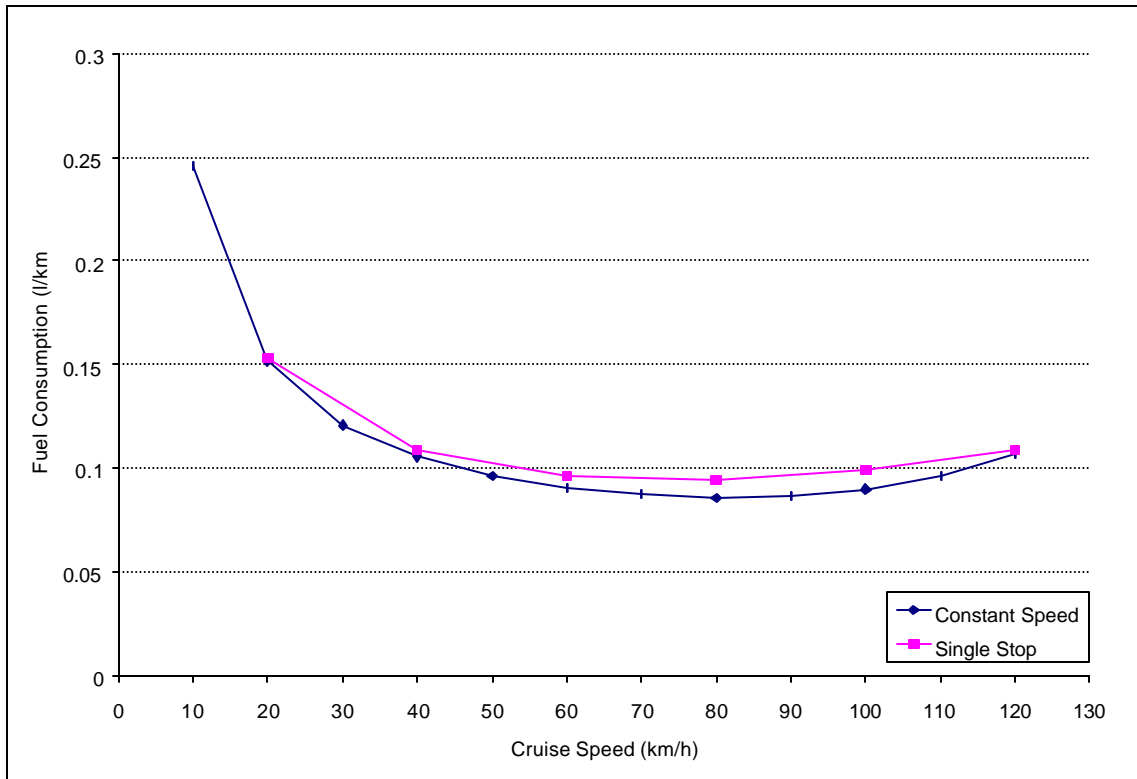


Figure 3-9. Impact of Single Vehicle Stop on Fuel Consumption Rate as a Function of Cruise Speed

Figure 3-10 illustrates that while maintaining an identical average speed (x-axis) the HC emissions are impacted significantly by the introduction of a vehicle stop (100% increase for an average speed of 80 km/h). However, it should be noted that the impact of a vehicle stop on HC emissions falls within the range of variability that is associated with different vehicle cruise speeds (ranging from 0.1 to 0.25 g/km). Similarly, CO and NO<sub>x</sub> emissions exhibit comparable trends, as illustrated in Figure 3-11 and Figure 3-12, respectively.

In summary, the introduction of a complete stop can increase a vehicle's emission rate by up to 100 percent when compared to a constant speed trip with identical average speeds. Alternatively, a vehicle's fuel consumption rate is marginally impacted by a typical vehicle stop (less than 10 percent increase).

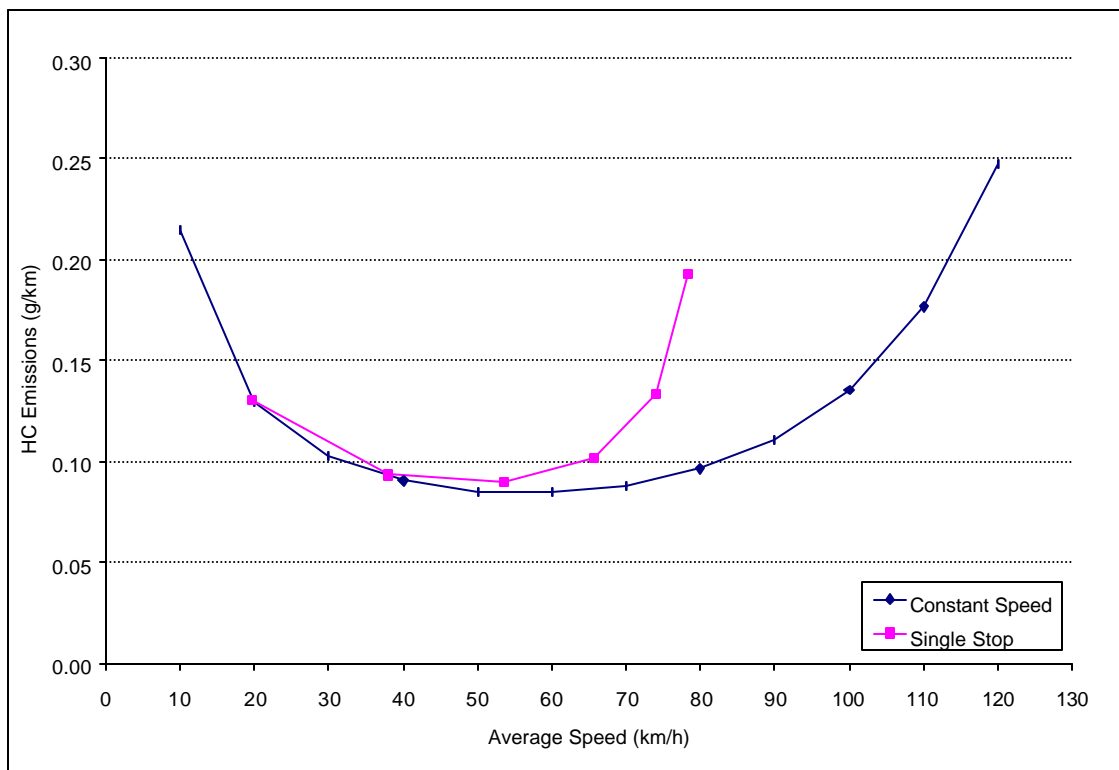


Figure 3-10. Impact of Single Vehicle Stop on HC Emission Rate as a Function of Average Speed

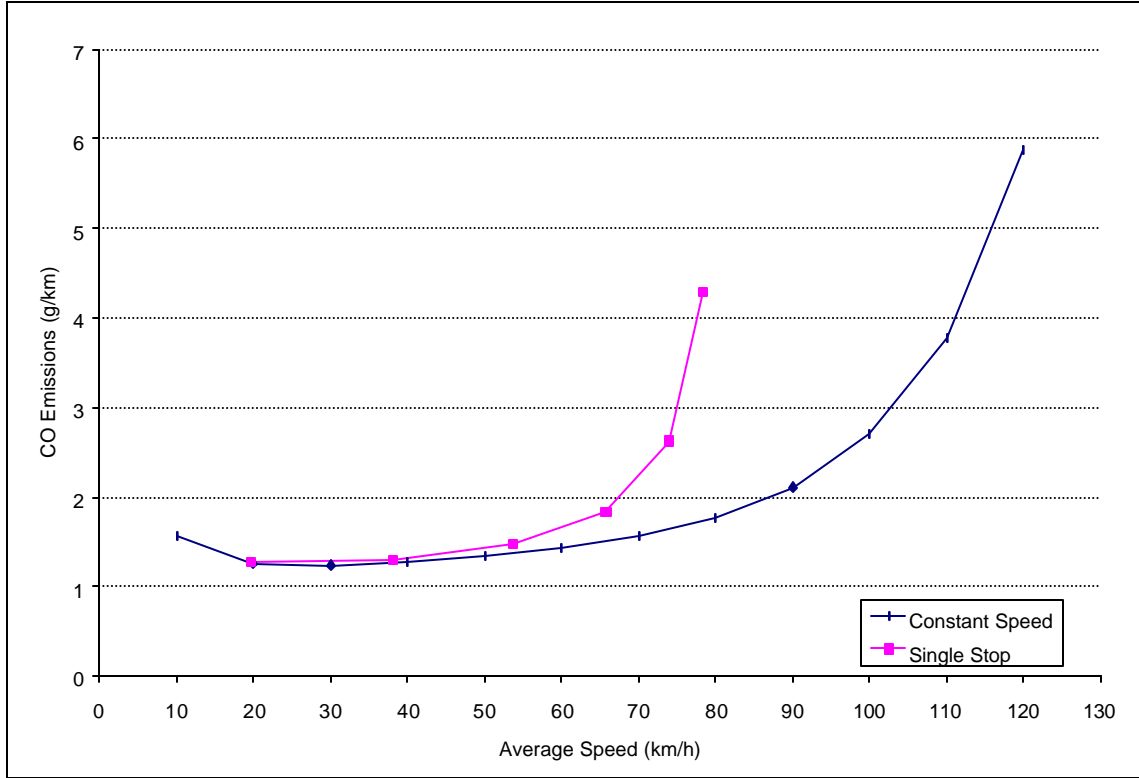


Figure 3-11. Impact of Single Vehicle Stop on CO Emission Rate as a Function of Average Speed

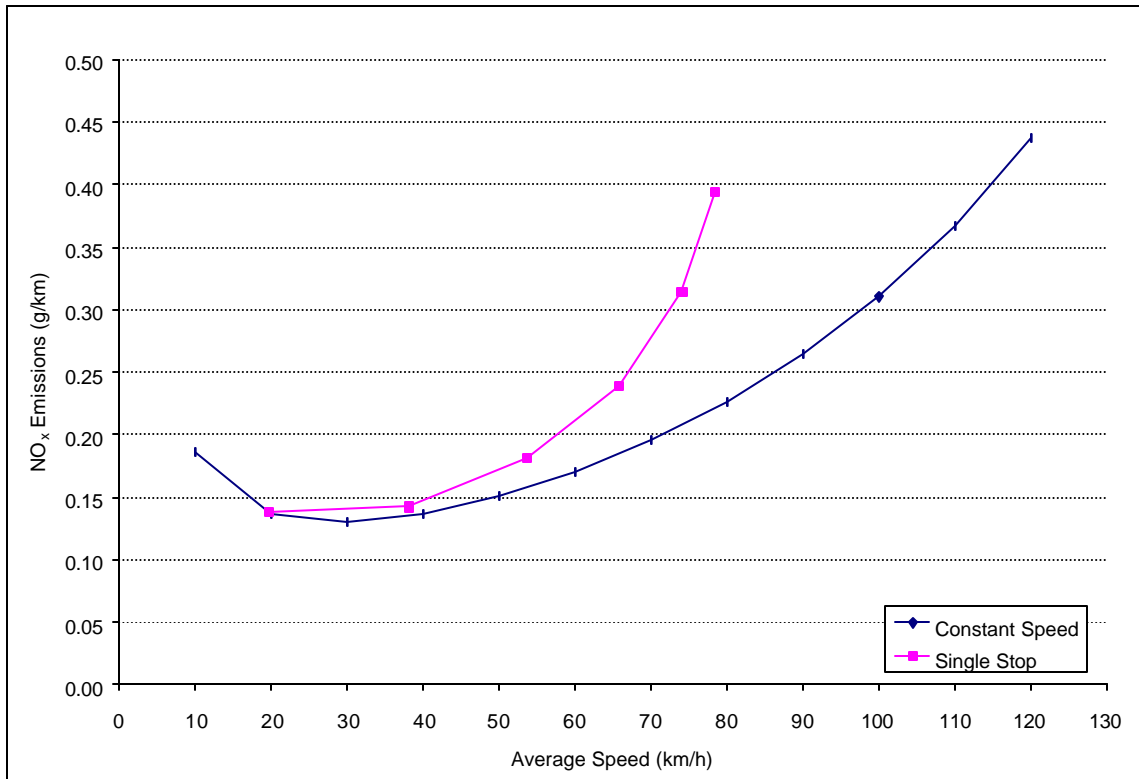


Figure 3-12. Impact of Single Vehicle Stop on NO<sub>x</sub> Emission Rate as a Function of Average Speed

### **3.4 Impact of Level of Acceleration on Vehicle Fuel Consumption and Emissions**

To further quantify the impact of vehicle stops on fuel consumption and emission rates, the analysis presented in this section systematically quantifies the impact of different levels of driver aggressiveness on various MOEs. Specifically, the impact of different levels of acceleration on vehicle fuel consumption and emissions is quantified.

While it is well documented that vehicle emissions are highly dependent on a vehicle's level of acceleration, especially at high speeds, this impact has not been systematically quantified. The objective of this section is to systematically quantify the impact of a vehicle stop involving different levels of acceleration on vehicle fuel consumption and emissions. Specifically, five different levels of acceleration, as illustrated in Figure 3-13, ranging from 20 to 100 percent the maximum feasible acceleration rate are applied to the previously described single-stop drive cycles, resulting in a total of 30 single-stop drive cycles (6 cruise speed levels  $\times$  5 acceleration levels). Again, as was the case in the previous scenarios, microscopic models (Ahn *et al.* and Rakha *et al.*, 1999) are applied to each cycle to compute the vehicle fuel consumption and emissions per unit distance.

For illustrative purposes the impact of different levels of acceleration on vehicle fuel consumption and emissions are initially analyzed for a single cruise speed. Subsequently, the interaction of different acceleration rates and cruise speeds are quantified.

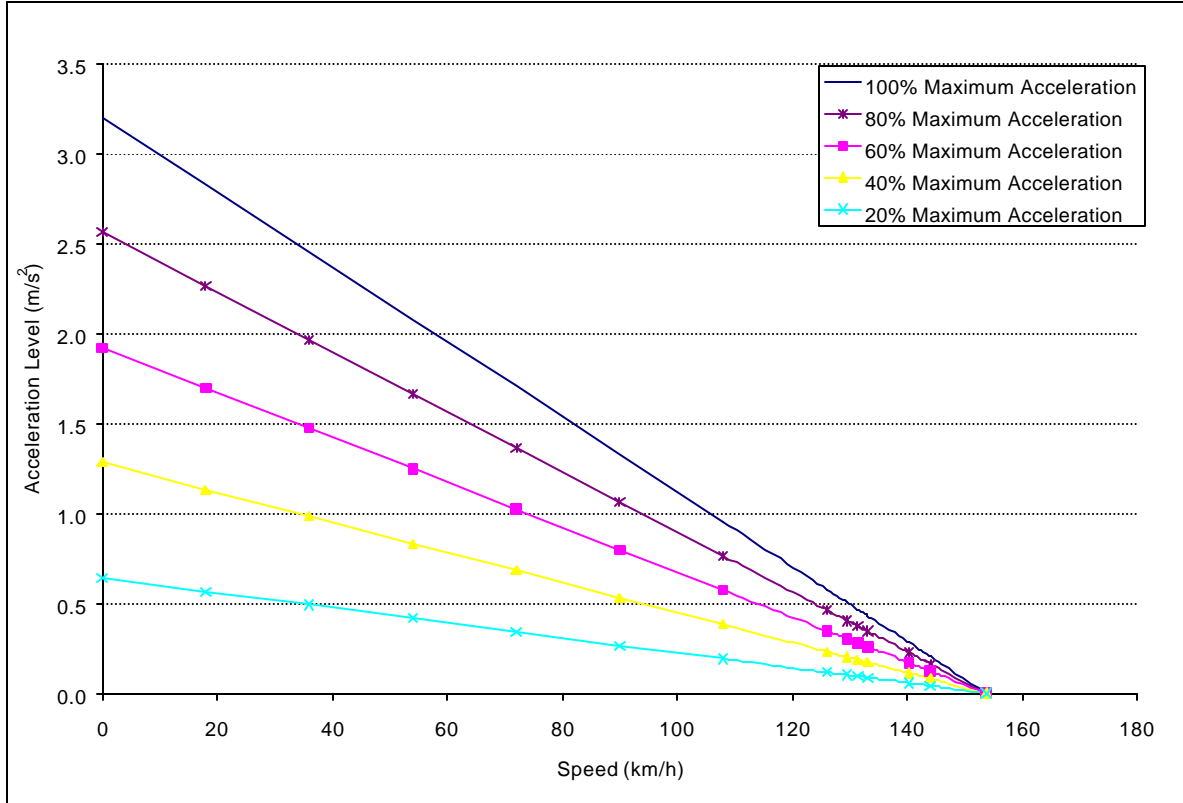


Figure 3-13. Acceleration Levels Employed in Construction of Single-Stop Drive Cycle Set

### 3.4.1 Impact of Level of Acceleration on Vehicle Fuel Consumption and Emission Rates for a Sample Cruise Speed

The five acceleration levels that were described earlier are initially applied to a single-stop drive cycle that involves cruising at a speed of 80 km/h, as illustrated in Figure 3-14 and 3-15. A summary of the drive cycle speed/acceleration distributions for the different levels of acceleration are presented in Table 3-3.

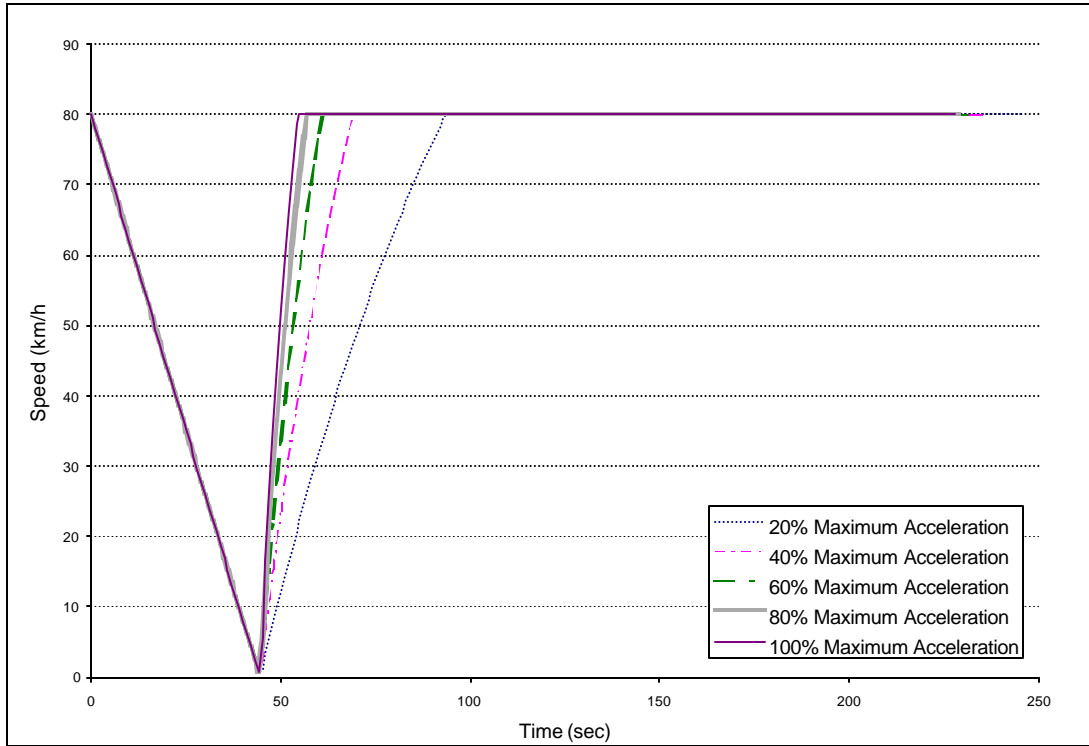


Figure 3-14. Temporal Variation in Single-Stop Speed Profile for Different Acceleration Levels (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

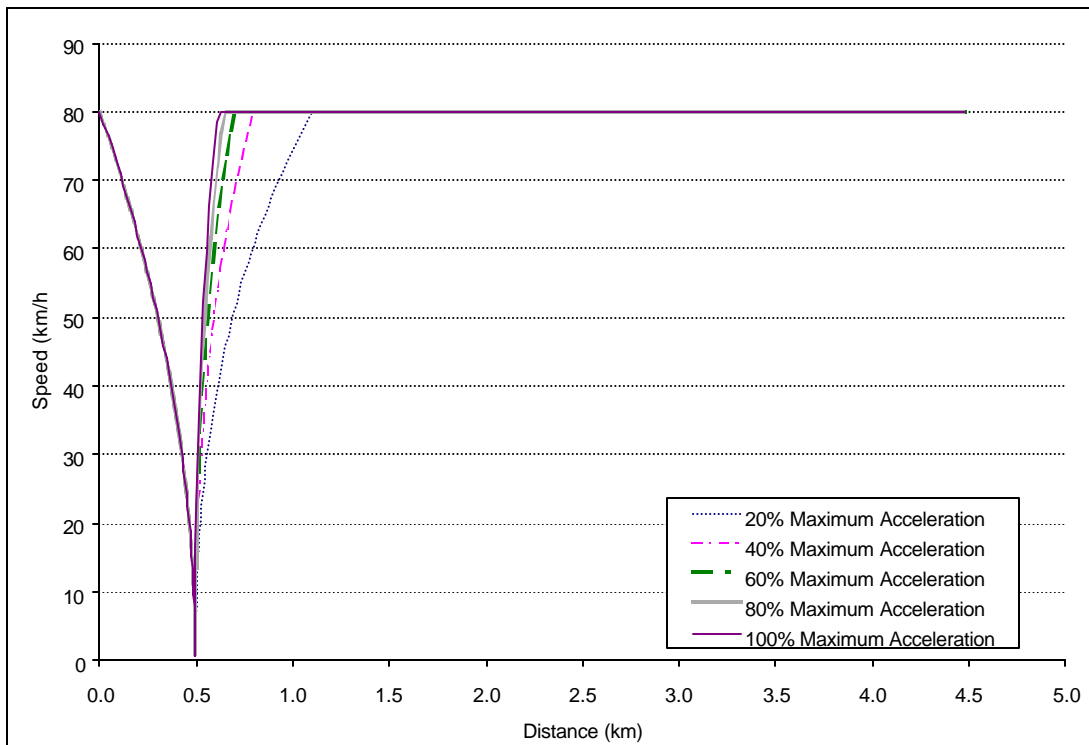


Figure 3-15. Spatial Variation in Single-Stop Speed Profile for Different Acceleration Levels (Cruise Speed=80 km/h, Travel Distance =4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

Table 3-3. Speed/Acceleration Distribution for Single-Stop Drive Cycles as a Function of Acceleration Level (Cruise Speed = 80 km/h, Deceleration Rate = -0.5 m/s<sup>2</sup>)

Acceleration=0.2a <sub>max</sub>											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5	2.27	2.23	2.27	2.27	2.23	2.27	2.23	2.27		18.07
	0.0				1.42	2.52	2.72	3.05	65.48		75.18
	0.5	1.83	1.95	2.11	0.85						6.74
	1.0										
	1.5										
	2.0										
	2.5										
	3.0										
3.5											
<b>Total</b>		4.10	4.18	4.39	4.55	4.75	5.00	5.28	67.75		100.00

Acceleration=0.4a <sub>max</sub>											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5	2.38	2.34	2.38	2.38	2.34	2.38	2.34	2.38		18.90
	0.0								70.73		70.73
	0.5				0.76	1.27	1.44	1.61	1.74		6.84
	1.0	0.98	1.02	1.10	0.42						3.53
	1.5										
	2.0										
	2.5										
	3.0										
3.5											
<b>Total</b>		3.36	3.36	3.48	3.57	3.61	3.82	3.95	74.85		100.00

Acceleration=0.6a <sub>max</sub>											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5	2.42	2.37	2.42	2.42	2.37	2.42	2.37	2.42		19.20
	0.0								73.77		73.77
	0.5								0.78		0.78
	1.0				0.47	0.91	0.95	1.08	0.43		3.84
	1.5	0.65	0.69	0.78							2.11
	2.0										
	2.5										
	3.0										
3.5											
<b>Total</b>		3.06	3.06	3.19	2.89	3.28	3.36	3.45	77.39		100.00

Acceleration=0.8a <sub>max</sub>											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5	2.43	2.39	2.43	2.43	2.39	2.43	2.39	2.43		19.35
	0.0								75.35		75.35
	0.5										0.00
	1.0							0.48	0.91		1.39
	1.5				0.39	0.65	0.74	0.30			2.09
	2.0	0.30	0.52	0.57	0.22						1.61
	2.5	0.22									0.22
	3.0										
3.5											
<b>Total</b>		2.96	2.91	3.00	3.04	3.04	3.17	3.17	78.70		100.00

Table 3-3. (Continued)

Acceleration=1.0a <sub>max</sub>											
		Speed (km/h)								Total	
		10	20	30	40	50	60	70	80		90
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5	2.45	2.40	2.45	2.45	2.40	2.45	2.40	2.45		19.43
	0.0								76.29		76.29
	0.5								0.04		0.04
	1.0								0.00		0.00
	1.5						0.13	0.66	0.70		1.48
	2.0				0.35	0.52	0.44				1.31
	2.5		0.44	0.44	0.17						1.05
	3.0	0.39									0.39
	3.5										
<b>Total</b>		2.84	2.84	2.88	2.97	2.93	3.01	3.06	79.48		100.00

An analysis of the results indicates that the impact of level of acceleration on vehicle fuel consumption is minor, as illustrated in Figure 3-16. Specifically, the figure illustrates a minor increase in fuel consumption as the level of acceleration increases (increase from 0.0941 l/km to 0.0985 l/km for an increase in the acceleration rate from 20 to 100 percent the maximum feasible rate). Alternatively, the HC and CO emissions are highly sensitive to the level of acceleration, as illustrated in Figure 3-17 and Figure 3-18. Specifically, the HC emission rate increases from 0.1 g/km at an acceleration rate of 20 percent the maximum rate to 0.45 g/km at the maximum feasible acceleration rate (an increase of 450 percent). The high HC and CO emissions that are associated with high levels of acceleration result from the lean fuel to air ratio at heavy engine loads and the bypassing of the catalytic converter, as was described in Chapter 2.

The NO<sub>x</sub> emissions, on the other hand, demonstrate a different trend when compared to HC and CO emissions, as illustrated in Figure 3-19. Specifically, the impact of the acceleration rate on NO<sub>x</sub> emissions is minor when compared to the impact of cruise speed on these emissions. Furthermore, the trend indicates a slight increase in NO<sub>x</sub> emissions as the level of acceleration increases (increase from 0.24 g/km to 0.30 g/km) and a subsequent decrease in NO<sub>x</sub> emissions at the maximum feasible acceleration rate. This decrease in NO<sub>x</sub> emissions is consistent with the literature (i.e. NO<sub>x</sub> emissions are highest at stoichiometric engine conditions).

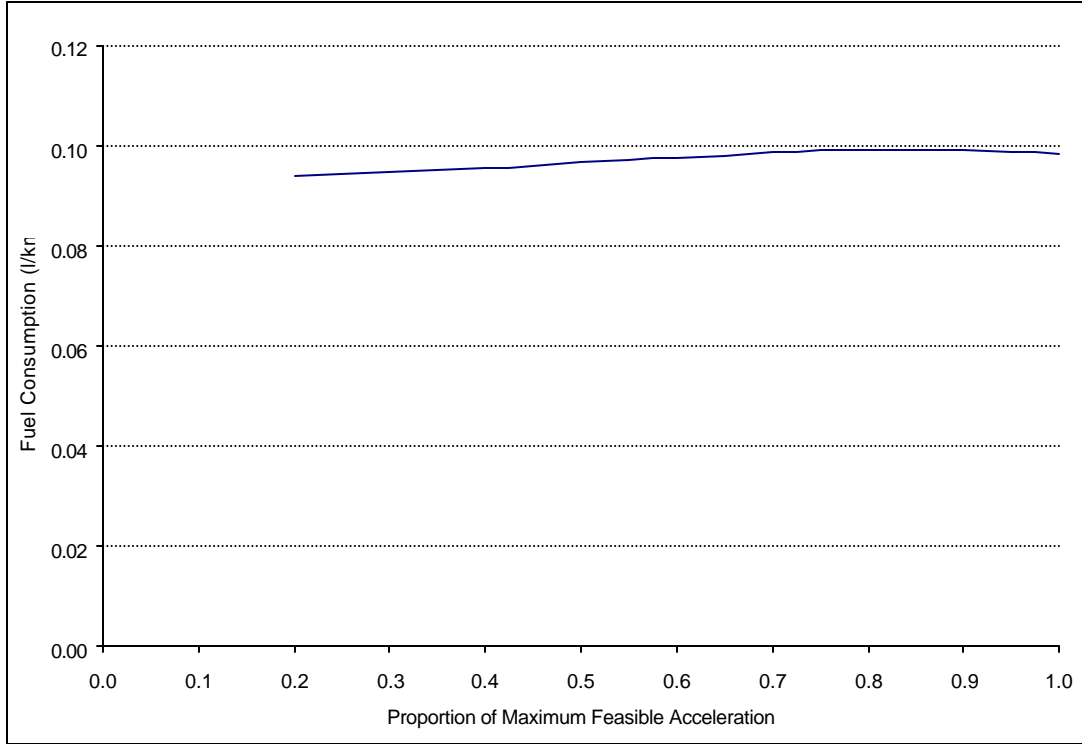


Figure 3-16. Variation in Fuel Consumption Rate as a Function of Acceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

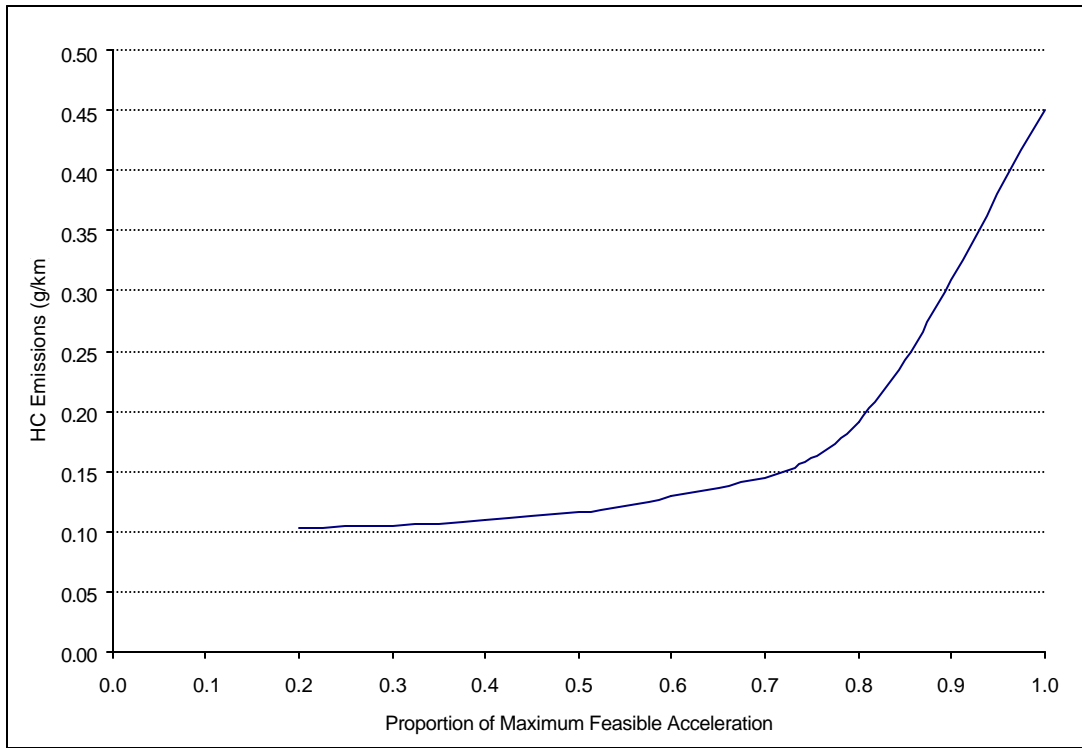


Figure 3-17. Variation in HC Emission Rate as a Function of Acceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

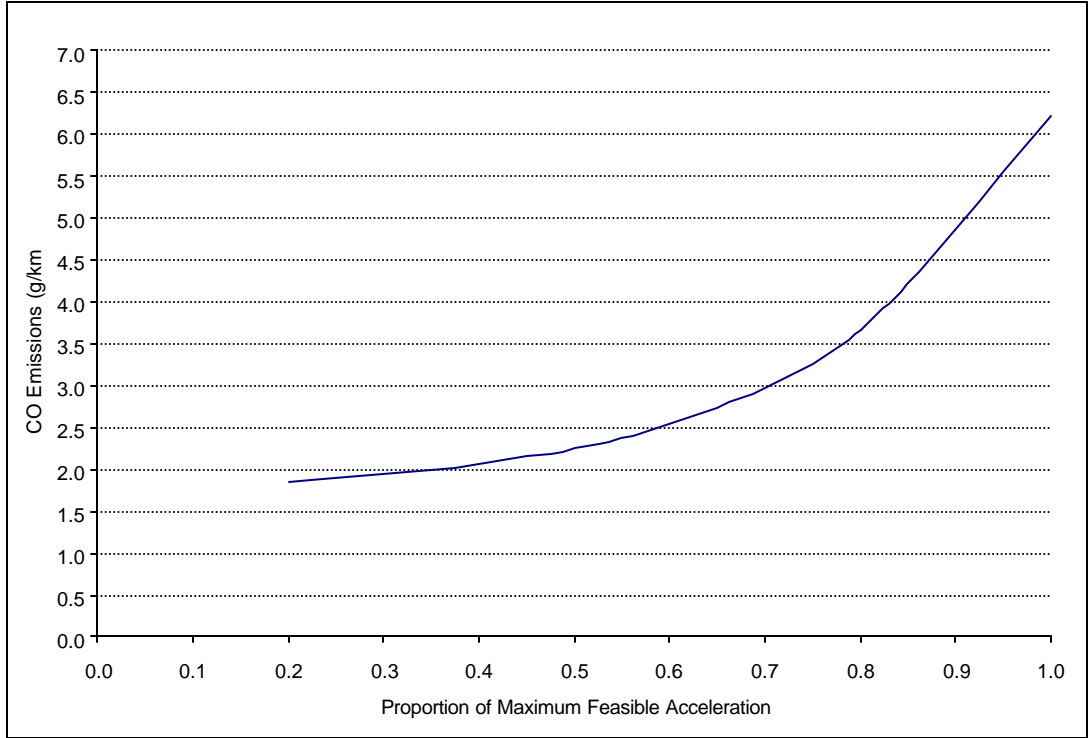


Figure 3-18. Variation in CO Emission Rate as a Function of Acceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

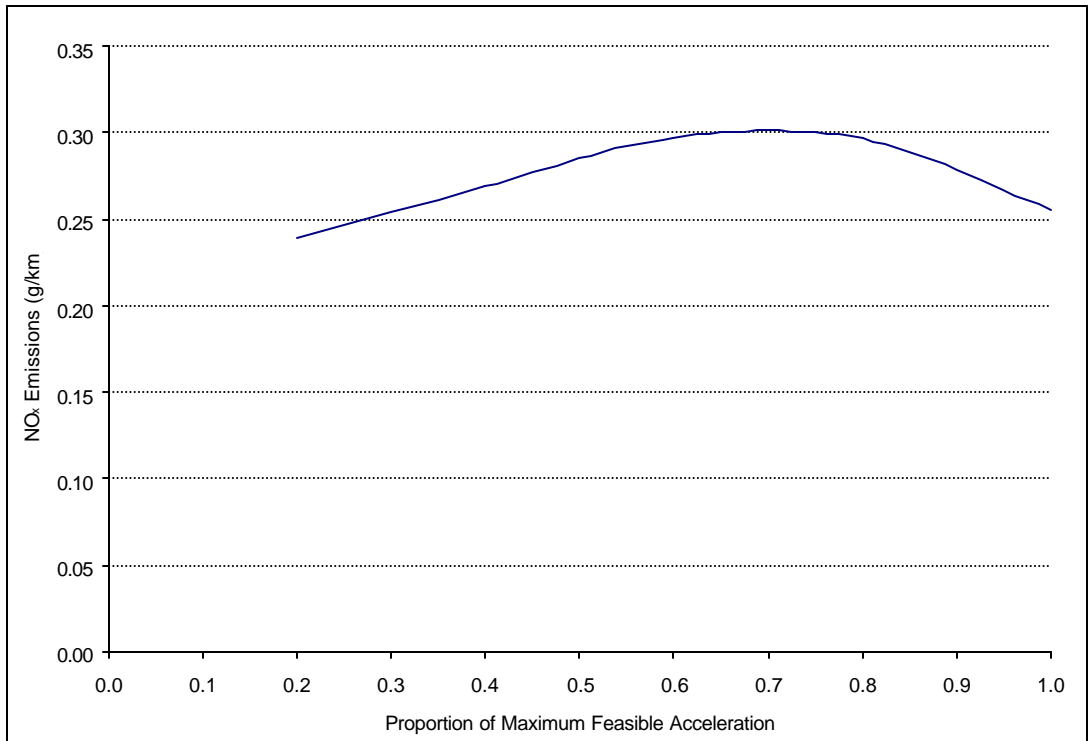


Figure 3-19. Variation in NO<sub>x</sub> Emission Rate as a Function of Acceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

### ***3.4.2 Combined Impact of Level of Acceleration and Cruise Speed on Vehicle Fuel Consumption and Emissions***

Depending on the aggressiveness of a driver the impact of vehicle stops on vehicle fuel consumption and emissions may vary. The objective of this section is to compare the impact of the level of acceleration that is associated with a vehicle stop at lower speeds with that at higher speeds. In conducting this analysis, five acceleration levels that were considered earlier are applied to the various full-stop scenarios that were described in the previous section. Fuel consumption and emission rates per unit distance for all resultant cycles are compared to a constant speed drive cycle at the same cruise speed, as illustrated in Figure 3-20, 3-21, 3-22, and 3-23.

Figure 3-20 demonstrates the non-linearity behavior of vehicle fuel consumption rates. In general, as the level of acceleration increases the vehicle fuel consumption rate increases. This finding demonstrates that the additional fuel consumption that is associated with a stop more than offsets the reduction in time that is spent in acceleration mode for higher levels of acceleration. For example Figure 3-24 illustrates the variation in mode of travel for a deceleration rate of  $-0.5 \text{ m/s}^2$  and an acceleration rate of  $0.2a_{\text{max}}$ . The figure clearly demonstrates a reduction in the distance traveled in cruise mode for higher approach speeds versus lower approach speeds.

The HC and CO emission rates demonstrate similar trends that involve an increase in vehicle emissions as the level of acceleration increases. Furthermore, one can observe from Figure 3-25 that vehicle HC emissions are more sensitive to acceleration rates than they are to cruise speed in the range of 0 to 120 km/h. Similarly, CO emissions demonstrate a higher sensitivity to the level of acceleration when compared to cruise speeds in the range of 0 to 120 km/h, as illustrated in Figure 3-26.

$\text{NO}_x$  emissions display a highly non-linearity nature with the emission rates typically increasing at acceleration rates in the range of 0.0 to  $0.8a_{\text{max}}$  and decreasing at acceleration rates in excess of  $0.8a_{\text{max}}$ .

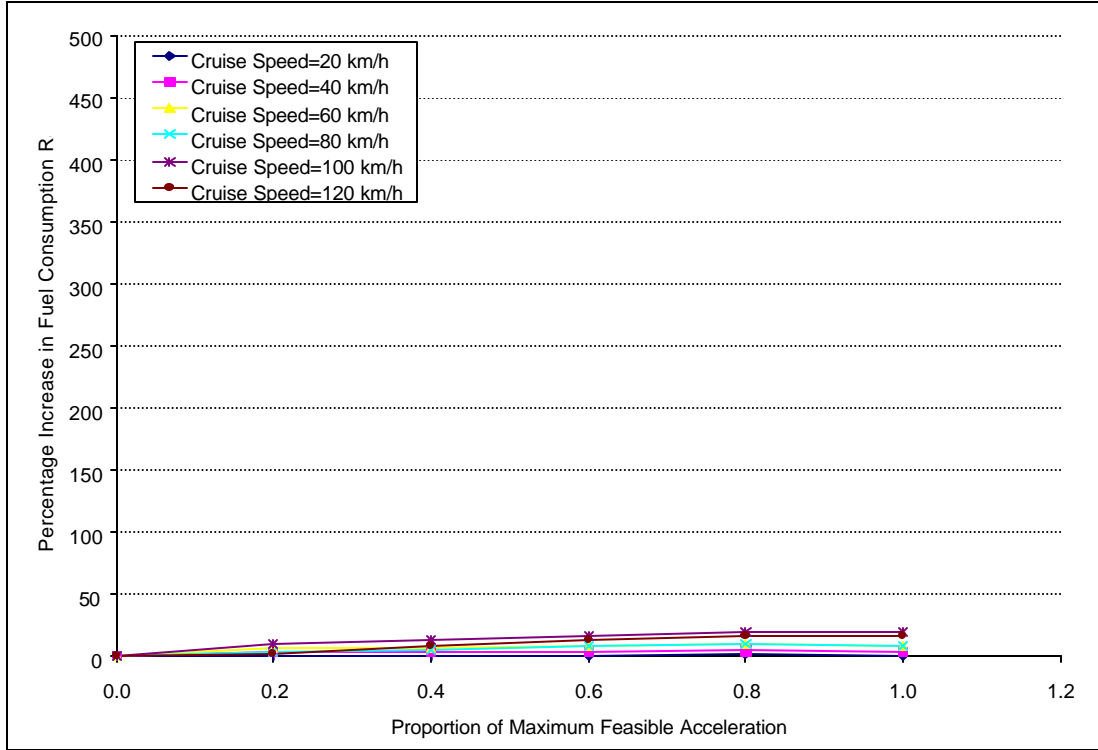


Figure 3-20. Percentage Increase in Fuel Consumption Rate as a Function of Level of Acceleration (Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

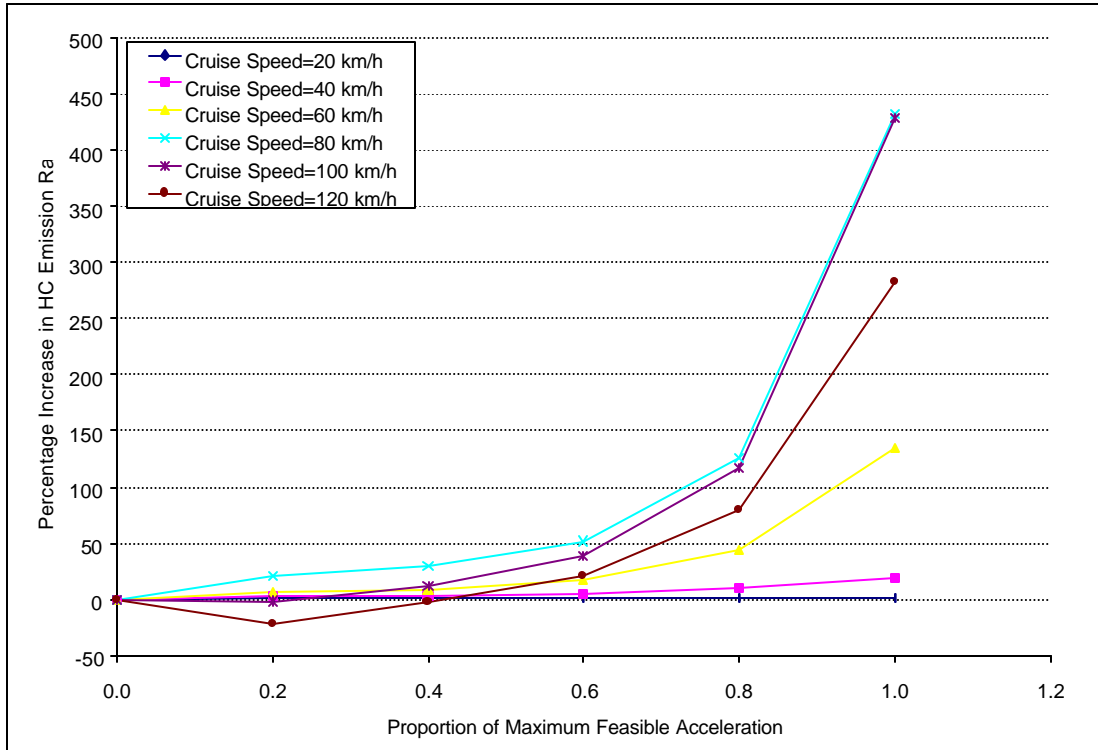


Figure 3-21. Percentage Increase in HC Emission Rate as a Function of Level of Acceleration (Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

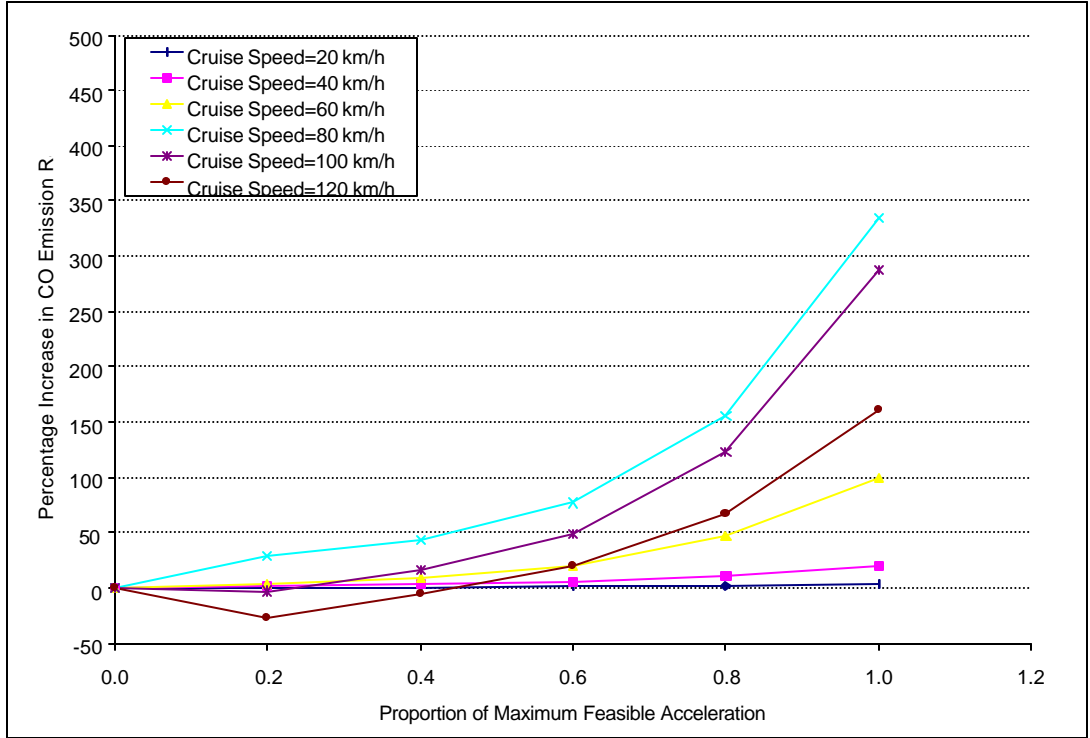


Figure 3-22. Percentage Increase in CO Emission Rate as a Function of Level of Acceleration (Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

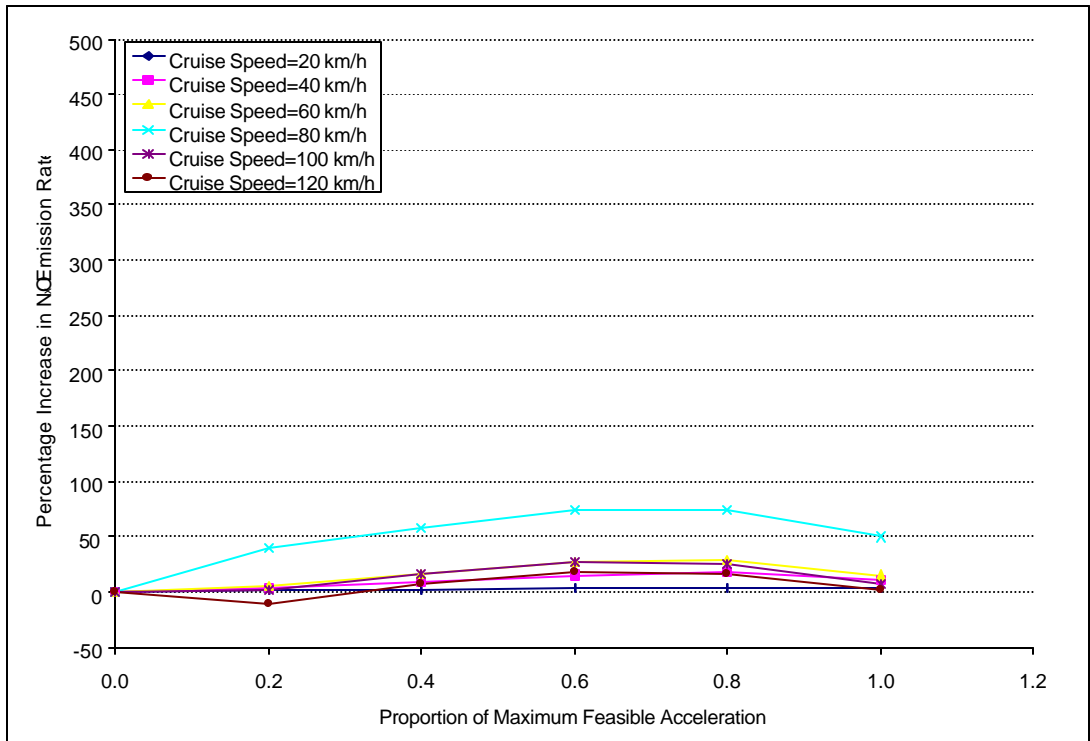


Figure 3-23. Percentage Increase in NO<sub>x</sub> Emission Rate as a Function of Level of Acceleration (Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

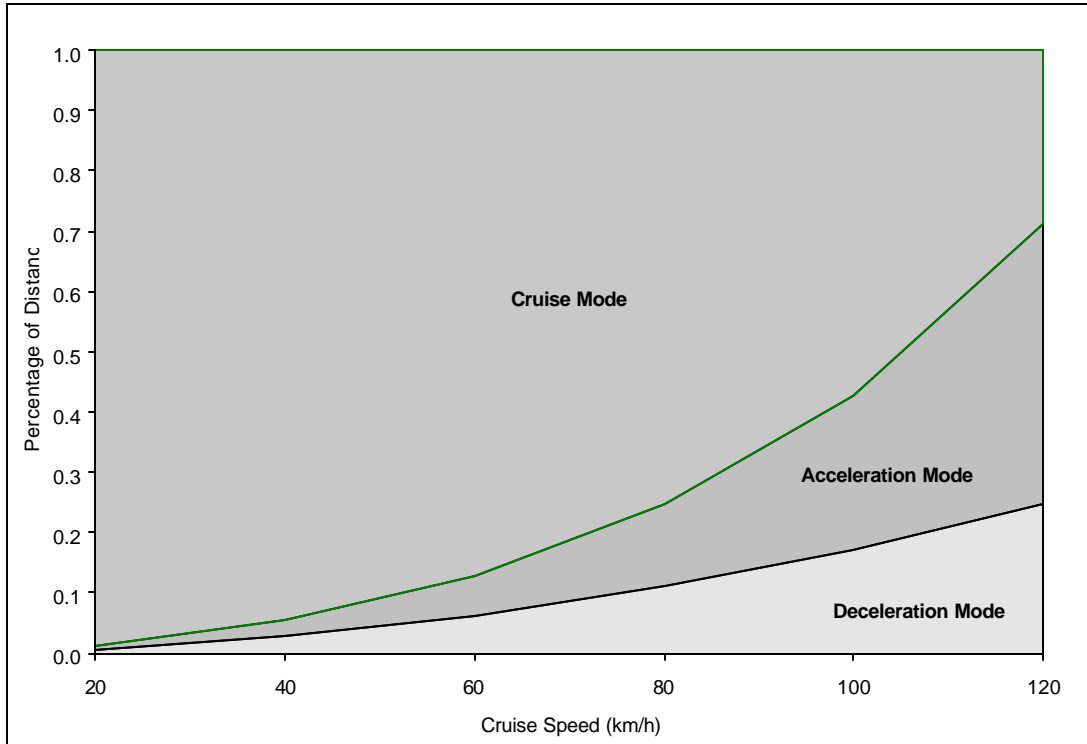


Figure 3-24. Variation in Mode of Travel for Single-Stop Drive Cycle as a Function of Cruise Speed (Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ )

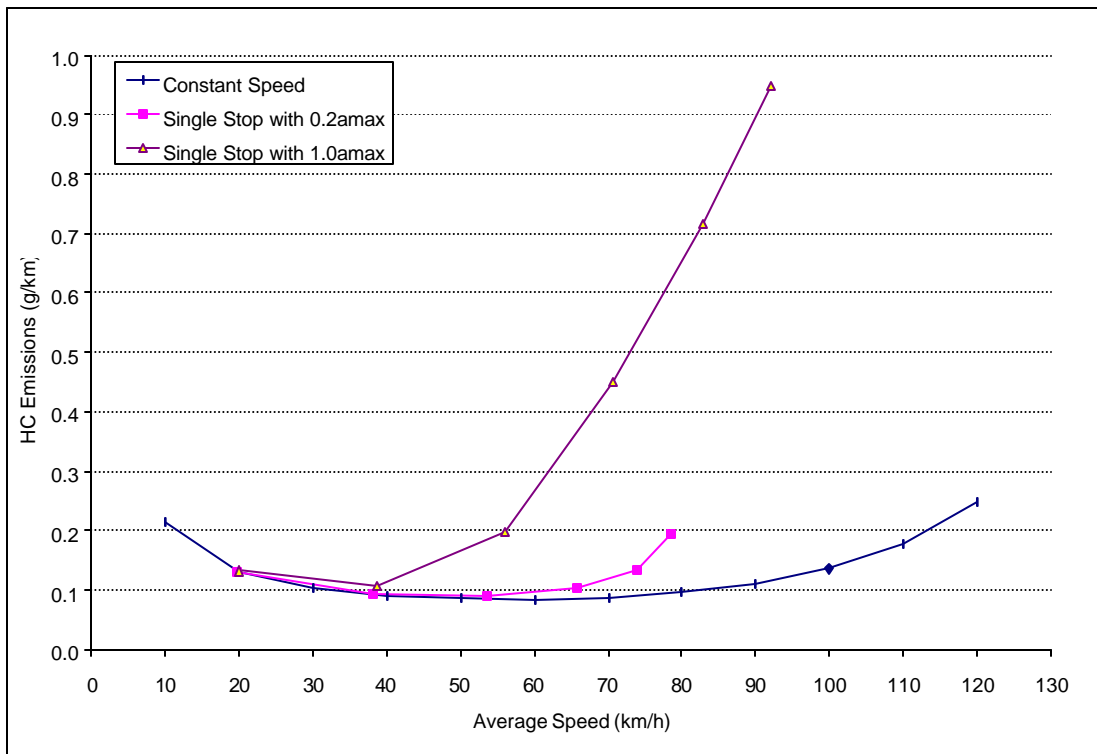


Figure 3-25. Impact of Level of Acceleration in HC Emission Rate as a Function of Average Speed (Distance = 4.5 km, Deceleration Rate for Single Stop Cycles =  $-0.5 \text{ m/s}^2$ )

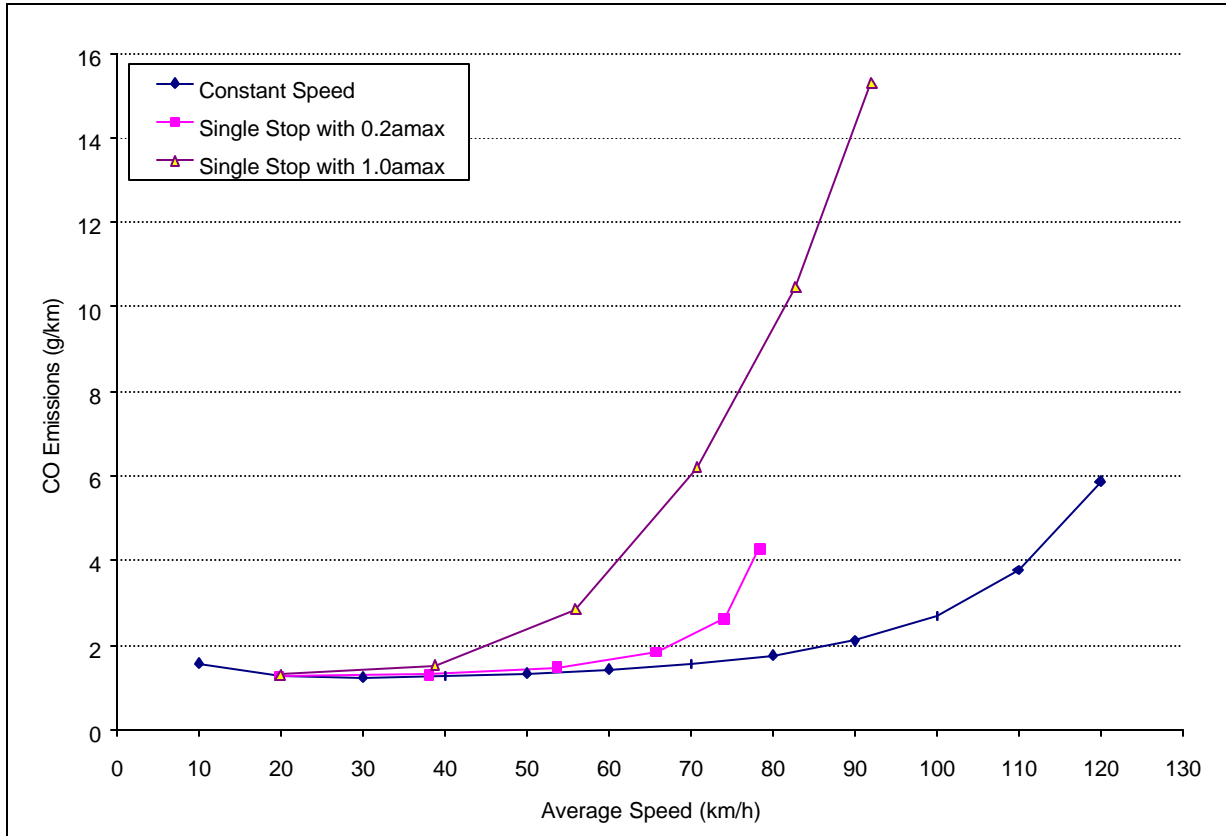


Figure 3-26. Impact of Level of Acceleration in CO Emission Rate as a Function of Average Speed (Distance = 4.5 km, Deceleration Rate for Single Stop Cycles =  $-0.5 \text{ m/s}^2$ )

As a vehicle's cruise speed increases the vehicle's fuel consumption and emission rate may increase or in some instances decrease when a vehicle stop is introduced to the trip depending on the aggressiveness of the driver. As illustrated in Figure 3-27, for a stop involving a deceleration rate of  $-0.5 \text{ m/s}^2$  and an acceleration rate of  $0.2a_{\text{max}}$ , the vehicle fuel consumption rate for both the deceleration mode and the acceleration mode decline as the cruise speed increases. Alternatively, the cruise speed fuel consumption rate increases as a function of the cruise speed. In the case of HC emissions, Figure 3-28 demonstrates a convex relationship between the emission rate and the cruise speed when the vehicle travels in cruise mode and in acceleration mode, while it reflects a monotonically decreasing function in deceleration mode. The CO and  $\text{NO}_x$  emission rates demonstrated similar trends to those presented for HC emissions. Consequently, for a fixed deceleration rate, the impact of the level of acceleration and cruise speed on vehicle fuel consumption or emissions is determined by the combined effect of the level of acceleration and the cruise speed. For example, an introduction of a vehicle stop that

involves a deceleration rate of  $-0.5 \text{ m/s}^2$  and an acceleration rate of  $0.2a_{\text{max}}$  to a constant speed trip of 80 km/h, results in an increase in the HC emissions when compared to the base constant cruise speed scenario, as illustrated in Figure 3-29. This increase is caused by the fact that the area under the constant speed scenario is less than the area under the single-stop scenario. Alternatively, Figure 3-30 demonstrates that for the same stop from a cruise speed of 120 km/h instead of 80 km/h, the HC emissions decrease compared to the base constant speed scenario (cruise speed of 120 km/h). The reduction in the HC emissions is caused by the lower emission rate that is associated with both the deceleration and acceleration modes, as illustrated in Figure 3-30.

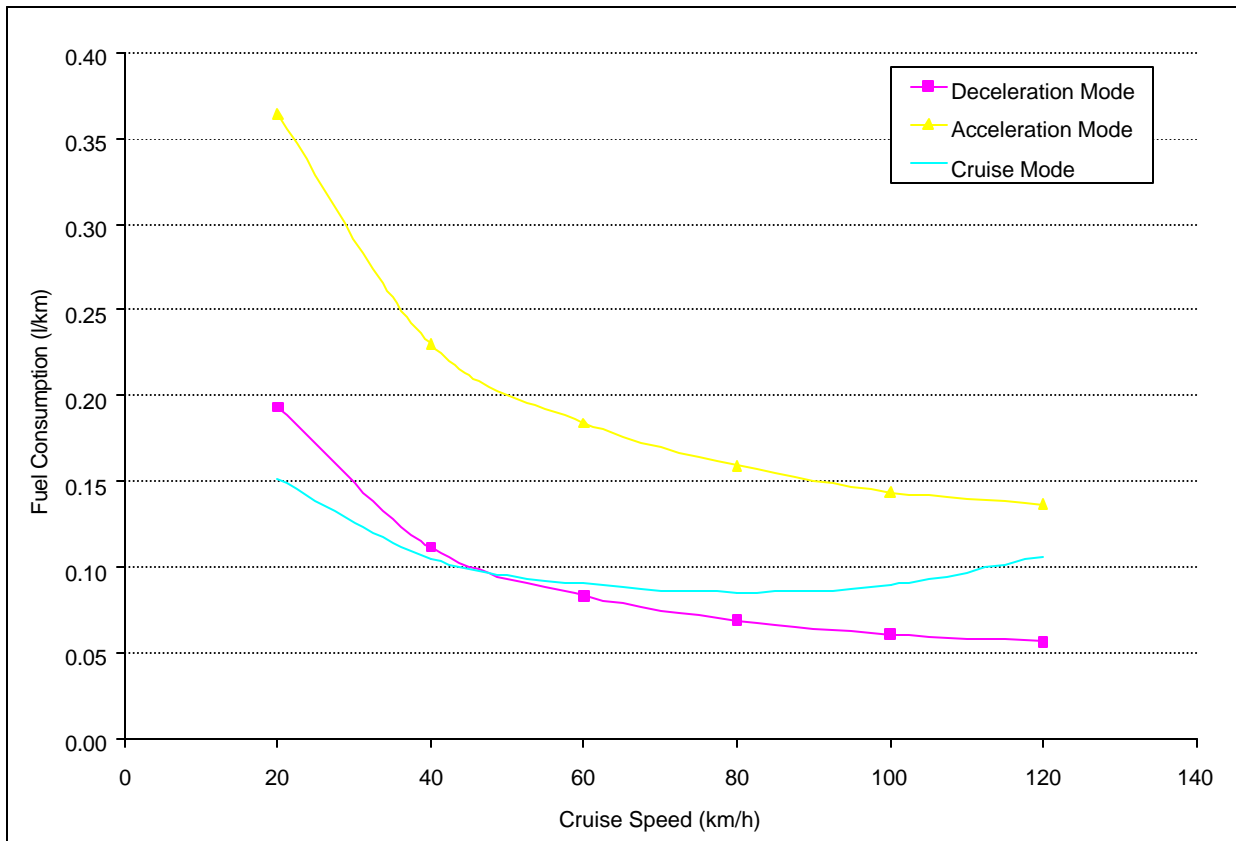


Figure 3-27. Fuel Consumption Rate in Different Operation Modes (Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{\text{max}}$ )

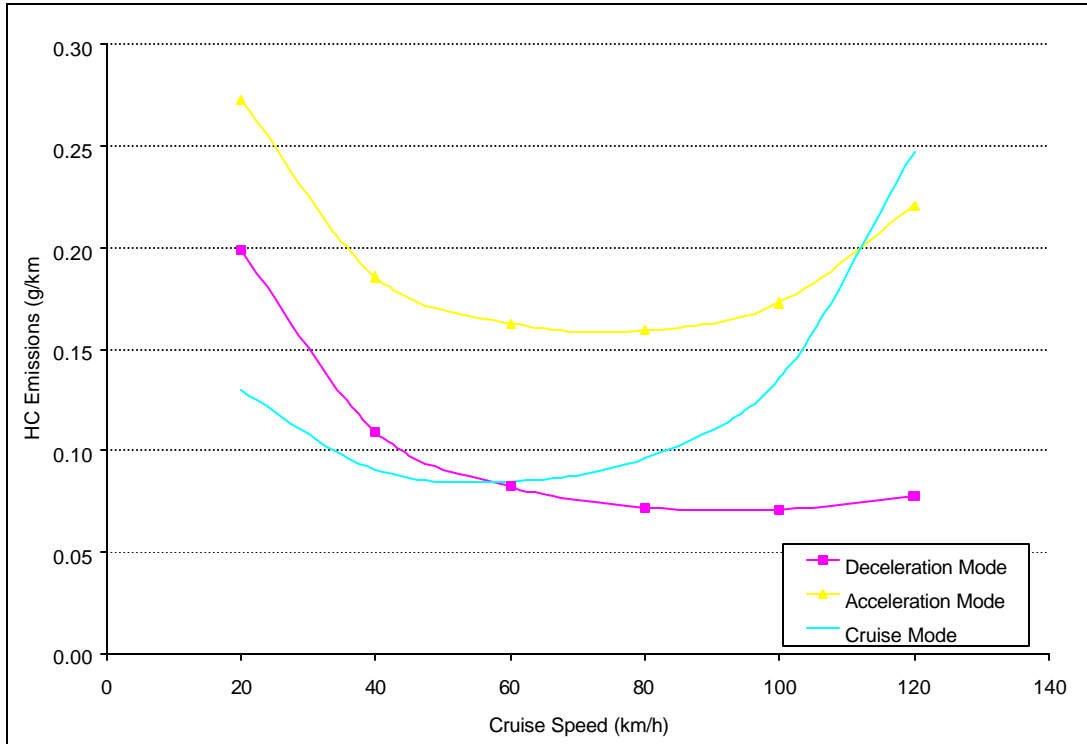


Figure 3-28. HC Emission Rate in Different Operation Modes (Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{max}$ )

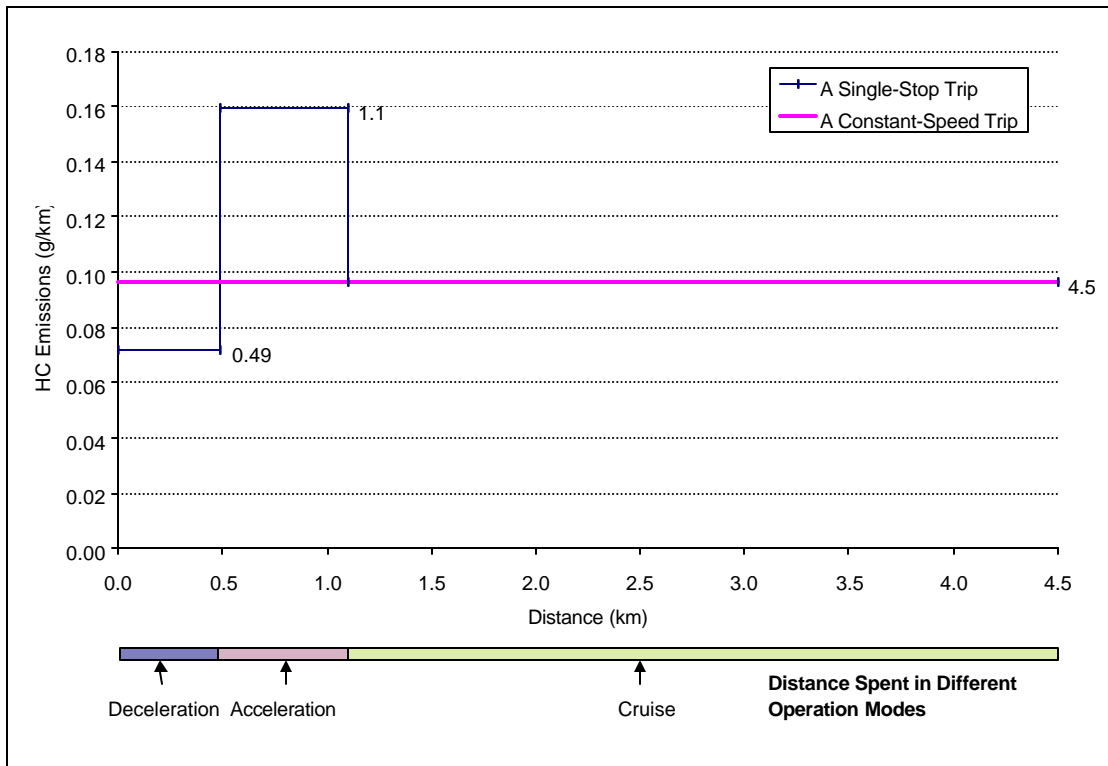


Figure 3-29. HC Emission Rate in Different Operation Modes (Distance = 4.5 km, Cruise Speed = 80 km/h, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{max}$ )

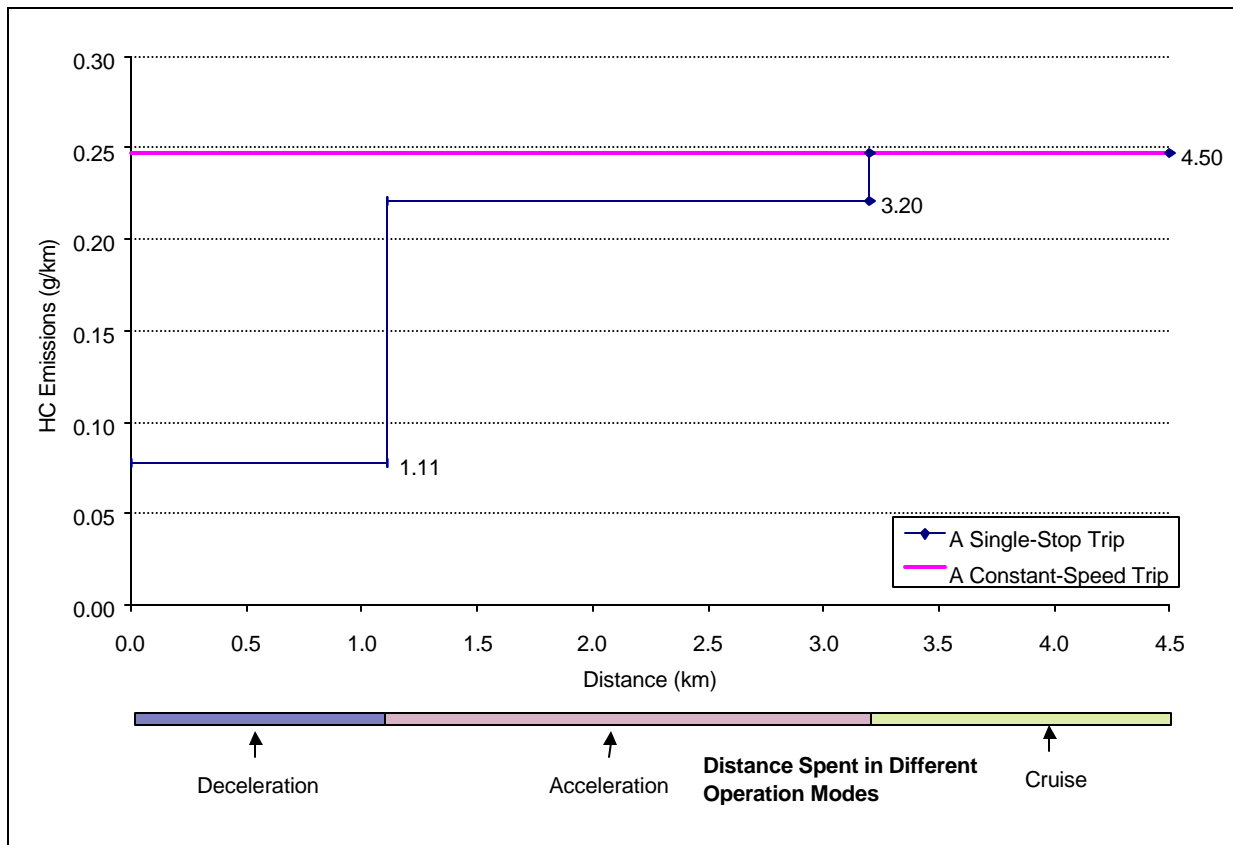


Figure 3-30. HC Emission Rate in Different Operation Modes (Distance = 4.5 km, Cruise Speed = 120 km/h, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{max}$ )

Consequently, emission rates for HC, CO, and  $\text{NO}_x$  do decrease occasionally by introducing vehicle stops into relatively high constant speed trips (speed of 120 km/h). These reductions in emissions can occur if the vehicle stops involve mild acceleration levels because the emission rates at high speeds exceed the emission rates associated with mild accelerations, as was illustrated earlier in Figure 3-10. Consequently, at high speeds the introduction of vehicle stops that involve extremely mild acceleration levels can actually reduce vehicle emission rates. While this finding might appear counter intuitive at first glance, it is demonstrated to be logical.

The composition of HC emissions by mode of travel demonstrates that while at high cruise speeds the vehicle operates in cruise mode for 30 percent of the total trip, the HC emissions that are associated with cruise travel exceed 30 percent of the total emissions. Again, this demonstrates that the emission rates at high cruise speeds exceed the emission rates for mild accelerations, as illustrated in Figure 3-31. The similar trend can also be found in vehicle fuel consumption, CO, and  $\text{NO}_x$  emissions.

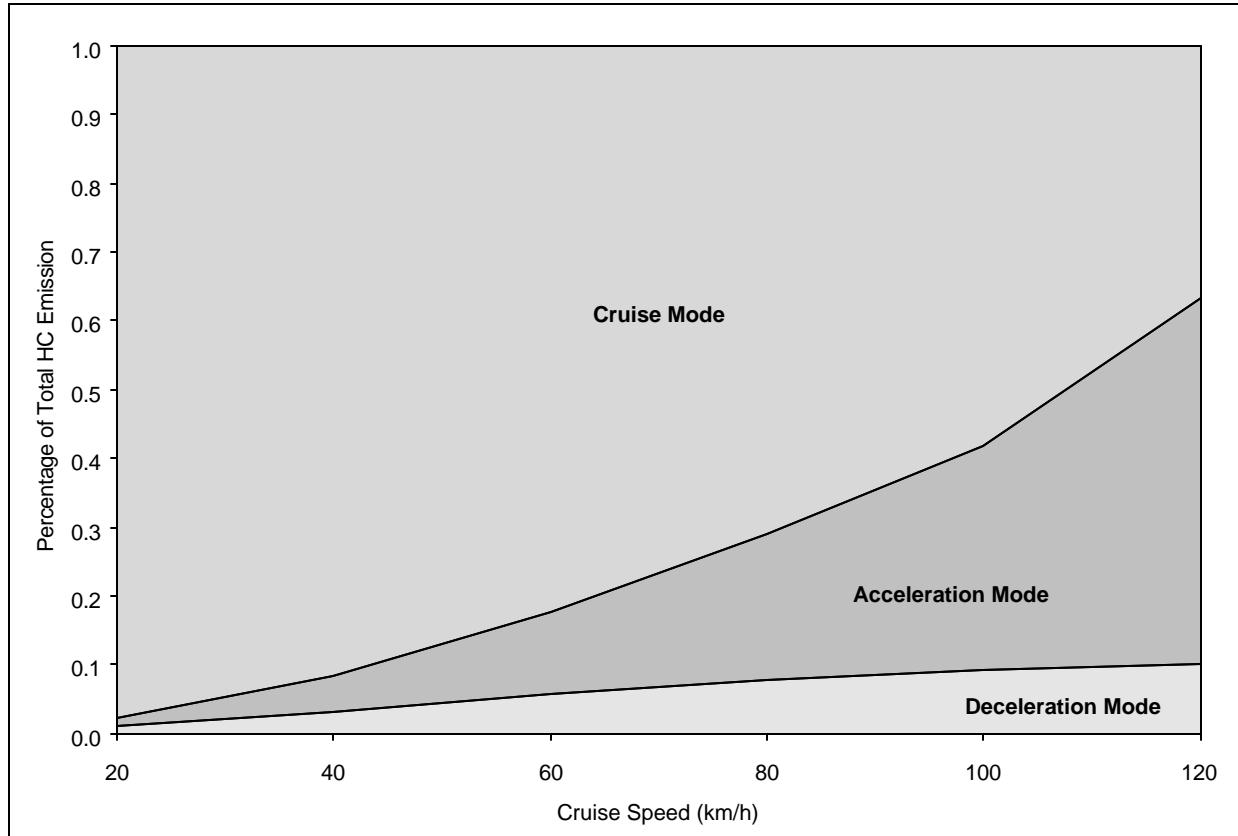


Figure 3-31. Variation in HC Emissions by Mode of Travel (Distance Traveled = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{max}$ )

### 3.5 Impact of Level of Deceleration on Vehicle Fuel Consumption and Emissions

The next step in quantifying the impact of vehicle stops on fuel consumption and emissions is to isolate the impact of vehicle decelerations on these MOEs. In conducting this analysis, six levels of constant deceleration rates are considered ranging from  $-0.25 \text{ m/s}^2$  to  $-1.5 \text{ m/s}^2$  at increments of  $-0.25 \text{ m/s}^2$ . The deceleration range that is considered is consistent with field observations that were presented earlier in this chapter.

Initially various deceleration rates are applied to a single cruise speed in order to quantify the impact of vehicle deceleration on various MOEs, Subsequently, different levels of cruise speeds are considered in order to capture the combined impact of deceleration and cruise speed on vehicle fuel consumption and emissions.

### 3.5.1 Impact of Level of Deceleration on Vehicle Fuel Consumption and Emission Rates for a Sample Cruise Speed

Different levels of deceleration are applied to a single-stop drive cycle that involves decelerating from a cruise speed of 80 km/h to a full stop followed by a subsequent acceleration to the 80 km/h cruise speed, as illustrated in Figure 3-32 and Figure 3-33. These drive cycles with varying levels of deceleration result in different speed/acceleration combinations, as summarized in Table 3-4. Specifically, for a deceleration rate of  $-0.25 \text{ m/s}^2$  the vehicle spends 33 percent of its trip in deceleration mode versus 6.4 percent when a deceleration rate of  $-1.5 \text{ m/s}^2$  is applied.

The variation in fuel consumption and emissions as a function of the deceleration level demonstrates that these MOEs are generally insensitive to the level of deceleration, as illustrated in Figure 3-34, Figure 3-35, and Figure 3-36. The CO emissions vary with the deceleration level in the same way as the HC emissions.

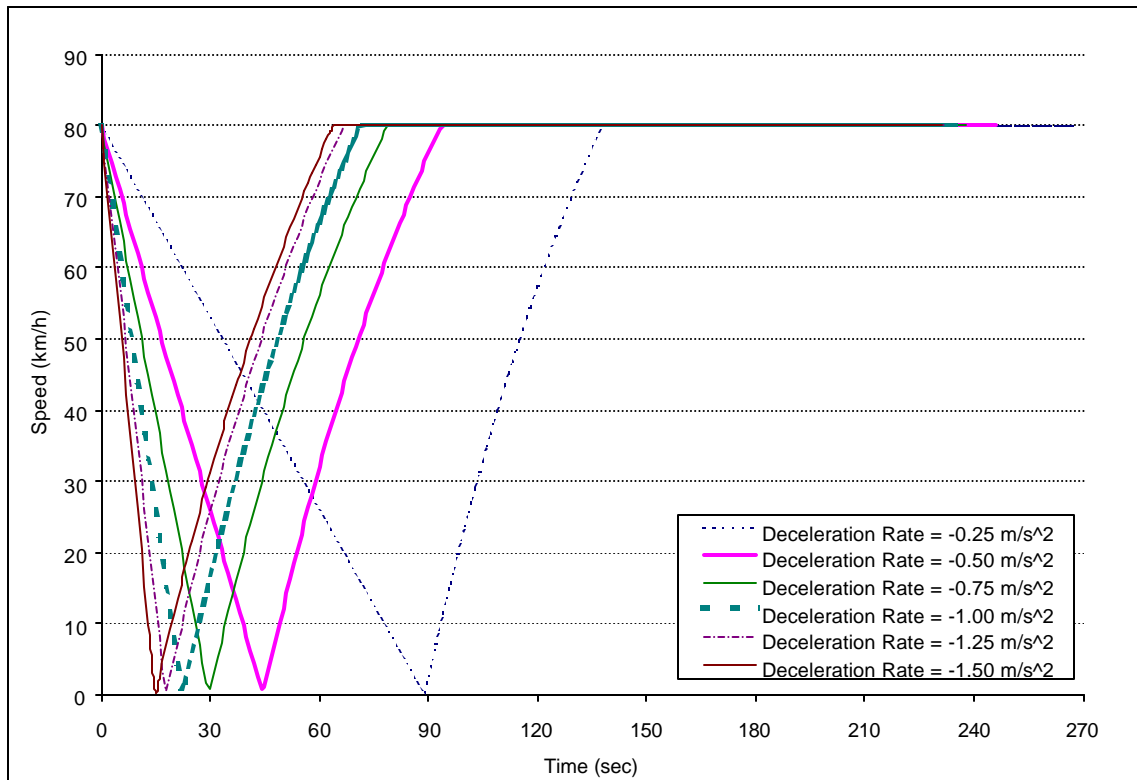


Figure 3-32. Temporal Variation in Single-Stop Speed Profile for Different Deceleration Levels (Cruise Speed = 80 km/h, Distance Traveled = 4.5 km, Acceleration Rate =  $0.2a_{max}$ )

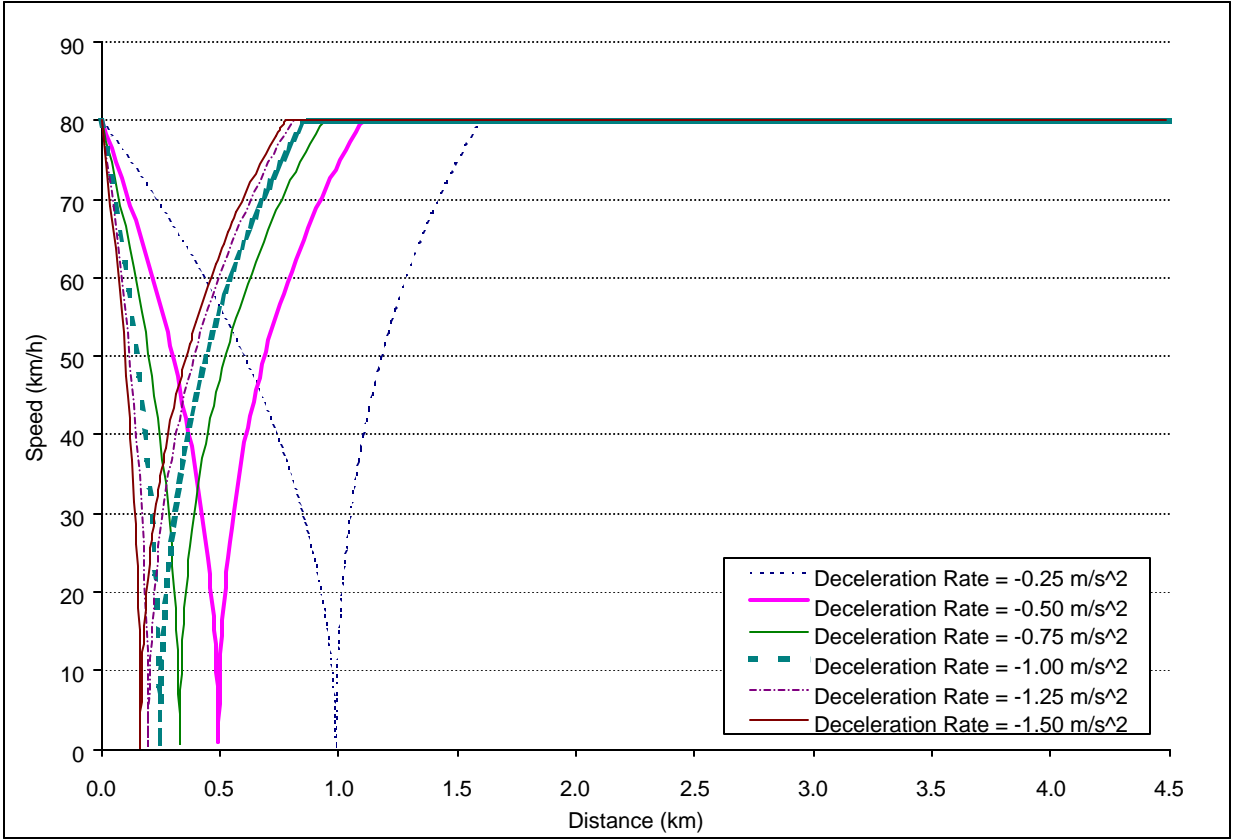


Figure 3-33. Spatial Variation in Single-Stop Speed Profile for Different Deceleration Levels (Cruise Speed = 80 km/h, Distance Traveled = 4.5 km, Acceleration Rate =  $0.2a_{max}$ )

Table 3-4. Speed/Acceleration Distribution for Single-Stop Drive Cycle (Cruise Speed = 80 km/h, Acceleration Rate =  $0.2a_{max}$ )

Deceleration = $-0.25 \text{ m/s}^2$											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration ( $\text{m/s}^2$ )	-1.5										
	-1.0										
	-0.5	4.14	4.14	4.14	4.17	4.14	4.14	4.14	4.14		33.13
	0.0				1.30	2.31	2.50	2.80	51.77		60.68
	0.5	1.68	1.79	1.94	0.78						6.19
	1.0										
Total		5.81	5.93	6.08	6.26	6.45	6.63	6.93	55.91		100.00
Deceleration = $-0.50 \text{ m/s}^2$											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration ( $\text{m/s}^2$ )	-1.5										
	-1.0										
	-0.5	2.27	2.23	2.27	2.27	2.23	2.27	2.23	2.27		18.07
	0				1.42	2.52	2.72	3.05	65.48		75.18
	0.5	1.83	1.95	2.11	0.85						6.74
	1.0										
Total		4.10	4.18	4.39	4.55	4.75	5.00	5.28	67.75		100.00
Deceleration = $-0.75 \text{ m/s}^2$											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration ( $\text{m/s}^2$ )	-1.5										
	-1	1.51	1.55	1.55	1.59	1.55	1.55	1.55	1.55		12.40
	-0.5	0.04									0.04
	0				1.47	2.60	2.81	3.14	70.60		80.61
	0.5	1.88	2.01	2.18	0.88						6.95
	1.0										
Total		3.43	3.56	3.73	3.94	4.15	4.36	4.69	72.15		100.00
Deceleration = $-1.00 \text{ m/s}^2$											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration ( $\text{m/s}^2$ )	-1.5										
	-1	1.15	1.19	1.19	1.19	1.15	1.19	1.19	1.19		9.44
	-0.5	0.04									0.04
	0				1.49	2.64	2.85	3.19	73.29		83.45
	0.5	1.91	2.04	2.21	0.89						7.06
	1										
Total		3.11	3.23	3.40	3.57	3.79	4.04	4.38	74.48		100.00
Deceleration = $-1.25 \text{ m/s}^2$											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration ( $\text{m/s}^2$ )	-1.5	0.90	0.95	0.95	0.99	0.95	0.95	0.95	0.99		7.60
	-1	0.04									0.04
	-0.5										
	0				1.50	2.66	2.88	3.22	74.96		85.22
	0.5	1.93	2.06	2.23	0.90						7.13
	1										
Total		2.88	3.01	3.18	3.39	3.61	3.82	4.17	75.95		100.00
Deceleration = $-1.50 \text{ m/s}^2$											
		Speed (km/h)									Total
		10	20	30	40	50	60	70	80	90	
Acceleration ( $\text{m/s}^2$ )	-1.5	0.78	0.78	0.82	0.82	0.78	0.82	0.78	0.82		6.40
	-1										
	-0.5	0.04									0.04
	0				1.51	2.68	2.90	3.24	76.06		86.39
	0.5	1.94	2.07	2.25	0.91						7.17
	1										
Total		2.77	2.85	3.07	3.24	3.46	3.72	4.02	76.88		100.00

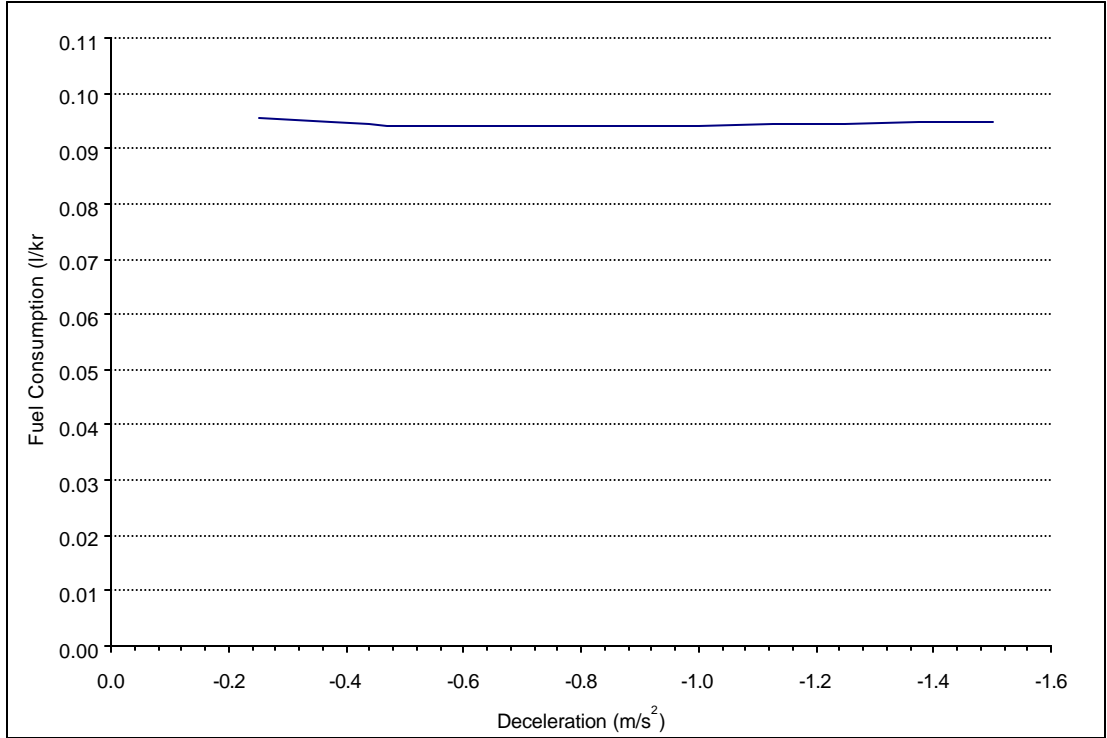


Figure 3-34. Variation in Fuel Consumption Rate as a Function of Deceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Acceleration Rate =  $0.2a_{max}$ )

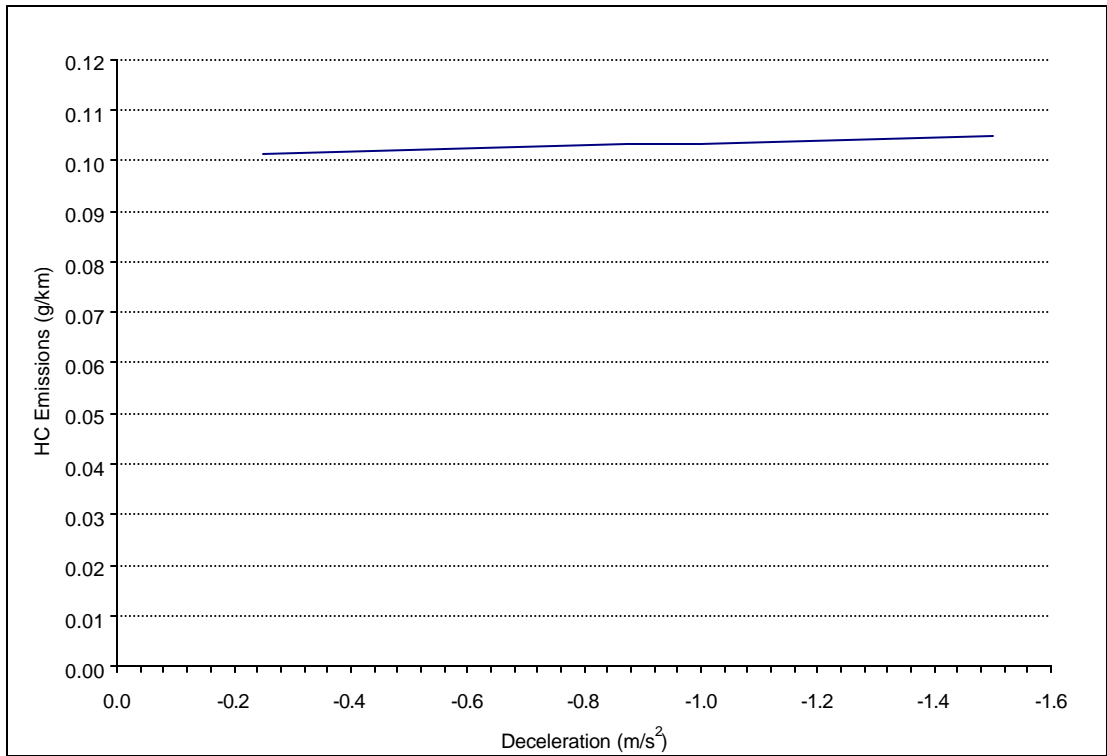


Figure 3-35. Variation in HC Emission Rate as a Function of Deceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Acceleration Rate =  $0.2a_{max}$ )

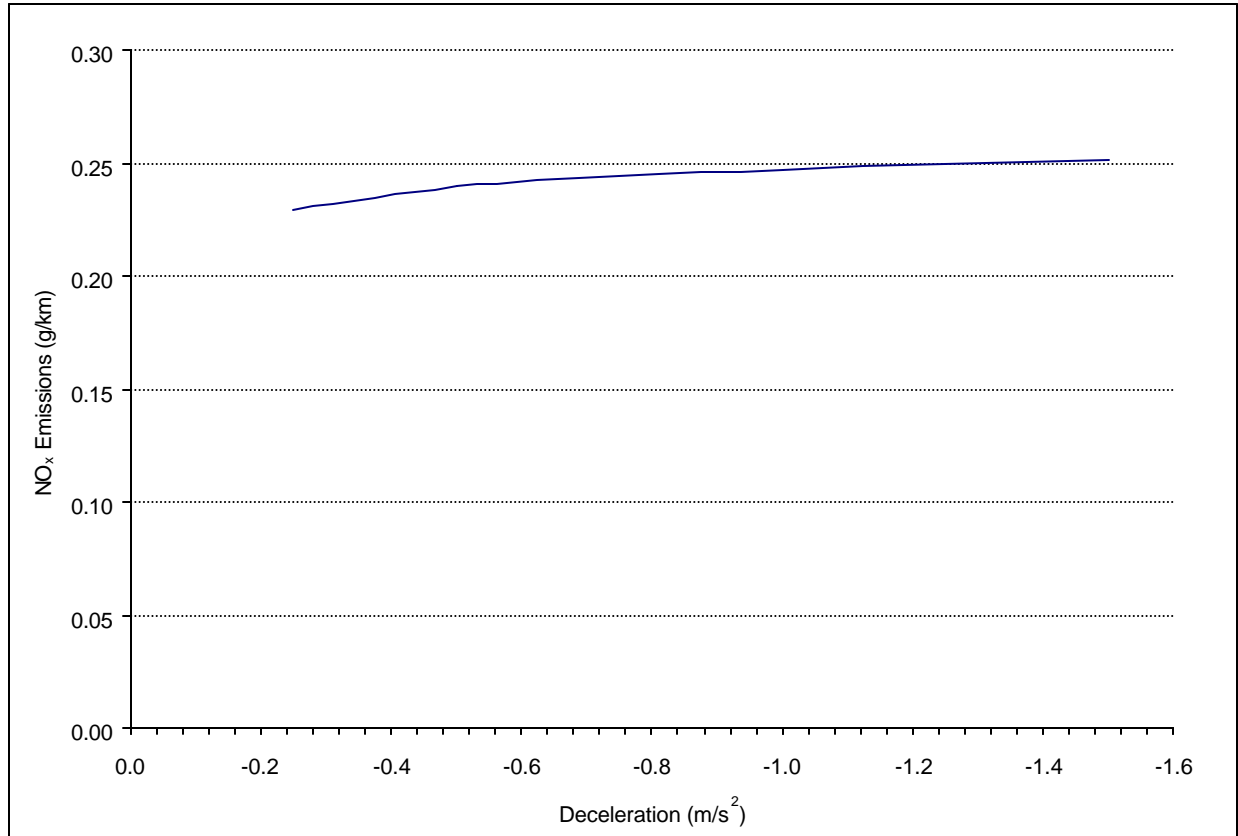


Figure 3-36. Variation in NO<sub>x</sub> Emission Rate as a Function of Deceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Acceleration Rate = 0.2a<sub>max</sub>)

### 3.5.2 Combined Impact of Level of Deceleration and Cruise Speed on Vehicle Fuel

#### Consumption and Emissions

In order to quantify the combined effect of vehicle deceleration and cruise speed on vehicle fuel consumption and emission rates, a total of 36 single-stop drive cycles involving 6 levels of cruise speed and 6 levels of deceleration were constructed.

As illustrated in Figure 3-37, the vehicle fuel consumption rate appears to be insensitive to the level of deceleration. Similarly, the impact of level of deceleration on HC emissions is also relatively small (within 40 percent) compared with the impact of the level of acceleration or cruise speed (exceed 100 percent), as demonstrated in Figure 3-38 or Figure 3-10. Specifically, the HC emission rate is less sensitive to the level of deceleration associated with lower cruise speeds than with higher cruise speeds. Similar finding can be drawn from the analysis of CO and

NO<sub>x</sub> emissions. The analysis in this section also verifies the previous finding that at high speeds the introduction of vehicle stops that involve extremely mild acceleration levels can actually reduce vehicle emission rates. Furthermore, it should be noted that, given a same level of acceleration, the combined effect of a vehicle's deceleration rate and cruise speed determines the direction that vehicle fuel consumption and emission rates may change, as was discussed in the previous section.

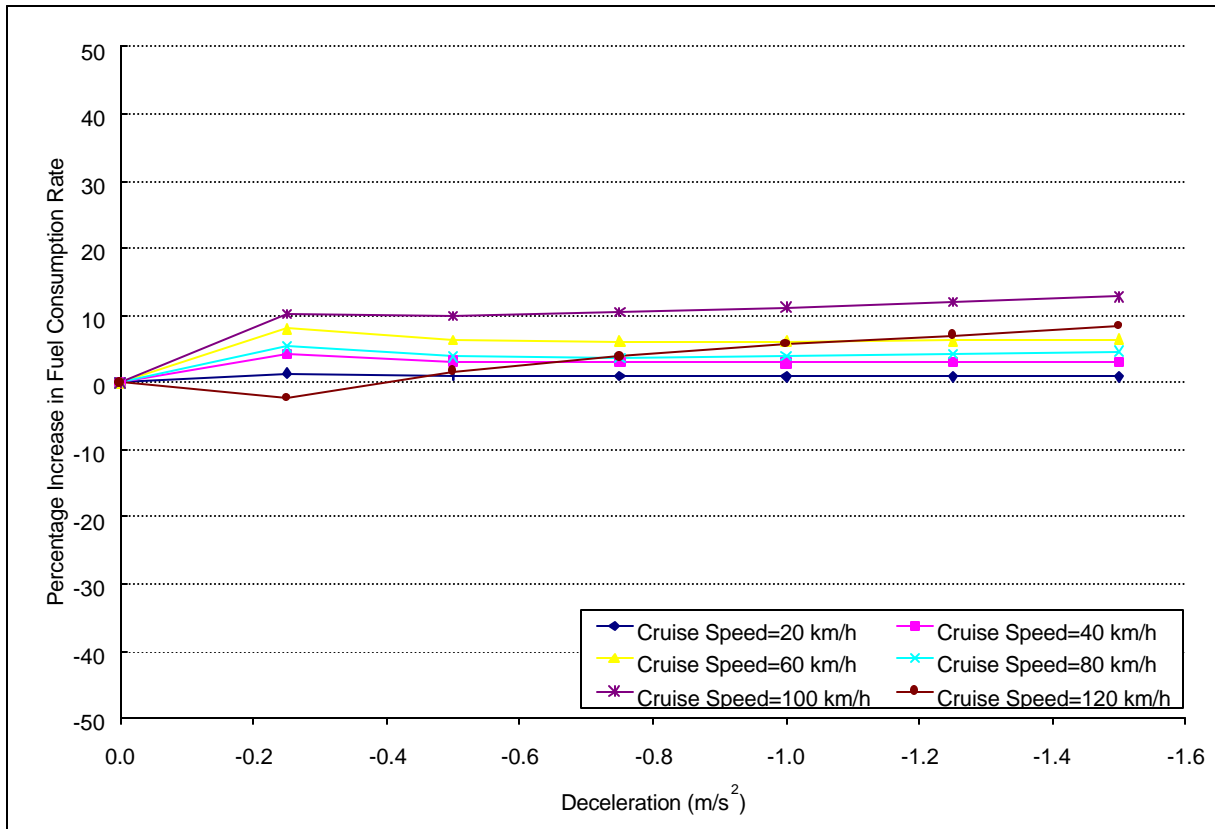


Figure 3-37. Percentage Increase in Fuel Consumption Rate as a Function of Vehicle Deceleration Rate (Distance Traveled = 4.5 km, Acceleration Rate =  $0.2a_{max}$ )

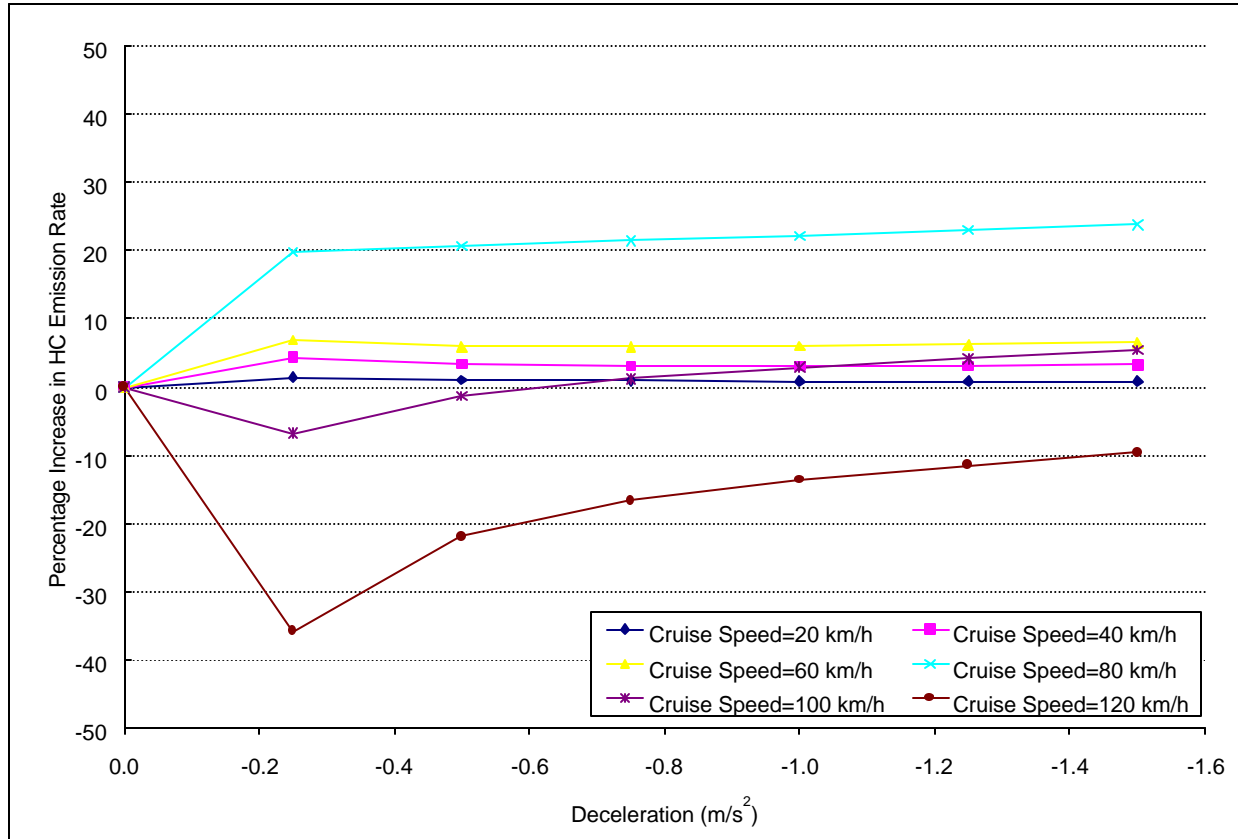


Figure 3-38. Percentage Increase in HC Emission Rate as a Function of Vehicle Deceleration Rate (Distance Traveled = 4.5 km, Acceleration Rate =  $0.2a_{max}$ )

### 3.6 Impact of Partial Stops on Vehicle Fuel Consumption and Emissions

The analyses presented in the previous sections only considered the impact of complete stops on vehicle fuel consumption and emissions. Alternatively, this section quantifies the impact of partial stops on vehicle fuel consumption and emissions using the base single-stop drive cycle set that was utilized in the previous analyses. Specifically, the single-stop drive cycles are modified using a speed variability factor ( $k_1$ ) that ranges from 0.0 to 1.0. The  $k_1$  factors are applied to the base single-stop drive cycles (6 cycles for cruise speeds ranging from 20 to 120 km/h at increments of 20 km/h) using Equation 3-1 and Equation 3-2, to generate multiple cycles with the same average speed, but different speed profiles, as illustrated in Figure 3-39 and Figure 3-40.

$$\bar{u} = \frac{\sum_{i=1}^n u_i}{n} \quad (3-1)$$

$$\tilde{u}_i = k_1(u_i - \bar{u}) + \bar{u} \quad (3-2)$$

Where:

$u_i$  = The instantaneous speed at instant "i"

$\bar{u}$  = The average speed for original speed profile

$\tilde{u}_i$  = The modified instantaneous speed at instant "i"

$n$  = The number of observations along the trip

$k_1$  = Speed variability factor

The number of vehicle stops for each cycle is computed using Equation 3-3, as the summation of the instantaneous partial stops. By maintaining the same average speed while varying the number of vehicle stops, it is possible to isolate the impact of vehicle stops on fuel consumption and emission rates.

$$S = \sum_i \frac{u_i - u_f}{u_f} \quad \forall i \ni u_i < u_{i-1} \quad (3-3)$$

Where:

$S$  = Number of vehicle stops

$u_i$  = Vehicle instantaneous speed at instant "i"

$u_f$  = Vehicle cruise speed during a trip

The application of the  $k_1$  factor alters the speed/acceleration distribution matrix while maintaining the same average speed, as demonstrated in Table 3-5. Specifically, a  $k_1$  factor of zero represents a trip at a constant speed with all observations in the 70 km/h and 0 m/s<sup>2</sup> bin. Alternatively, a  $k_1$  factor of one results in a speed/acceleration distribution that covers a wide range of speed/acceleration combinations.

It should be noted that a constant deceleration rate of  $-0.5 \text{ m/s}^2$  and a linearly decaying acceleration rate as a function of the vehicle speed were considered. The acceleration rate was assumed 20 percent the maximum feasible rate based on a limited field data characterization, as described earlier.

The results of the analysis indicate that for typical acceleration and deceleration rates the impact of stops on vehicle fuel consumption is relatively minor (increase of about 10 percent for an increase in the number of stops from 0.0 to 0.6 stops/km), as illustrated in Figure 3-41. Alternatively, the emission rates of HC, CO, and  $\text{NO}_x$  increase by 19, 23, and 30 percent, respectively for an increase in vehicle stops from 0.0 to 0.6 stops/km.

The percentage increase in vehicle fuel consumption and emission rates as a function of the number of vehicle stops relative to the base constant speed scenario, as illustrated in Figure 3-45, 3-46, 3-47, and 3-48. The figures demonstrate considerable increase in vehicle fuel consumption and emission rates as the number of stops increases especially at high cruise speeds. Specifically, the fuel consumption increases by 27 percent, while the HC, CO, and  $\text{NO}_x$  emissions increase by 104, 148, 78 percent, respectively.

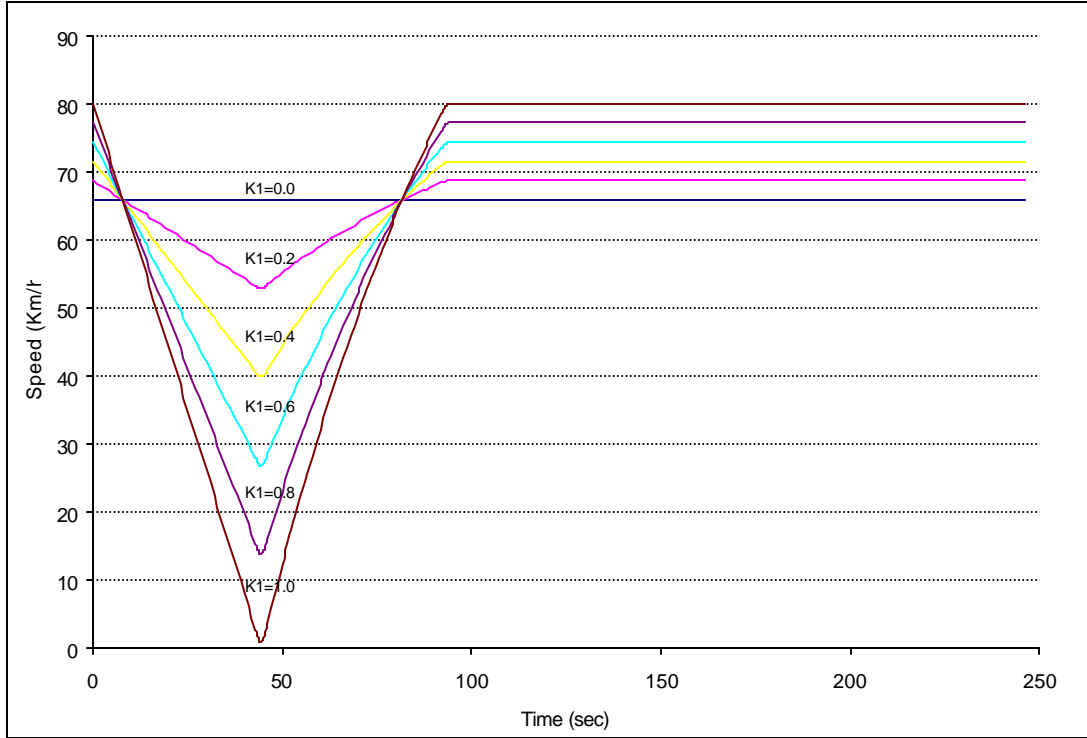


Figure 3-39. Temporal Variation in Single-Stop Speed Profile as a Function of  $k_1$  (Cruise Speed = 80 km/h, Distance Traveled = 4.5 km)

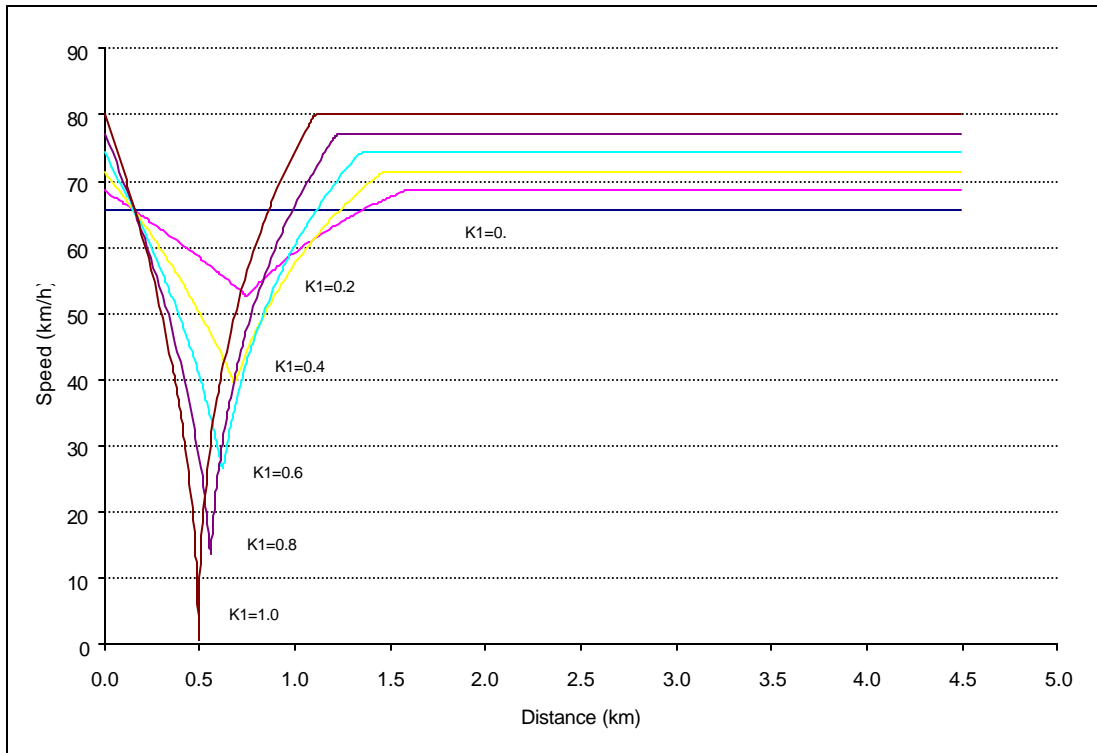


Figure 3-40. Spatial Variation in Single-Stop Speed Profile as a Function of  $k_1$  (Cruise Speed = 80 km/h, Distance Traveled = 4.5 km)

Table 3-5. Speed/Acceleration Distribution of Single-Stop Drive Cycle Set as a Function of  $k_1$  Factor (Cruise Speed=80 km/h)

<b><math>k_1 = 0.0</math></b>											
		Speed (km/h)								Total	
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5										
	0.0							100.00			100.00
	0.5										
	1.0										
Total								100.00			100.00
<b><math>k_1 = 0.2</math></b>											
		Speed (km/h)								Total	
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5						8.33	9.75			18.07
	0.0						7.43	74.49			81.93
	0.5										
	1.0										
Total							15.76	84.24			100.00
<b><math>k_1 = 0.4</math></b>											
		Speed (km/h)								Total	
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5				0.32	5.61	5.65	5.65	0.85		18.07
	0.0				0.24	4.87	5.89	7.55	63.36		81.93
	0.5										
	1.0										
Total					0.57	10.48	11.54	13.20	64.22		100.00
<b><math>k_1 = 0.6</math></b>											
		Speed (km/h)								Total	
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5			1.38	3.78	3.74	3.78	3.78	1.62		18.07
	0.0			1.14	3.21	3.70	4.26	5.08	64.54		81.93
	0.5										
	1.0										
Total				2.52	6.99	7.43	8.04	8.85	66.17		100.00
<b><math>k_1 = 0.8</math></b>											
		Speed (km/h)								Total	
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5		1.95	2.80	2.84	2.80	2.80	2.84	2.03		18.07
	0.0		0.85	2.44	2.64	3.01	3.33	3.78	65.15		81.19
	0.5		0.73								0.73
	1.0										
Total			3.53	5.24	5.48	5.81	6.13	6.62	67.18		100.00
<b><math>k_1 = 1.0</math></b>											
		Speed (km/h)								Total	
		10	20	30	40	50	60	70	80	90	
Acceleration (m/s <sup>2</sup> )	-1.0										
	-0.5	2.27	2.23	2.27	2.23	2.27	2.23	2.27	2.27		18.07
	0.0				0.65	2.48	2.76	3.05	65.48		74.41
	0.5	1.83	1.95	2.11	1.62						7.51
	1.0										
Total		4.10	4.18	4.39	4.51	4.75	5.00	5.32	67.75		100.00

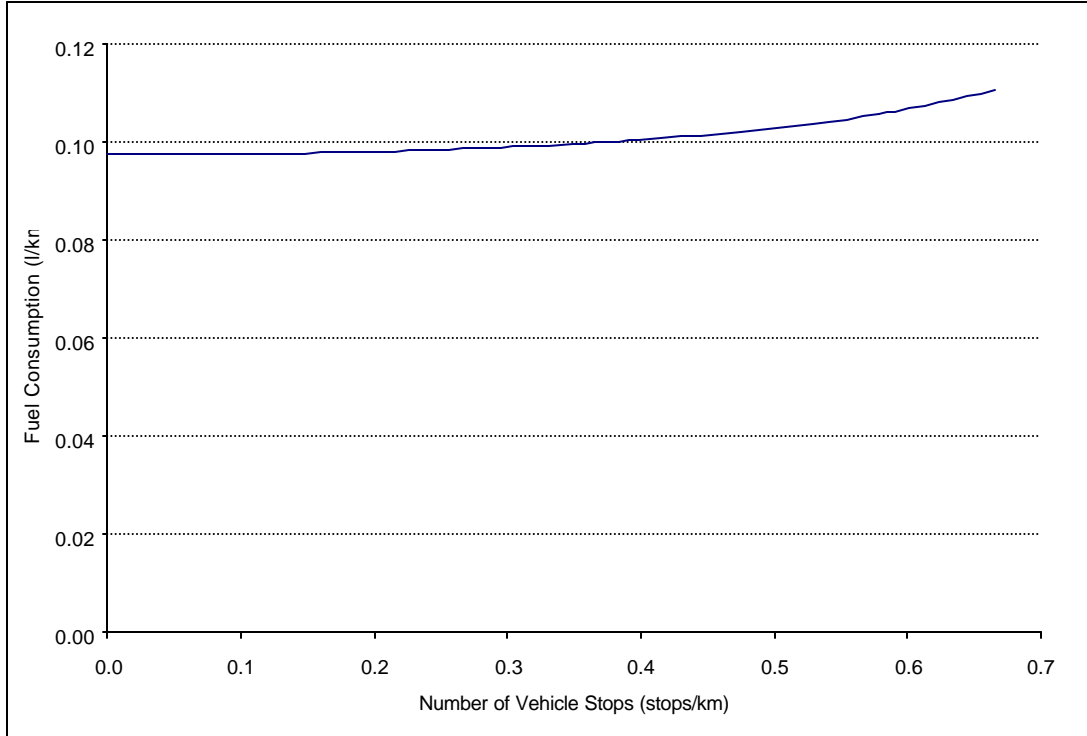


Figure 3-41. Variation in Fuel Consumption Rate as a Function of Number of Vehicle Stops (Cruise Speed = 80 km/h, Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{max}$ )

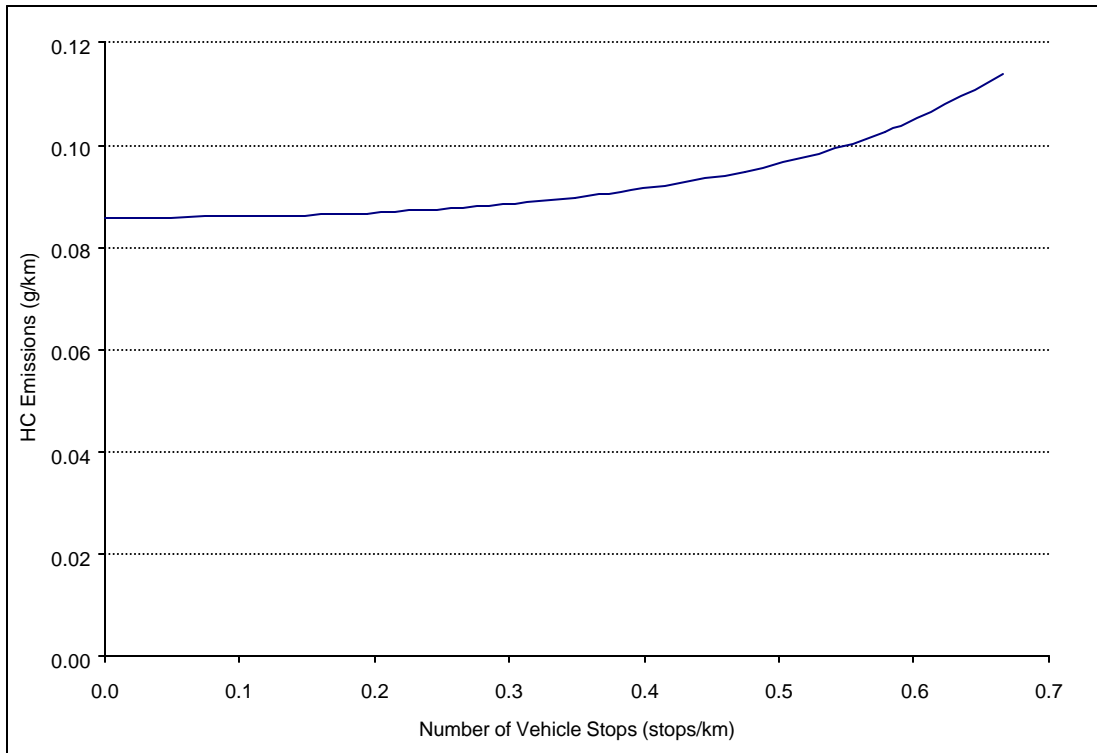


Figure 3-42. Variation in HC Emission Rate as a Function of Number of Vehicle Stops (Cruise Speed = 80 km/h, Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{max}$ )

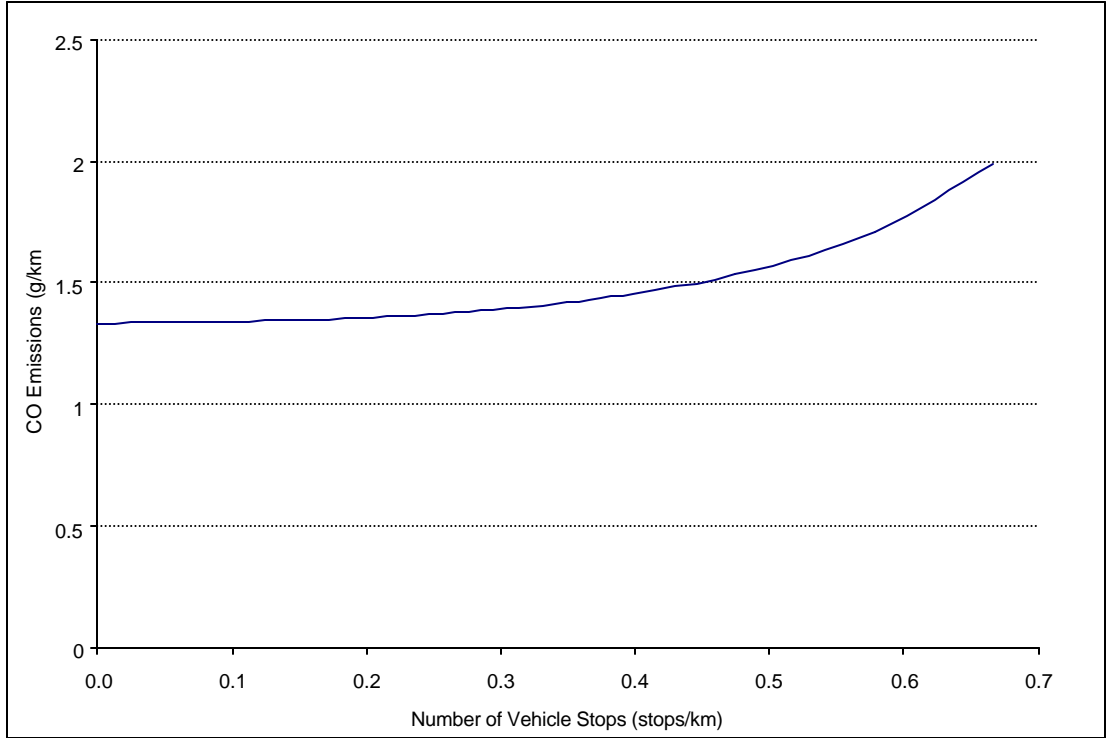


Figure 3-43. Variation in CO Emissions Rate as a Function of Number of Vehicle Stops (Cruise Speed = 80 km/h, Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{max}$ )

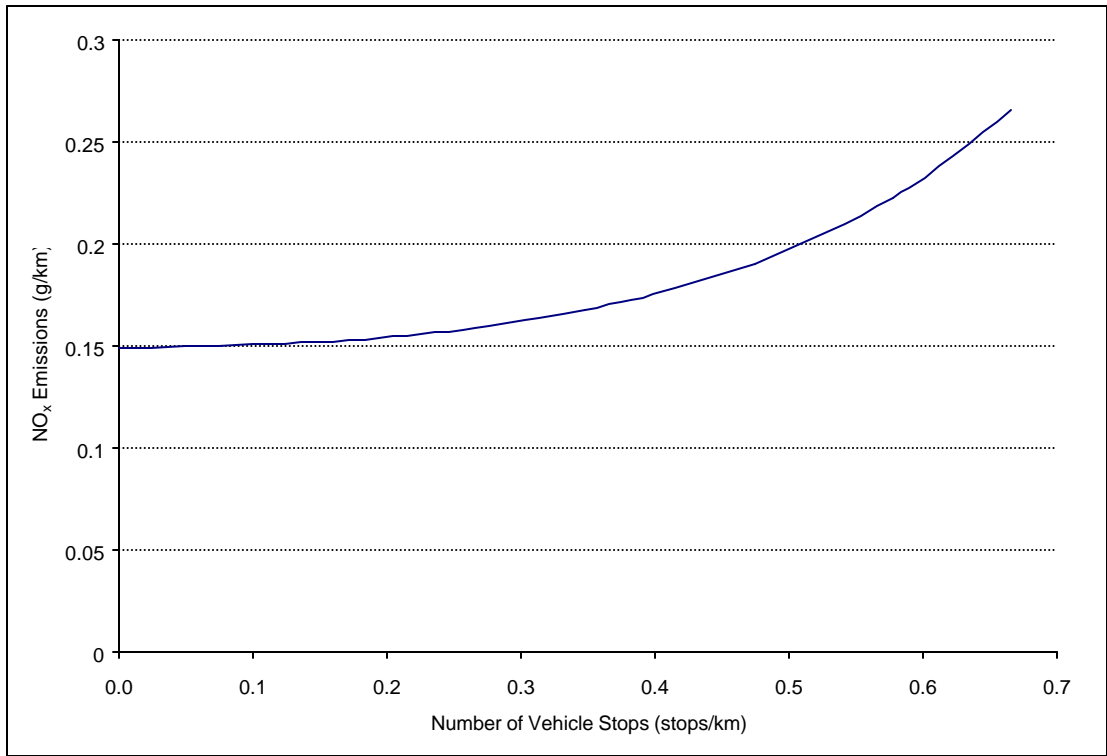


Figure 3-44. Variation in NO<sub>x</sub> Emission Rate as a Function of Number of Vehicle Stops (Cruise Speed = 80 km/h, Distance = 4.5 km, Deceleration Rate =  $-0.5 \text{ m/s}^2$ , Acceleration Rate =  $0.2a_{max}$ )

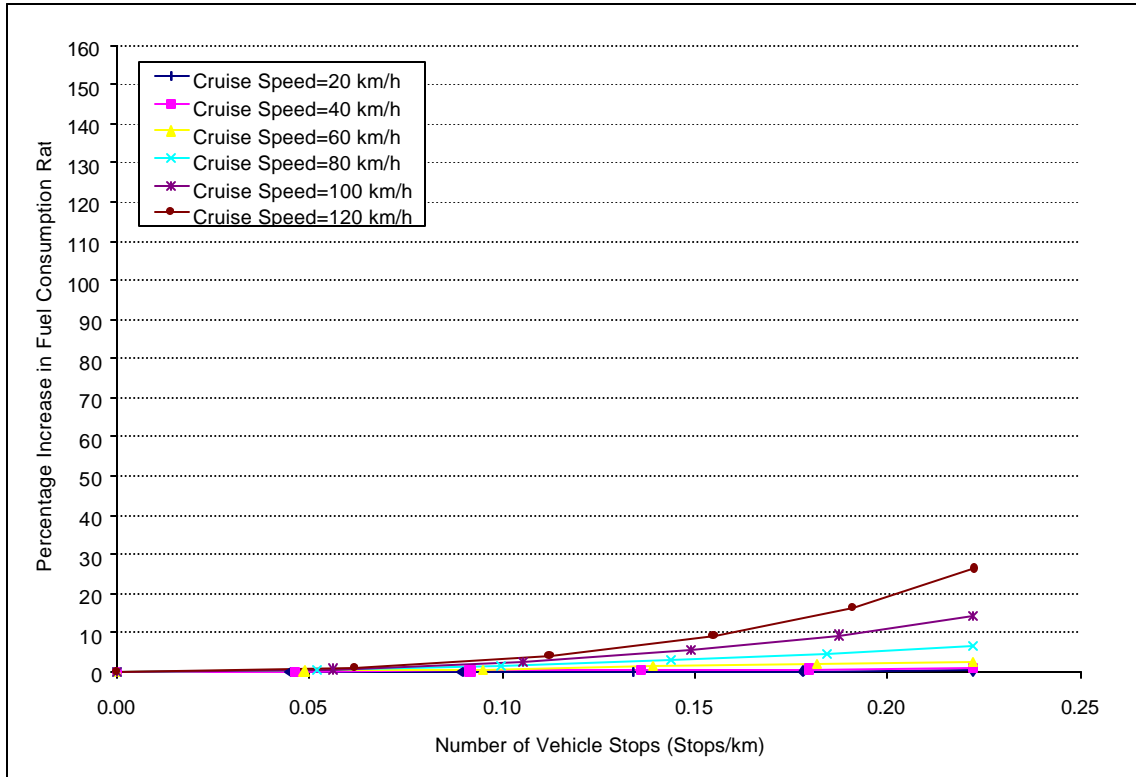


Figure 3-45. Percentage Increase in Fuel Consumption Rate as a Function of Number of Vehicle Stops

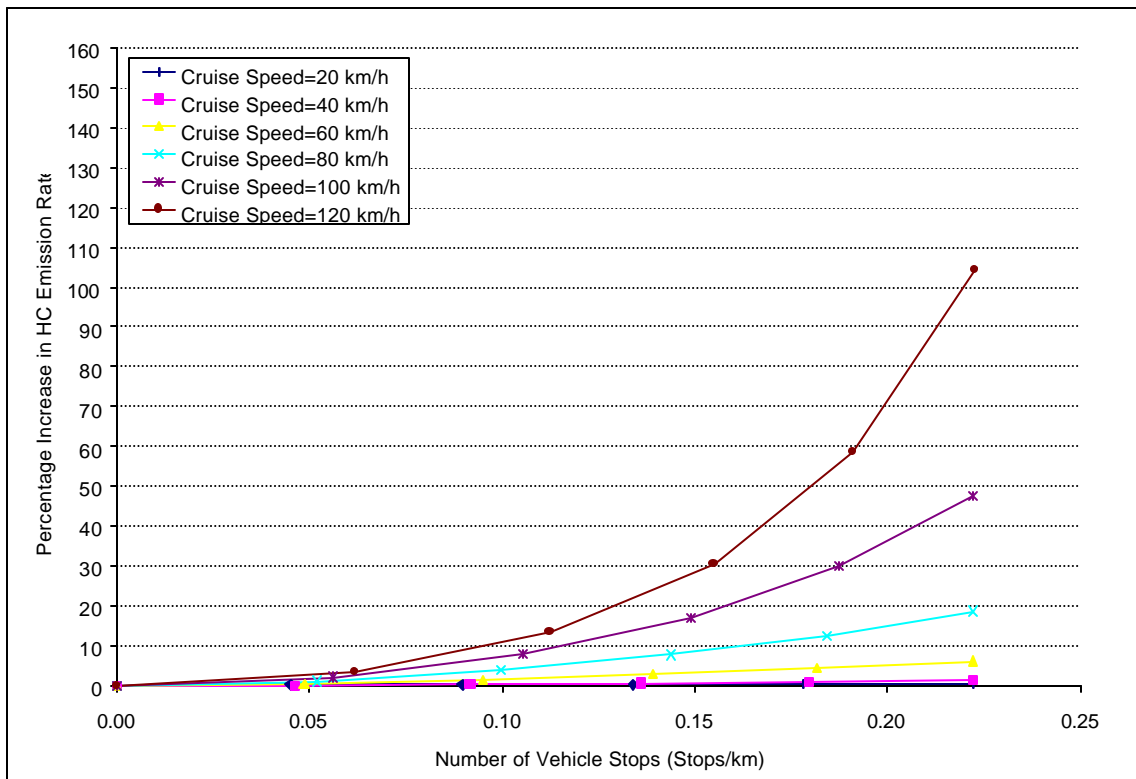


Figure 3-46. Percentage Increase in HC Emission Rate as a Function of Number of Vehicle Stops

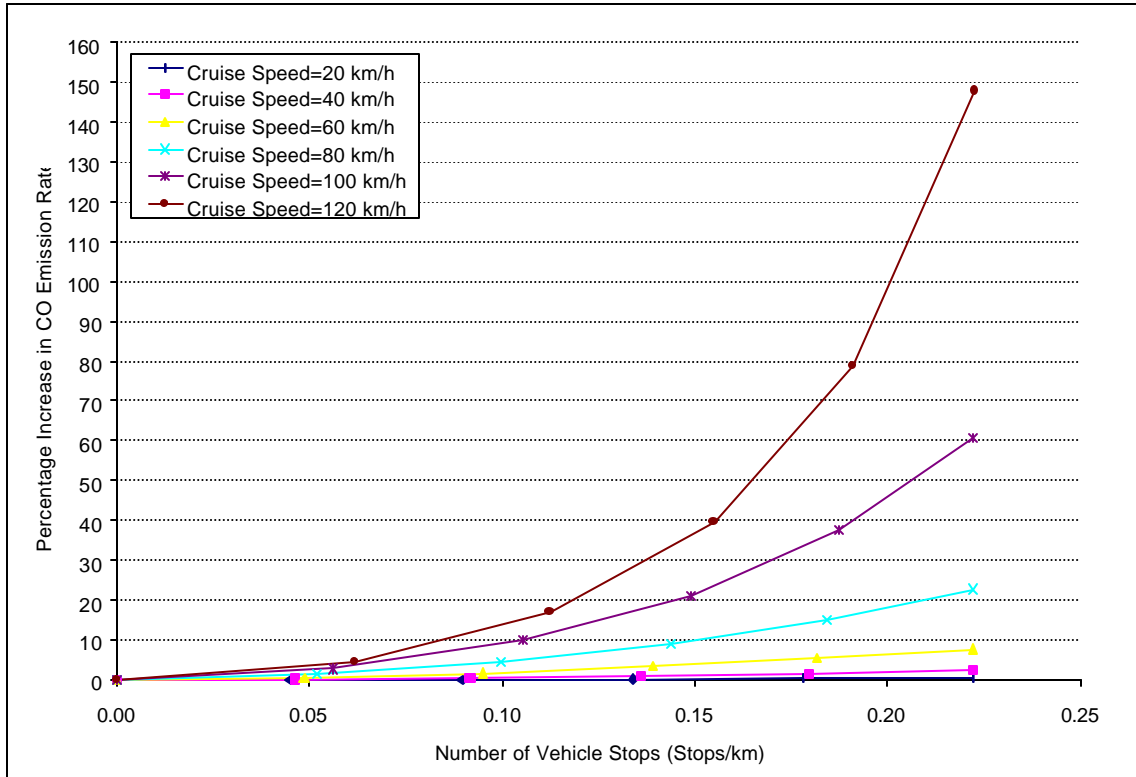


Figure 3-47. Percentage Increase in CO Emission Rate as a Function of Number of Vehicle Stops

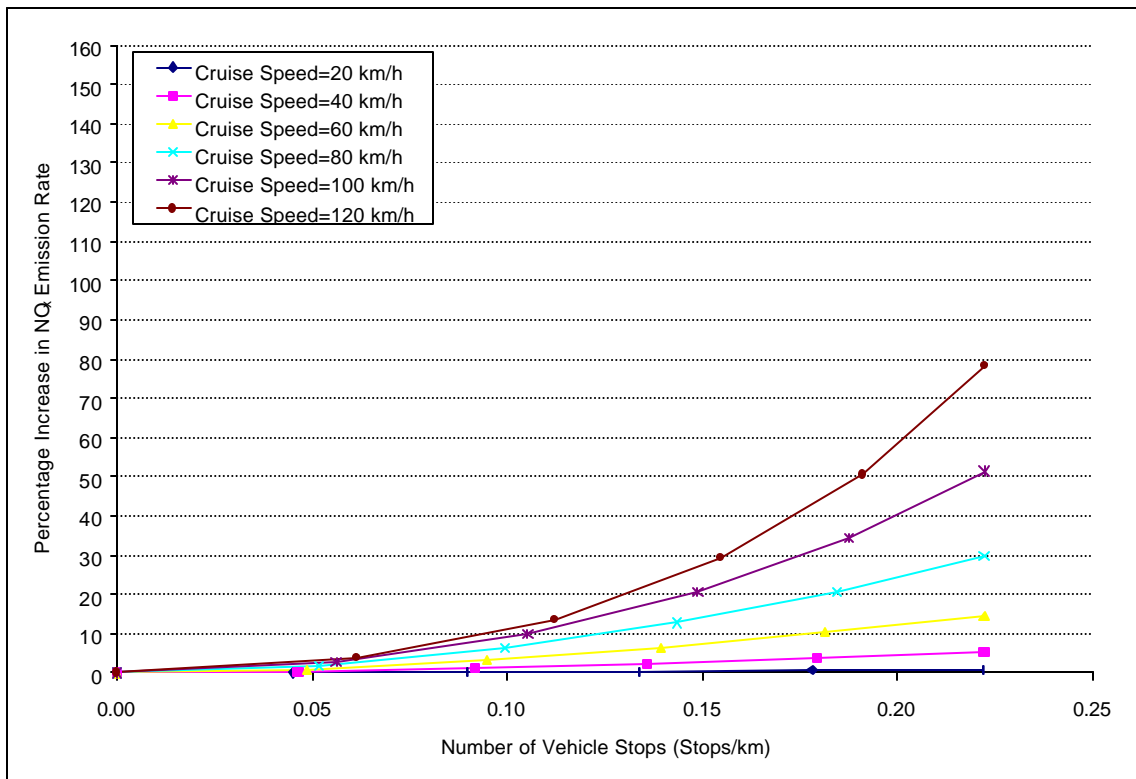


Figure 3-48. Percentage Increase in NO<sub>x</sub> Emission Rate as a Function of Number of Vehicle Stops

### 3.7 Summary of Findings

The impact of vehicle stops and their associated levels of acceleration and deceleration on vehicle fuel consumption and emission rates are quantified in this chapter. The analysis that is presented indicates that vehicle fuel consumption and emission rates increase considerably as the number of vehicle stops increases especially at high cruise speeds. However, vehicle fuel consumption is more sensitive to the cruise speed level than to vehicle stops.

The aggressiveness of a vehicle stop does have an impact on vehicle fuel consumption and emissions. Specifically, the HC and CO emission rates are highly sensitive to the level of acceleration when compared to cruise speed in the range of 0 to 120 km/h. Alternatively, NO<sub>x</sub> emissions typically increase at acceleration rates in the range of 0.0 to 0.8a<sub>max</sub> and decrease at acceleration rates in excess of 0.8a<sub>max</sub>. The impact of the deceleration level on all MOEs is relatively small, compared with the other factors considered in this chapter. Furthermore, the combined effect of the level of acceleration, the level of deceleration, and the cruise speed determines the direction that vehicle fuel consumption and emissions may change. Contrary to traditional understanding, this study demonstrates that at high speeds the introduction of vehicle stops that involve extremely mild acceleration levels can actually reduce vehicle emission rates.

Having quantified the impact of vehicle stops on fuel consumption and emissions in this chapter, the following chapter analyzes the impact of average speed and speed variability on vehicle fuel consumption and emission rates.

## **CHAPTER 4 : IMPACT OF SPEED VARIABILITY ON VEHICLE FUEL CONSUMPTION AND EMISSION RATES**

Chapter 3 quantified the impact of vehicle cruise speed and vehicle stops and their associated levels of acceleration and deceleration on vehicle fuel consumption and emission rates. This chapter extends the analysis that was conducted in Chapter 3 by quantifying the impact of speed variability on vehicle fuel consumption and emission rates using three standard Federal Test Procedure (FTP) drive cycle sets in addition to the single-stop drive cycles that were developed in Chapter 3. The FTP drive cycles include the FTP city cycle, the US06 cycle, and the New York cycle. As was the case in Chapter 3, for each of the drive cycles vehicle fuel consumption and emissions are computed using microscopic models developed by Ahn *et al.* (1999).

Finally, this chapter investigates the appropriateness of average speed and speed variability as explanatory variables for estimating fuel consumption and emission rates. Specifically, the proportion of the squared error explained by each of these explanatory variables is quantified and compared.

### **4.1 Description and Characterization of Standard Drive Cycles**

As mentioned earlier, the data used for this analysis included three standard drive cycles, namely; the FTP city cycle, the New York City cycle and the US06 cycle. These cycles cover a wide range of traffic conditions including city and freeway driving, mild and aggressive accelerations, and high speed and low speed driving. Consequently, these cycles appear to cover a wide range of driving behaviors.

The three drive cycles are briefly described and characterized in this section.

#### ***4.1.1 The FTP City Drive Cycle***

The current FTP city drive cycle is officially called the Urban Dynamometer Driving Schedule (UUDS). It was developed to simulate a vehicle operating over a typical home to work commuting trip in Los Angeles that covers both arterial and freeway driving. Consequently this cycle is also called the LA City Cycle. The cycle involves an initial 505 seconds of travel after a cold start and 867 seconds of travel in hot stabilized conditions. The city drive cycle has been the standard drive cycle for the certification of LDVs (light-duty vehicles) and LDTs (light-duty trucks) since 1972. In 1975, the cycle was modified to repeat the initial 505 seconds following a 10-minute soak at the end of the cycle. Therefore, the current cycle consists of three bags of emissions, bag 1 is representative of a cold start over a 505-second period, bag 2 is representative of hot stabilized emissions, and bag 3 represents hot start emissions over the same 505-second speed profile of bag 1, as illustrated in Figure 4-1.

The average speed for the entire cycle is 31 km/h, with a maximum cruise speed of 91 km/h and a maximum acceleration rate of  $1.5 \text{ m/s}^2$ , as demonstrated in Table 4-1. Consequently, this drive cycle does not characterize aggressive driving behavior.

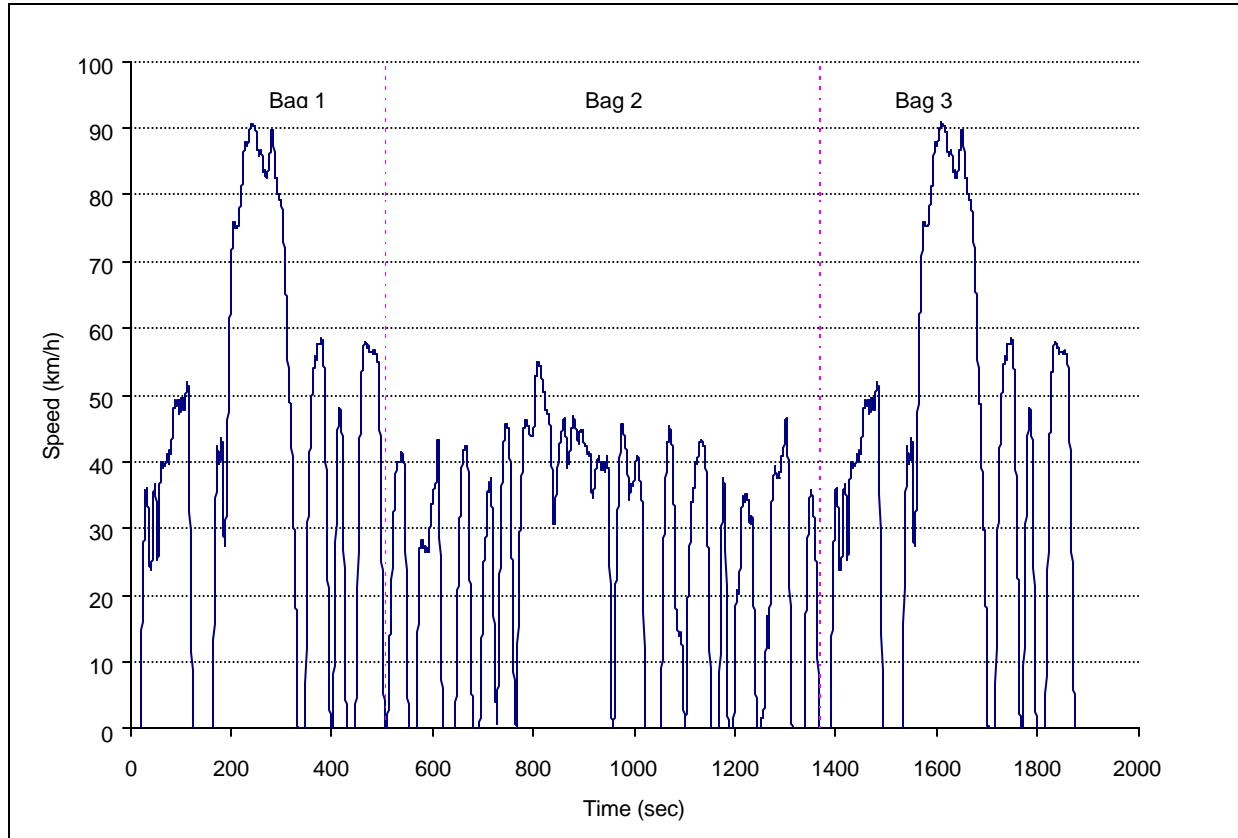


Figure 4-1. Speed Profile of FTP City Cycle

Table 4-1. Speed/Acceleration Characterization of the FTP City Cycle

		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130		140
Acceleration (m/s <sup>2</sup> )	-4.0															
	-3.5															
	-3.0															
	-2.5															
	-2.0															
	-1.5	1.17	2.34	2.26	1.97	0.80	0.15									
	-1.0	1.17	0.36	0.80	1.46	0.73	0.44	0.22	0.15							
	-0.5	0.80	0.95	0.95	4.53	7.59	2.70	0.07	0.80	2.04	0.22					
	0.0	18.91	0.44	2.77	10.88	10.44	3.21		1.39	2.48	0.58					
	0.5	1.09	0.95	2.34	2.12	0.73	0.22	0.29								
	1.0	2.26	2.19	1.17	0.58	0.22	0.07									
	1.5															
2.0																
2.5																
3.0																
3.5																
Total	25.40	7.23	10.29	21.53	20.51	6.79	0.58	2.34	4.53	0.80						

### 4.1.2 The New York City Cycle

The New York City cycle reflects city driving during heavy congestion. Specifically, vehicle speeds are low and vehicle movements consist primarily of vehicle stops, starts, and

accelerations, as illustrated in Figure 4-2. The average speed for this cycle is 11 km/h, with a maximum cruise speed is 44 km/h and a maximum acceleration is 2.7 m/s<sup>2</sup>, as summarized in Table 4-2. This drive cycle only involves travel along congested arterial roadways, however, it does include significant vehicle accelerations.

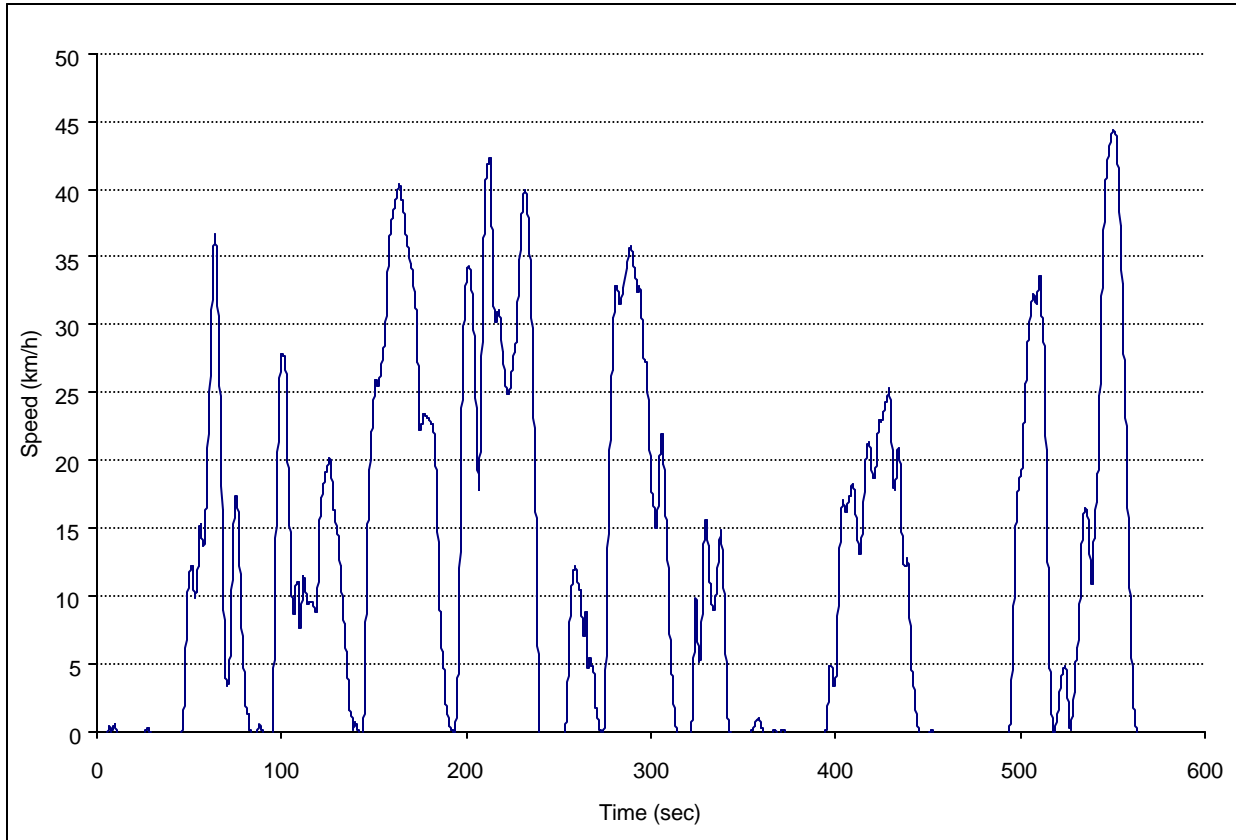


Figure 4-2. Speed Profile of New York City Drive Cycle

Table 4-2. Speed/Acceleration Characterization of the New York City Drive Cycle

		Speed (km/h)														Total
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-4															
	-3.5															
	-3		0.17													0.17
	-2.5		0.33	0.33												0.67
	-2		0.17	1.17	0.50											1.84
	-1.5	1.34	1.84	0.83	0.67	0.33										5.01
	-1	2.00	2.67	0.83	1.34	0.17										7.01
	-0.5	8.35	3.84	2.84	3.17	0.50										18.70
	0	38.90	4.67	3.84	3.67	1.00										52.09
	0.5	2.17	3.01	1.00	1.34											7.51
	1	2.50	0.83	0.67	0.33											4.34
	1.5	0.50	0.67	0.33	0.17											1.67
	2	0.50		0.17												0.67
	2.5	0.17	0.17													0.33
	3															
	3.5															
Total	56.43	18.36	12.02	11.19	2.00										100.00	

### 4.1.3 The US06 Cycle

As one of the Supplemental Federal Test Procedure (SFTP) cycles, the US06 drive cycle was designed to reflect aggressive driving behavior including rapid speed fluctuations (high speeds and/or high accelerations) while a vehicle operates in a hot-stabilized mode. The average speed for the US06 cycle is 77 km/h, with a maximum speed of 129 km/h and a maximum acceleration of 3.7 m/s<sup>2</sup>, as illustrated in Figure 4-3 and Table 4-3. As demonstrated in Table 4-3 the US06 drive cycle does cover a wide range of speed/acceleration combinations, including travel at relatively high speeds and aggressive accelerations.

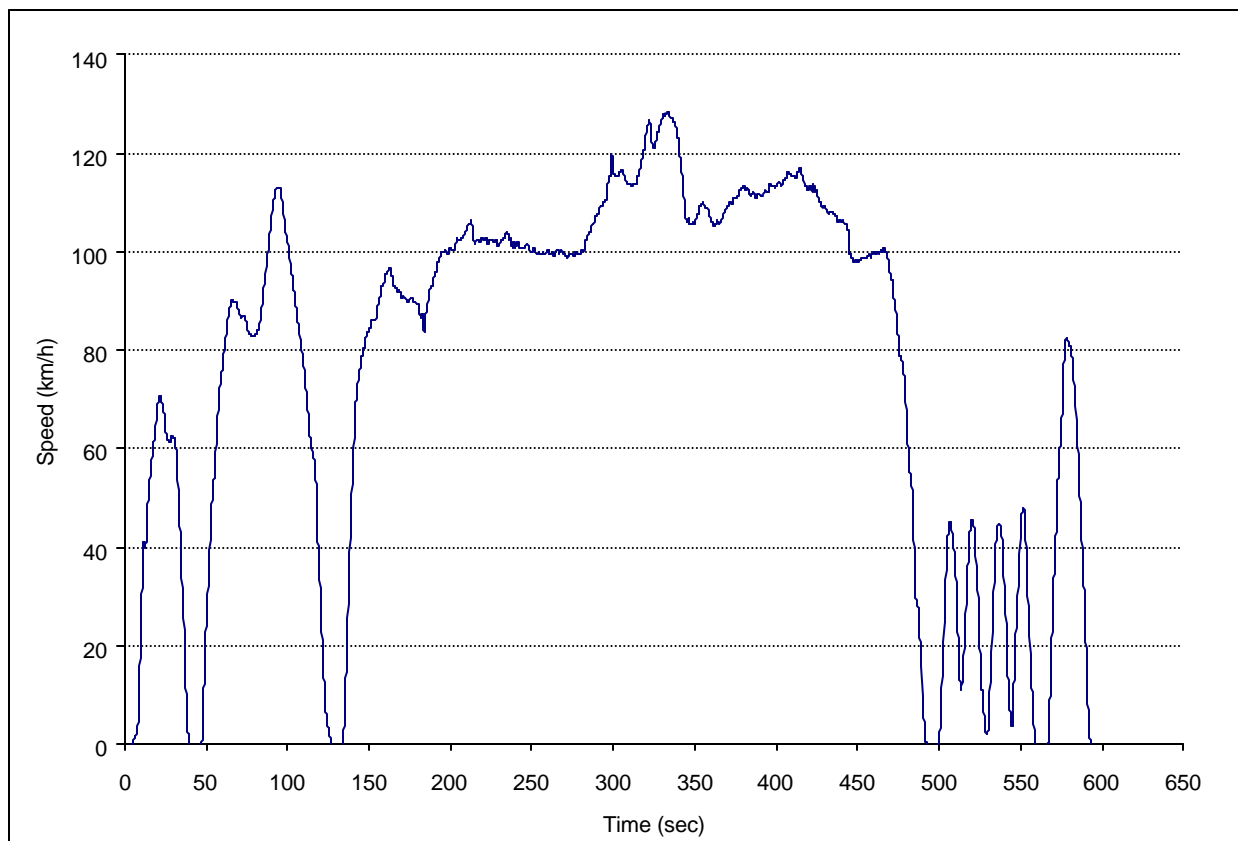


Figure 4-3. Speed Profile of US06 Drive Cycle

Table 4-3. Speed/Acceleration Characterization of the US06 Drive Cycle

		Speed (km/h)														Total
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-4.0															0.17
	-3.5					0.17										1.00
	-3.0		0.17	0.67	0.17											3.33
	-2.5	0.17	0.50	0.50	1.16	0.50	0.50									3.49
	-2.0	0.50	0.67	0.17	0.50	0.50	0.33	0.50	0.33							3.49
	-1.5	0.17	0.17	0.17	0.17	0.33	0.17	0.50	0.67	0.50		0.33	0.33			6.49
	-1.0	1.00	0.17			0.33	0.33		0.67	1.00	1.16	0.83	0.67	0.33		24.13
	-0.5	0.50		0.17		0.67		1.00	0.33	2.66	4.33	8.15	5.16	1.16		41.76
	0.0	7.99	0.17			0.33		0.50	0.33	2.83	8.32	11.48	7.99	1.83		5.66
	0.5					0.33	0.33	0.33	1.16	1.33	1.16	0.50	0.17	0.33		2.50
	1.0	0.17		0.17	0.17	0.17	0.67	0.50	0.17	0.17			0.33			3.16
	1.5	0.33	0.33	0.50	1.00	0.50	0.33	0.17								2.50
	2.0	0.17	0.67	0.50	0.50	0.17	0.17	0.17	0.17							1.83
	2.5	0.67	0.33	0.50	0.17	0.17										0.17
	3.0		0.17													0.33
	3.5	0.33														
	<b>Total</b>	<b>11.98</b>	<b>3.33</b>	<b>3.33</b>	<b>3.83</b>	<b>4.16</b>	<b>2.83</b>	<b>3.66</b>	<b>3.83</b>	<b>8.49</b>	<b>14.98</b>	<b>21.30</b>	<b>14.64</b>	<b>3.66</b>	<b>100.00</b>	

## 4.2 Construction of Modified Drive Cycles

For purposes of this study and in order to systematically demonstrate the inadequacy of average speed as a sole explanatory variable, the three drive cycles that were described earlier are modified to construct a number of additional hypothetical drive cycles. This section not only describes how these hypothetical drive cycles are constructed, but also characterizes these drive cycles.

### 4.2.1 Speed Variability Factor ( $k_1$ )

The objective of this section is to determine the sensitivity of fuel consumption and emissions to the variability of speed about the average speed. In doing so, a speed variability factor ( $k_1$ ) is applied to the FTP city cycle, the New York cycle, and the US06 cycle. Equation 3-1 and Equation 3-2 show how an average speed for a cycle is computed and how the speed variability factor ( $k_1$ ) is applied to vary the variability about the average speed. By altering  $k_1$ , different speed profiles are generated for each cycle while maintaining the same average speed. Figure 4-4, 4-6, and 4-8 illustrate the resultant drive cycles for the FTP city cycle, the New York City cycle and the US06 cycle, respectively, using different values of the speed variability factor. The speed/acceleration matrix for each of these drive cycles is shown in Table 4-4, 4-5, and 4-6. It should be noted that some observations in the three cycles are unrealistic, i.e. some accelerations exceed the maximum feasible accelerations and some decelerations exceed the maximum

decelerations observed in the ORNL data. Therefore, a robust form of acceleration smoothing that was employed to the GPS field data is also applied to these cycles. Figure 4-5, 4-7, and 4-9 illustrate the frequencies of accelerations observed in these cycles as a proportion of the maximum feasible acceleration.

As shown in Figure 4-5 and Figure 4-7, over 90 percent of the observations for each resultant cycle experience accelerations in the range of 0 to 50 percent the maximum feasible acceleration. These acceleration levels are consistent with the field data that were described in the previous chapter. The cycles that are derived from the US06 cycle do involve some high levels of accelerations that exceed the maximum acceleration level observed in the field data. However, the majority of observations in these cycles still experience accelerations in the range of 0 up to 50 percent the maximum feasible acceleration, as illustrated in Figure 4-9. In general, the acceleration distributions of these cycles follow the similar trends as their associated original cycles.

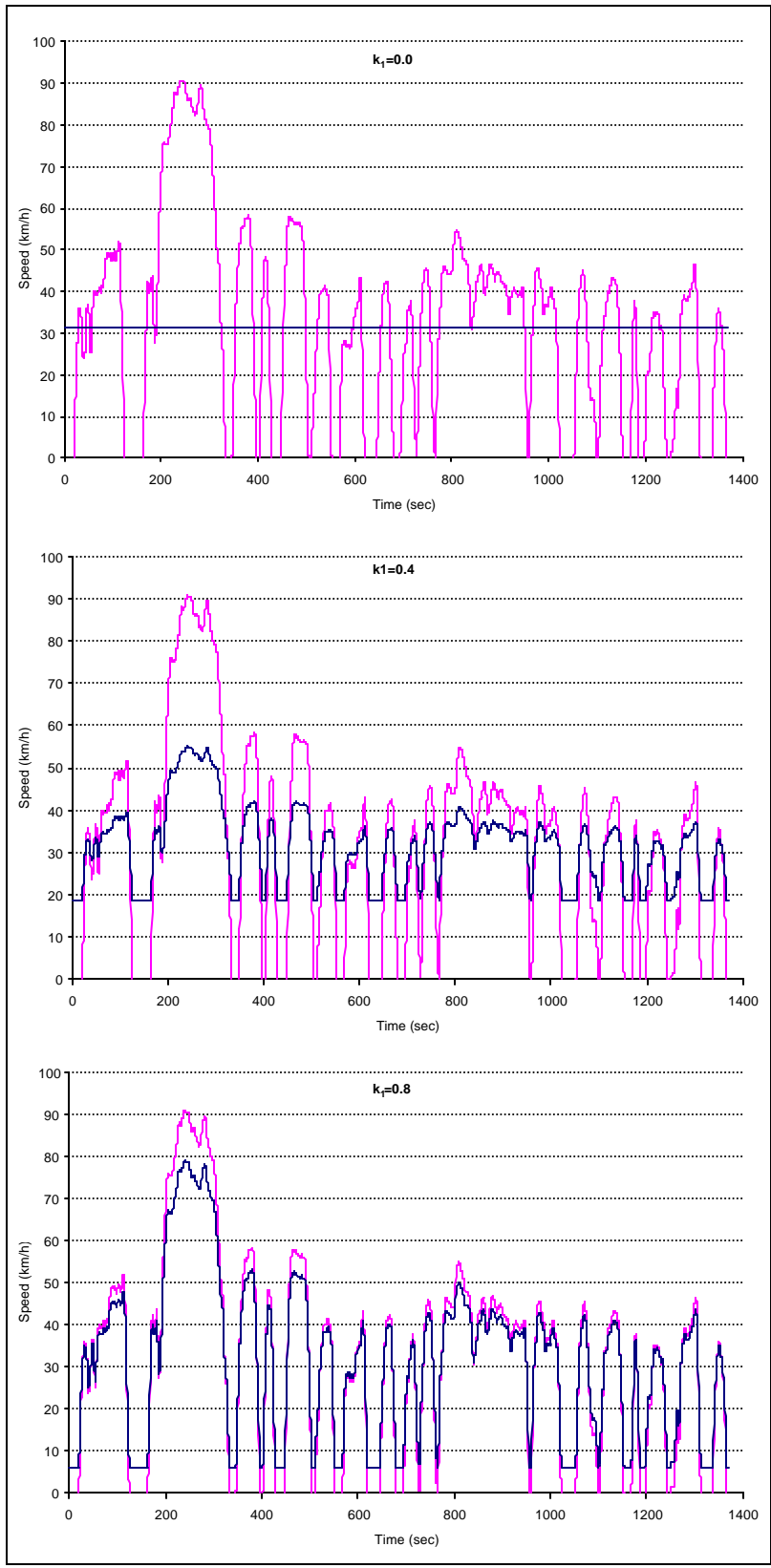


Figure 4-4. Speed Profile of Modified FTP City Cycle as a Function of the  $k_1$  Factor

Table 4-4. Speed/Acceleration Characterization of Modified FTP City Cycle

k <sub>1</sub> =0.0													
		Speed (km/h)											Total
		10	20	30	40	50	60	70	80	90	100	110	
Acceleration (m/s <sup>2</sup> )	-2.0												
	-1.5												
	-1.0												
	-0.5												
	0.0				100.00								
	0.5												
	1.0												
1.5													
<b>Total</b>				100.00									
k <sub>1</sub> =0.2													
		Speed (km/h)											Total
		10	20	30	40	50	60	70	80	90	100	110	
Acceleration (m/s <sup>2</sup> )	-2.0												
	-1.5												
	-1.0												
	-0.5		8.10	23.58	2.99								
	0.0		28.10	32.92	4.31								
	0.5												
	1.0												
1.5													
<b>Total</b>		36.20	56.50	7.30									
k <sub>1</sub> =0.4													
		Speed (km/h)											Total
		10	20	30	40	50	60	70	80	90	100	110	
Acceleration (m/s <sup>2</sup> )	-2.0												
	-1.5												
	-1.0			4.67	2.12								
	-0.5		0.80	4.60	16.72	3.21	2.55						
	0.0		19.78	6.72	26.57	4.01	3.50						
	0.5		0.51	3.87	0.36								
	1.0												
1.5													
<b>Total</b>		21.09	19.85	45.77	7.23	6.06							
k <sub>1</sub> =0.6													
		Speed (km/h)											Total
		10	20	30	40	50	60	70	80	90	100	110	
Acceleration (m/s <sup>2</sup> )	-2.0												
	-1.5												
	-1.0		2.12	4.38	3.72	0.44							
	-0.5		1.61	2.34	11.02	5.62	0.95	2.48					
	0.0		19.56	4.45	21.75	5.84	1.31	3.43					
	0.5		3.65	3.80	1.24	0.29							
	1.0												
1.5													
<b>Total</b>		26.93	14.96	37.74	12.19	2.26	5.91						
k <sub>1</sub> =0.8													
		Speed (km/h)											Total
		10	20	30	40	50	60	70	80	90	100	110	
Acceleration (m/s <sup>2</sup> )	-2.0												
	-1.5		2.41	2.55	1.46	0.36							
	-1.0	0.66	1.02	1.17	2.12	0.73	0.22						
	-0.5	0.73	1.02	1.17	7.01	7.01	1.75	0.95	2.34				
	0.0	18.98	0.88	3.14	15.33	8.47	2.34	1.31	3.21				
	0.5	0.88	0.95	2.63	1.75	0.51	0.15	0.07					
	1.0	0.73	2.55	1.09	0.22	0.15							
1.5													
<b>Total</b>	21.97	8.83	11.75	27.88	17.23	4.45	2.34	5.55					

Table 4-4. (Continued)

<b>k<sub>1</sub>=1.0</b>		Speed (km/h)											Total		
		10	20	30	40	50	60	70	80	90	100	110		120	
Acceleration (m/s <sup>2</sup> )	-2.0														
	-1.5	1.17	2.34	2.26	1.97	0.80	0.15							8.69	
	-1.0	1.17	0.36	0.80	1.46	0.73	0.44	0.22	0.15					5.33	
	-0.5	0.80	0.95	0.95	4.53	7.59	2.70	0.07	0.80	2.04	0.22			20.66	
	0.0	18.91	0.44	2.77	10.88	10.44	3.21		1.39	2.48	0.58			51.09	
	0.5	1.09	0.95	2.34	2.12	0.73	0.22	0.29						7.74	
	1.0	2.26	2.19	1.17	0.58	0.22	0.07							6.50	
1.5															
Total		25.40	7.23	10.29	21.53	20.51	6.79	0.58	2.34	4.53	0.80			100.00	

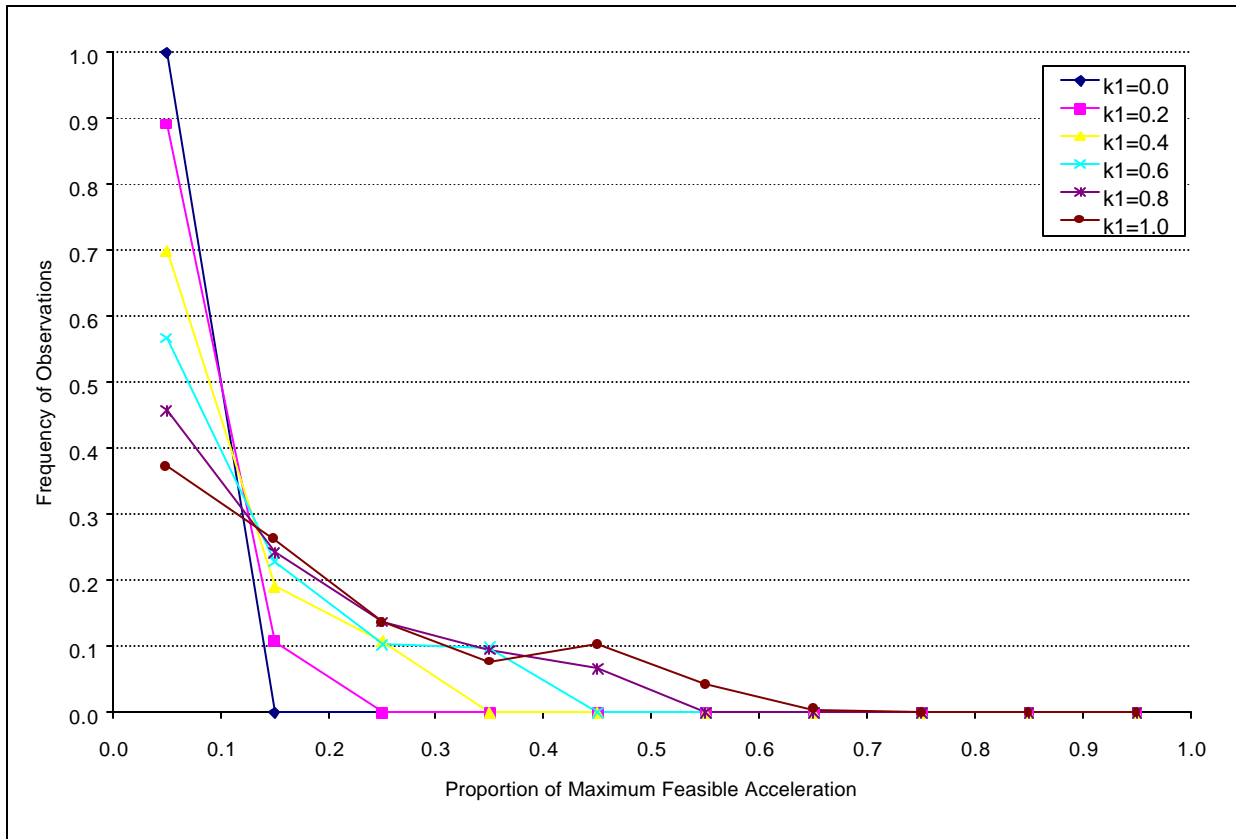


Figure 4-5. Acceleration Distribution of Modified FTP City Cycle as a Function of  $k_1$

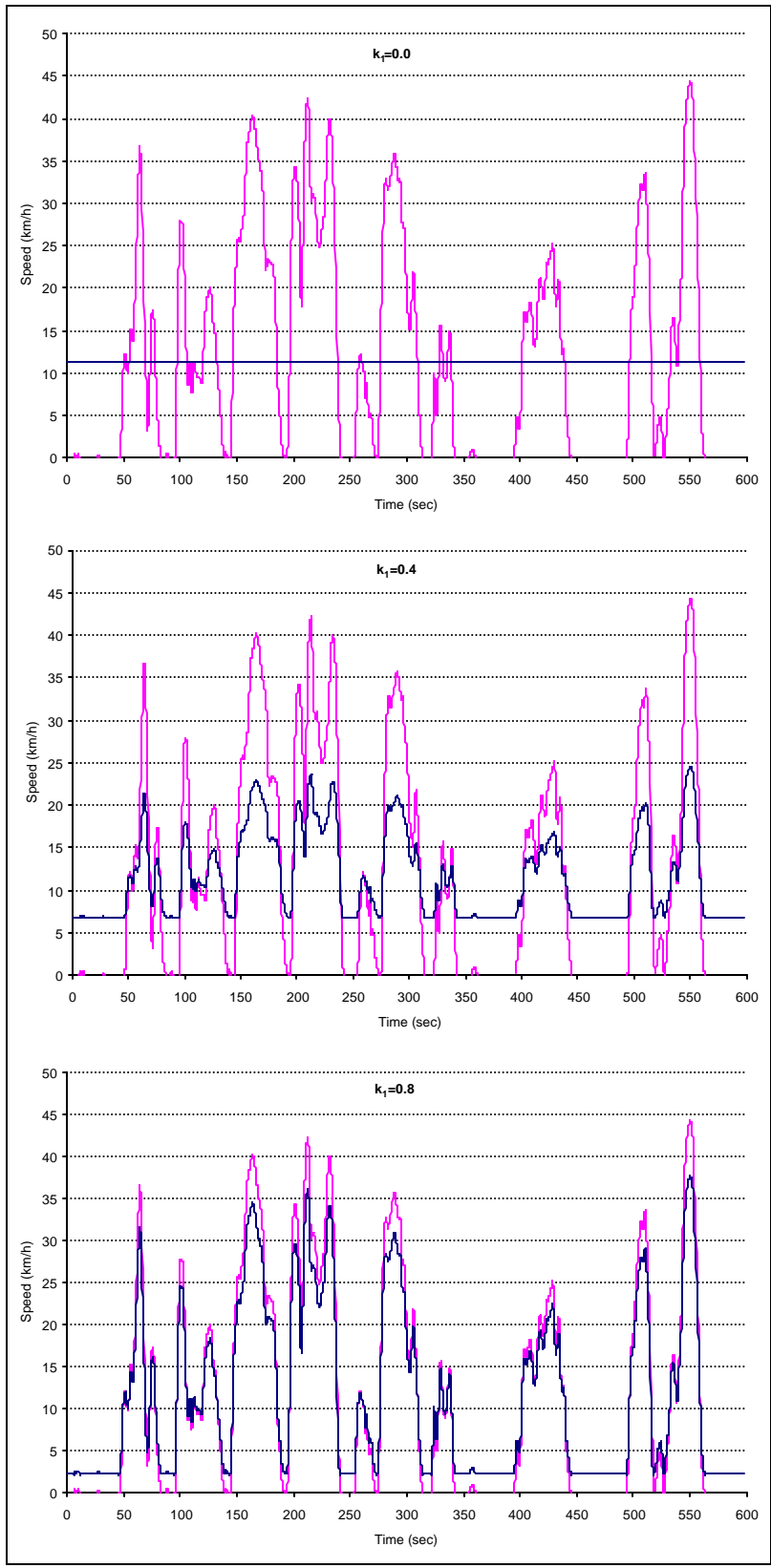


Figure 4-6. Speed Profile of Modified New York City Cycle as a Function of  $k_1$  Factors

Table 4-5. Speed/Acceleration Distribution of Modified New York City Cycle as a Function of  $k_1$

k <sub>1</sub> =0.0												
		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration (m/s <sup>2</sup> )	-2.0											
	-1.5											
	-1.0											
	-0.5											
	0.0		100.00									100.00
	0.5											
	1.0											
	1.5											
	2.0											
	2.5											
3.0												
<b>Total</b>		100.00										100.00
k <sub>1</sub> =0.2												
		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration (m/s <sup>2</sup> )	-2.0											
	-1.5											
	-1.0		0.17									0.17
	-0.5	6.68	26.54									33.22
	0.0	40.23	26.04									66.28
	0.5		0.33									0.33
	1.0											
	1.5											
	2.0											
	2.5											
3.0												
<b>Total</b>		46.91	53.09									100.00
k <sub>1</sub> =0.4												
		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration (m/s <sup>2</sup> )	-2.0											
	-1.5		0.17									0.17
	-1.0	0.33	3.51	0.67								4.51
	-0.5	8.68	16.19	3.84								28.71
	0.0	41.07	17.53	4.01								62.60
	0.5	1.34	2.34									3.67
	1.0	0.17	0.17									0.33
	1.5											
	2.0											
	2.5											
3.0												
<b>Total</b>		51.59	39.90	8.51								100.00
k <sub>1</sub> =0.6												
		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration (m/s <sup>2</sup> )	-2.0											
	-1.5		1.34	0.17								1.50
	-1.0	1.67	3.01	3.17								7.85
	-0.5	9.02	9.02	5.51	0.50							24.04
	0.0	40.07	10.85	6.34	0.33							57.60
	0.5	2.50	3.17	1.34								7.01
	1.0	0.67	0.83	0.17								1.67
	1.5	0.17	0.17									0.33
	2.0											
	2.5											
3.0												
<b>Total</b>		54.09	28.38	16.69	0.83							100.00

Table 4-5. (Continued)

k <sub>1</sub> =0.8												
		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration (m/s <sup>2</sup> )	-2.0											
	-1.5	0.67	2.00	1.67	0.50						4.84	
	-1.0	1.84	2.67	1.67	0.67						6.84	
	-0.5	8.85	6.34	4.51	2.17						21.87	
	0.0	40.23	6.51	6.01	2.50						55.26	
	0.5	2.17	2.67	1.84	0.50						7.18	
	1.0	1.00	1.00	0.83							2.84	
	1.5	0.67		0.17							0.83	
	2.0	0.17	0.17								0.33	
	2.5											
3.0												
Total		55.59	21.37	16.69	6.34						100.00	

k <sub>1</sub> =1.0												
		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration (m/s <sup>2</sup> )	-2.0											
	-1.5	1.50	3.01	2.34	1.17	0.33					8.35	
	-1.0	1.84	2.67	0.83	1.34	0.17					6.84	
	-0.5	8.35	3.84	2.84	3.17	0.50					18.70	
	0.0	38.40	4.67	3.84	3.67	1.00					51.59	
	0.5	2.17	3.01	1.00	1.34						7.51	
	1.0	2.50	0.83	0.67	0.33						4.34	
	1.5	0.50	0.67	0.33	0.17						1.67	
	2.0	0.50		0.17							0.67	
	2.5	0.17	0.17								0.33	
3.0												
Total		55.93	18.86	12.02	11.19	2.00					100.00	

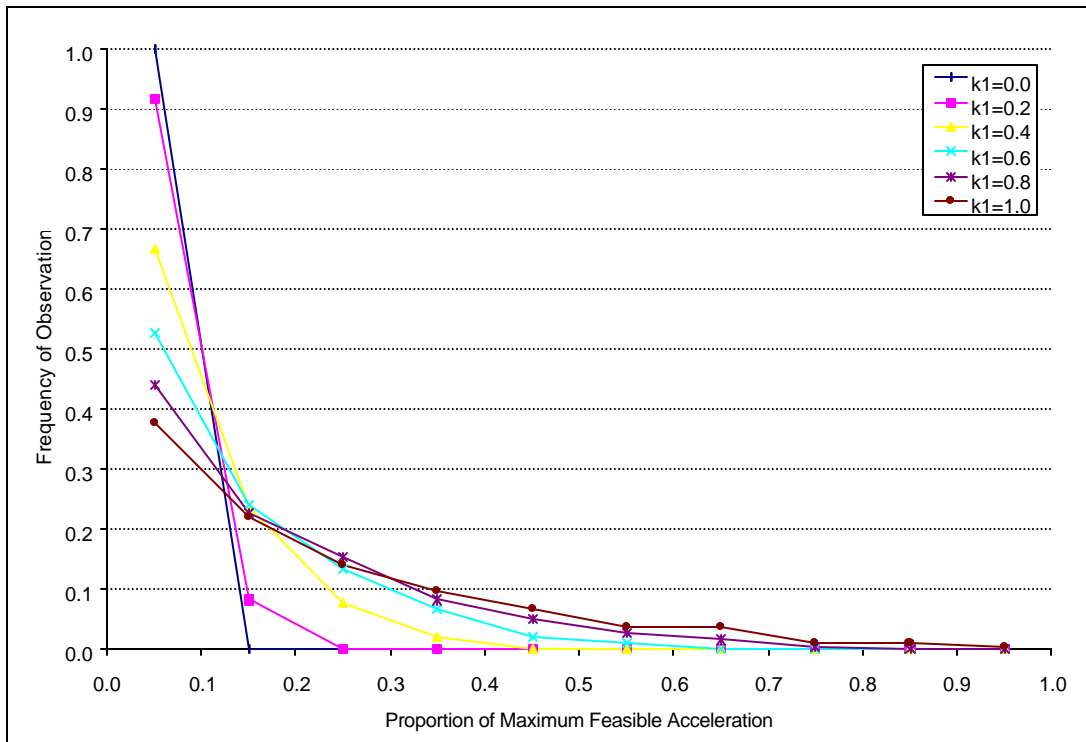


Figure 4-7. Acceleration Distribution of Modified New York Cycle as a Function of k<sub>1</sub>

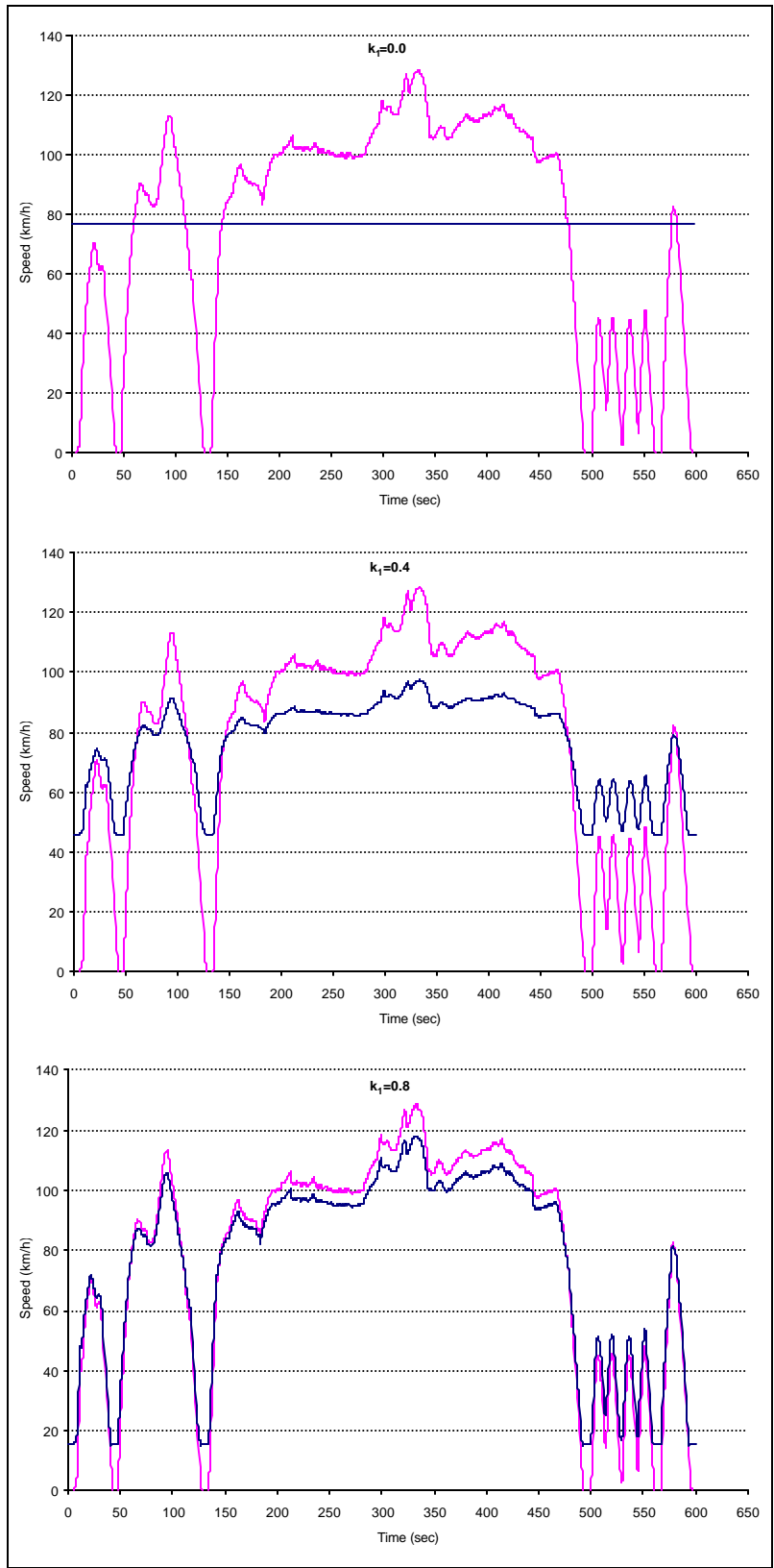


Figure 4-8. Speed Profile of Modified US06 Cycle as a Function of  $k_1$

Table 4-6. Speed/Acceleration Distribution of Modified US06 Cycle as a Function of  $k_1$

$k_1=0.0$		Speed (km/h)														Total
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2															
	-1.5															
	-1.0															
	-0.5															
	0.0								100.00							100.00
	0.5															
	1.0															
	1.5															
	2.0															
	2.5															
3.0																
3.5																
Total									100.00							100.00
$k_1=0.2$		Speed (km/h)														Total
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5															
	-1.0							1.00	0.17							1.16
	-0.5							7.32	12.98	20.63						40.93
	0.0							13.14	11.98	30.45						55.57
	0.5							2.16	0.17							2.33
	1.0															
	1.5															
	2.0															
	2.5															
3.0																
3.5																
Total								23.63	25.29	51.08						100.00
$k_1=0.4$		Speed (km/h)														Total
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5							1.00	0.17							1.16
	-1.0					0.50	3.00	2.83	1.16	0.17	0.17					7.82
	-0.5					1.66	0.33	2.00	4.33	17.14	7.65					33.11
	0.0					8.15	0.17	1.66	4.99	23.79	10.65					49.42
	0.5					0.50	3.00	2.00	0.67							6.16
	1.0					1.00	1.00	0.33								2.33
	1.5															
	2.0															
	2.5															
3.0																
3.5																
Total						11.81	8.49	8.99	11.15	41.10	18.47					100.00
$k_1=0.6$		Speed (km/h)														Total
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5				0.83	2.66	2.66	1.00	0.17							7.32
	-1.0				1.00	0.17	0.67	0.33	1.66	0.67	0.67	0.50				5.66
	-0.5				1.16	0.17	0.83	1.16	1.50	6.49	15.14	2.66				29.12
	0.0				8.15		0.67	0.67	1.83	7.49	23.96	3.49				46.26
	0.5				0.33	0.17	0.50	1.66	0.50	0.50	0.67					4.33
	1.0				0.83	1.83	1.66	0.50	0.17							4.99
	1.5				1.16	0.50	0.33									2.00
	2.0				0.33											0.33
	2.5															
3.0																
3.5																
Total					13.81	5.49	7.32	5.32	5.82	15.14	40.43	6.66				100.00

Table 4-6. (Continued)

<b>k<sub>t</sub>=0.8</b>																
		<b>Speed (km/h)</b>													<b>Total</b>	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
<b>Acceleration (m/s<sup>2</sup>)</b>	-2.0															
	-1.5			2.16	2.50	2.50	1.33	0.83	0.67		0.17	0.17				10.32
	-1.0		0.33	0.17		0.33	0.50	0.67	0.83	1.50	0.83	0.83	0.67			6.66
	-0.5		0.83			0.17	0.67	1.00	0.67	4.66	8.32	8.32	1.16			25.79
	0.0		7.49				0.50	0.50	0.83	4.83	14.98	11.81	2.16			43.09
	0.5		0.17			0.33	0.50	0.83	1.16	1.00	0.67	0.67	0.17			5.49
	1.0		0.17	0.17	0.33	0.83	0.67	0.50								2.66
	1.5		0.33	0.67	1.16	0.83	0.33	0.17	0.17							3.66
	2.0		0.50	0.67	0.50	0.17	0.17									2.00
	2.5		0.17	0.17												0.33
3.0																
3.5																
<b>Total</b>		9.98	3.99	4.49	5.16	4.66	4.49	4.33	11.98	24.96	21.80	4.16			100.00	

<b>k<sub>t</sub>=1.0</b>																
		<b>Speed (km/h)</b>													<b>Total</b>	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
<b>Acceleration (m/s<sup>2</sup>)</b>	-2															
	-1.5	1.50	2.00	2.33	2.66	2.16	1.00	1.16	1.00	0.50		0.33	0.17			14.81
	-1	0.17				0.33	0.33		0.67	1.00	1.16	0.83	0.83	0.33		5.66
	-0.5	0.33				0.50		1.00	0.33	2.66	4.33	8.15	5.16	1.16		23.63
	0	5.99			0.17	0.33		0.50	0.33	2.83	8.32	11.48	7.99	1.66		39.60
	0.5		0.17			0.33	0.33	0.33	1.00	1.33	1.16	0.50	0.50	0.50		6.16
	1	0.17			0.17	0.17	0.50	0.33	0.33	0.17						1.83
	1.5	0.50	0.17	0.67	1.00	0.50	0.67	0.33	0.17							3.99
	2	0.17	0.67	0.50	0.50	0.33	0.17									2.33
	2.5	0.50	0.50	0.50	0.17											1.66
	3	0.33														0.33
	3.5															
	<b>Total</b>	9.65	3.49	3.99	4.66	4.66	3.00	3.66	3.83	8.49	14.98	21.30	14.64	3.66		100.00

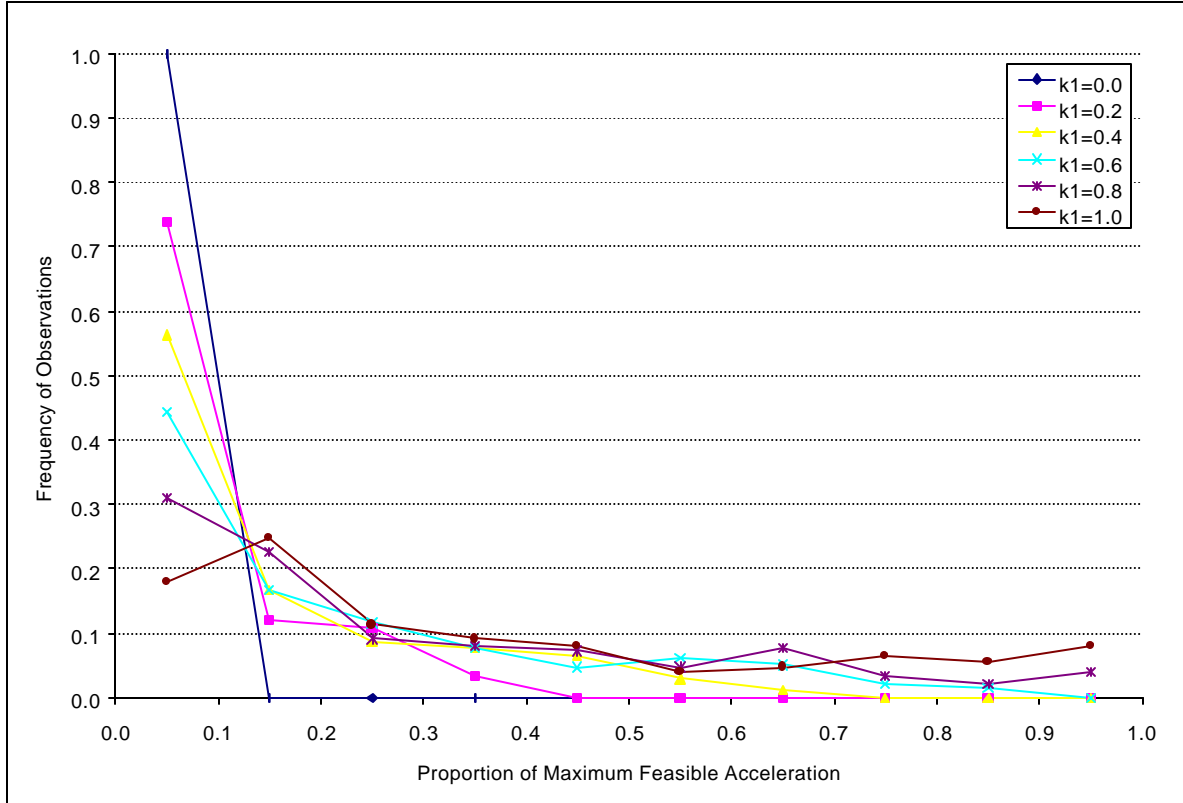


Figure 4-9. Acceleration Distribution of Modified US06 Cycle as a Function of  $k_1$

#### 4.2.2 Speed Mean Factor ( $k_2$ )

The second modification to the standard drive cycles involved an increase in the average speed by adding a constant ( $k_2$ ) to instantaneous speeds, as expressed in Equation 4-1. The speed profiles of the modified FTP city cycles are illustrated in Figure 4-10, and the speed profiles of the modified New York City cycles are shown in Figure 4-11. It should be noted that the US06 cycle was not modified because it included speeds that were barely within the feasible regime of the microscopic energy and emission models (between 0 and 120 km/h). Five constants ( $k_2$ ) are considered in the analysis ranging from 0 to 20 km/h at increments of 5 km/h. The addition of a constant to each speed ensures that the acceleration levels remain constant, however, the speed/acceleration combination is altered (i.e., one observes the same acceleration at higher speeds).

$$\tilde{u}_i = u_i + k_2 \forall i \quad (4-1)$$

The impact of different  $k_2$  factors on the base drive cycles are demonstrated in Table 4-7 and Table 4-8. Specifically, the tables summarize the speed/acceleration distribution for the modified FTP city cycle and the modified New York City cycle, respectively. As illustrated in Figure 4-12, the acceleration distributions of these modified cycles is similar to the original FTP city cycle, and over 90 percent of the observations experience accelerations in the range of 0 to 60 percent the maximum feasible accelerations. These speed/acceleration combinations are consistent with the field data that were described earlier. Similar findings can be drawn from Figure 4-13 for the modified cycles that are derived from the New York City cycle.

It should be noted that the speed mean factor  $k_2$  maintains the same distribution of accelerations, as demonstrated in the total column of Table 4-7. However, one can observe a shift in the speed observations for different values of  $k_2$ .

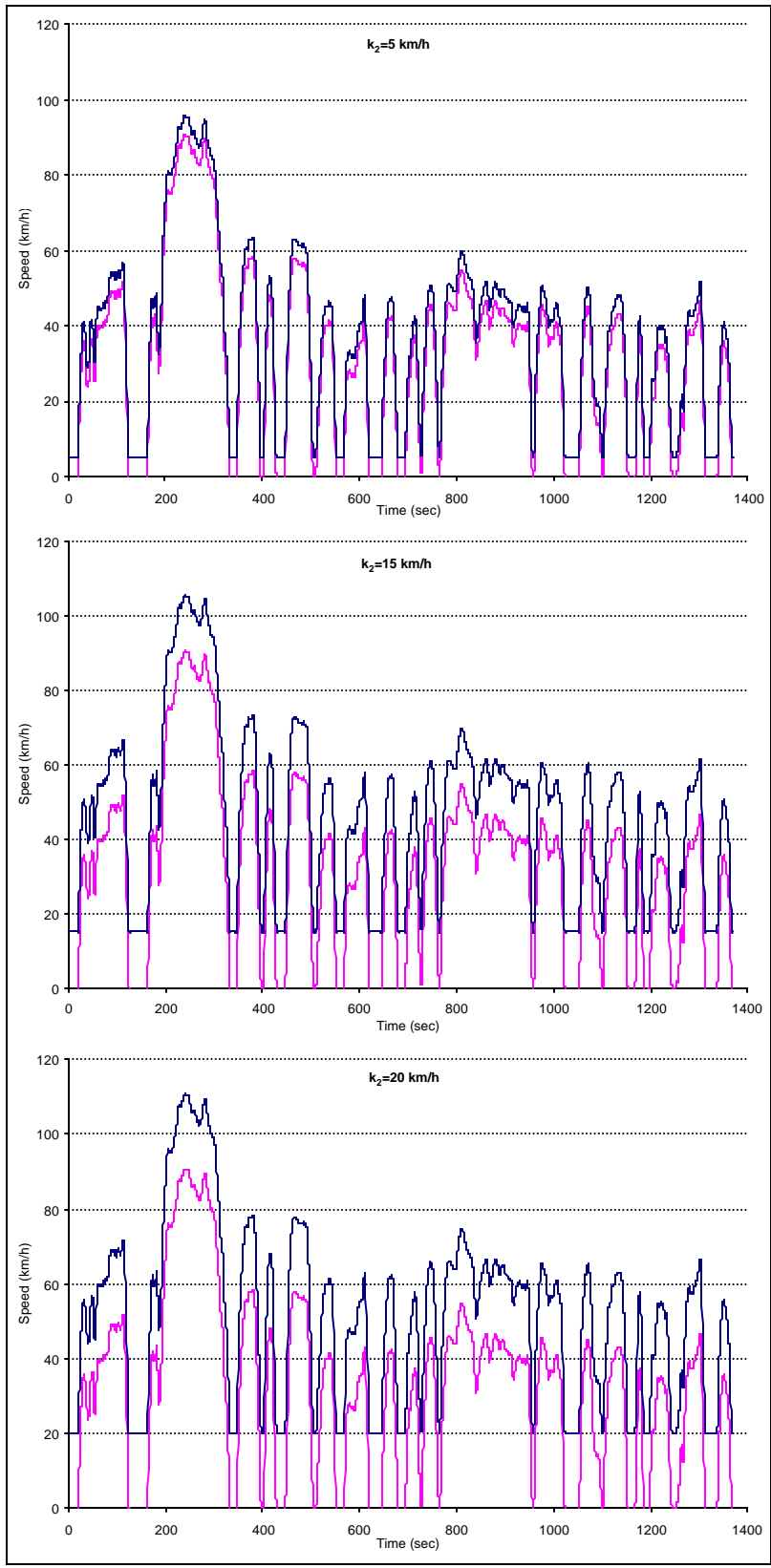


Figure 4-10. Speed Profile of Modified FTP City Cycle as a Function of  $k_2$

Table 4-7. Speed/Acceleration Distribution of Modified FTP City Cycle as a Function of  $k_2$

K2=0 km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5	1.17	2.34	2.26	1.97	0.80	0.15									8.69
	-1.0	1.17	0.36	0.80	1.46	0.73	0.44	0.22	0.15							5.33
	-0.5	0.80	0.95	0.95	4.53	7.59	2.70	0.07	0.80	2.04	0.22					20.66
	0.0	18.91	0.44	2.77	10.88	10.44	3.21		1.39	2.48	0.58					51.09
	0.5	1.09	0.95	2.34	2.12	0.73	0.22	0.29								7.74
	1.0	2.26	2.19	1.17	0.58	0.22	0.07									6.50
	1.5															
	2.0															
<b>Total</b>		25.40	7.23	10.29	21.53	20.51	6.79	0.58	2.34	4.53	0.80					100.00
K2=5 km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5	0.15	2.12	2.63	2.12	1.39	0.29									8.69
	-1.0	0.73	0.58	0.29	1.24	1.53	0.44	0.29	0.22							5.33
	-0.5	0.73	0.58	0.51	2.34	7.45	4.45	1.46	0.15	1.53	1.46					20.66
	0.0	18.69	0.44	1.02	5.40	14.60	4.23	2.26	0.22	2.12	2.12					51.09
	0.5	0.88	0.66	1.46	2.63	1.53	0.22	0.22	0.15							7.74
	1.0	1.24	2.19	1.68	0.80	0.36	0.22									6.50
	1.5															
	2.0															
<b>Total</b>		22.41	6.57	7.59	14.53	26.86	9.85	4.23	0.73	3.65	3.58					100.00
K2=10 km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5		1.17	2.34	2.26	1.97	0.80	0.15								8.69
	-1.0		1.17	0.36	0.80	1.46	0.73	0.44	0.22	0.15						5.33
	-0.5		0.80	0.95	0.95	4.53	7.59	2.70	0.07	0.80	2.04	0.22				20.66
	0.0	17.96	0.95	0.44	2.77	10.88	10.44	3.21		1.39	2.48	0.58				51.09
	0.5	0.51	0.58	0.95	2.34	2.12	0.73	0.22	0.29							7.74
	1.0	0.44	1.82	2.19	1.17	0.58	0.22	0.07								6.50
	1.5															
	2.0															
<b>Total</b>		18.91	6.50	7.23	10.29	21.53	20.51	6.79	0.58	2.34	4.53					99.20
K2=15 km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5		0.15	2.12	2.63	2.12	1.39	0.29								8.69
	-1.0		0.73	0.58	0.29	1.24	1.53	0.44	0.29	0.22						5.33
	-0.5		0.73	0.58	0.51	2.34	7.45	4.45	1.46	0.15	1.53	1.46				20.66
	0.0	18.69	0.44	1.02	5.40	14.60	4.23	2.26	0.22	2.12	2.12					51.09
	0.5	0.88	0.66	1.46	2.63	1.53	0.22	0.22	0.15							7.74
	1.0	1.24	2.19	1.68	0.80	0.36	0.22									6.50
	1.5															
	2.0															
<b>Total</b>		22.41	6.57	7.59	14.53	26.86	9.85	4.23	0.73	3.65	3.58					100.00
K2=20 km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5			1.17	2.34	2.26	1.97	0.80	0.15							8.69
	-1.0			1.17	0.36	0.80	1.46	0.73	0.44	0.22	0.15					5.33
	-0.5			0.80	0.95	0.95	4.53	7.59	2.70	0.07	0.80	2.04	0.22			20.66
	0.0	17.96	0.95	0.44	2.77	10.88	10.44	3.21		1.39	2.48	0.58				51.09
	0.5	0.51	0.58	0.95	2.34	2.12	0.73	0.22	0.29							7.74
	1.0	0.44	1.82	2.19	1.17	0.58	0.22	0.07								6.50
	1.5															
	2.0															
<b>Total</b>		18.91	6.50	7.23	10.29	21.53	20.51	6.79	0.58	2.34	4.53	0.80				100.00

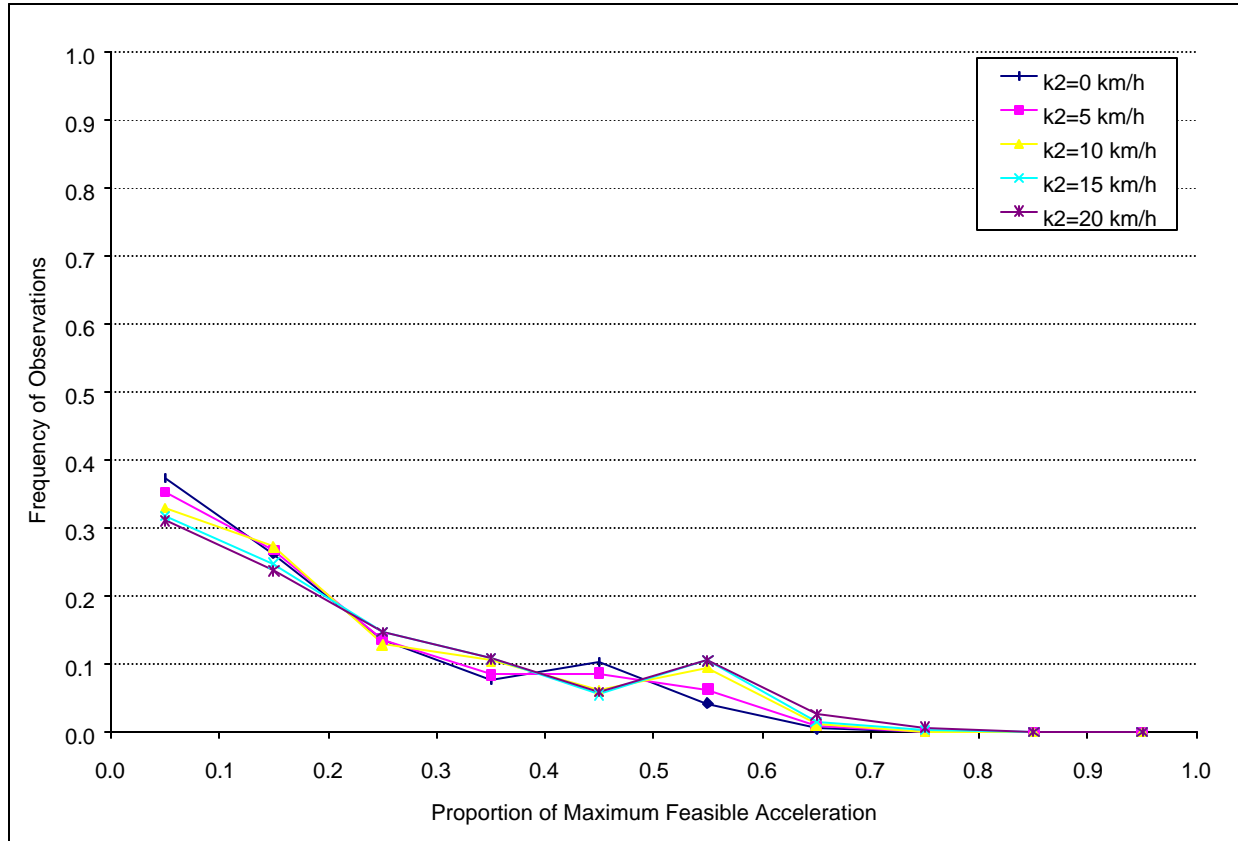


Figure 4-11. Acceleration Distribution of Modified FTP City Cycle as a Function of  $k_2$

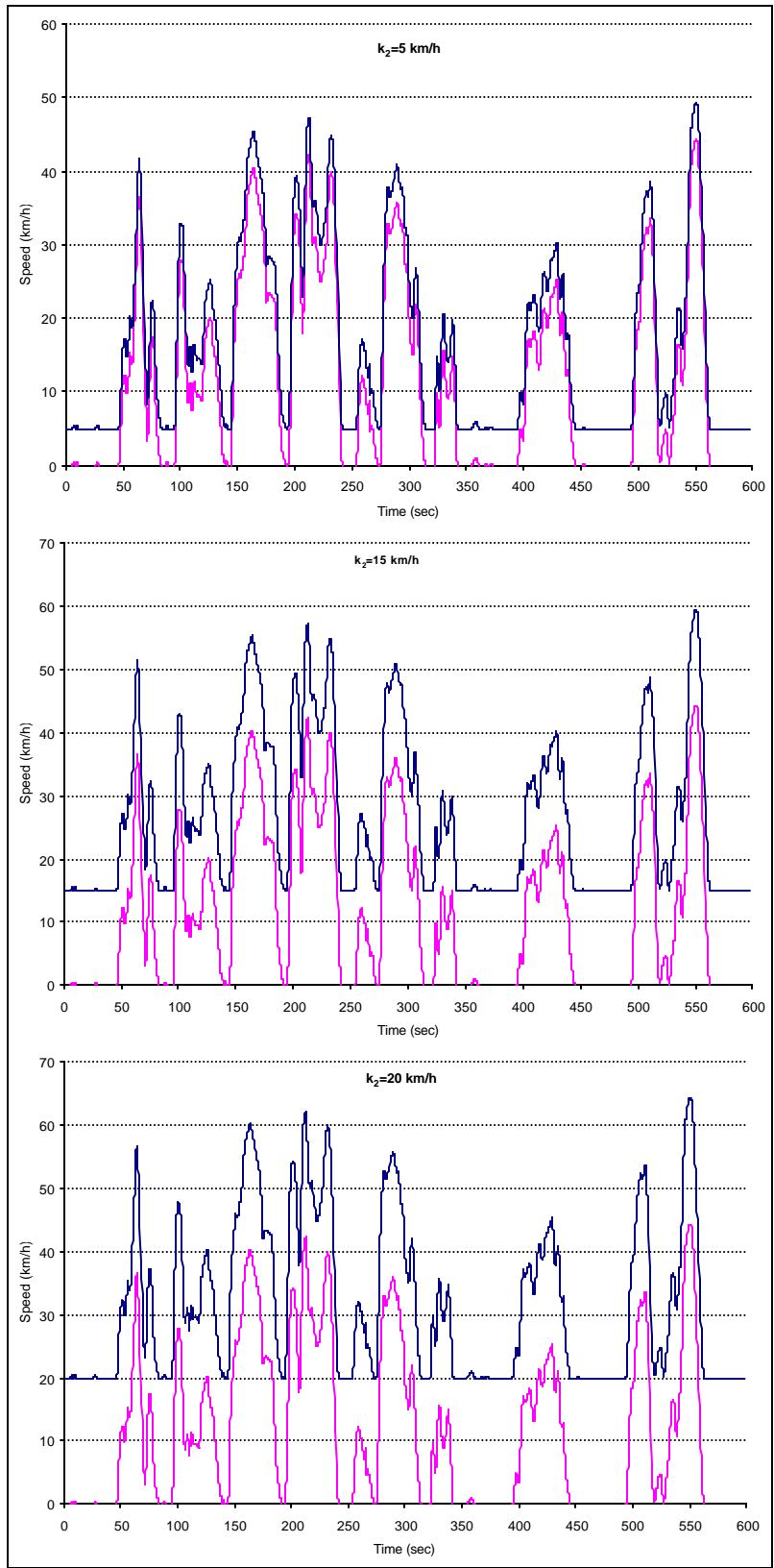


Figure 4-12. Speed Profile of Modified New York City Cycle as a Function of  $k_2$

Table 4-8. Speed/Acceleration Distribution of Modified New York City Cycle as a Function of  $k_2$

$K_2=0$ km/h		Speed (km/h)										Total
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0	1.50	3.01	2.34	1.17	0.33						8.35
	-1.5	1.84	2.67	0.83	1.34	0.17						6.84
	-1.0	8.35	3.84	2.84	3.17	0.50						18.70
	-0.5	38.40	4.67	3.84	3.67	1.00						51.59
	0.0	2.17	3.01	1.00	1.34							7.51
	0.5	2.50	0.83	0.67	0.33							4.34
	1.0	0.50	0.67	0.33	0.17							1.67
	1.5	0.50		0.17								0.67
	2.0	0.17	0.17									0.33
	2.5											
3.0												
<b>Total</b>		55.93	18.86	12.02	11.19	2.00						100.00
$K_2=5$ km/h		Speed (km/h)										Total
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0											
	-1.5	0.17	2.84	2.67	1.84	0.83						8.35
	-1.0	1.00	2.34	1.67	1.34	0.50						6.84
	-0.5	6.34	3.67	3.67	3.17	1.84						18.70
	0.0	37.23	2.84	5.34	3.84	2.34						51.59
	0.5	1.00	2.67	1.84	1.84	0.17						7.51
	1.0	1.50	1.34	0.83	0.50	0.17						4.34
	1.5	0.33	0.33	0.67	0.33							1.67
	2.0	0.33	0.17	0.17								0.67
	2.5		0.17	0.17								
3.0												
<b>Total</b>		47.91	16.36	17.03	12.85	5.84						100.00
$K_2=10$ km/h		Speed (km/h)										Total
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0											0.00
	-1.5		1.50	3.01	2.34	1.17	0.33					8.35
	-1.0		1.84	2.67	0.83	1.34	0.17					6.84
	-0.5		8.35	3.84	2.84	3.17	0.50					18.70
	0.0	33.89	4.51	4.67	3.84	3.67	1.00					51.59
	0.5	0.33	1.84	3.01	1.00	1.34						7.51
	1.0	0.33	2.17	0.83	0.67	0.33						4.34
	1.5		0.50	0.67	0.33	0.17						1.67
	2.0		0.50		0.17							0.67
	2.5		0.17	0.17								
3.0												
<b>Total</b>		34.56	21.37	18.86	12.02	11.19	2.00					100.00
$K_2=15$ km/h		Speed (km/h)										Total
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0											
	-1.5		0.17	2.84	2.67	1.84	0.83					8.35
	-1.0		1.00	2.34	1.67	1.34	0.50					6.84
	-0.5		6.34	3.67	3.67	3.17	1.84					18.70
	0.0		37.23	2.84	5.34	3.84	2.34					51.59
	0.5		1.00	2.67	1.84	1.84	0.17					7.51
	1.0		1.50	1.34	0.83	0.50	0.17					4.34
	1.5		0.33	0.33	0.67	0.33						1.67
	2.0		0.33	0.17	0.17							0.67
	2.5			0.17	0.17							
3.0												
<b>Total</b>			47.91	16.36	17.03	12.85	5.84					100.00

Table 4-8. (Continued)

		Speed (km/h)										Total
		10	20	30	40	50	60	70	80	90	100	
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0											
	-1.5			1.50	3.01	2.34	1.17	0.33				8.35
	-1.0			1.84	2.67	0.83	1.34	0.17				6.84
	-0.5			8.35	3.84	2.84	3.17	0.50				18.70
	0.0	33.89	4.51	4.67	3.84	3.67	1.00					51.59
	0.5	0.33	1.84	3.01	1.00	1.34						7.51
	1.0	0.33	2.17	0.83	0.67	0.33						4.34
	1.5			0.50	0.67	0.33	0.17					1.67
	2.0			0.50	0.17	0.17						0.83
	2.5			0.17								
	3.0											
Total			34.56	21.37	18.86	12.02	11.19	2.00				100.00

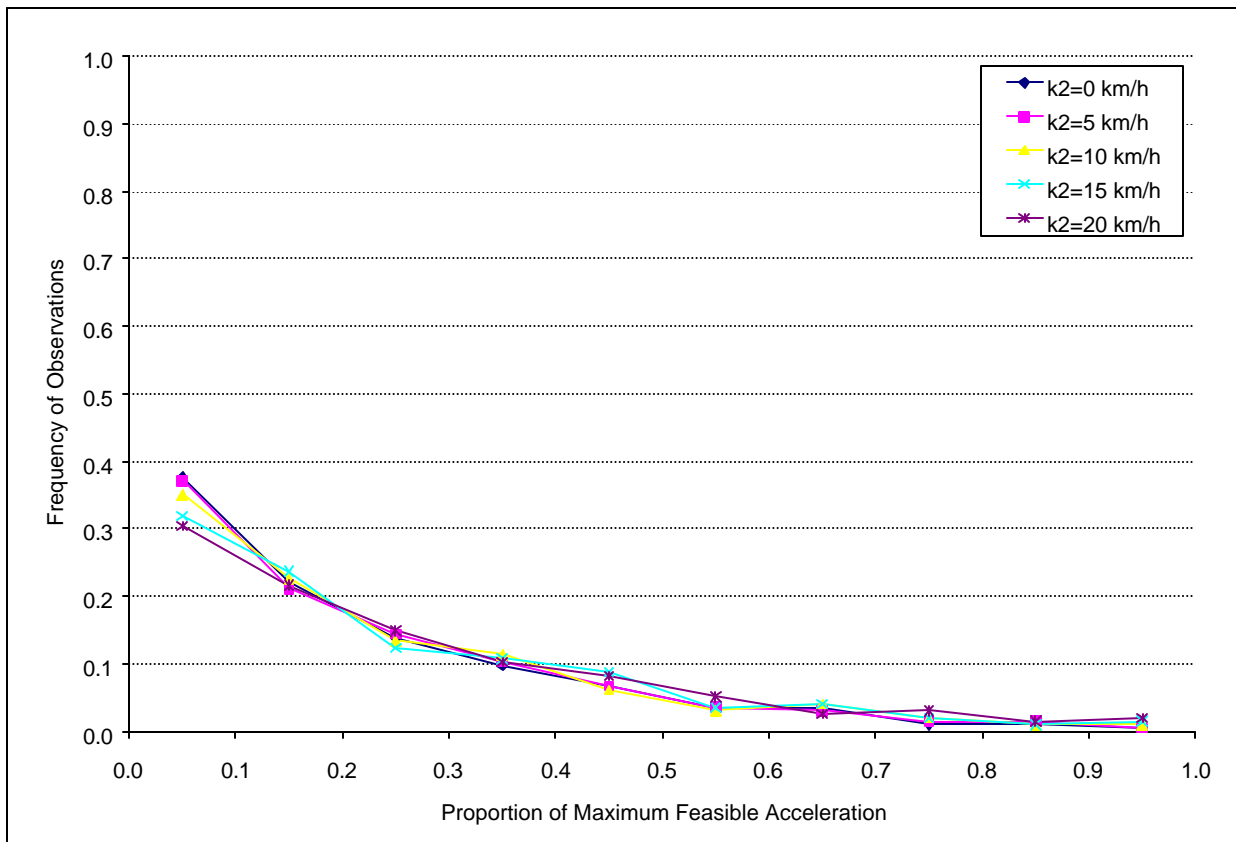


Figure 4-13. Acceleration Distribution of Modified New York City Cycle as a Function of  $k_2$

#### 4.2.3 Speed Mean and Variability Factor ( $k_3$ )

The third modification to the base drive cycles involves changes in the speed mean and variability. The modification is conducted by adding a constant ( $k_3$ ) to the speeds that exceed the average speed, as illustrated in Figure 4-14 for the FTP city cycle and Figure 4-16 for the New

York City cycle. Five constants ( $k_3$ ) are considered ranging from 5 km/h to 25 km/h at increments of 5 km/h. Table 4-9 and Table 4-10 show the speed-acceleration matrixes for these resultant cycles. The acceleration distribution as proportions of the maximum feasible accelerations is illustrated in Figure 4-15 for the modified FTP city cycle and Figure 4-17 for the modified New York City cycle.

As illustrated in Figure 4-15 and Figure 4-17, the acceleration distributions of these cycles are similar with the majority of observations experiencing accelerations in the range of 0 to 60 percent the maximum feasible acceleration. It should be noted, however, that the observations with levels of accelerations beyond the feasible range are higher in comparison to Figure 4-5 ( $k_1$ ) and Figure 4-11 ( $k_2$ ). The  $k_3$  factor increases the average speed by  $k_3/2$  and increases the variability about the average speed. The impact of the  $k_3$  factor on the speed/acceleration composition of the drive cycle illustrates an extension of the data coverage, as demonstrated in Table 4-9 and Table 4-10.

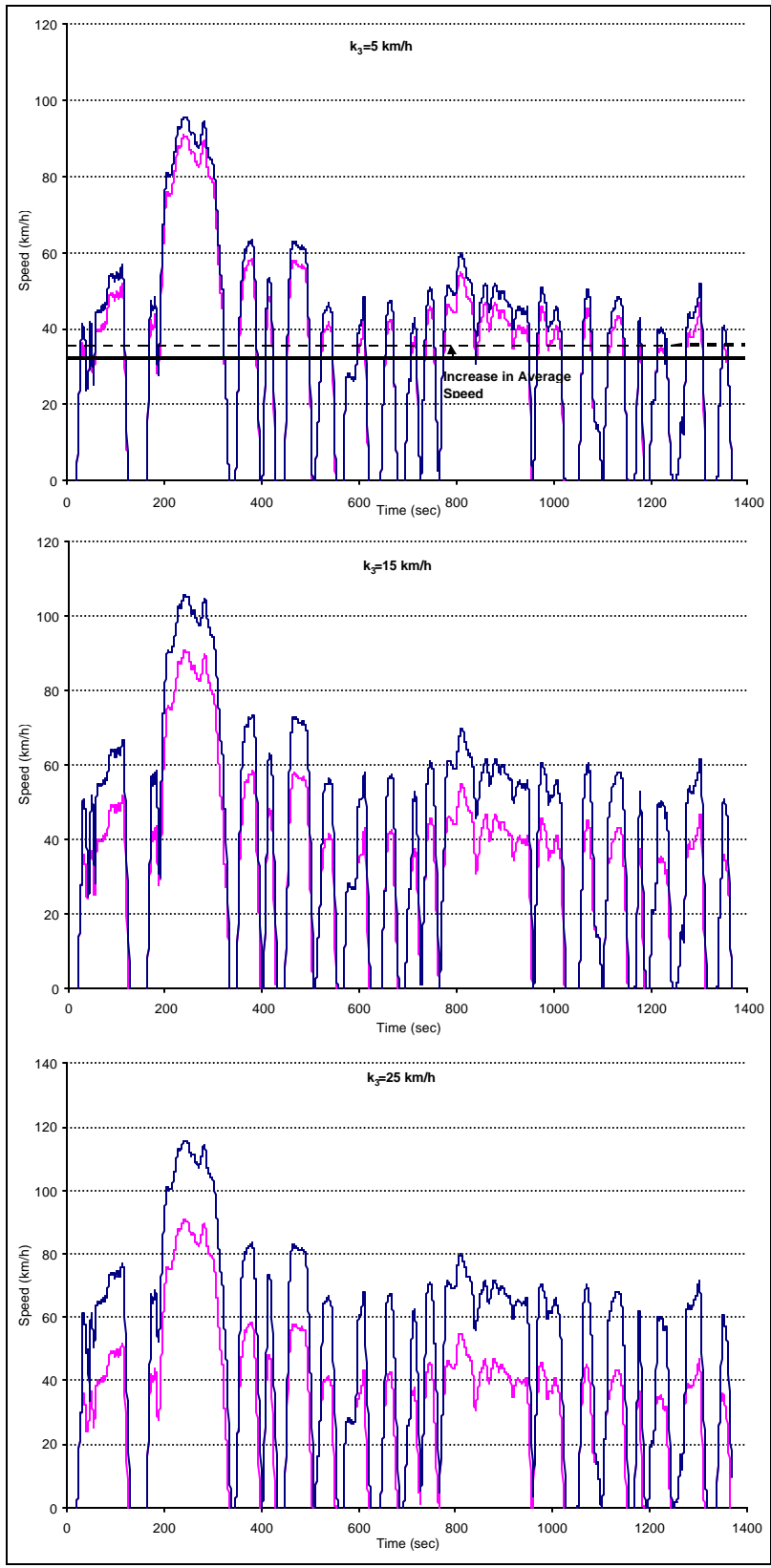


Figure 4-14. Speed Profile of Modified FTP City Cycle as a Function of  $k_3$

Table 4-9. Speed/Acceleration Distribution of Modified FTP City Cycle as a Function of  $k_3$

$K_3=5$ km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5	1.46	2.04	2.41	2.85	1.39	0.29									10.44
	-1.0	0.95	0.36	0.44	0.51	1.53	0.44	0.29	0.22							4.74
	-0.5	0.58	0.95	0.80	1.17	7.45	4.45	1.46	0.15	1.53	1.46					20.00
	0.0	18.54	0.44	2.63	2.92	14.60	4.23	2.26	0.22	2.12	2.12					50.07
	0.5	1.09	0.95	1.82	1.02	1.53	0.22	0.22	0.15							7.01
	1.0	2.26	2.19	0.80	0.22	0.29	0.22									5.99
	1.5			0.07	0.58											0.66
	2.0			0.51	0.15											0.66
	2.5			0.36	0.07											0.44
3.0																
<b>Total</b>		24.89	6.93	9.85	9.49	26.79	9.85	4.23	0.73	3.65	3.58					100.00
$K_3=10$ km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5	1.39	2.26	2.48	2.77	2.48	0.80	0.15								12.34
	-1.0	0.80	0.15	0.07		1.24	0.73	0.44	0.22	0.15						3.80
	-0.5	0.80	0.88	0.80	0.07	4.31	7.59	2.70	0.07	0.80	2.04	0.22				20.29
	0.0	17.52	0.44	2.41		9.78	10.44	3.21		1.39	2.48	0.58				48.25
	0.5	1.09	0.95	1.82		1.17	0.73	0.22	0.29							6.28
	1.0	2.26	2.19	0.80	0.44	0.44	0.22	0.07								6.42
	1.5					0.66										0.66
	2.0					0.36	0.07									0.44
	2.5					0.95	0.58									1.53
3.0																
<b>Total</b>		23.87	6.86	9.34	4.89	19.49	20.51	6.79	0.58	2.34	4.53	0.80				100.00
$K_3=15$ km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5	1.46	2.34	2.26	2.85	2.77	1.39	0.29								13.36
	-1.0	0.66	0.15		0.15	0.66	1.53	0.44	0.29	0.22						4.09
	-0.5	0.66	0.73	0.73		1.46	7.45	4.45	1.46	0.15	1.53	1.46				20.07
	0.0	16.57	0.44	2.26		2.26	14.38	4.23	2.26	0.22	2.12	2.12				46.86
	0.5	1.09	0.95	1.75		0.44	1.24	0.22	0.22	0.15						6.06
	1.0	2.26	2.19	0.80		0.36	0.15	0.22								5.99
	1.5					0.22	0.07									0.29
	2.0					1.31	0.44									1.75
	2.5					0.95	0.58									1.53
3.0																
<b>Total</b>		22.70	6.79	8.76	4.89	8.61	26.20	9.85	4.23	0.73	3.65	3.58				100.00
$K_3=20$ km/h		Speed (km/h)													Total	
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5	1.39	2.34	2.34	2.63	2.55	1.97	0.80	0.15							14.16
	-1.0	0.51	0.15			0.73	1.46	0.73	0.44	0.22	0.15					4.38
	-0.5	0.58	0.66	0.73		0.22	4.38	7.59	2.70	0.07	0.80	2.04	0.22			20.00
	0.0	15.40	0.44	2.12		0.22	9.20	10.44	3.21		1.39	2.48	0.58			45.47
	0.5	1.02	0.95	1.75			0.66	0.51	0.22	0.29						5.40
	1.0	2.26	2.19	0.80		0.07	0.29	0.22	0.07							5.91
	1.5					0.44	0.07	0.07								0.58
	2.0					1.24	1.24	0.22								2.70
	2.5					0.80	0.58									1.39
3.0																
<b>Total</b>		21.17	6.72	8.54	4.45	5.47	18.25	20.36	6.79	0.58	2.34	4.53	0.80			100.00

Table 4-9. (Continued)

K <sub>3</sub> =25 km/h		Speed (km/h)														Total
		10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Acceleration (m/s <sup>2</sup> )	-2.0															
	-1.5	1.24	2.26	2.26	2.55	2.92	2.12	1.39	0.29							
	-1.0	0.58	0.15			0.22	1.24	1.53	0.44	0.29	0.22					
	-0.5	0.51	0.51	0.66			1.75	7.30	4.45	1.46	0.15	1.53	1.46			
	0.0	14.38	0.44	2.12		0.22	1.97	13.65	4.16	2.26	0.22	2.12	2.12			
	0.5	1.02	0.95	1.68			0.66	0.73	0.22	0.22	0.15					
	1.0	2.12	2.19	0.80			0.29	0.22	0.22							
	1.5						0.29	0.36								
	2.0				1.09	1.61	0.66									
	2.5			0.80	0.58											
3.0																
Total		19.85	6.50	8.32	4.23	4.96	8.98	25.18	9.78	4.23	0.73	3.65	3.58		100.00	

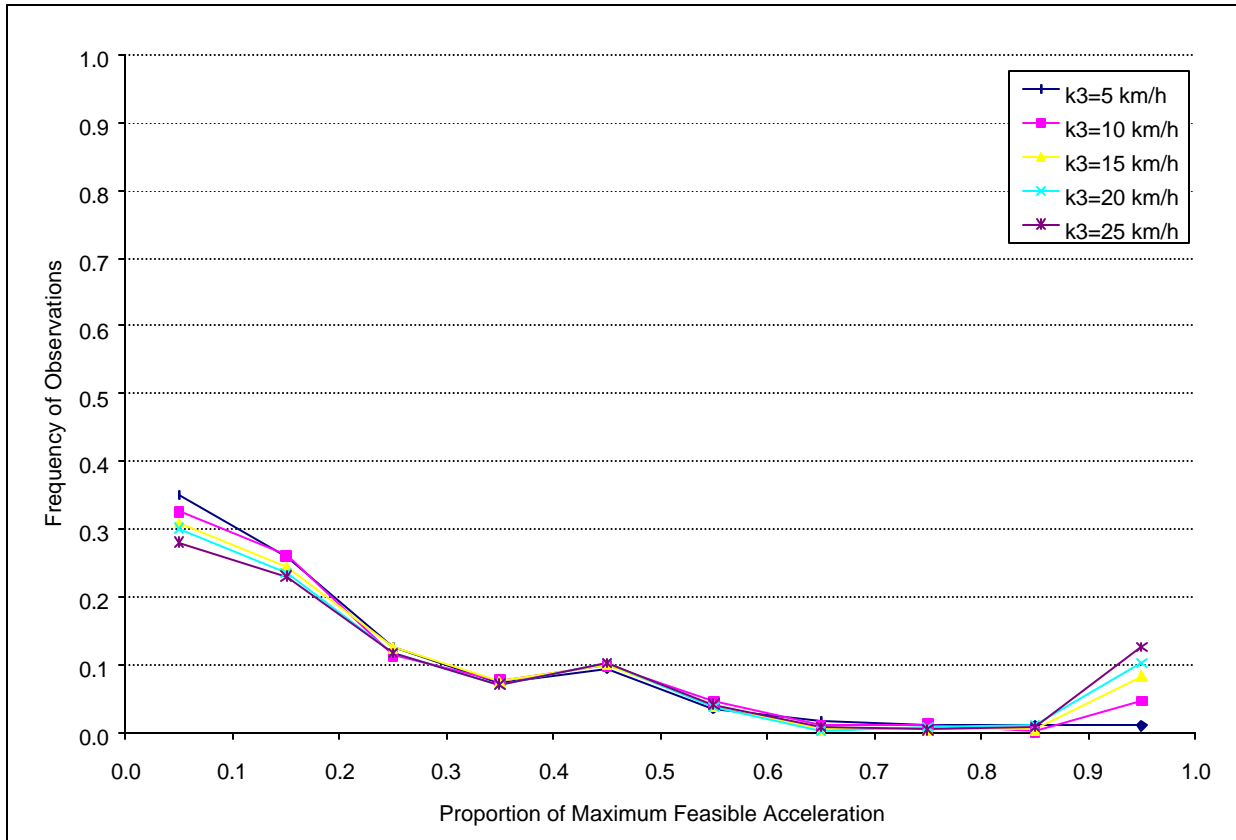


Figure 4-15. Acceleration Distribution of Modified FTP City Cycle as a Function of  $k_3$

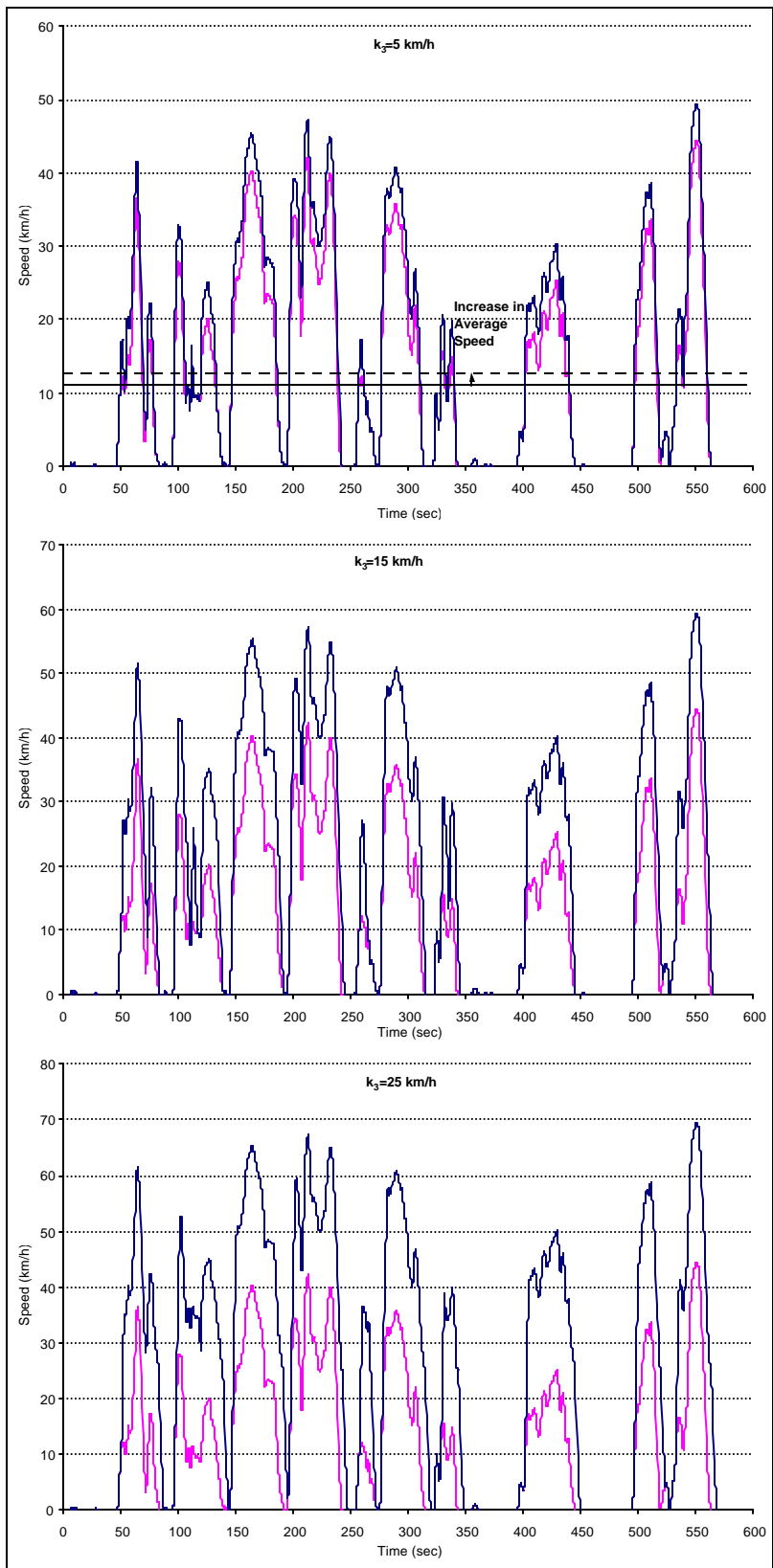


Figure 4-16. Speed Profile of Modified New York City Cycle as a Function of  $k_3$

Table 4-10. Speed/Acceleration Distribution of Modified New York City Cycle as a Function of  $k_3$

K <sub>3</sub> =5 km/h												
	Speed (km/h)										Total	
	10	20	30	40	50	60	70	80	90	100		
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0	1.34	4.51	2.67	1.84	0.83						11.19
	-1.5	1.84	0.83	1.67	1.34	0.50						6.18
	-1.0	7.18	1.17	3.67	3.17	1.84						17.03
	-0.5	37.90	1.34	5.34	3.84	2.34						50.75
	0.0	1.67	1.17	1.67	1.84	0.17						6.51
	0.5	1.67	0.33	1.00	0.50	0.17						3.67
	1.0	0.50	0.50	0.50	0.17							1.67
	1.5	0.50	0.33	0.33								1.17
	2.0	0.83	0.33									1.17
	2.5	0.67										0.67
	3.0											
3.5												
<b>Total</b>	<b>54.09</b>	<b>10.52</b>	<b>16.86</b>	<b>12.69</b>	<b>5.84</b>							<b>100.00</b>

K <sub>3</sub> =10 km/h												
	Speed (km/h)										Total	
	10	20	30	40	50	60	70	80	90	100		
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0											
	-1.5	1.84	4.17	3.51	2.34	1.17	0.33					13.36
	-1.0	1.00	0.50	2.34	0.83	1.34	0.17					6.18
	-0.5	6.18	0.17	2.84	2.84	3.17	0.50					15.69
	0.0	37.23	0.17	4.01	3.84	3.67	1.00					49.92
	0.5	1.67		2.00	1.00	1.17						5.84
	1.0	1.50		0.50	0.50	0.33						2.84
	1.5	0.33	0.33	0.33	0.33	0.17						1.50
	2.0	0.17	0.83	0.33	0.17							1.50
	2.5		0.83	0.33								1.17
	3.0	2.00										
3.5												
<b>Total</b>	<b>51.92</b>	<b>7.01</b>	<b>16.19</b>	<b>11.85</b>	<b>11.02</b>	<b>2.00</b>						<b>100.00</b>

K <sub>3</sub> =15 km/h												
	Speed (km/h)										Total	
	10	20	30	40	50	60	70	80	90	100		
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0											
	-1.5	2.00	3.84	4.34	2.67	1.84	0.83					15.53
	-1.0	0.67		1.50	1.67	1.34	0.50					5.68
	-0.5	5.18		1.50	3.67	3.17	1.84					15.36
	0.0	35.89		0.83	4.51	3.67	2.34					47.25
	0.5	1.50		1.17	1.67	1.67	0.17					6.18
	1.0	1.50		0.67	0.50	0.33	0.17					3.17
	1.5	0.33	0.17	0.17	0.67	0.17						1.50
	2.0	0.17			0.67							0.83
	2.5		1.84	0.83								2.67
	3.0	1.84										
3.5												
<b>Total</b>	<b>49.08</b>	<b>5.84</b>	<b>11.02</b>	<b>16.03</b>	<b>12.19</b>	<b>5.84</b>						<b>100.00</b>

K <sub>3</sub> =20 km/h												
	Speed (km/h)										Total	
	10	20	30	40	50	60	70	80	90	100		
Acceleration (m/s <sup>2</sup> )	-2.5											
	-2.0											
	-1.5	1.84	3.34	3.67	3.17	2.34	1.17	0.33				15.86
	-1.0	1.00		0.83	2.34	0.83	1.34	0.17				6.51
	-0.5	4.01		1.17	3.51	2.67	3.17	0.50				15.03
	0.0	33.72		0.67	3.51	3.84	3.51	1.00				46.24
	0.5	1.50		0.33	2.34	0.83	1.00					6.01
	1.0	1.50			0.50	0.33	0.33					2.67
	1.5	0.33		0.17	0.33	0.33	0.17					1.34
	2.0	0.17		0.50	0.50	0.33						1.50
	2.5		1.67	1.50	0.17							3.34
	3.0	1.50										
3.5												
<b>Total</b>	<b>45.58</b>	<b>5.01</b>	<b>8.85</b>	<b>16.36</b>	<b>11.52</b>	<b>10.68</b>	<b>2.00</b>					<b>100.00</b>

Table 4-10. (Continued)

K <sub>3</sub> =25 km/h		Speed (km/h)										Total	
		10	20	30	40	50	60	70	80	90	100		
Acceleration (m/s <sup>2</sup> )	-2.5												
	-2.0												
	-1.5	1.84	3.17	2.67	2.84	2.67	1.84	0.83					15.86
	-1.0	1.17		0.67	2.17	1.50	1.34	0.50					7.35
	-0.5	2.67		1.84	3.01	3.34	3.01	1.84					15.69
	0.0	31.39		0.17	1.84	4.51	3.34	2.34					43.57
	0.5	1.34			2.17	1.50	1.50	0.17					6.68
	1.0	1.50		0.17	0.33	0.50	0.50	0.17					3.17
	1.5	0.33			0.33	0.50	0.17						1.34
	2.0	0.17		0.17	0.83	0.67							1.84
	2.5		1.34	1.67	0.17								3.17
	3.0	1.34											
	3.5												
Total		41.74	4.51	7.35	13.69	15.19	11.69	5.84					100.00

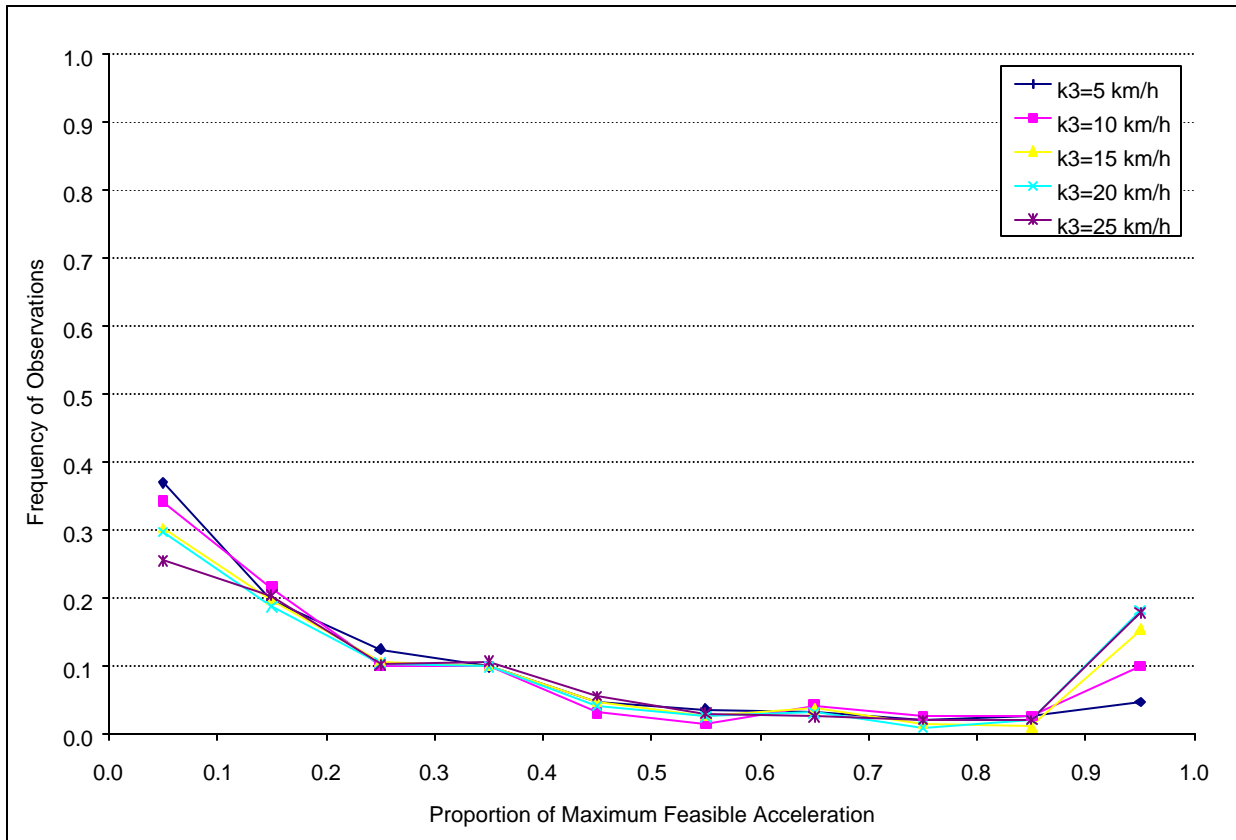


Figure 4-17. Acceleration Distribution of Modified New York City Cycle as a Function of k<sub>3</sub>

## **4.3 Impact of Average Speed and Speed Variability on Vehicle Fuel Consumption and Emissions**

The speed variability defined as the level of variation about the average speed is a potential explanatory variable for estimating vehicle fuel consumption and emissions. The objective of this section is to quantify the impact of speed variability on vehicle fuel consumption and emissions on the one hand, and to verify the appropriateness of using both the average speed and speed variability as explanatory variables for vehicle fuel consumption and emission estimates.

### ***4.3.1 Inadequacy of the Average Speed as a Single Explanatory Variable***

The utilization of average speed as a sole explanatory variable for estimating vehicle fuel consumption and emissions is inadequate, as was discussed in the previous chapter. Specifically, Chapter 3 demonstrated that vehicle fuel consumption and emissions vary with the aggressiveness of the driver.

An ANOVA statistical test is conducted in this section to further verify the inadequacy of average speed, using the modified drive cycles based on the  $k_i$  factor. Figure 4-18 compares vehicle fuel consumption and emission rates for these modified cycles against constant-speed trips.

As illustrated in Figure 4-18 the fuel consumption rates for different  $k_i$  factors result in fuel consumption estimates within the variability that is associated with different cruise speeds. However, this is not the case for vehicle emissions, as illustrated in Figure 4-18. Specifically, the HC and CO emission rates exhibit significant variations with the application of various speed variability factors at high speeds (i.e. the modified US06 drive cycle), and minor variations at low speeds (i.e. the modified FTP city cycle and New York City cycle), for the same average speed.

To further analyze the impact of speed variability on vehicle fuel consumption and emissions, ANOVA tests are applied to these data. The results of the ANOVA tests are summarized in Table 4-11.

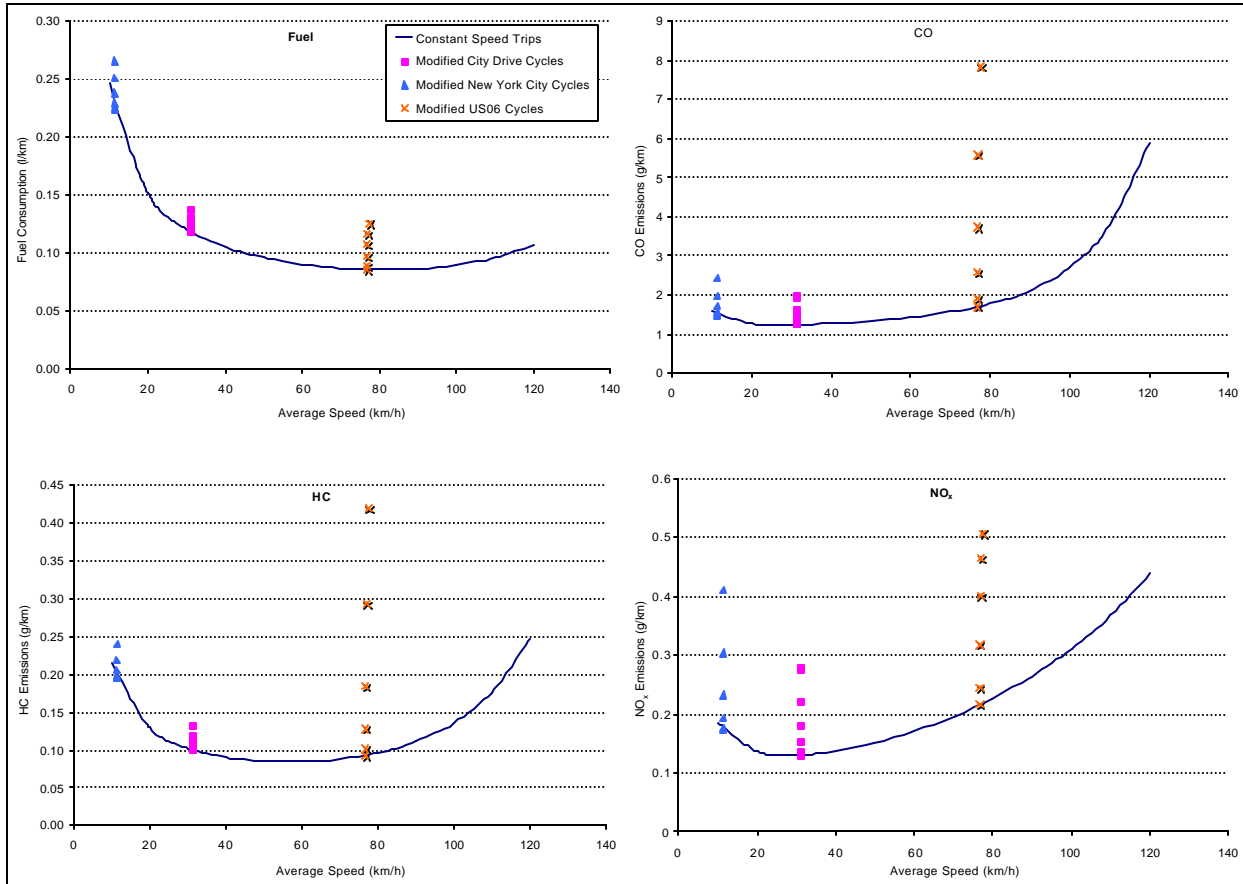


Figure 4-18. Impact of Average Speed and Speed Variability on Vehicle Fuel Consumption and Emission Rates

Table 4-11. Error in Vehicle Fuel Consumption and Emissions Explained by Average Speed

a. Dependent Variable: FUEL					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	0.09906347	0.00707596	36.42	0.0001
Error	15	0.00291415	0.00019428		
Corrected Total	29	0.10197761			
	R-Square	C.V.	Root MSE	FUEL Mean	
	0.971424	10.02131	0.01393831	0.13908667	
Source	DF	Anova SS	Mean Square	F Value	Pr > F
SPD	14	0.09906347	0.00707596	36.42	0.0001

<b>b. Dependent Variable: HC</b>					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	0.08314852	0.00593918	1.04	0.4706
Error	15	0.08592860	0.00572857		
Corrected Total	29	0.16907711			
	R-Square	C.V.	Root MSE	HC Mean	
	0.491779	48.31518	0.07568734	0.15665333	
Source	DF	Anova SS	Mean Square	F Value	Pr > F
SPD	14	0.08314852	0.00593918	1.04	0.4706
<b>c. Dependent Variable: CO</b>					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	42.327	3.023	1.51	0.219
Error	15	30.021	2.001		
Corrected Total	29	72.349			
	R-Square	C.V.	Root MSE	CO Mean	
	0.585	61.715	1.415	2.292	
Source	DF	Anova SS	Mean Square	F Value	Pr > F
SPD	14	42.327	3.023	1.51	0.219
<b>d. Dependent Variable: NO<sub>x</sub></b>					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	0.213	0.0152	1.76	0.1437
Error	15	0.130	0.0087		
Corrected Total	29	0.343			
	R-Square	C.V.	Root MSE	NO <sub>x</sub> Mean	
	0.622	37.391	0.0930	0.249	
Source	DF	Anova SS	Mean Square	F Value	Pr > F
SPD	14	0.21319849	0.01522846	1.76	0.1437

The ANOVA tests indicate that the variation in fuel consumption as a function of average speed is statistically significant ( $p = 0.0001$ ). This conclusion is consistent with Figure 4-18, which demonstrates that the variation in fuel consumption within an average speed (different  $k_1$  factors) is less than the variability between average speeds.

Alternatively, the ANOVA test results indicate that the average speed is not a statistically significant variable in characterizing vehicle emissions. These conclusions are consistent with Figure 4-18, which demonstrates a larger variability within an average speed versus between average speeds.

### ***4.3.2 Impact of Average Speed and Speed Variability***

Given that average speed does not constitute a valid single explanatory variable for estimating vehicle emissions, additional variables are introduced, including speed variability. The speed variability is computed using Equation 4-2 as the mean square error (MSE) about the average speed.

$$s_u^2 = \frac{\sum_{i=1}^n (u_i - \bar{u})^2}{n} \quad (4-2)$$

A total of 1200 drive cycles are utilized to conduct the analysis that is presented. These 1200 drive cycles include 1080 variations to the base single-stop cycle and 120 variations to the base FTP city cycle and New York City cycle. Specifically, the 1080 single-stop cycles are constructed using a combination of 6 speed variability factors ( $k_1=0.0, 0.2, \dots, 1.0$ ), 6 cruise speed levels (20 km/h, 40 km/h, ... , 100 km/h), 6 deceleration levels ( $-0.25\text{m/s}^2, -0.5 \text{ m/s}^2, \dots, -1.5 \text{ m/s}^2$ ), and 5 acceleration levels ( $0.2a_{\text{max}}, 0.4a_{\text{max}}, \dots, 1.0a_{\text{max}}$ ). Similarly, modified FTP city and New York City cycles are constructed using 6 speed variability factors ( $k_1=0.0, 0.2, \dots, 1.0$ ), 5 speed mean factors ( $k_2 = 0 \text{ km/h}, 5 \text{ km/h}, \dots, 20 \text{ km/h}$ ), and 5 speed mean and variability factors ( $k_3 = 5 \text{ km/h}, 10 \text{ km/h}, \dots, 25 \text{ km/h}$ ). The combinations of the three factors were applied to the FTP city cycle and New York City cycle to generate 120 drive cycles.

Fuel consumption and emissions are computed for each cycle by applying the microscopic models that were described earlier. Using the average speed and speed variability as independent variables, regression models are developed that compute the various MOEs, as summarized in Table 4-12.

Table 4-12. Impact of the Average Speed and Speed Variability on Vehicle Fuel Consumption and Emission Rates

#	Model	No.of Independent Variables	R <sup>2</sup>
1	Fuel=f( $\hat{u}$ )	1	0.4882
2	Fuel=f( $\sigma^2_u$ )	1	0.0160
3	Fuel=f( $\hat{u}, \sigma^2_u$ )	2	0.6249
<hr/>			
1	HC=f( $\hat{u}$ )	1	0.4355
2	HC=f( $\sigma^2_u$ )	1	0.1174
3	HC=f( $\hat{u}, \sigma^2_u$ )	2	0.4546
<hr/>			
1	CO=f( $\hat{u}$ )	1	0.4732
2	CO=f( $\sigma^2_u$ )	1	0.4523
3	CO=f( $\hat{u}, \sigma^2_u$ )	2	0.7010
<hr/>			
1	NO <sub>x</sub> =f( $\hat{u}$ )	1	0.6157
2	NO <sub>x</sub> =f( $\sigma^2_u$ )	1	0.4894
3	NO <sub>x</sub> =f( $\hat{u}, \sigma^2_u$ )	2	0.8395

As shown in Table 4-12, the average speed explains 49 and 61 percent of the error in fuel consumption and NO<sub>x</sub> emissions, respectively. However, adding the factor of speed variability into each of these two models leads to a significant increase in the regression coefficient of determination (R<sup>2</sup>). The regression models indicate that the combination of speed and speed variability provide a relatively good fit to NO<sub>x</sub> emissions (R<sup>2</sup> = 0.84), however, they do not provide a good fit to HC emissions (R<sup>2</sup> = 0.45). The CO and fuel consumption fit is marginal (R<sup>2</sup> = 0.70 and 0.62).

#### 4.4 Summary of Findings

This chapter has demonstrated the inadequacy of average speed as a sole explanatory variable for computing vehicle fuel consumption and emissions. The addition of speed variability as an explanatory variable results in better models (R<sup>2</sup> increases). Furthermore, this chapter has demonstrated the need for other explanatory variables to accurately compute the various MOEs. The development of these models is described in the following chapter.

## **CHAPTER 5 : STATISTICAL MODEL DEVELOPMENT AND VALIDATION**

It is apparent that microscopic models based on instantaneous speed and acceleration data provide good estimates of vehicle fuel consumption and emissions, however, the use of these models does require that second-by-second speed/acceleration data be available. Given that the availability of second-by-second speed and acceleration data may not be feasible, the statistical models that are developed in this thesis use aggregate trip variables for vehicle fuel consumption and emission estimates. The models are demonstrated to be consistent with the microscopic models ( $R^2$  ranges from 0.88 to 0.96).

In this Chapter, first, potential explanatory variables are identified and calculated for each of the test drives developed in the Chapter 3 and Chapter 4. The test drives include 1080 trips derived from the base single-stop cycle, 120 trips data derived from the standard drive cycles (the FTP city cycle and the New York City cycle), and 301 trips collected using GPS technology along a signalized arterial in Phoenix. Accordingly, the fuel consumption and emissions per unit distance are estimated by applying the microscopic model (Ahn and Rakha *et al.*, 1999) for each trip. Next, the statistical models are developed based on the trip variables and validated against data gathered by the EPA on a dynamometer.

### **5.1 Identification of Potential Explanatory Trip Variables**

As was demonstrated in Chapter 4 the use of average speed as a sole explanatory variable is not sufficient for estimating vehicle fuel consumption and emissions. Potential explanatory variables include average speed, speed variability, number of vehicle stops, acceleration noise, deceleration noise, the total noise, the kinetic energy consumed, and the power exert by the vehicle.

The average speed, the number of vehicle stops and the speed variability along the entire trip are computed using Equation 3-1, Equation 3-3, and Equation 4-2, respectively.

The acceleration noise is not a new term, instead it is a variable that was developed in the late 1950's in order to quantify the smoothness of flow in a traffic stream. Drew (1968) mentions that "the term *noise* is used to indicate the disturbance of the flow, comparable to the coined phrase *video noise*, which is used to describe the fluttering of the video signal on a television set." Drew mentions that acceleration noise received considerable attention as a possible measurement of traffic flow quality for two basic reasons. First, it is dependent on the three basic elements of the traffic stream, namely, (1) the driver, (2) the road, and (3) the traffic condition. Second, it is in effect, a measurement of the smoothness of flow in a traffic stream. Specifically, the acceleration noise (standard deviation of accelerations) can be considered as the disturbance of the vehicle's speed from a uniform speed.

The acceleration noise that is present on a road in the absence of traffic is termed the *natural noise* of the driver on the road (Herman *et al.*, 1959). Several factors affect acceleration noise, such as the roadway geometry, the type of control on the roadway, and the level of congestion on the roadway. Specifically, field studies in the early 1960's indicated that the acceleration noise increased with an increase in congestion (Jones and Potts, 1962).

Jones and Potts (1962) developed a mathematical equation for approximating the acceleration noise. Specifically, assuming the acceleration profile, which is illustrated in Figure 5-1, Jones and Potts computed the average acceleration using Equation 5-1 and the acceleration noise using Equation 5-2. The details of the derivation are beyond the scope of the thesis, however, it is worthwhile mentioning that Equation 5-2 only computes the acceleration noise when the vehicle is in motion (speed is greater than zero). A modified acceleration noise estimate is proposed for purposes of this analysis, as demonstrated in Equation 5-3. The first modification is that for long trips ( $T$  large) the average acceleration that is computed in Equation 5-1 tends to zero. Consequently, in Equation 5-3 it is assumed that the average acceleration is zero. The second modification to the Jones and Potts formulation is that Equation 5-3 weights each acceleration observation by the vehicle speed because acceleration levels at higher speeds result in higher fuel consumption and emission estimates than equivalent acceleration levels at lower speeds. Equations 5-4 and 5-5 further separate the positive acceleration noise (accelerations) from the

negative acceleration noise (decelerations) because fuel consumption and emission estimates are more sensitive to acceleration levels than they are to deceleration levels.

It should be noted that Drew (1968) demonstrated that the kinetic energy of a traffic stream can be computed using Equation 5-6 where  $\alpha$  is a unitless constant. Furthermore, Drew demonstrated that there is an internal energy or lost energy associated with the traffic stream, which manifests itself in erratic motion and is nothing but the acceleration noise. Consequently, Capelle (1966) hypothesized that the internal energy or acceleration noise measured over a segment of roadway is equal to the total fuel consumed. The model was tested against freeway data and demonstrated a good fit, however that was not the case for arterial streets (Rowan, 1967). It is felt that the proposed modification to the computation of acceleration noise, together with the separation of positive and negative acceleration noise could provide better explanatory variables. Furthermore, it is proposed that the total kinetic energy also be computed for the entire trip for a single vehicle using Equation 5-7 and be utilized as an additional explanatory variable. It should be noted that the difference between Equations 5-6 and 5-7 is that Equation 5-6 computes the kinetic energy for all vehicles in the traffic stream while Equation 5-7 computes the kinetic energy for a single vehicle.

A final explanatory variable that will be considered is related to the power exerted along a trip. The power is equal to the force multiplied by the speed, which means that the instantaneous residual power is a function of the product of the instantaneous speed and acceleration levels ( $u_i a_i$ ). Consequently, the total power exerted is computed using Equation 5-8 where  $m$  is the mass of the vehicle that is a constant and  $a_i$  is greater than zero.

$$\bar{a} = \frac{1}{T} \int_0^T a(t_i) dt = \frac{1}{T} [v(T) - v(0)] \quad (5-1)$$

$$A = \sqrt{\frac{1}{T} \int_0^T [a(t_i) - \bar{a}]^2 dt} = \sqrt{\frac{1.465^2 (\Delta v)^2}{T} \sum_{i=0}^T \frac{1}{\Delta t_i}} \quad (5-2)$$

$$A = \sqrt{\frac{\sum_{i=1}^n a_i^2 u_i}{\sum_{i=1}^n u_i}} \quad (5-3)$$

$$A^+ = \sqrt{\frac{\sum_i a_i^2 u_i}{\sum_i u_i}} \quad \forall i \ni a_i > 0 \quad (5-4)$$

$$A^- = \sqrt{\frac{\sum_i a_i^2 u_i}{\sum_i u_i}} \quad \forall i \ni a_i < 0 \quad (5-5)$$

$$E_k = a k u^2 \quad (5-6)$$

$$E_k = \mathbf{b} \sum_{i=1}^n u_i^2 \quad (5-7)$$

$$P = m \sum_{i=1}^n u_i a_i \quad \forall i \ni a_i > 0 \quad (5-8)$$

Where:

$u_i$  = instantaneous speed at instant  $i$ .

$u_f$  = facility free-speed (km/h)

$a_i$  = instantaneous acceleration (km/h/s)

$S$  = number of vehicle stops

$A$  = acceleration noise

$A^+$  = acceleration noise for positive accelerations only

$A^-$  = acceleration noise for negative accelerations only

$M$  = vehicle mass (kg)

$K$  = traffic density (veh/km)

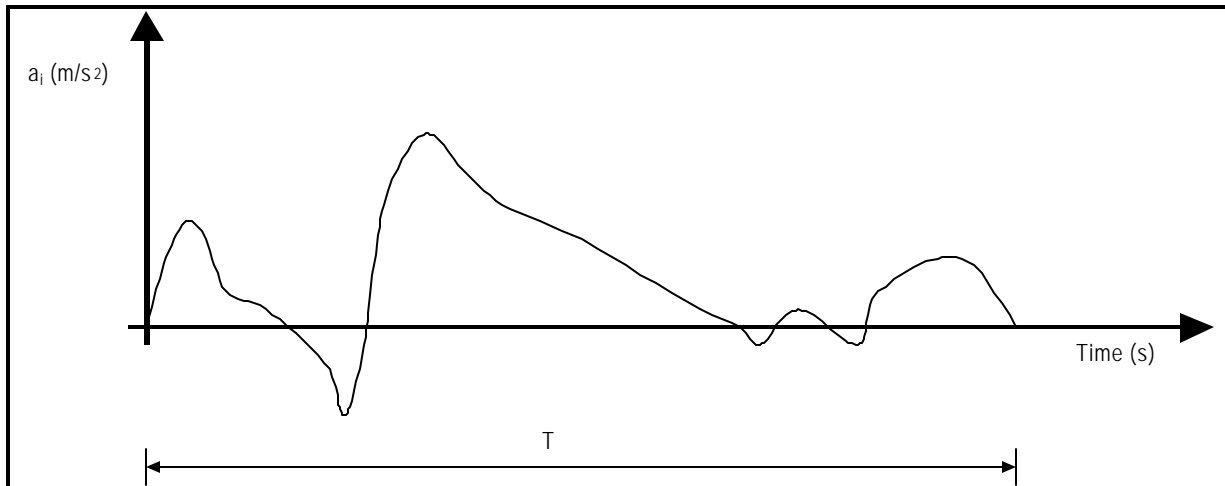


Figure 5-1. Acceleration Profile for a Sample Trip

These potential explanatory variables are computed for each of the 1501 test-drives that were developed for this analysis. In addition, the fuel consumption and emissions were estimated by applying the microscopic fuel consumption and emission models to the instantaneous speed estimates.

## 5.2 Development of Statistical Models

Utilizing the estimates of the various independent variables for each of the 1501 trips together with the corresponding MOEs, statistical regression models were developed for a typical average vehicle. Prior to developing the models, each dependent variable (fuel consumption, HC, CO, and NO<sub>x</sub> emissions) are plotted against each independent variable in an attempt to identify the type of relationship between the dependent and independent variable (See Appendix B). As shown in these plots, the relationship between each dependent variable and each independent variable is difficult to identify.

To develop the best-fit statistical models, initially, simple statistical models including a single explanatory variable are considered. Next, multiple explanatory variables are systematically added to the regression models. The best models are the models that produce the highest adjusted coefficient of determination with the fewest number of independent variables. In addition, an attempt was made to ensure that multicollinearity did not exist among the independent variables.

The general format of these regression models presented in Equation 5-9 or Equation 5-10.

$$\text{Log}(\text{MOE})_e = (\text{CON})_e + \sum_{i=1}^n P_i * V_i \quad (5-9)$$

$$(\text{MOE})_e = (\text{CON})_e + \sum_{i=1}^n P_i * V_i \quad (5-10)$$

Where:

$(\text{MOE})_e$  = Dependent variable for MOE "e" including fuel consumption, HC, CO, and  $\text{NO}_x$  estimates.

$(\text{CON})_e$  = Constant for MOE "e"

$n$  = Number of independent variables included in the model,  $n \leq 10$

$P_i$  = Coefficient for independent variable "i"

$V_i$  = Independent variable "i"

### **5.2.1 Contribution of Each Variable to Fuel Consumption and Emission Estimates**

Each of the eight variables identified in the section 5.1 is used as a single independent variable for each of the dependent variables (Fuel consumption and emissions). As shown in the plots (Appendix B), the relationship between each dependent variable (fuel, HC, CO, and  $\text{NO}_x$ ) and the average speed is non-linear, thus two additional potential explanatory variables are introduced. These variables include the inverse of the average speed and the average speed squared. To avoid any negative MOE estimates, a log-transformation is applied to each model. The resulting coefficient of determination ( $R^2$ ) indicates the portion of the sum of squared error that is explained by the independent variable, as summarized in Table 5-1. For example, speed variability explains most of the sum of squared error associated with fuel consumption, HC, and  $\text{NO}_x$  emissions, while the variable, as positive power is the biggest factor for estimating CO emissions.

### ***5.2.2 Other Models Considered with One or Two Independent Variables***

Dion *et al.* (1999 and 2000) developed mesoscopic fuel consumption and emission models as a function of average speed, the number of vehicle stops, and the duration of stopped delay. Furthermore, several models were developed for estimating fuel consumption estimates using the reciprocal of average speed (Evans and Herman 1978, Lam 1985). Consequently, the initial regression models that are developed use the combination of average speed and vehicle stops as independent variables. In addition, the use of the reciprocal of average speed to estimate vehicle fuel consumption is considered. These models are developed using the same data set (1501 trips) without a log-transformation and with a log-transformation, as summarized in Table 5-2. The use of a log-transformation ensures positive estimates for the various MOEs.

The optimal model is selected using two criteria:

1. Ensure positive regression coefficients. If that is not the case then a log-transformation is applied to the data in order to ensure positive MOE estimates.
2. Select the model that provides the highest coefficient of determination ( $R^2$ ).

Figure 5-2, Figure 5-3, and Figure 5-4 show the comparison of vehicle fuel consumption and emission rates per unit distance that are estimated by the models listed in Table 5-2 against the microscopic model MOE estimates for the total of 1501 test-drives. As shown in Table 5-2 and Figure 5-2, Figure 5-3, and Figure 5-4, the model with both average speed and speed variability provides the best fit to the microscopic model among all tests for each dependent variable.

Table 5-1. Fuel Consumption and Emissions Estimates Models with One Variable

Model Sequence	Model	R <sup>2</sup>
<b>Log(Fuel) = f(x)</b>		
1	Log(Fuel)= f( $\sigma^2_u$ )	0.6026
2	Log(Fuel)= f(A)	0.5664
3	Log(Fuel)= f(E <sub>k</sub> )	0.5581
4	Log(Fuel)= f(S)	0.3918
5	Log(Fuel)= f(A <sup>-</sup> )	0.3568
6	Log(Fuel)= f( $\hat{u}$ )	0.3305
7	Log(Fuel)= f( $\hat{u}^2$ )	0.2821
8	Log(Fuel)= f(1/ $\hat{u}$ )	0.2708
9	Log(Fuel)= f(A <sup>+</sup> )	0.1145
10	Log(Fuel)= f(P)	0.0025
<b>Log(HC) = f(x)</b>		
1	Log(HC)= f( $\sigma^2_u$ )	0.5811
2	Log(HC)= f(A)	0.4082
3	Log(HC)= f(P)	0.3157
4	Log(HC)= f(A <sup>-</sup> )	0.2918
5	Log(HC)= f(S)	0.2046
6	Log(HC)= f(A <sup>+</sup> )	0.0961
7	Log(HC)= f( $\hat{u}^2$ )	0.0359
8	Log(HC)= f( $\hat{u}$ )	0.0142
9	Log(HC)= f(E <sub>k</sub> )	0.0133
10	Log(HC)= f(1/ $\hat{u}$ )	0.0001
<b>Log(CO) = f(x)</b>		
1	Log(CO)= f(P)	0.6259
2	Log(CO)= f( $\hat{u}^2$ )	0.4137
3	Log(CO)= f( $\hat{u}$ )	0.3776
4	Log(CO)= f( $\sigma^2_u$ )	0.3338
5	Log(CO)= f(1/ $\hat{u}$ )	0.2307
6	Log(CO)= f(A)	0.1625
7	Log(CO)= f(E <sub>k</sub> )	0.1379
8	Log(CO)= f(A <sup>-</sup> )	0.1194
9	Log(CO)= f(S)	0.0364
10	Log(CO)= f(A <sup>+</sup> )	0.0186
<b>Log(NO<sub>x</sub>) = f(x)</b>		
1	Log(NO <sub>x</sub> )= f( $\sigma^2_u$ )	0.7185
2	Log(NO <sub>x</sub> )= f(A)	0.4622
3	Log(NO <sub>x</sub> )= f(P)	0.3502
4	Log(NO <sub>x</sub> )= f(A <sup>-</sup> )	0.2595
5	Log(NO <sub>x</sub> )= f(S)	0.1983
6	Log(NO <sub>x</sub> )= f(1/ $\hat{u}$ )	0.1333
7	Log(NO <sub>x</sub> )= f( $\hat{u}$ )	0.1151
8	Log(NO <sub>x</sub> )= f( $\hat{u}^2$ )	0.1039
9	Log(NO <sub>x</sub> )= f(A <sup>+</sup> )	0.0195
10	Log(NO <sub>x</sub> )= f(E <sub>k</sub> )	0.0001

Table 5-2. Fuel Consumption and Emission Estimate Models Considered

Model Sequence	Model	R <sup>2</sup>
<b>Log(Fuel) = f(x)</b>		
1	Log(Fuel)= f( $\hat{u}$ )	0.3305
2	Log(Fuel)= f(1/ $\hat{u}$ )	0.2708
3	Log(Fuel)= f( $\hat{u}$ , S)	0.5256
4	Log(Fuel)= f(1/ $\hat{u}$ , S)	0.4743
5	Log(Fuel)= f( $\hat{u}$ , $\sigma^2_u$ )	0.8472
6	Log(Fuel)= f(1/ $\hat{u}$ , $\sigma^2_u$ )	0.9080
<b>HC = f(x) or Log(HC) =f(x)</b>		
1	HC= f( $\hat{u}$ )	0.0162
2	Log(HC)= f( $\hat{u}$ , S)	0.3011
3	Log(HC)= f( $\hat{u}$ , $\sigma^2_u$ )	0.6214
<b>Log(CO) = f(x)</b>		
1	Log(CO)= f( $\hat{u}$ )	0.3776
2	Log(CO)= f( $\hat{u}$ , S)	0.5851
3	Log(CO)= f( $\hat{u}$ , $\sigma^2_u$ )	0.7960
<b>Log(NO<sub>x</sub>) = f(x)</b>		
1	Log(NO <sub>x</sub> )= f( $\hat{u}$ )	0.1151
2	Log(NO <sub>x</sub> )= f( $\hat{u}$ , S)	0.5963
3	Log(NO <sub>x</sub> )= f( $\hat{u}$ , $\sigma^2_u$ )	0.9052

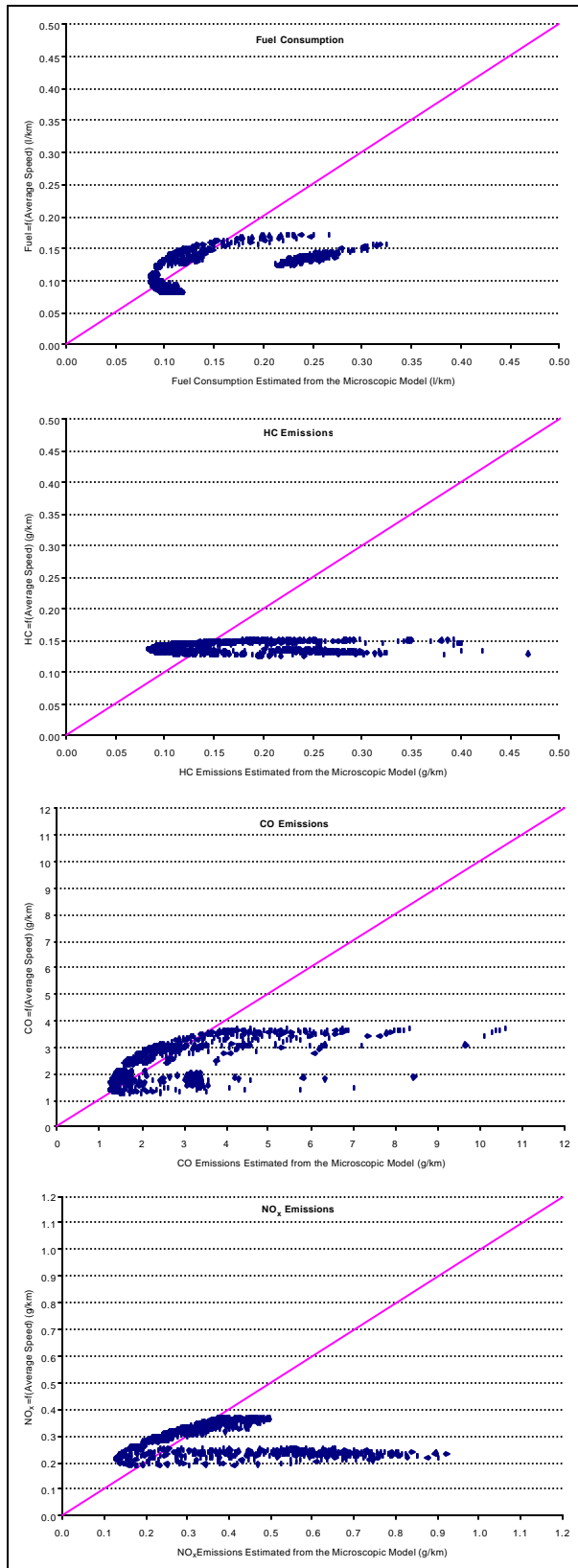


Figure 5-2. Comparison of MOEs Estimated by the Microscopic Model and the Model as a Function of Average Speed Alone

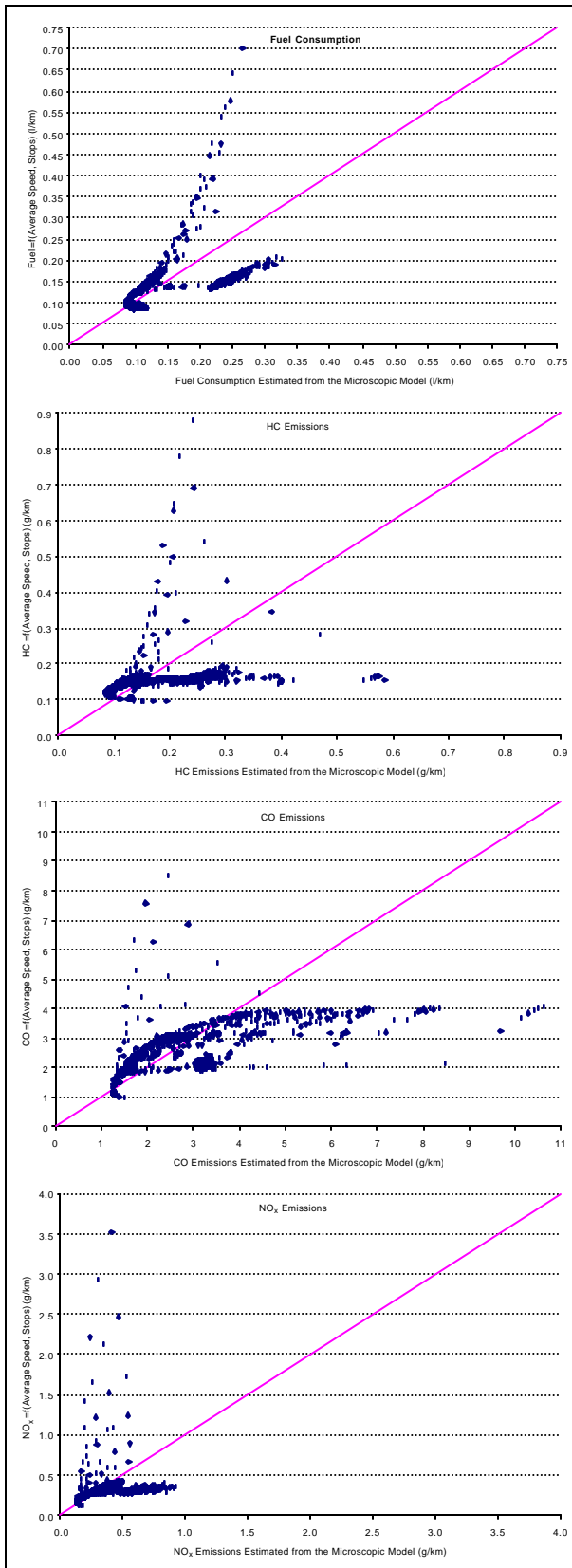


Figure 5-3. Comparison of MOEs Estimated by the Microscopic Model and the Model as a Function of Average Speed and Number of Vehicle Stops

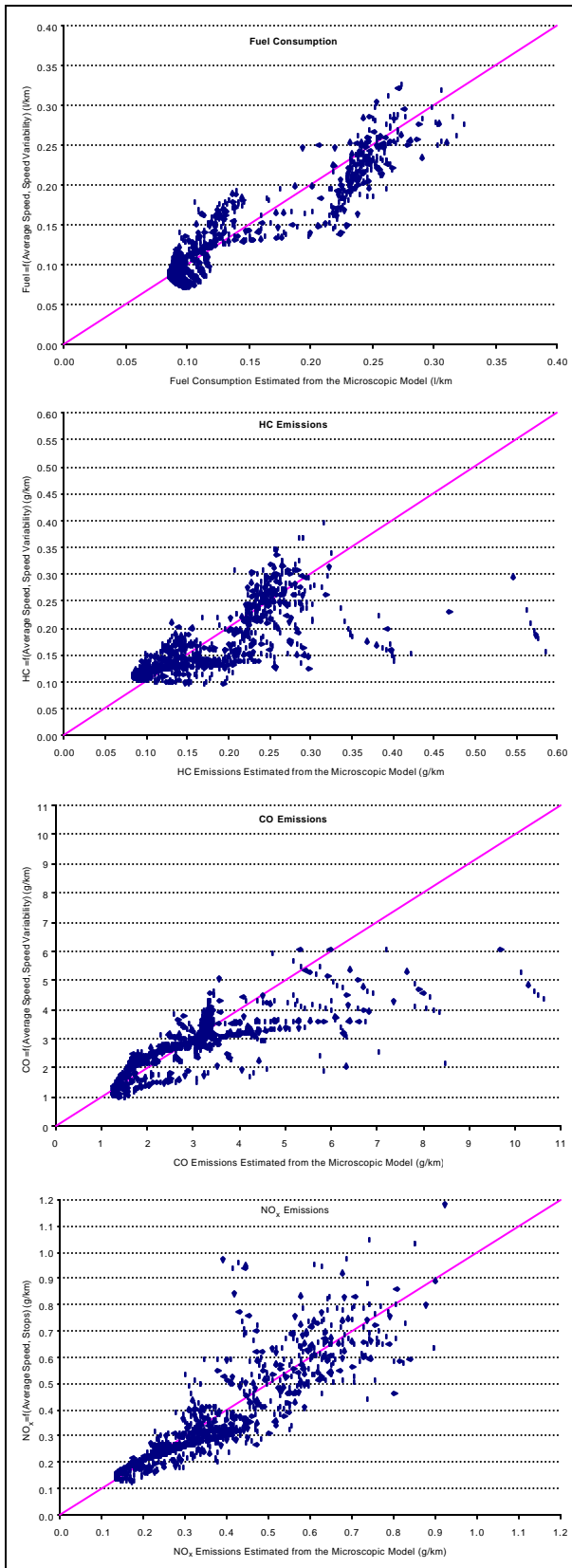


Figure 5-4. Comparison of MOEs Estimated by the Microscopic Model and the Model as a Function of Average Speed and Speed Variability

### ***5.2.3 Selection of Statistical Models***

Having developed some initial simple regression models, this section describes a further analysis that considers different all possible 8 independent variables. In addition, the reciprocal of average speed and the square of average speed are considered. To do so, first, the function of variable selection in SAS is applied to each dependent variable (both without log-transformation and with log-transformation), and then several candidate models are selected based on two criteria, which are listed in Figure 5-5. Second, the selected candidate models are compared to one another according to three criteria that are listed in Figure 5-5, then the optimal statistical model for each dependent variable is identified considering the balance among criteria and priority of each criteria.

Figure 5-5 illustrates the model selection procedure and the associated criteria. The best model is identified as the model that produces the highest adjusted coefficient of determination (Adjusted  $R^2$ ), involves the fewest independent variables as possible, and eliminates the independent variables that have multicollinearities to the extent possible (Multicollinearity test is shown in Appendix C.)

The following subsection describes the model selection for estimating CO emission rates using log-transformed data. This description serves as an illustration example. The same procedure is also applied for selecting models to predict vehicle fuel consumption, HC, and  $\text{NO}_x$  emission rates.

#### **5.2.3.1 Determination of CO Statistical Model**

As explained in Figure 5-5, the first step is to select the candidate models for estimating CO emission rates using the SAS variable selection function. The procedure starts with the simplest model and then considers more complex models with multiple independent variables. For example, SAS initially select the best ten models considering a single independent variable, then progressively evaluates models with more independent variables, as tabulated in Table 5-3.

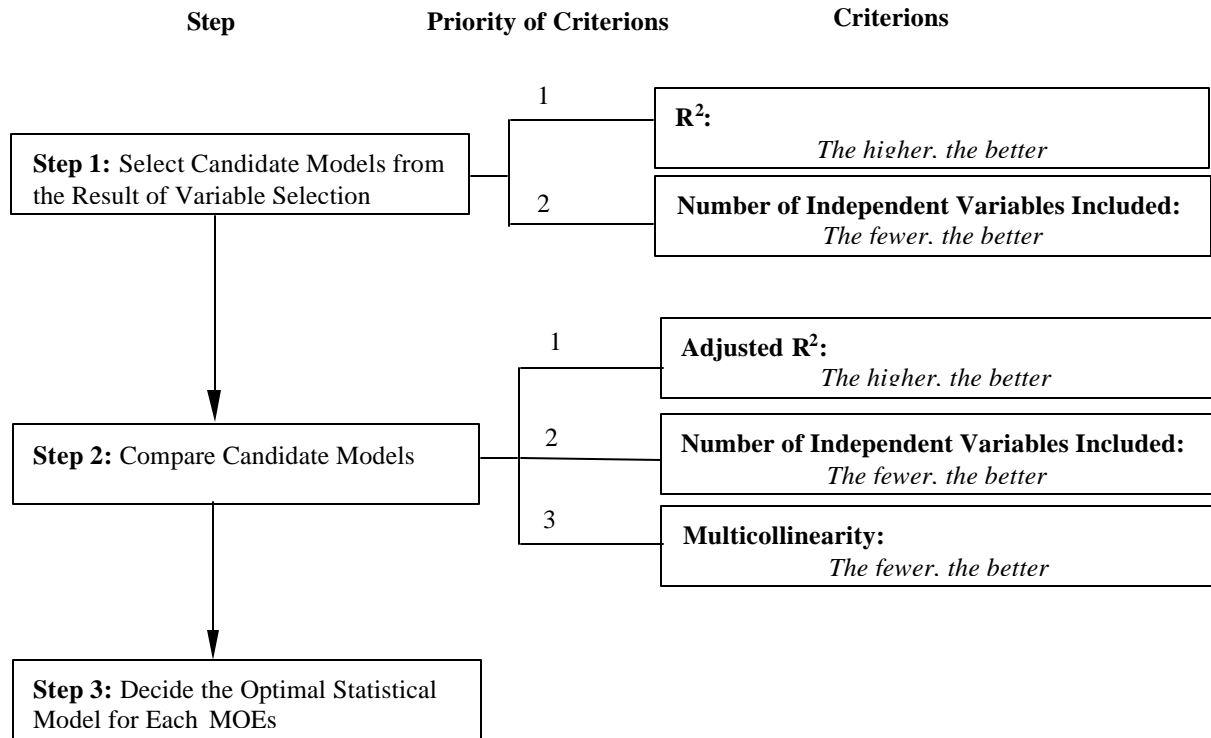


Figure 5-5. Flow Chart for the Selection of the optimal statistical model

As shown in Table 5-3, a model with all ten independent variables result in a coefficient of determination ( $R^2$ ) of 0.9254, which is the highest achievable  $R^2$ . However, in this model the independent variables as the average speed, the reciprocal of the average speed, the average speed squared, the number of vehicle stops, the total noise, and the kinetic energy do not pass the multicollinearity test. With fewer independent variables included in a model, the value of  $R^2$  will decrease. In selecting the optimum model, an attempt is made to ensure that the balance between the value of  $R^2$  and the number of independent variables while ensuring minimum multicollinearity. By screening all models shown in Table 5-3, the following candidate models are selected for future analysis.

Table 5-3. Summary of Variable Selection for Estimating CO Emission Rates

Log(CO)=f(x)						
No. of Variables	R <sup>2</sup>	Variables				
1	0.6259	P				
1	0.4137	$\hat{u}^2$				
1	0.3776	$\hat{u}$				
1	0.3338	$\sigma^2_{u1}$				
1	0.2307	1/ $\hat{u}$				
1	0.1625	A				
1	0.1379	E <sub>K</sub>				
1	0.1194	A <sup>-</sup>				
1	0.0364	S				
1	0.0186	A <sup>+</sup>				
2	0.8627	$\hat{u}^2$	$\sigma^2_{u1}$			
2	0.7963	$\hat{u}$	$\sigma^2_{u1}$			
2	0.7689	$\hat{u}^2$	A			
2	0.7612	$\sigma^2_{u1}$	E <sub>K</sub>			
2	0.7274	$\hat{u}$	A			
2	0.7180	$\sigma^2_{u1}$	P			
2	0.6959	$\hat{u}^2$	E <sub>K</sub>			
2	0.6704	A	P			
2	0.6622	$\hat{u}^2$	P			
2	0.6541	$\hat{u}$	P			
3	0.8878	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$		
3	0.8868	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>		
3	0.8816	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$		
3	0.8785	$\hat{u}^2$	$\sigma^2_{u1}$	P		
3	0.8781	$\hat{u}^2$	$\sigma^2_{u1}$	A		
3	0.8768	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>-</sup>		
3	0.8735	$\hat{u}^2$	$\sigma^2_{u1}$	E <sub>K</sub>		
3	0.8726	$\hat{u}^2$	$\sigma^2_{u1}$	S		
3	0.8608	$\hat{u}$	1/ $\hat{u}$	$\sigma^2_{u1}$		
3	0.8360	$\hat{u}$	$\sigma^2_{u1}$	P		
4	0.9047	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>	E <sub>K</sub>	
4	0.9046	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>	
4	0.8993	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	P	
4	0.8977	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>	
4	0.8959	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	A	
4	0.8953	$\hat{u}^2$	$\sigma^2_{u1}$	E <sub>K</sub>	P	
4	0.8952	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>-</sup>	
4	0.8928	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	P	
4	0.8913	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>	P	
4	0.8909	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	E <sub>K</sub>	
5	0.9129	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>	E <sub>K</sub>
5	0.9116	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>	E <sub>K</sub>	P
5	0.9081	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>	P
5	0.9076	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	A <sup>+</sup>
5	0.9063	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	E <sub>K</sub>	P
5	0.9058	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	A	A <sup>+</sup>
5	0.9047	$\hat{u}^2$	$\sigma^2_{u1}$	S	A <sup>+</sup>	E <sub>K</sub>
5	0.9047	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u1}$	S	A <sup>+</sup>
5	0.9047	$\hat{u}^2$	$\sigma^2_{u1}$	A	A <sup>+</sup>	E <sub>K</sub>

Table 5-3. (Continued)

No. of Variables	R <sup>2</sup>	Variables									
6	0.9184	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	E <sub>K</sub>	P				
6	0.9152	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	E <sub>K</sub>	P				
6	0.9147	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	E <sub>K</sub>				
6	0.9133	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A <sup>+</sup>	E <sub>K</sub>				
6	0.9129	$\hat{u}$	$\hat{u}^2$		A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>				
6	0.9129	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A	A <sup>+</sup>	E <sub>K</sub>				
6	0.9119	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P				
6	0.9119	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A <sup>+</sup>	E <sub>K</sub>	P				
6	0.9116	$\hat{u}^2$	$\sigma^2_{u_i}$	A	A <sup>+</sup>	E <sub>K</sub>	P				
6	0.9113	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	P				
7	0.9202	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	E <sub>K</sub>	P			
7	0.9192	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A <sup>+</sup>	E <sub>K</sub>	P			
7	0.9189	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P			
7	0.9184	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A	A <sup>+</sup>	E <sub>K</sub>	P			
7	0.9178	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	E <sub>K</sub>	P			
7	0.9166	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A <sup>+</sup>	E <sub>K</sub>	P			
7	0.9159	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P			
7	0.9154	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	E <sub>K</sub>			
7	0.9153	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A	A <sup>+</sup>	E <sub>K</sub>	P			
7	0.9151	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A	A <sup>+</sup>	E <sub>K</sub>			
8	0.9229	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	E <sub>K</sub>	P		
8	0.9206	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A	A <sup>+</sup>	E <sub>K</sub>	P		
8	0.9204	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P		
8	0.9203	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A <sup>+</sup>	E <sub>K</sub>	P		
8	0.9199	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	E <sub>K</sub>	P		
8	0.9193	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P		
8	0.9192	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P		
8	0.9187	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	E <sub>K</sub>	P		
8	0.9180	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>-</sup>	E <sub>K</sub>	P		
8	0.9167	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	P		
9	0.9246	$\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P	
9	0.9237	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	E <sub>K</sub>	P	
9	0.9215	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	A	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P	
9	0.9215	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P	
9	0.9204	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P	
9	0.9189	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	A <sup>-</sup>	P	
9	0.9189	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>-</sup>	E <sub>K</sub>	P	
9	0.9169	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	
9	0.9063	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	S	A	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P	
9	0.9007	$\hat{u}$	1/ $\hat{u}$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P	
10	0.9254	$\hat{u}$	1/ $\hat{u}$	$\hat{u}^2$	$\sigma^2_{u_i}$	S	A	A <sup>+</sup>	A <sup>-</sup>	E <sub>K</sub>	P

**Model 1.**  $\text{Log}(\text{CO}) = f(\hat{u}, 1/\hat{u}, \hat{u}^2, \sigma^2_{u_i}, S, A, A^+, A^-, E_k, P)$ , adjusted  $R^2 = 0.9249$

All independent variables defined are included in the model, the highest adjusted correlation coefficient is reached while six independent variables do not pass the multicollinearity test.

**Model 2.**  $\text{Log}(\text{CO}) = f(\hat{u}, \hat{u}^2, \sigma^2_u, A^+, E_k, P)$ , adjusted  $R^2 = 0.9181$

Compared to the model with all independent variables, the adjusted  $R^2$  for this model is only reduced by 0.006 to 0.9181 while only six independent variables are required. However, a number of independent variables including the average speed, the average speed squared and the kinetic energy do not pass the multicollinearity test. Clearly, two of the independent variables, namely the average speed and the average speed squared are correlated.

**Model 3.**  $\text{Log}(\text{CO}) = f(1/\hat{u}, \hat{u}^2, \sigma^2_u, A^+, E_k, P)$ , adjusted  $R^2 = 0.9149$

The adjusted  $R^2$  is almost equal to  $R^2$  in Model 2. This model only includes a single independent variable that does not pass the multicollinearity test (kinetic energy).

By examining the model set with five independent variables, it is found that with one more independent variable removed, the adjusted  $R^2$  remains within the range of 0.91-0.92 for the first two best models in this model set. These two models are discussed as follows.

**Model 4.**  $\text{Log}(\text{CO}) = f(\hat{u}, \hat{u}^2, \sigma^2_u, A^+, E_k)$ , adjusted  $R^2 = 0.9126$

Like Model 2, the adjusted  $R^2$  is within the range of 0.91-0.92, however three independent variables do not pass the multicollinearity test. Model 4 is better than Model 2 because it includes fewer independent variables.

**Model 5.**  $\text{Log}(\text{CO}) = f(\hat{u}^2, \sigma^2_u, A^+, E_k, P)$ , adjusted  $R^2 = 0.9113$

Like Model 3, the adjusted  $R^2$  for Model 5 remains within the range of 0.91-0.92. This model, however, includes an independent variable that does not pass the multicollinearity test (kinetic energy). Again, based on the selection criteria Model 5 is preferred over Model 3 because it includes fewer independent variables.

**Model 6.**  $\text{Log}(\text{CO}) = f(1/\hat{u}, \hat{u}^2, \sigma^2_u, A^+, E_k)$ , adjusted  $R^2 = 0.9090$

Compared with Model 5, the adjusted  $R^2$  drops slightly while the kinetic energy variable does not pass the multicollinearity test. Model 6 is easier to be used when compared to Model 5 because the reciprocal of the average speed can be easily computed once the

average speed is computed, however, the power variable requires acceleration estimates in addition to speed.

Again, the first two models in the four-independent-variable model set include models with the adjusted  $R^2$  in the range of 0.90. These two models are discussed below.

*Model 7.*  $\text{Log}(\text{CO}) = f(\hat{u}^2, \sigma^2_u, A^+, E_k)$ , adjusted  $R^2 = 0.9044$

Like Model 6, the adjusted  $R^2$  is within the range of 0.90-0.91. One independent variable (kinetic energy) does not pass the multicollinearity test. Based on the selection criteria, Model 7 is better than Model 6 because Model 7 requires fewer independent variables while  $R^2$  is similar.

*Model 8.*  $\text{Log}(\text{CO}) = f(\hat{u}, \hat{u}^2, \sigma^2_u, A^+)$ , adjusted  $R^2 = 0.9043$

The adjusted  $R^2$  for Model 8 and Model 7 are similar, however, two independent variables do not pass the multicollinearity test. Using the selection criteria, Model 8 is superior to Model 7 because it is easier to compute its independent variables. In addition, Model 8 is superior because it involves fewer independent variables.

By analyzing the SAS results that are summarized in Table 5-3 one can observe that a reduction in the number of independent variables from 4 to 3 results in a significant reduction in  $R^2$ . Consequently, Model 8 is selected as the optimal model for estimating CO emissions.

### **5.2.3.2 Determination of Statistical Models**

The same model selection procedure is applied to each dependent variable. Table 5-4 lists the models selected as candidate models for further comparison for each dependent variable using log-transformed data. It should be noted that the first candidate model for each dependent variable is the model that includes all 10 independent variables, and then the optimal model is selected progressively based on the selection criteria.

The optimal statistical models that were selected for the four dependent variables are shown as Equation 5-11, 5-12, 5-13 and 5-15. The coefficients for equations are listed in Table 5-5.

$$\text{Log}(Fuel) = a_0 + a_1 * 1/\bar{u} + a_2 * \bar{u}^2 + a_3 * \mathbf{S}_u^2 + a_4 * S + a_5 * A + a_6 * E_k \quad (5-11)$$

$$\text{Log}(HC) = b_0 + b_1 * \bar{u} + b_2 * \bar{u}^2 + b_3 * \mathbf{S}_u^2 + b_4 * A^+ + b_5 * E_k \quad (5-12)$$

$$\text{Log}(CO) = c_0 + c_1 * \bar{u} + c_2 * \bar{u}^2 + c_3 * \mathbf{S}_u^2 + c_4 * P \quad (5-13)$$

$$\text{Log}(NOx) = d_0 + d_1 * \bar{u}^2 + d_2 * \mathbf{S}_u^2 + d_3 * A + d_4 * E_k \quad (5-15)$$

The developed statistical models compute fuel consumption and emission rates to within 88-90 percent of those computed using the microscopic models that were presented in Chapter 2 (Ahn *et al.*, 1999). A comparison of the proposed model estimates to the microscopic model estimates demonstrates a fairly good fit with most observations symmetric around the line of perfect correlation, as illustrated in Figure 5-6. It should be noted, however, that multicollinearities of independent variables exist for the HC and CO estimate models. If these variables are removed from the regression model, the R<sup>2</sup> is reduced significantly. Consequently, these variables are kept in the model.

All results from SAS are documented in Appendix C.

Table 5-4 Candidate Models for Estimating Vehicle Fuel Consumption rate and Emission rates of HC, CO, and NO<sub>x</sub>

#	Model	Number of Independent Variables	Adjusted R <sup>2</sup>	Multicollinearity
<b>Log(Fuel) = f(x)</b>				
1	Log(Fuel)= f( $\dot{u}$ , 1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , S, A, A <sup>+</sup> , E <sub>k</sub> , P)	9	0.9652	$\dot{u}$ , $\dot{u}^2$
2	Log(Fuel)= f( $\dot{u}$ , 1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , S, A, E <sub>k</sub> , P)	7	0.9632	
3	Log(Fuel)= f(1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , S, A, E <sub>k</sub> )	6	0.9564	
4	Log(Fuel)= f( $\dot{u}$ , 1/ $\dot{u}$ , $\sigma^2_u$ , S, A, E <sub>k</sub> )	6	0.9528	
5	Log(Fuel)= f(1/ $\dot{u}$ , $\sigma^2_u$ , S, A, E <sub>k</sub> )	5	0.9328	
<b>Log(HC) = f(x)</b>				
1	Log(HC)= f( $\dot{u}$ , 1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , S, A, A <sup>+</sup> , A <sup>-</sup> , E <sub>k</sub> , P)	10	0.8950	$\dot{u}$ , 1/ $\dot{u}$ , $\dot{u}^2$ , S, A, E <sub>k</sub>
2	Log(HC)= f( $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , S, A <sup>+</sup> , E <sub>k</sub> )	6	0.8863	$\dot{u}$ , $\dot{u}^2$ , E <sub>k</sub>
3	Log(HC)= f( $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A, A <sup>+</sup> , E <sub>k</sub> )	6	0.8837	$\dot{u}$ , $\dot{u}^2$ , E <sub>k</sub>
4	Log(HC)= f(1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , S, A <sup>+</sup> , E <sub>k</sub> )	6	0.8831	$\dot{u}^2$ , E <sub>k</sub>
5	Log(HC)= f( $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> , E <sub>k</sub> )	5	0.8820	$\dot{u}$ , $\dot{u}^2$ , E <sub>k</sub>
6	Log(HC)= f(1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> , E <sub>k</sub> )	5	0.8690	$\dot{u}^2$ , E <sub>k</sub>
7	Log(HC)= f( $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> )	5	0.8642	$\dot{u}$ , $\dot{u}^2$
<b>Log(CO) = f(x)</b>				
1	Log(CO)= f( $\dot{u}$ , 1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , S, A, A <sup>+</sup> , A <sup>-</sup> , E <sub>k</sub> , P)	10	0.9249	$\dot{u}$ , 1/ $\dot{u}$ , $\dot{u}^2$ , S, A, E <sub>k</sub>
2	Log(CO)= f( $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> , E <sub>k</sub> , P)	6	0.9181	$\dot{u}$ , $\dot{u}^2$ , E <sub>k</sub>
3	Log(CO)= f(1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> , E <sub>k</sub> , P)	6	0.9149	E <sub>k</sub>
4	Log(CO)= f( $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> , E <sub>k</sub> )	5	0.9126	$\dot{u}$ , $\dot{u}^2$ , E <sub>k</sub>
5	Log(CO)= f( $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> , E <sub>k</sub> , P)	5	0.9113	E <sub>k</sub>
6	Log(CO)= f(1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> , E <sub>k</sub> )	5	0.9090	E <sub>k</sub>
7	Log(CO)= f( $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> , E <sub>k</sub> )	5	0.9044	E <sub>k</sub>
8	Log(CO)= f( $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A <sup>+</sup> )	5	0.9043	$\dot{u}$ , $\dot{u}^2$
<b>Log(NO<sub>x</sub>) = f(x)</b>				
1	Log(NO <sub>x</sub> )= f( $\dot{u}$ , 1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , S, A, A <sup>+</sup> , E <sub>k</sub> , P)	9	0.9679	$\dot{u}$ , $\dot{u}^2$
2	Log(NO <sub>x</sub> )= f( $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A, E <sub>k</sub> )	5	0.9660	
3	Log(NO <sub>x</sub> )= f(1/ $\dot{u}$ , $\dot{u}^2$ , $\sigma^2_u$ , A, E <sub>k</sub> )	5	0.9650	
4	Log(NO <sub>x</sub> )= f( $\dot{u}^2$ , $\sigma^2_u$ , A, E <sub>k</sub> )	5	0.9582	
5	Log(NO <sub>x</sub> )= f( $\dot{u}$ , $\sigma^2_u$ , A, E <sub>k</sub> )	5	0.9557	
6	Log(NO <sub>x</sub> )= f( $\dot{u}^2$ , $\sigma^2_u$ , E <sub>k</sub> )	3	0.9446	

Table 5-5. Coefficients for the Equations

<i>Log(Fuel)</i>			<i>Log(HC)</i>		
Coefficient	Estimated Parameter	Standard Error	Coefficient	Estimated Parameter	Standard Error
a <sub>0</sub>	-2.50108115	0.00991891	b <sub>0</sub>	-1.67590199	0.01966997
a <sub>1</sub>	14.42540394	0.23634302	b <sub>1</sub>	-0.02568464	0.00070774
a <sub>2</sub>	0.00004447	0.00000176	b <sub>2</sub>	0.00028429	0.00000529
a <sub>3</sub>	0.00332904	0.00008969	b <sub>3</sub>	0.00562839	0.00011408
a <sub>5</sub>	-0.38201644	0.01229086	b <sub>5</sub>	0.30972638	0.01799754
a <sub>5</sub>	1.29025950	0.04703663	b <sub>5</sub>	-0.00000015	0.00000001
a <sub>6</sub>	-0.00000015	0.00000001			
Adjusted R <sup>2</sup>	0.9564		Adjusted R <sup>2</sup>	0.8820	
<i>Log(CO)</i>			<i>Log(NO<sub>x</sub>)</i>		
Coefficient	Estimated Parameter	Standard Error	Coefficient	Estimated Parameter	Standard Error
c <sub>0</sub>	0.32973440	0.02032049	d <sub>0</sub>	-1.86507714	0.00732696
c <sub>1</sub>	-0.01138260	0.00068310	d <sub>1</sub>	0.00013772	0.00000259
c <sub>2</sub>	0.00018832	0.00000531	d <sub>2</sub>	0.00676264	0.00009877
c <sub>3</sub>	0.00637895	0.00008053	d <sub>3</sub>	0.59257820	0.02687022
c <sub>5</sub>	0.239321822	0.01806450	d <sub>5</sub>	-0.00000020	0.00000001
Adjusted R <sup>2</sup>	0.9043		Adjusted R <sup>2</sup>	0.9582	

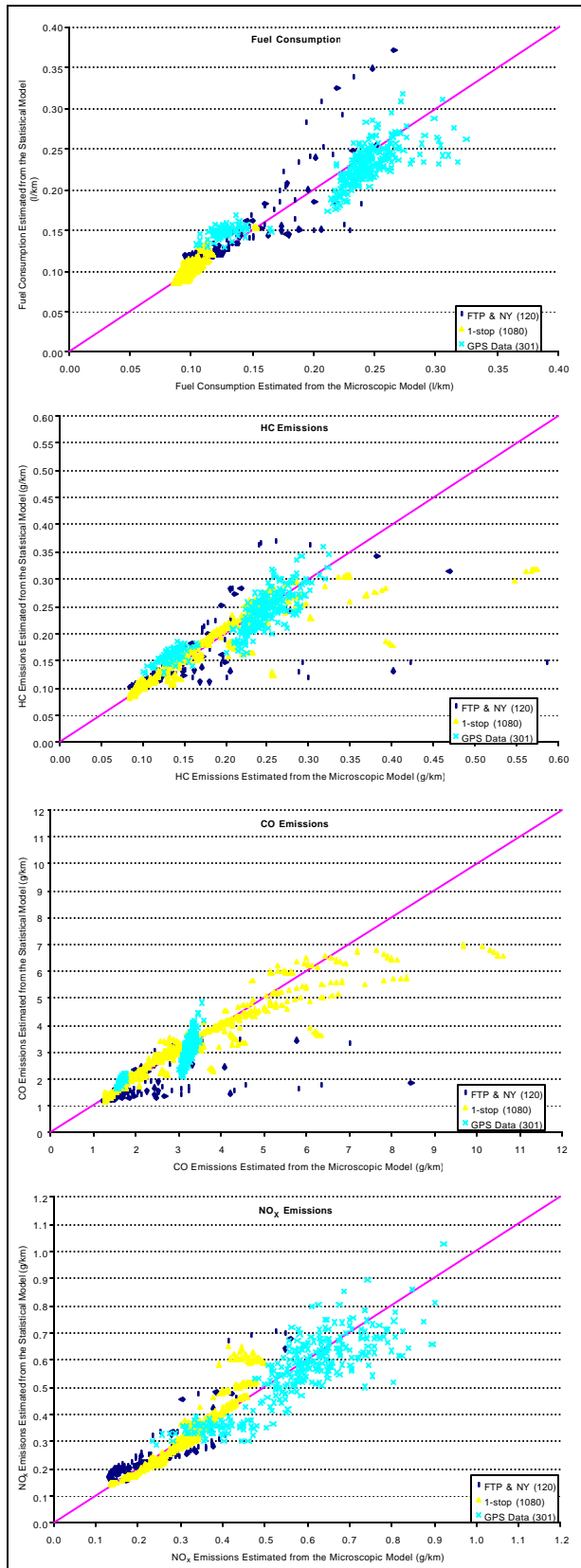


Figure 5-6. Comparison of the Statistical Models and the Microscopic Models for Estimating Vehicle Fuel Consumption and Emission Rate

## 5.3 Model Validation

### 5.3.1 Model Validation Data

Data collected on a dynamometer by the EPA are used to validate the statistical models developed above for estimating HC, CO, and NO<sub>x</sub> emission rates. There is no field data available for the validation of the fuel consumption model.

The EPA database includes second-by-second measurements of speed and emissions of HC, CO, CO<sub>2</sub>, and NO<sub>x</sub> for a total of 101 vehicles over a minimum of 14 drive cycles, as summarized in Table 5-6.

*Table 5-6 EPA New Facility-Specific Area-wide Drive Cycles*

<b>Drive Cycle Sequence</b>	<b>Drive Cycle Description</b>
1	LOS A-B Arterial/Collectors Trace (12.28 minutes)
2	LOS C-D Arterial/Collectors Trace (10.58 minutes)
3	LOS E-F Arterial/Collectors Trace (8.50 minutes)
4	High speed Freeway
5	LOS A-C Freeway Trace (8.60 minutes)
6	FNYC
7	LOS D Freeway Trace (6.77 minutes)
8	LOS E Freeway Trace ( 7.60 minutes)
9	LOS F Freeway Trace (7.37 minutes)
10	LOS G Freeway Trace (6.50 minutes)
11	LA92
12	Local Roadways (8.75 minutes)
13	Ramp (5.53 minutes)
14	Area-wide Non-Freeway Urban Travel

All test vehicles in the EPA database are classified into clean, normal, high and very high emitters for each of HC, CO, and NO<sub>x</sub> emissions based on their emission rates while driving the FTP city cycle. The ORNL data used for the development of the microscopic model do not include any high emitters, thus the statistical models developed in the thesis

can only be considered to estimate emissions for clean and/or normal vehicles. Therefore, validation is made based on those data that include clean and normal vehicles for each of HC, CO and NO<sub>x</sub> emissions in the EPA database. The mean emission rate per kilometer for each drive cycle is computed as the average of emission rate across all clean and normal test vehicles in each cycle. The 95-percentile and 5-percentile of emission rates per kilometer are also calculated for each cycle.

### ***5.3.2 Validation of State-of-Practice Statistical Models***

A first step in validating the proposed statistical models is to validate the current state-of-practice models. Specifically, three models are considered to represent the current state-of-practice. The first of these models uses the average speed as a single explanatory variable. The second model uses the average speed and number of vehicle stops. The third and final model considers the average speed and speed variability. A comparison of these three models against the microscopic model estimates demonstrated a poor fit as illustrated in Figure 5-2, 5-3, and 5-4.

As illustrated in Figure 5-7, the emission rates of HC, CO, and NO<sub>x</sub> using the first and third model ( $f(\hat{u})$  and  $f(\hat{u}, \sigma^2_u)$ ) are within the 95 percent confidence limits. Using the second model ( $f(\hat{u}, s)$ ) the HC and CO emissions are within the confidence limits, however, the NO<sub>x</sub> emissions fall outside the confidence limits. It should also be noted that the models with average speed alone as an independent variable can only explain less than 2%, 38%, and 12% of HC, CO, and NO<sub>x</sub> emission rates, respectively. The models with both average speed and number of vehicle stops can explain 30%, 58%, and 50% of HC, CO, and NO<sub>x</sub> emission rate, respectively. The models with both average speed and speed variability have much better performance. Furthermore, as shown in Figure 5-7, the EPA data represents a large variation within a cycle, and some vehicles are unreasonable to be claimed as clean or normal vehicles.

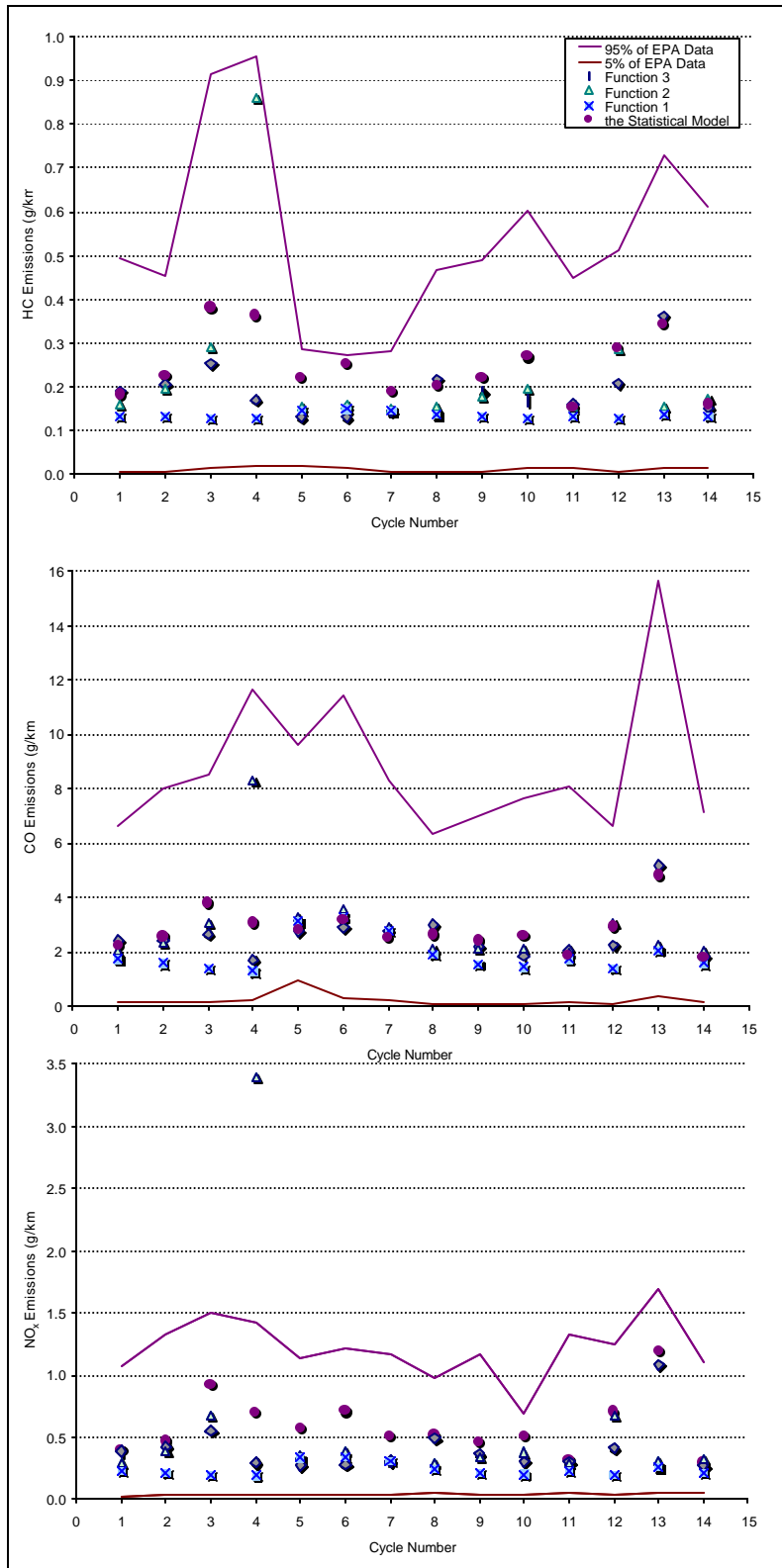


Figure 5-7. Comparison of Emission Rates Estimated by Four Models

### ***5.3.3 Validation of Proposed Statistical Models***

It is assumed that the speed-acceleration profile for each EPA drive cycle is the same regardless of the test vehicles, so the statistical models are applied to only one trip for each drive cycle. Figure 5-8 illustrates the comparison of emission rates of HC, CO, and NO<sub>x</sub> estimated by the statistical models and observed in the EPA database. All data are documented in Appendix D.

In general, the statistical models estimate HC, CO and NO<sub>x</sub> emission rates within the confidence limits of the EPA data. Compared with the mean emission rates calculated from the EPA database, the statistical models overestimate the HC and NO<sub>x</sub> emission rates while underestimate the CO emission rates.

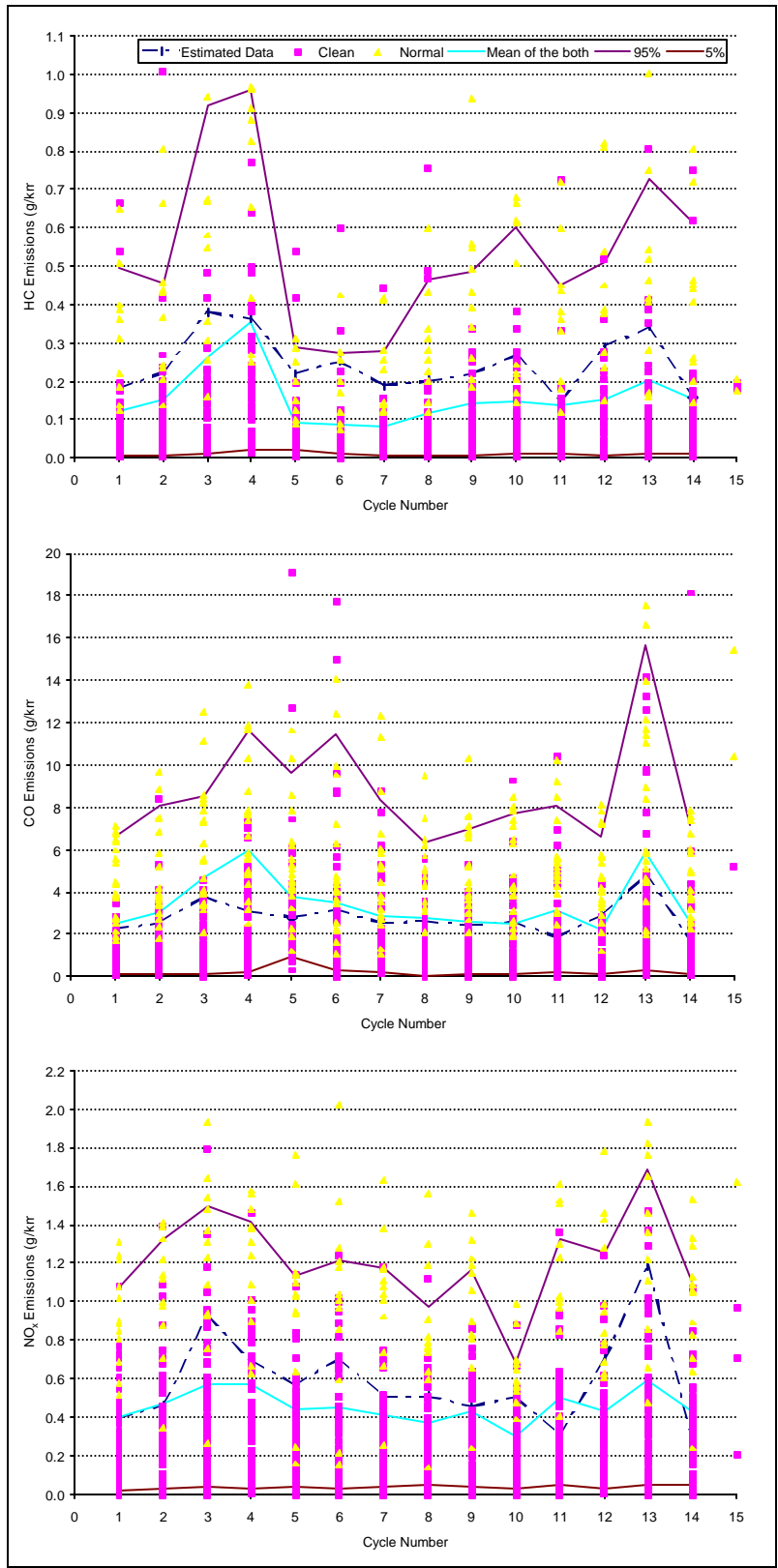


Figure 5-8 Comparison of Emissions Estimated by the Statistical Models and observed from the EPA Database (Note: X-axis is the cycle number, which is indicated in Table 5-6. And the cycle number of 15 refers to the US06 cycle)

## 5.4 Summary of Findings

The speed variability, the number of vehicle stops, the total noise, the acceleration noise, the deceleration noise, the kinetic energy and the positive power per unit of distance along a trip, together with the average trip speed, the reciprocal of the average speed and the average speed squared, are identified as potential explanatory variables for estimating vehicle fuel consumption and emission rates (per unit of distance). A total of 1501 trips that were generated in Chapter 3 are used as the data source. Vehicle fuel consumption and emission rates are computed by applying the microscopic model to the 1501 trips. Using SAS statistical models are derived based on these defined variables.

The statistical models predict vehicle fuel consumption and emission rates within the range of 88%-96% accuracy. In addition, the statistical models estimate HC, CO and NO<sub>x</sub> emission rates within the range of 95 percentile and 5 percentile of emission rates observed in the EPA database for the predefined normal and clean vehicles.

## CHAPTER 6 : CONCLUSIONS AND RECOMMENDATION

### 6.1 Summary of the Thesis

This thesis demonstrated the inadequacy of the average speed alone for vehicle fuel consumption and emission estimates, and systematically analyzed the impacts of different factors on vehicle fuel consumption and emissions. Furthermore, the thesis also identified several aggregate trip variables as potential explanatory variables based on characterized cycle data as well as field data. Using these potential explanatory variables, statistical models were developed to estimate fuel consumption and emission rates of HC, CO, and NO<sub>x</sub>. Finally EPA validated the statistical models against data that collected on a chassis dynamometer.

The study of the thesis supports the following conclusions:

- The average speed is insufficient for vehicle fuel consumption and emission rate estimations.
- The speed variability defined as the speed variation about the average speed is the most important factor in explaining the error in MOE estimates.
- Emissions of HC and CO are more sensitive to the level of acceleration than to the average speed, the number of vehicle stops, and the level of deceleration, while vehicle fuel consumption and NO<sub>x</sub> is more sensitive to the average speed than to the other three variables.
- At high speeds the introduction of vehicle stops that involve extremely mild acceleration levels can actually reduce vehicle emission rates.
- The speed variability, the number of vehicle stops, the total noise or the acceleration noise, and the kinetic energy are the critical explanatory variables for predicting fuel consumption and emission rates, besides the average speed (or the reciprocal of the average speed, or the average speed squared).

- The statistical models predict fuel consumption rate and emissions rates of HC, CO, and NO<sub>x</sub> within the accuracy of 0.88-0.96 when compared to the microscopic models.
- The statistical models predict emission rates of HC, CO, and NO<sub>x</sub> within the 95 percentile confidence limits of the EPA data.
- Considering the mean value of emission rates in the EPA database for the clean and normal vehicles, in general, the statistical models overestimate HC and NO<sub>x</sub> emissions rates while underestimate CO emissions rates.

Comparing the proposed statistical models with the current state-of-practice, the statistical models provide the better estimates for vehicle fuel consumption and emissions because speed variances about the average speed along a trip is considered in these models. On the other hand, the statistical models only require several aggregate trip variables as input while generating reasonable estimates that are consistent with microscopic model estimates.

## 6.2 Model Limitations

Given that the statistical models are derived using microscopic model estimates of vehicle fuel consumption and emission rates, the models suffer from a number of limitations including:

- The models suffer from the limitations in the microscopic models (Ahn and Rakha, 1999). These include the following:
  - The effects of start mode (cold-start and hot-start) and ambient temperature on energy and emissions are not considered.
  - The models are invalid at vehicle speed and acceleration levels that are beyond the boundaries observed in the ORNL data.
- The characterized cycle data may not represent the real-world vehicle operation.
  - The single stop cycles are characterized by varying a level of acceleration, a level of deceleration, a maximum speed and/or a scale factor  $k_1$ ; while the FTP city cycle, the New York City cycle and/or the US06 cycle are characterized by applying factors  $k_1$ ,

$k_2$  and/or  $k_3$ . Thus some unrealistic speed-acceleration combinations may be generated through these processes.

- In order to conform to the speed-acceleration envelope defined in the microscopic models, the data smoothing is applied to the drive cycles.
- The potential explanatory variables identified in the study may not fully represent the embedded relationship between the movement of a vehicle and fuel that is required for the movements, or the relationship between the movement of a vehicle and emissions of HC, CO, and NO<sub>x</sub> that are generated by the movement.
- Uncertainties exist in the EPA database, which are used for model validation. Specifically, the classification of vehicles (i.e. clean, normal, high, and super emitter) needs further refinement.

### **6.3 Future Research**

To overcome the limitations discussed above, the following areas can be future analyzed:

- Incorporate more field data that cover higher speed and acceleration levels beyond the boundary of the microscopic models.
- Refine the microscopic models to consider the impact of start mode, ambient temperature.
- Use more field data to refine and validate the statistical fuel consumption and emission models.
- Develop lookup tables that characterize proposed explanatory variables for typical roadway sections under different levels of congestion in order to enable the usage of proposed models as a post-processor to planning models.
- Quantify the energy and environmental impact of disaggregating the vehicle population into individual vehicle types vs. using an aggregate composite vehicle.

## REFERENCES

- K. Ahn., A.A. Trani, H. Rakha, and M. Van Aerde (1999), "*Microscopic Fuel Consumption and Energy Emission Models*," Presented at the Transportation Research Board 78th Annual Meeting, January.
- K. Ahn (1999), "*Microscopic Fuel Consumption and Energy Emission Models*", Master Thesis, Virginia Polytechnic Institute and State University, December
- D.G. Capelle (1966), "*An Investigation of Acceleration Noise as a Measure of Freeway Level of Service*", Doctoral dissertation, Texas A&M University, College Station.
- D. Drew (1968), "*Traffic Flow Theory and Control*", McGraw Hill, 68-13626.
- Environmental Protection Agency (EPA) (1993), "*Federal Test Procedure Review Project: Preliminary Technical Report, Office of MOBILE5 Sources*", May
- R. Herman, E. Montroll, R. Potts, and R. Rothery (1959), "*Traffic Dynamics: Analysis of Stability in Car Following*", Operations Research, Vol. 7, pp. 86-106
- T. Jones and R. Potts (1955), "*The Measurement of Acceleration Noise: A Traffic Parameter*", Operations Research, Vol. 10, pp. 755-763.
- P. Newman and J. Kenworthy (1992), "*Winning Back the Cities*", Pluto Press, Leichhardt NSW, Australia, pp. 39-50. Quoting C. Hass-Klau (ed.), "*New Ways to Managing Traffic, Built Environment*", 12 (1/2)
- H. Rakha, M. Van Aerde, K. Ahn and A.A. Trani (1999), "*Requirements for Evaluating the Environmental Impacts of Intelligent Transportation Systems using Speed and Acceleration Data*", Presented at the Transportation Research Board 78<sup>th</sup> Annual Meeting, January, [Paper # 990702].
- N. Rowan (1967), "*An Investigation of Acceleration Noise as a Measure of the Quality of Traffic Service on Major Streets*", Doctoral dissertation, Texas A&M University, College Station.
- Transportation Research Board (TRB) (1995), "*Expanding Metropolitan Highways Implications for Air Quality and Energy Use*", Special Report 255, National Academy Press
- B. West, R. McGill, J. Hodgson, S. Sluder, and D. Smith (1997), "*Development of Data-Based Light-Duty Modal Emissions and Fuel consumption Models*," Society of Automotive Engineers Paper No. 972910.

François Dion, Michel Van Aerde, and Hesham Rakha (1999), "*Mesosopic Fuel Consumption and Vehicle Emission Rate Estimation as a Function of Average Speed and Number of Stops*", Paper presented at the Transportation Research Board 79<sup>th</sup> Annual Meeting, Washington, D.C.

François Dion, Michel Van Aerde, and Hesham Rakha (2000), "*Fuel Consumption and Vehicle Emission Rate Estimation as a Function of Average Speed and Number of Stops and Stop Duration*", Paper submitted to Transportation Research B.

Luis Ferreira (1985), "*Modeling Urban Fuel Consumption: Some Empirical Evidence*", Transportation Research A, Vol. 19A, No. 3, Pergamon Press Ltd.

EPA (1992), "*Overview: The Clean Air Act Amendments of 1990*"

EPA (1992), "*1992 Transportation & Air Quality Planning Guidelines*"

EPA (1993), "*Automobiles and Carbon Monoxide*", EPA 500-F-92-005, Jan

EPA (1993), "*Automobiles and Ozone*", EPA 500-f-92-006, Jan

EPA (1997), "*National Air Quality and Emissions Trends Reports, 1996*"

EPA (1998), "*1997 National Air Quality: Status and Trends*"

U.S. Department of Transportation, Federal Highway Administration, "*A Summary: Transportation Programs and Provisions of the Clean Air Act Amendments of 1990*"

U.S. Department of Transportation, Federal Highway Administration, "*A Summary: Air Quality Programs and Provisions of the Intermodal Surface Transportation Efficiency Act of 1991*"

M. Baker (1995), "*Fuel Consumption and Emission Models for Evaluating Traffic Control and Route Guidance Strategies*", Master Thesis, Queen's University, Kingston, Ontario, Canada

Michael Replogle (1993), "*Transportation Conformity and Demand Management: Vital Strategies for Clean Air Attainment*", Environmental Defense Fund, April

Matthew Barth, Feng An, Joseph Norbeck, and Marc Ross (1999), "*Modal Emissions Modeling: A Physical Approach*", Transportation Research Record 1520, Washington D.C.

K. Post, J. H. Kent, J. Tomlin, and N. Carruthers (1985), "*Fuel Consumption and Emission Modeling by Power Demand and a Comparison with Other Models*", Transportation Research A, Vol. 18A, No. 3, Pergamon Press Ltd.

Feng An and Marc Ross (1993), *"Model of Fuel Economy with Applications to Driving Cycles and Traffic Management"*, Transportation Research Record 1516, Washington, D.C.

C.S. Fisk (1989), *"The Australian Road Research Board Instantaneous Model of Fuel Consumption"*, Transportation Research B, Vol. 23B, No. 5, Pergamon Press Ltd.

Rahmi Akcelik (1989), *"Efficiency and Drag in the Power-Based Model of Fuel Consumption"*, Transportation Research B, Vol. 23B, No. 5, Pergamon Press Ltd.

T.F. Fwa and B.W. Ang (1992), *"Estimating Automobile Fuel Consumption in Urban Traffic"*, Transportation Research Record 1366, Washington, D.C.

Man-Feng Chang, Leonard Evans, Robert Herman, and Paul Wasielewski (1979), *"Gasolin Consumption in Urban Traffic"*, Transportation Research Record 599, Washington D.C.

Terry N. Lam (1985), *"Estimating Fuel Consumption from Engine Size"*, Journal of Transportation Engineering, Vol. 111, No.5, July

M. H. L. Waters (1992), *"State-of-the-Art Review 3: Road Vehicle Fuel Economy"*, Transport and Road Research Laboratory, Department of Transportation, HMSO, London

International Energy Agency (1991), *"Fuel Efficiency of Passenger Cars"*, OECD/IEA, Paris

OECD(1991), *"Toward Clean and Fuel Efficient Automobiles: Proceedings of an International Conference, Berlin 25-27 March 1991"*, Paris

National Research Council (1992), *"Automobile Fuel Economy: How far should we go?"*, National Academy Press, Washington, D.C.

U.S. Department of Transportation (1995), *"Workshop on Transportation Air Quality Analysis (Participant's Notebook)"*, FHWA-151-95-011

Brett C. Singer and Robert A. Harley (1996), *"Fuel-Based Motor Vehicle Emission Inventory"*, Journal of Air & Waste Management Association, Vol. 56, June

Brett C. Singer, Thomas W. Kirchstetter, Robert A. Harley, Gary R. Kendall, and James M. Hesson (1999), *"A Fuel-Based Approach to Estimating Motor Vehicle Cold-Start Emissions"*, Journal of Air & Waste Management Association, Vol. 59, February

Simon Wshington, John D. Leonard, Craig A. Roberts, Troy Young, Daniel Sperling, and Jan Botha (1998), *"Forecasting Vehicle Modes of Operation Needed as Input to 'Modal' Emissions Models"*, Internal Journal of Vehicle Design, Vol. 20, Inderscience Enterprises Ltd.

William Bachman, Wayne Sarasua, and Randall Guensler (1996), "*Geographic Information System Framework for Modeling Mobile-Source Emissions*", Transportation Research Record 1551, Washington, D.C.

Ignatius Fomunung, Simon Washington, Randall Guensler, and William Bachman (1999), "*Performance Evaluation of Measure Emission Rates: A Comparison to Mobile5a*", the Paper at Transportation Research Board 79<sup>th</sup> Annual Meeting, Washington, D.C.

David C. LeBlanc, Michael D. Meyer, F. Michael Saunders, and James A. Mulholland (1995), "*Carbon Monoxide Emissions from Road Driving: Evidence of Emissions Due to Power Enrichment*", Transportation Research Record 1555, Washington, D.C.

Jean Wolf, Randall Guensler, Simon Washington, and William Bachman (1998), "*High-Emitting Vehicle Characterization Using Regression Tree Analysis*", Transportation Research Record 1651, Washington, D.C.

David C. Biggs and Rahmi Akcelik (1986), "*Models for Estimation of Car Fuel Consumption in Urban Traffic*", ITE Journal, July

Matthew Barth, Theodore Younglove, Tom Wenzwl, George Scora, Feng An, Marc Ross, and Joseph Norbeck (1997), "*Analysis of Modal Emissions From Diverse In-Use Vehicle Fleet*", Transportation Research Record 1587, Washington, D.C.

Feng An, Matthew Barth, George Scora, and Marc Ross (1998), "*Modeling Enleanment Emissions for Light-Duty Vehicles*", Transportation Research Record 1651, Washington, D.C.

Feng An, Matthew Barth, Joseph Norbeck, and Marc Ross (1997), "*Development of Comprehensice Modal Emissions Model: Operating Under Hot-Stabilized Conditions*", Transportation Research Record 1587, Washington, D.C.

Matthew J. Barth, Eric Johnston, and Ramakrishna R. Tadi (1996), "*Using GPS Technology to Relate Macroscopic and Microscopic Traffic Parameters*", Transportation Research Record 1520, Washington, D.C.

David J. Brzezinski and Terry P. Newell (1998), "*Mobile6: A Revised Model for Estimation of Highway Vehicle Emissions*", Presented at The Air & Waste Management Association Eight Annual Conference on Emission Inventories, EPA520-s-99-001

Larry Landman (2000), "*Cycle Correction Factors in Mobile6*", Presented at the Transportation Research Board 79th Annual Meeting, January

Larry Landman (2000), "*Separation of Hot Stabilized and Start Emission in Mobile6* ", Presented at the Transportation Research Board 79th Annual Meeting, January

Coordinating Research Council (1999), *"Investigation of Emission Factors in the California EMFAC7G Model"*, March

Patrick DeCorla-Souza, Jerry Everett, Jason Cosby, and Peter Lim, *"Trip-Based Approach to Estimate Emissions with Environmental Protection Agency's MOBILE Model"*, Transportation Research Record 1555, Washington, D.C.

Jack Faucett Associates (1995), *"Evaluation of MOBILE Vehicle Emission Model"*, U.S. Department of Transportation

EPA (1993), *"Mobile5a User Guide"*

Rudolf J. Freund and Ramon C. Littell (1992), *"SAS System for Regression"*, SAS Institute Inc.

EPA (1997), *"Development of Speed Correction Cycles"*, Prepared by Sierra Research Inc., June

## **APPENIDX A**

## A.1 MatLab Program for Constructing Speed-Acceleration Matrix (for GPS Field Data)

% read data from field\_data.txt. f\_data(:,1) is speed in km/h/s, f\_data(:,2) is acceleration in m/s<sup>2</sup>.

```
for i=1:4

    f1=fopen(['field_data', num2str(i), '.prn']);
    f_data=fscanf(f1, '%g %g', [2 inf]);
    f_data=f_data';

    [n,m]=size(f_data);

    s=floor(f_data(:,1)/10)+1;          % convert speed data into 1,2,3,4,5,...12
    a=floor((f_data(:,2)+3.5)*2);      % convert acceleration data into 1,2,3,4,...,11, -3: 0.5: 3

    no_obs=zeros(12,11);

    for k=1:n

        for no_a=1:12
            for no_spd=1:11

                if (a(k)==no_a & s(k)==no_spd)
                    no_obs(no_a,no_spd)=no_obs(no_a,no_spd)+1;
                end
            end
        end
    end

    f2=fopen(['obs_', num2str(i), '.txt'], 'w');
    fprintf(f2, '%5.0f %5.0f %5.0f %5.0f %5.0f %5.0f %5.0f %5.0f %5.0f %4.0f %4.0f \n', no_obs);

    fclose(f1);
    fclose(f2);

end
```

## A.2 Matlab Program for Generating Single Stop Trips Set

```
% Initial value for a and s
s0=20:20:120;      % speed km/h
d0=-0.25:-0.25:-1.5; % deceleration m/s^2
a0=0.2:0.2:1;      % acceleration in percentage of amax
k=0:0.2:1.0;       % speed variability factor

for i=1:6 % deceleration
    for j=1:5 % acceleration
        for r=1:6 % speed
            for p=1:6 % speed variability factor

                s=s0(r);
                d=d0(i)*3.6; % deceleration, revert m/s^2 to km/h/s
                a=a0(j); % acceleration in percentage of amax
                svf=k(p); % speed variability factor

                data(1,1)=d;data(1,2)=s;
                t=1;

                % deceleration
                while data(t,2)>0

                    data(t+1,2)=data(t,2)+data(t,1)*0.1;
                    data(t+1,1)=data(t,1);

                    t=t+1;
                end

                if data(t,2)==0
                    data(t,1)=3.6*a*(10.57762-0.07504*data(t,2)*5280/(1.6*3600))*1600/5280; %initial acceleration
                else data(t,2)<0
                    data(t,2)=0;
                    data(t-1,1)=(data(t,2)-data(t-1,2))/0.1;
                    data(t,1)=3.6*a*(10.57762-0.07504*data(t,2)*5280/(1.6*3600))*1600/5280;
                end

                % acceleration
                while data(t,2)< s
                    t=t+1;

                    data(t,2)=data(t-1,2)+data(t-1,1)*0.1;
                    data(t,1)=3.6*a*(10.57762-0.07504*data(t,2)*5280/(1.6*3600))*1600/5280;

                end
            if data(t,2)==s

                data(t,1)=0;

            else data(t,2)>s

                data(t,2)=s;
                data(t-1,1)=(data(t,2)-data(t-1,2))/0.1;

            end
        end
    end
end
```

```

end

dist=sum(data(:,2))/3.6*0.1;    % distance in meter

% cruise condition

while abs(dist-10000)>= 0.5*s/3.6*0.1

    data(t,1)=0;
    data(t,2)=s;

    dist=dist+data(t,2)/3.6*0.1 ;    % distance in meter

    t=t+1;

end
ave_spd=dist/n1*36;            % distance in meter, ave speed in km/h
data(:,2)=svf.*(data(:,2)-ave_spd)+ave_spd;    % speed factored by speed variability factor.

for v=1:n1-1

    data(v,1)=(data(v+1,2)-data(v,2))/0.1;            % acceleration in km/h/s

end

data(n1,1)=0;

f1=fopen(['data_',num2str(i),num2str(j),num2str(r),num2str(p)'.txt'],'w');
fprintf(f1,'%2.5f %3.2f\n',data); % variable data including whole data point.

fclose(f1);

clear data;
end
end
end
end

```

## A.3 Matlab Program for Generating Drive Cycles Set

### A.3.1 Application of $k_1$ and $k_2$

```
% read data from data_1.txt (ftp), data_2.txt(ny), data_3.txt (us06)
k=0:0.2:1.0; % Speed variance factor

for i=1:3 % i represents ftp, ny, us06 data
    f1=fopen(['data_',num2str(i),'.txt']);
    f_data=fscanf(f1,'%g',[1 inf]);
    f_data=f_data';
    [n,m]=size(f_data);

    for j=1:5 % j represents various average speed conditions
        data=zeros(n,2);diff=zeros(n);
        data(:,2)=f_data.*1.6+(j-1)*5; % generate profile, input speed data into data matrix in column 2 (km/h)
        dist=sum(data(:,2))/3600; % distance in km
        ave_spd=dist/(n/3600); % average speed in km/h
        diff=data(:,2)-ave_spd; % difference between instantaneous speed and average speed

        for k_fac=1:6; % Speed Variability factor
            data(:,2)=k(k_fac).*diff+ave_spd; % generate five different data sets

            for row=1:n-1 % generate acceleration
                data(row,1)=data(row+1,2)-data(row,2);
                acc_max=11.53922-0.07504*data(row,2); % max acceleration

                if data(row,1)>=acc_max % constrained by max acc. (km/h/s)
                    data(row,1)=acc_max;
                end

                if data(row,1)<=-5.4 % constrained by max deceleration (km/h/s)
                    data(row,1)=-5.4;
                end
                data(row+1,2)=data(row,2)+data(row,1); % smoothed speed according to acceleration
            end

            data(n,1)=0; % define the final acceleration
            % write to file spd(i).txt
            f2=fopen(['spd_smooth',num2str(i),num2str(j),num2str(k_fac),'.txt'],'w');
            fprintf(f2,'%2.5f %2.5f\n',data');
            fclose(f2);
        end
    end
end
fclose(f1);
end
```

### A.3.2 Application of k1 and k3

```
% read data from data_1.txt (ftp), data_2.txt(ny)
k=0:0.2:1.0; % Speed Variability factor around ave speed

for i=1:2 % i represents ftp, ny
f1=fopen(['data_',num2str(i),'txt']);
f_data=fscanf(f1,'%g',[1 inf]);
f_data=f_data';

[n,m]=size(f_data);

data=zeros(n,2);
data(:,2)=f_data.*1.6; % input speed data into data matrix in columne 2 (km/h)
dist=sum(data(:,2))/3600; % distance in km
ave0=dist/(n/3600); % initial average speed in km/h

for j=1:5 % j represents various average speed conditions
for p=1:n % generate different speed sets

if data(p,2)>ave0;
data(p,2)=f_data(p,1).*1.6+j*5;
end

end

dist=sum(data(:,2))/3600; % distance in km
ave_spd=dist/(n/3600); % average speed in km/h

diff=data(:,2)-ave_spd; % difference between instantous speed and average speed

for k_fac=1:6; % Speed Variability factor

data(:,2)=k(k_fac).*diff+ave_spd; % generate speed with k factor

for row=1:n-1 % generate acceration

data(row,1)=data(row+1,2)-data(row,2); % acceleration km/h/s
acc_max=11.53922-0.07504*data(row,2); %max acceration

if data(row,1)>=acc_max % constrained by max acc. (km/h/s)
data(row,1)=acc_max;
end

if data(row,1)<=-5.4 % constrained by max deceleration (km/h/s)
data(row,1)=-5.4;
end

data(row+1,2)=data(row,2)+data(row,1); % smoothed speed according to acceleration

end

data(n,1)=0; % define the final acceleration

% write to file spd(i,j,k_fac).txt, i is cycle,
```

```
% j is speed incremental for speed over ave speed
% k_fac is Speed Variability factor around ave_spd

f2=fopen(['spd_smooth',num2str(i+2),num2str(j),num2str(k_fac),'.txt'],'w');
fprintf(f2,'%2.5f %2.5f\n',data);
fclose(f2);

end
end

clear data ;
fclose(f1);

end
```

## A.4 Matlab Program for Computing Critical Variables and Fuel consumption and Emissions

```

% Read data from file, including acceleration (km/h/sec)--colume1 and speed (km/h)--colume2

del=-0.25:-0.25:-1.5;acc=0.2:0.2:1;spd=20:20:120;k_fac=0:0.2:1.0;t=0;
b=zeros(1080,17);

for i=1:6; % deceleration, -0.25:-0.25:-1.5
    for j=1:5; % acceleration, 0.2:0.2:1
        for r=1:6; % speed 20:20:120
            for p=1:6; % Speed variability factor
                f1=fopen(['data_',num2str(i),num2str(j),num2str(r),num2str(p),'.txt']);
                f_data=fscanf(f1,'%g %g',[2 inf]);
                f_data=f_data';

[n,m]=size(f_data);

s_max=max(f_data(:,2)); % max speed
s_sum=sum(f_data(:,2)); % sum of speed
k_eng=sum(f_data(:,2).^2); % kinetic energy/Beta
dist=s_sum*0.1/3600; % All data points are in 0.1 second interval,dist in km

ave_spd=s_sum/n; % distance in km, ave_spd in km/h
spd_var=sum((f_data(:,2)-ave_spd).^2)/n; % speed variance
no_stp=0;acc_noise1=0;del_noise1=0;noise1=0;p1=0;p2=0;
del_fuel=0;del_hc=0;del_co=0;del_no=0;acc_fuel=0;acc_hc=0;acc_co=0;acc_no=0;c_fuel=0;c_hc=0;c_co=0;c_no=0;
del_spd=0;acc_spd=0;
pow=0;

for w=1:n
    a=f_data(w,1);s=f_data(w,2);

    if a<0 % deceleration portion

del_fuel=del_fuel+exp(-7.66602+0.027398*s-0.00022*s^2+1.09e-06*s^3-0.011*a+0.007117*s*a-4.72e-05*a*s^2+2.30e-
07*a*s^3-0.00488*a^2+0.000901*a^2*s-9.20e-06*a^2*s^2+5.49e-08*a^2*s^3-8.6e-05*a^3-5e-06*a^3*s-3.02e-
07*a^3*s^2+3.00e-09*a^3*s^3);
del_hc=del_hc+exp(-0.75584+0.021283*s-0.00013*s^2+7.39e-07*s^3-0.00921*a+0.011364*a*s-0.0002*a*s^2+8.45e-
07*a*s^3+0.036223*a^2+0.000226*a^2*s+4.03e-08*a^2*s^2-3.49e-08*a^2*s^3+0.003968*a^3-9e-05*a^3*s+2.42e-06*a^3*s^2-
1.57e-08*a^3*s^3);
del_co=del_co+exp(0.748215+0.080043*s-0.00094*s^2+4.35e-06*s^3+0.086662*a+0.01022*a*s-8.2e-05*a*s^2-1.15e-
07*a*s^3+0.069929*a^2-0.00323*a^2*s+8.97e-05*a^2*s^2-5.83e-07*a^2*s^3+0.008779*a^3-0.00063*a^3*s+1.41e-05*a^3*s^2-
8.08e-08*a^3*s^3);
del_no=del_no+exp(-1.19275+0.031987*s-9.3e-06*s^2+2.46e-07*s^3+0.187657*a+0.01337*a*s-7.9e-05*a*s^2+4.01e-
07*a*s^3+0.000243*a^2+0.007162*a^2*s-9.59e-05*a^2*s^2+4.29e-07*a^2*s^3-0.00166*a^3+0.000668*a^3*s-9.60e-
06*a^3*s^2+4.01e-08*a^3*s^3);
del_noise1=del_noise1+a^2*s; % calculate del noise in method 1
p1=p1+1;
del_spd=del_spd+s; % sum speed in del portion

elseif a>0

acc_fuel=acc_fuel+exp(-7.69989+0.029364*s-0.00026*s^2+1.28e-06*s^3+0.2506*a+0.00467*s*a+2.05e-06*a*s^2-2.15e-
07*a*s^3-0.01189*a^2-0.00014*a^2*s-1.40e-05*a^2*s^2+1.23e-07*a^2*s^3+0.000563*a^3-4.2e-05*a^3*s+2.05e-06*a^3*s^2-
1.63e-08*a^3*s^3);

```

```

acc_hc=acc_hc+exp(-0.87605+0.03627*s-0.00045*s^2+2.55e-06*s^3+0.081221*a+0.009246*a*s-0.00046*a*s^2+4.00e-
06*a*s^3+0.037039*a^2-0.00618*a^2*s+2.96e-04*a^2*s^2-1.86e-06*a^2*s^3-0.00255*a^3+0.000468*a^3*s-1.79e-
05*a^3*s^2+3.86e-08*a^3*s^3);
acc_co=acc_co+exp(0.657294+0.091823*s-0.00122*s^2+5.99e-06*s^3+0.301574*a-0.01726*a*s+0.000205*a*s^2-1.48e-
08*a*s^3+0.017143*a^2-0.00032*a^2*s+1.39e-04*a^2*s^2-7.63e-07*a^2*s^3-0.00148*a^3+8.42e-05*a^3*s-5.72e-06*a^3*s^2-
7.33e-08*a^3*s^3);
acc_no=acc_no+exp(-1.21962+0.031785*s+9.27e-06*s^2+6.53e-08*s^3+0.528203*a+0.017114*a*s+2.94e-05*a*s^2-1.27e-
06*a*s^3-0.07912*a^2+0.00327*a^2*s-1.46e-04*a^2*s^2+8.65e-07*a^2*s^3+0.005422*a^3-0.00038*a^3*s+1.06e-05*a^3*s^2-
4.37e-08*a^3*s^3);

acc_noise1=acc_noise1+a^2*s; % calculate acc noise in method 1
p2=p2+1;
acc_spd=acc_spd+s; % sum speed in acc portion
pow=pow+a*s; % positive power/m

else

c_fuel=c_fuel+exp(-7.69989+0.029364*s-0.00026*s^2+1.28e-06*s^3+0.2506*a+0.00467*s*a+2.05e-06*a*s^2-2.15e-07*a*s^3-
0.01189*a^2-0.00014*a^2*s-1.40e-05*a^2*s^2+1.23e-07*a^2*s^3+0.000563*a^3-4.2e-05*a^3*s+2.05e-06*a^3*s^2-1.63e-
08*a^3*s^3);
c_hc=c_hc+exp(-0.87605+0.03627*s-0.00045*s^2+2.55e-06*s^3+0.081221*a+0.009246*a*s-0.00046*a*s^2+4.00e-
06*a*s^3+0.037039*a^2-0.00618*a^2*s+2.96e-04*a^2*s^2-1.86e-06*a^2*s^3-0.00255*a^3+0.000468*a^3*s-1.79e-
05*a^3*s^2+3.86e-08*a^3*s^3);
c_co=c_co+exp(0.657294+0.091823*s-0.00122*s^2+5.99e-06*s^3+0.301574*a-0.01726*a*s+0.000205*a*s^2-1.48e-
08*a*s^3+0.017143*a^2-0.00032*a^2*s+1.39e-04*a^2*s^2-7.63e-07*a^2*s^3-0.00148*a^3+8.42e-05*a^3*s-5.72e-06*a^3*s^2-
7.33e-08*a^3*s^3);
c_no=c_no+exp(-1.21962+0.031785*s+9.27e-06*s^2+6.53e-08*s^3+0.528203*a+0.017114*a*s+2.94e-05*a*s^2-1.27e-
06*a*s^3-0.07912*a^2+0.00327*a^2*s-1.46e-04*a^2*s^2+8.65e-07*a^2*s^3+0.005422*a^3-0.00038*a^3*s+1.06e-05*a^3*s^2-
4.37e-08*a^3*s^3);

end
end

noise1=sqrt((acc_noise1+del_noise1)/s_sum); % calculate the noise level

if noise1==0; % consider constant speed situation
del_noise1=0;
acc_noise1=0;
else % consider non-constant speed situation
del_noise1=sqrt(del_noise1/del_spd); % divided by total no. of observations
acc_noise1=sqrt(acc_noise1/acc_spd); % divided by Total no. of observations
end

for g=1:n-1 % calculate no_stp
d_spd=f_data(g+1,2)-f_data(g,2);

if d_spd<0
no_stp=no_stp+abs((f_data(g+1,2)-f_data(g,2))/s_max);
end
end

t=t+1;
b(t,1)=t; % number of record
b(t,2)=del(i);b(t,3)=acc(j);b(t,4)=spd(r);b(t,5)=k_fac(p); % del acc max_spd spd_vari_fac
b(t,6)=ave_spd; % ave speedin km/h
b(t,7)=spd_var/dist; % spd variance per km

```



```

no_stp=0;fuel=0;hc=0;co=0;no=0;
acc_fuel=0;acc_hc=0;acc_co=0;acc_no=0;acc_time=0;acc_dist=0;acc_spd=0;
del_fuel=0;del_hc=0;del_co=0;del_no=0;del_time=0;del_dist=0;del_spd=0;
c_fuel=0;c_hc=0;c_co=0;c_no=0;c_time=0;c_dist=0;

for w=1:n
    a=f_data(w,1);s=f_data(w,2);

% acceleration mode

    if a>0

acc_fuel=acc_fuel+exp(-7.536973+0.027035*s-0.000229*s^2+1.13e-06*s^3+0.1232803*a+0.0039933*s*a-1.55e-
05*a*s^2+3.82e-08*a*s^3+0.0132439*a^2+6.307e-05*a^2*s+6.46e-07*a^2*s^2-1.56e-08*a^2*s^3-0.0009*a^3-4.23e-
05*a^3*s+1.91e-07*a^3*s^2-2.56e-09*a^3*s^3);
acc_hc=acc_hc+exp(-0.728042+0.022738*s-0.00017*s^2+1.48e-06*s^3+0*a+0.0084259*a*s-7.8e-05*a*s^2+4.26e-
07*a*s^3+0.0194108*a^2-0.000416*a^2*s+2.59e-05*a^2*s^2-1.34e-07*a^2*s^3-7.06e-05*a^3-7.79e-05*a^3*s+2.08e-
06*a^3*s^2-9.97e-09*a^3*s^3);
acc_co=acc_co+exp(0.887447+0.0647*s-0.000653*s^2+3.49e-06*s^3+0.1356454*a+0.0032142*a*s+7.057e-05*a*s^2-4.87e-
07*a*s^3+0.0253733*a^2-0.000701*a^2*s+3.39e-05*a^2*s^2-1.97e-07*a^2*s^3-0.00102*a^3+0*a^3*s-8.86e-
07*a^3*s^2+0*a^3*s^3);
acc_no=acc_no+exp(-1.067682+0.0423073*s-0.000144*s^2+4.31e-07*s^3+0.2318123*a+0.0128586*a*s-9.92e-
05*a*s^2+2.26e-07*a*s^3+0.0073636*a^2+0.0021769*a^2*s-4.05e-05*a^2*s^2+1.51e-07*a^2*s^3-0.00072*a^3-
0.000221*a^3*s+1.22e-06*a^3*s^2-7.22e-09*a^3*s^3);

acc_time=acc_time+1;           % time spent in acceleration mode
acc_dist=acc_dist+s*0.1/3600;   % distance spent in acceleration mode
acc_spd=acc_spd+s;

% deceleration mode

    elseif a<0

del_fuel=del_fuel+exp(-7.536973+0.027035*s-0.000229*s^2+1.13e-06*s^3+0.1232803*a+0.0039933*s*a-1.55e-
05*a*s^2+3.82e-08*a*s^3+0.0132439*a^2+6.307e-05*a^2*s+6.46e-07*a^2*s^2-1.56e-08*a^2*s^3-0.0009*a^3-4.23e-
05*a^3*s+1.91e-07*a^3*s^2-2.56e-09*a^3*s^3);
del_hc=del_hc+exp(-0.728042+0.022738*s-0.00017*s^2+1.48e-06*s^3+0*a+0.0084259*a*s-7.8e-05*a*s^2+4.26e-
07*a*s^3+0.0194108*a^2-0.000416*a^2*s+2.59e-05*a^2*s^2-1.34e-07*a^2*s^3-7.06e-05*a^3-7.79e-05*a^3*s+2.08e-
06*a^3*s^2-9.97e-09*a^3*s^3);
del_co=del_co+exp(0.887447+0.0647*s-0.000653*s^2+3.49e-06*s^3+0.1356454*a+0.0032142*a*s+7.057e-05*a*s^2-4.87e-
07*a*s^3+0.0253733*a^2-0.000701*a^2*s+3.39e-05*a^2*s^2-1.97e-07*a^2*s^3-0.00102*a^3+0*a^3*s-8.86e-
07*a^3*s^2+0*a^3*s^3);
del_no=del_no+exp(-1.067682+0.0423073*s-0.000144*s^2+4.31e-07*s^3+0.2318123*a+0.0128586*a*s-9.92e-05*a*s^2+2.26e-
07*a*s^3+0.0073636*a^2+0.0021769*a^2*s-4.05e-05*a^2*s^2+1.51e-07*a^2*s^3-0.00072*a^3-0.000221*a^3*s+1.22e-
06*a^3*s^2-7.22e-09*a^3*s^3);

del_time=del_time+1;           % time spent in acceleration mode
del_dist=del_dist+s*0.1/3600;   % distance spent in acceleration mode
del_spd=del_spd+s;

% cruise mode

    else

```

```

c_fuel=c_fuel+exp(-7.536973+0.027035*s-0.000229*s^2+1.13e-06*s^3+0.1232803*a+0.0039933*s*a-1.55e-05*a*s^2+3.82e-
08*a*s^3+0.0132439*a^2+6.307e-05*a^2*s+6.46e-07*a^2*s^2-1.56e-08*a^2*s^3-0.0009*a^3-4.23e-05*a^3*s+1.91e-07*a^3*s^2-
2.56e-09*a^3*s^3);
c_hc=c_hc+exp(-0.728042+0.022738*s-0.00017*s^2+1.48e-06*s^3+0*a+0.0084259*a*s-7.8e-05*a*s^2+4.26e-
07*a*s^3+0.0194108*a^2-0.000416*a^2*s+2.59e-05*a^2*s^2-1.34e-07*a^2*s^3-7.06e-05*a^3-7.79e-05*a^3*s+2.08e-
06*a^3*s^2-9.97e-09*a^3*s^3);
c_co=c_co+exp(0.887447+0.0647*s-0.000653*s^2+3.49e-06*s^3+0.1356454*a+0.0032142*a*s+7.057e-05*a*s^2-4.87e-
07*a*s^3+0.0253733*a^2-0.000701*a^2*s+3.39e-05*a^2*s^2-1.97e-07*a^2*s^3-0.00102*a^3+0*a^3*s-8.86e-
07*a^3*s^2+0*a^3*s^3);
c_no=c_no+exp(-1.067682+0.0423073*s-0.000144*s^2+4.31e-07*s^3+0.2318123*a+0.0128586*a*s-9.92e-05*a*s^2+2.26e-
07*a*s^3+0.0073636*a^2+0.0021769*a^2*s-4.05e-05*a^2*s^2+1.51e-07*a^2*s^3-0.00072*a^3-0.000221*a^3*s+1.22e-
06*a^3*s^2-7.22e-09*a^3*s^3);

c_time=c_time+1;           % time spent in acceleration mode
c_dist=c_dist+s*0.1/3600;   % distance spent in acceleration mode

end
end

ave_spd_del=del_spd/del_time; % ave speed in deceleration portion
ave_spd_acc=acc_spd/acc_time; % ave speed in acceleration portion
dist=acc_dist+del_dist+c_dist; %total distance
time=acc_time+del_time+c_time; % total time in 0.1 sec
fuel=acc_fuel+del_fuel+c_fuel; % total fuel in liter
hc=acc_hc+del_hc+c_hc;       % total hc in mg
co=acc_co+del_co+c_co;       % total co in mg
no=acc_no+del_no+c_no;       % total no in mg

t=t+1;
b(1,t)=t; % number of record
%b(2,t)= del(i);b(3,t)=acc;b(4,t)=spd(r);b(5,t)=k_fact; % for del_11.txt--del_66.txt del acc max_spd spd_vari_fac
b(2,t)= del(j);b(3,t)=acc(j);b(4,t)=spd(r);b(5,t)=k_fact; % for acc_11.txt--acc_56.txt del acc max_spd spd_vari_fac
b(6,t)=dist; % total dist in km
b(7,t)=ave_spd; % ave speed in km/h for a whole trip
b(8,t)=fuel*0.1/dist; % total fuel per km
b(9,t)=hc*0.1/(1000*dist); % total hc per km
b(10,t)=co*0.1/(1000*dist); % total co per km
b(11,t)=no*0.1/(1000*dist); %total NOx per km

% deceleration model

b(12,t)=ave_spd_del;
b(13,t)=del_dist/dist; % percent of distance spent in deceleration
b(14,t)=del_time/time; % percent of time spent in deceleration
b(15,t)=del_fuel/fuel; % percent of fuel used in deceleration
b(16,t)=del_hc/hc; % percent of hc used in deceleration
b(17,t)=del_co/co; % percent of co used in deceleration
b(18,t)=del_no/no; % percent of no used in deceleration
b(19,t)=del_fuel*0.1/del_dist; %fuel used in deceleration per km (l/km)
b(20,t)=del_hc*0.1/(1000*del_dist); %hc used in deceleration per km (g/km)
b(21,t)=del_co*0.1/(1000*del_dist); % co used in deceleration per km (g/km)
b(22,t)=del_no*0.1/(1000*del_dist); % no used in deceleration per km (g/km)

% acceleration model

b(23,t)=ave_spd_acc;

```



## **APPENDIX B**

## B.1 Fuel Consumption Rates as a Function of an Independent Variable

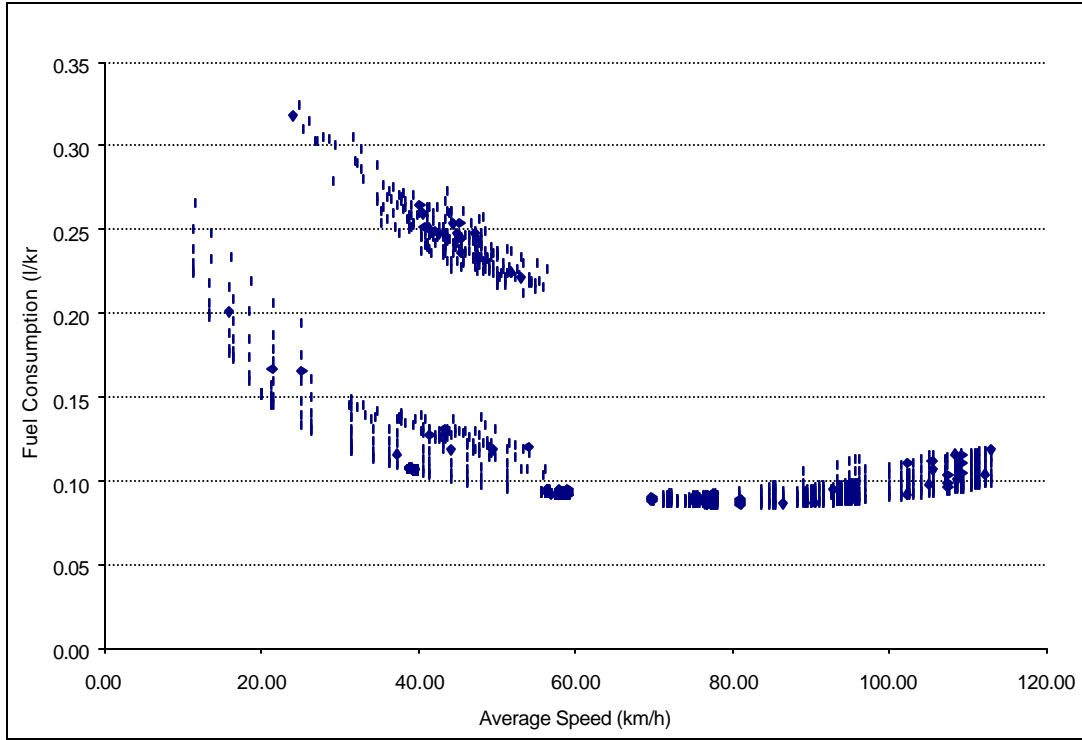


Figure B-1. Fuel Consumption vs. Average Speed

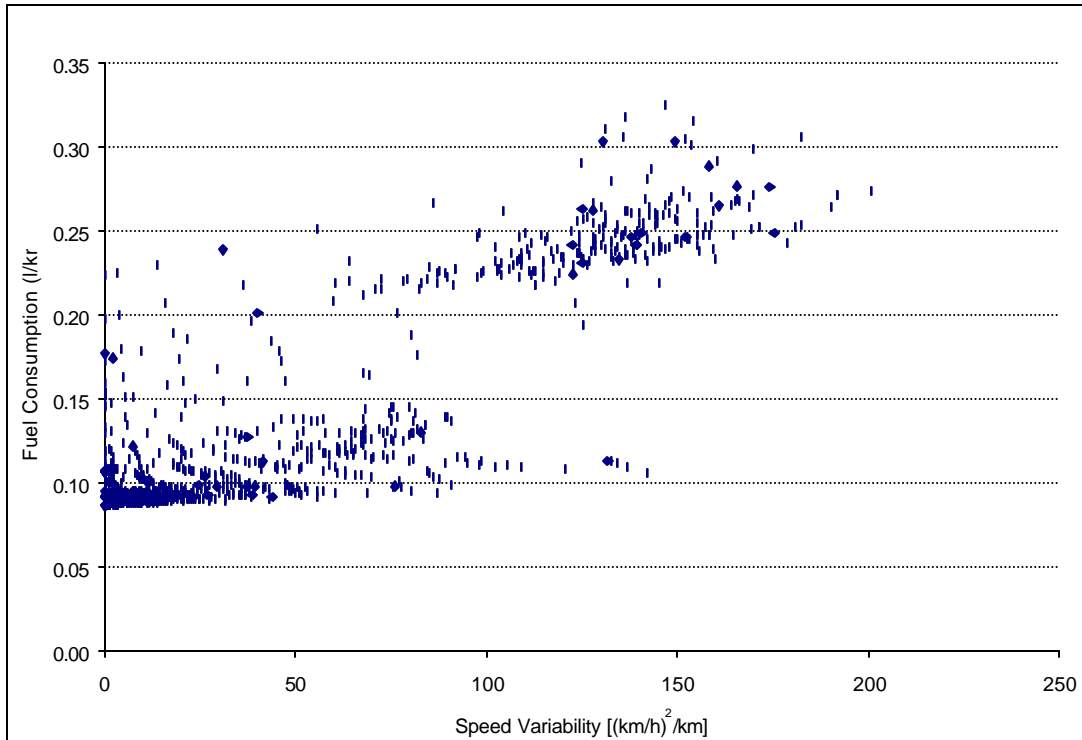


Figure B-2. Fuel Consumption vs. Speed Variability

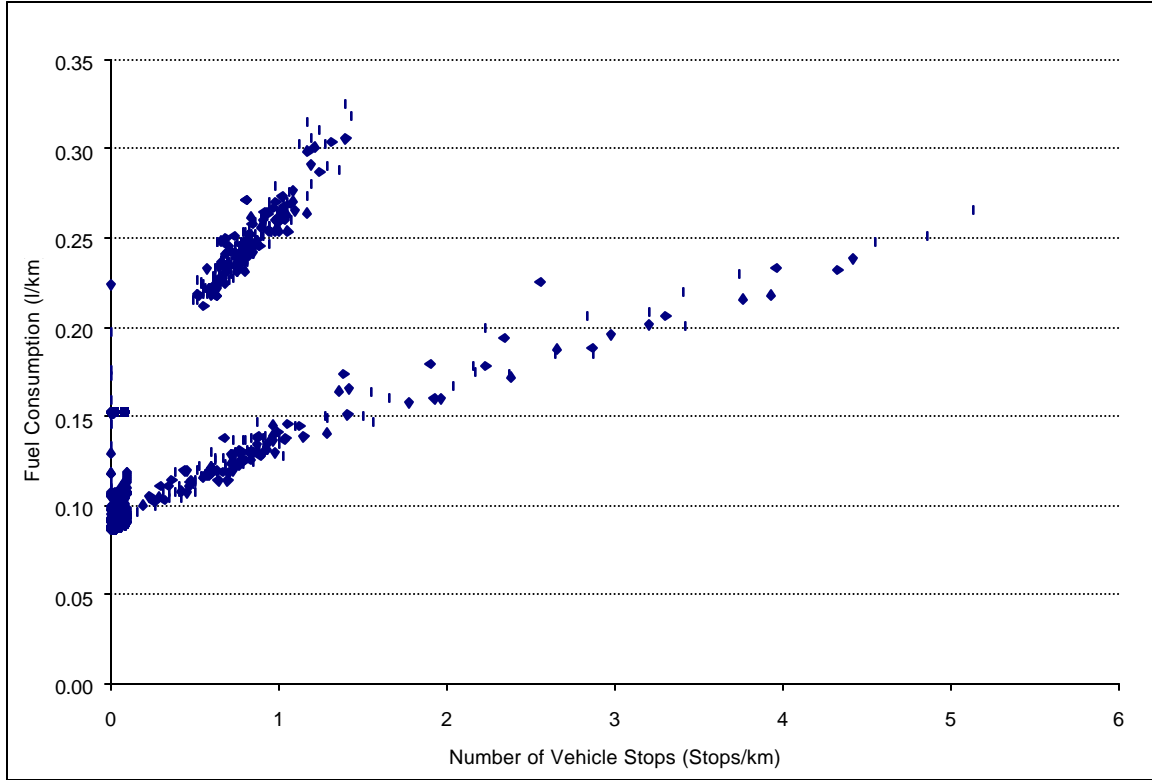


Figure B-3. Fuel Consumption vs. Number of Vehicle Stops

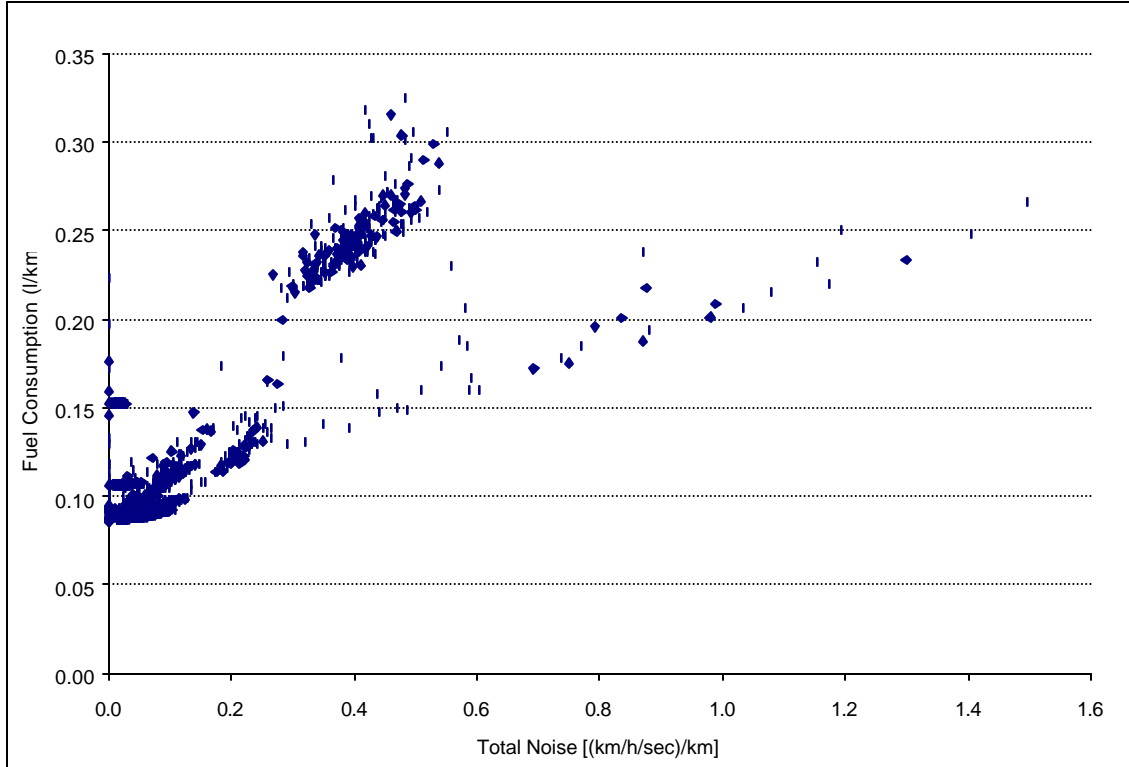


Figure B-4. Fuel Consumption vs. Total Noise

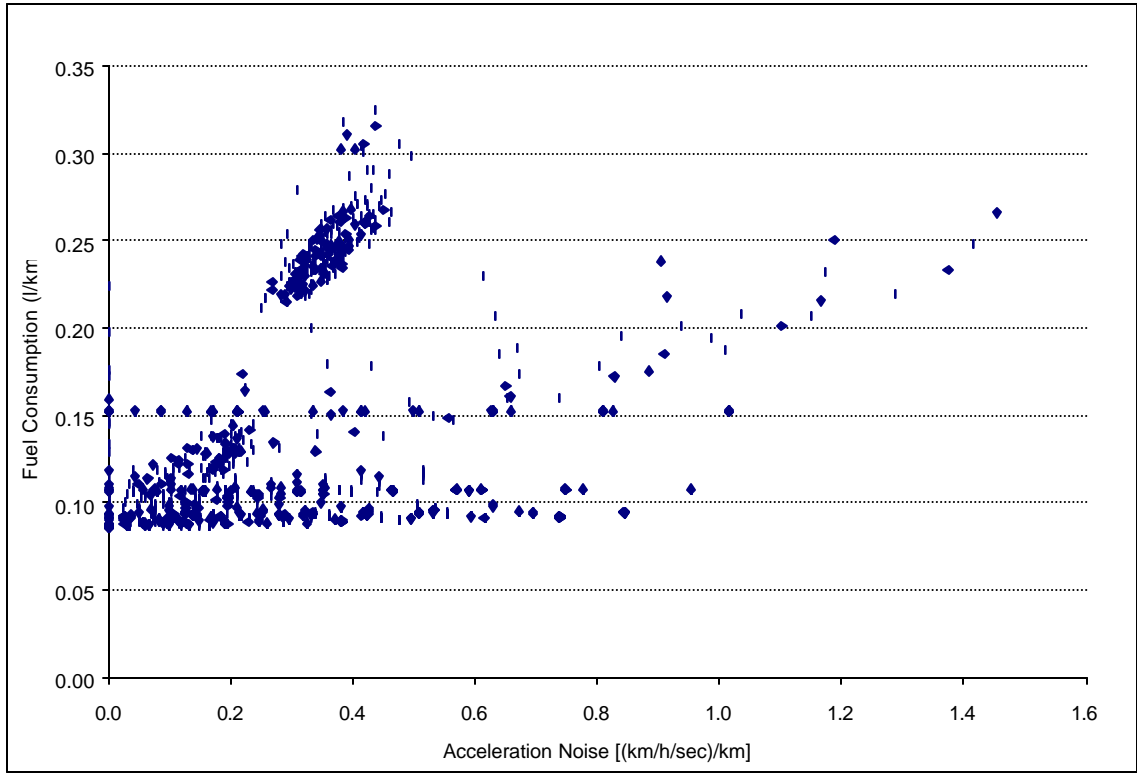


Figure B-5. Fuel Consumption vs. Acceleration Noise

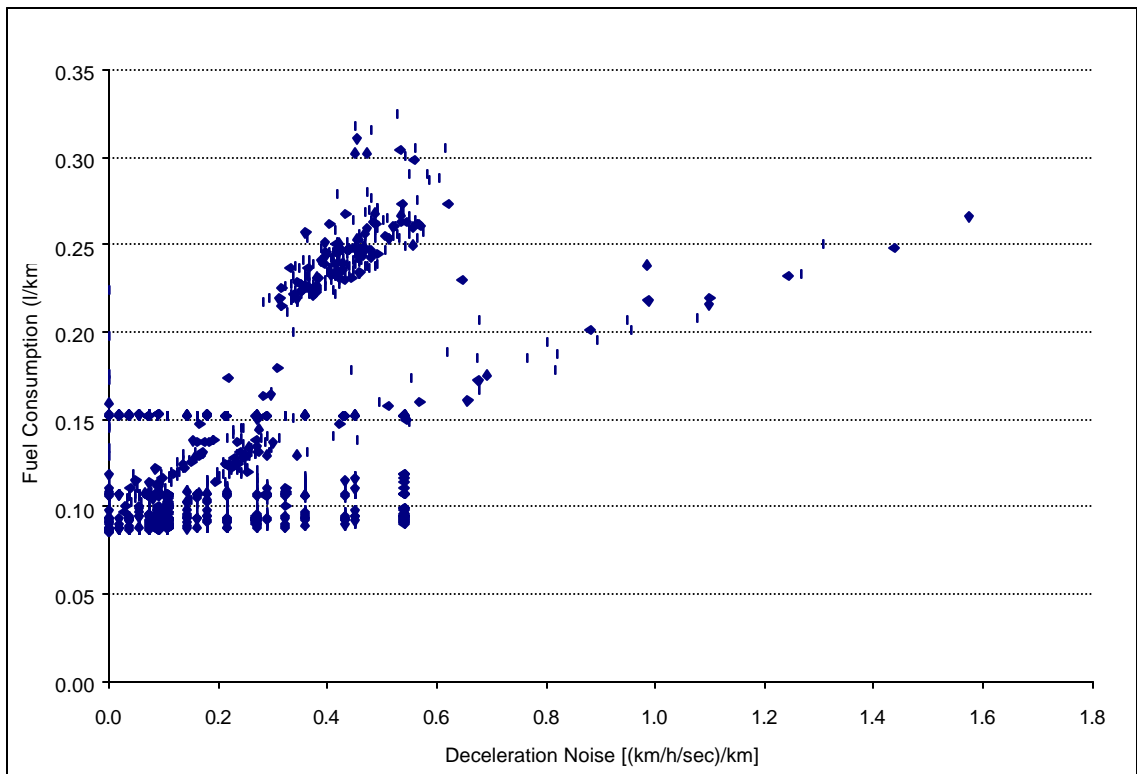


Figure B-6. Fuel Consumption vs. Deceleration Noise

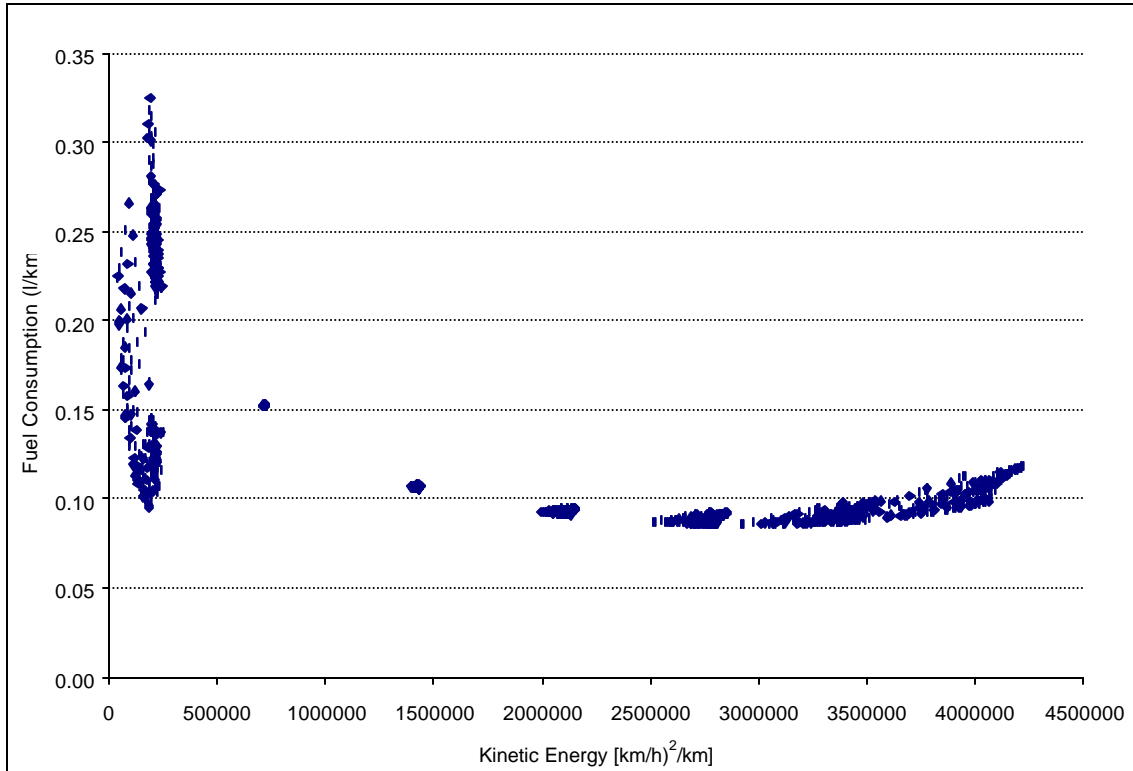


Figure B-7. Fuel Consumption vs. Kinetic Energy

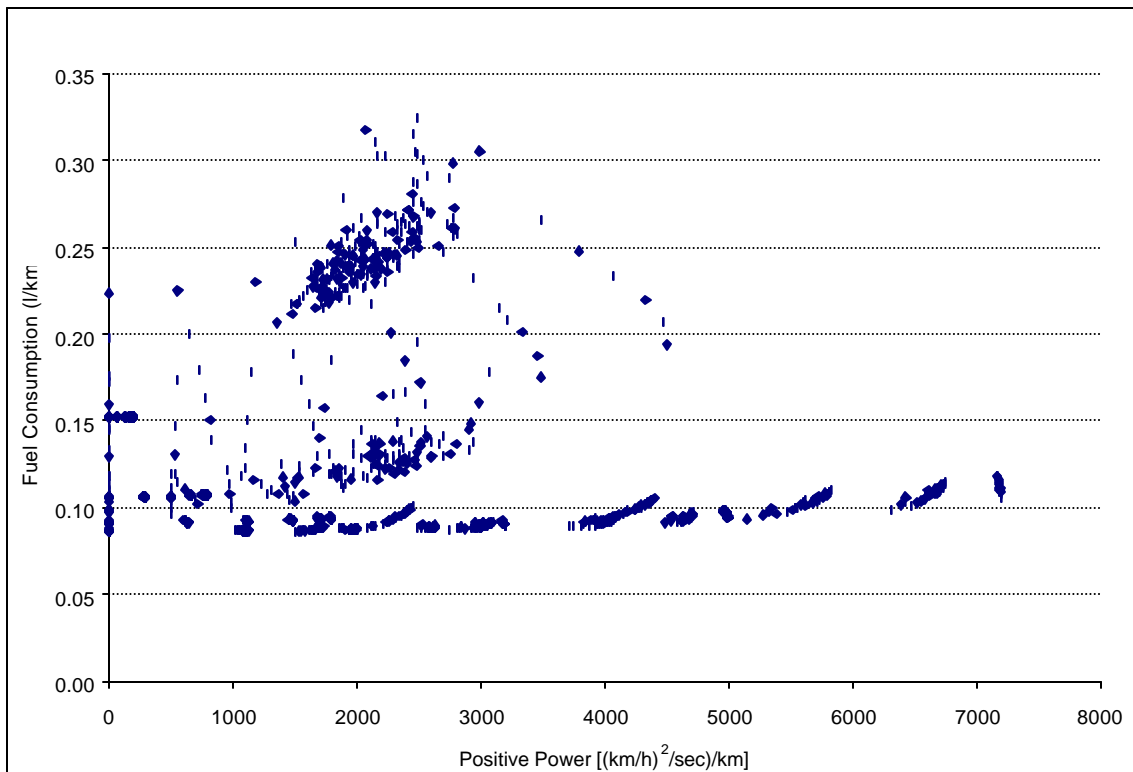


Figure B-8. Fuel Consumption vs. Power

## B.2 HC Emission Rates as a Function of an Independent Variable

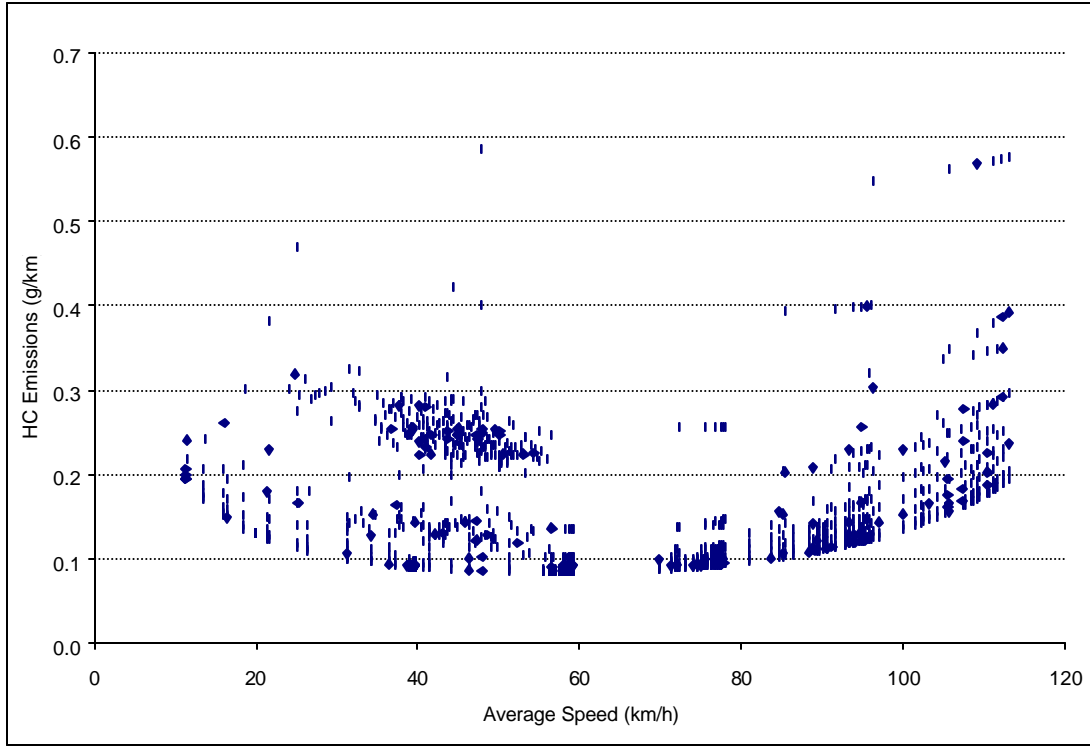


Figure B-9. HC Emissions vs. Average Speed

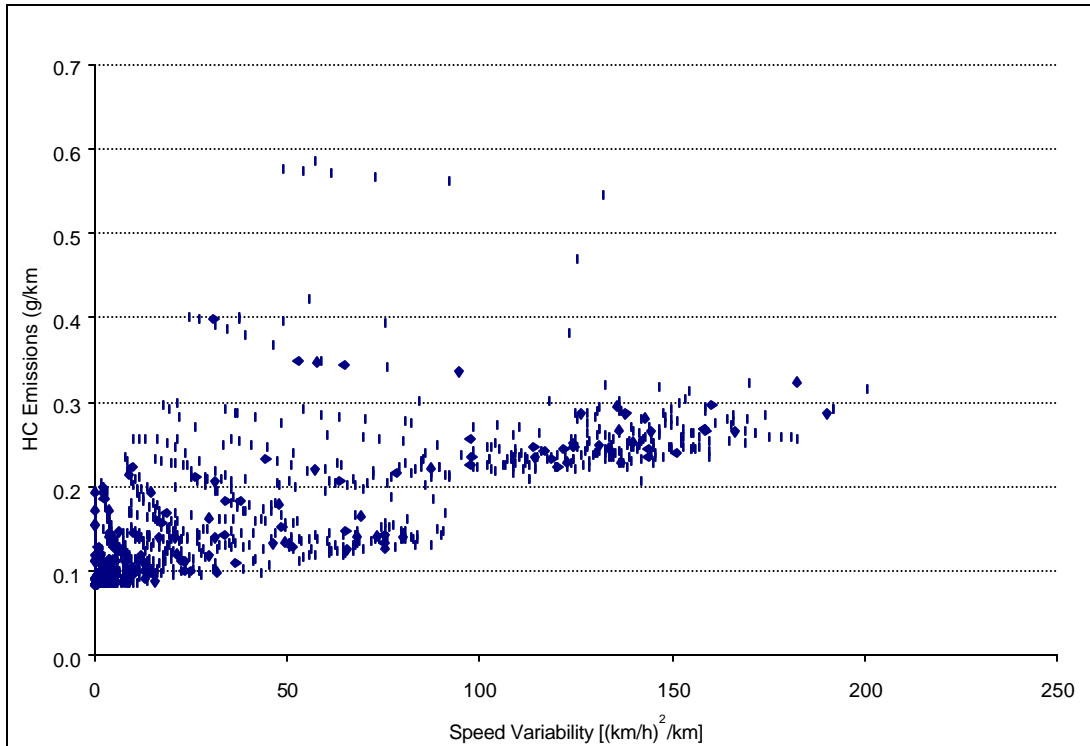


Figure B-10. HC Emissions vs. Speed Variability

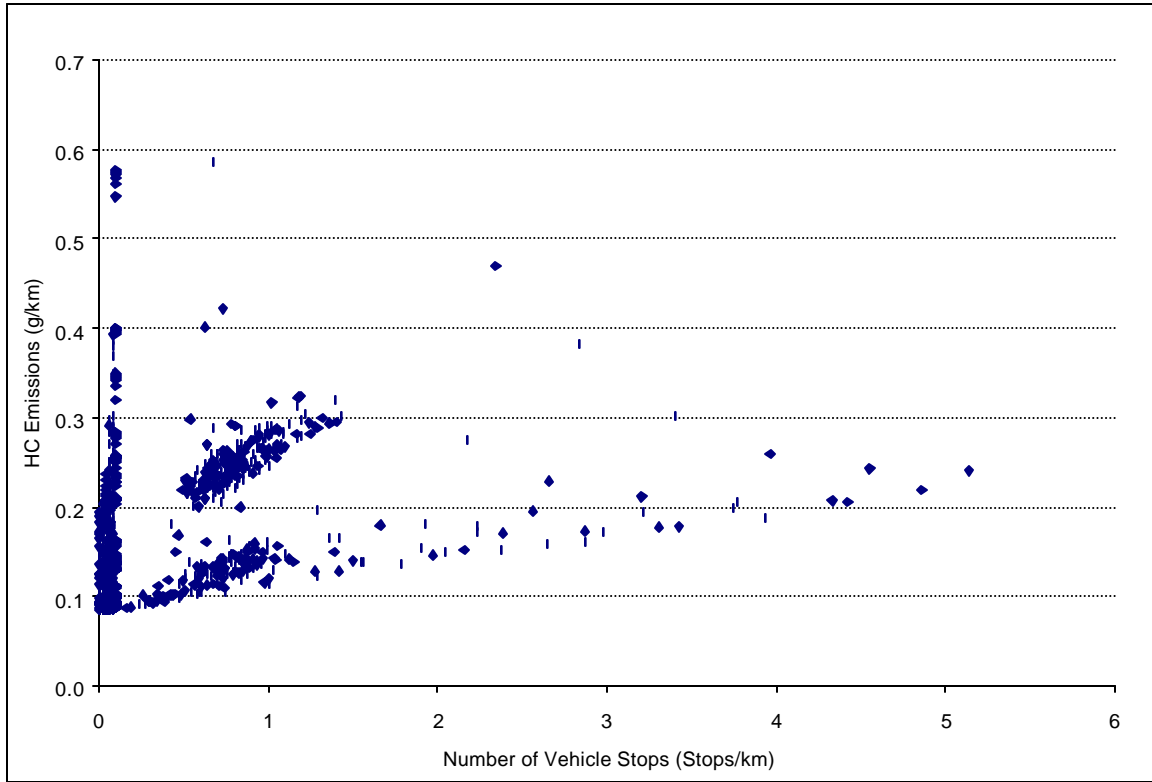


Figure B-11. HC Emissions vs. Number of Vehicle Stops

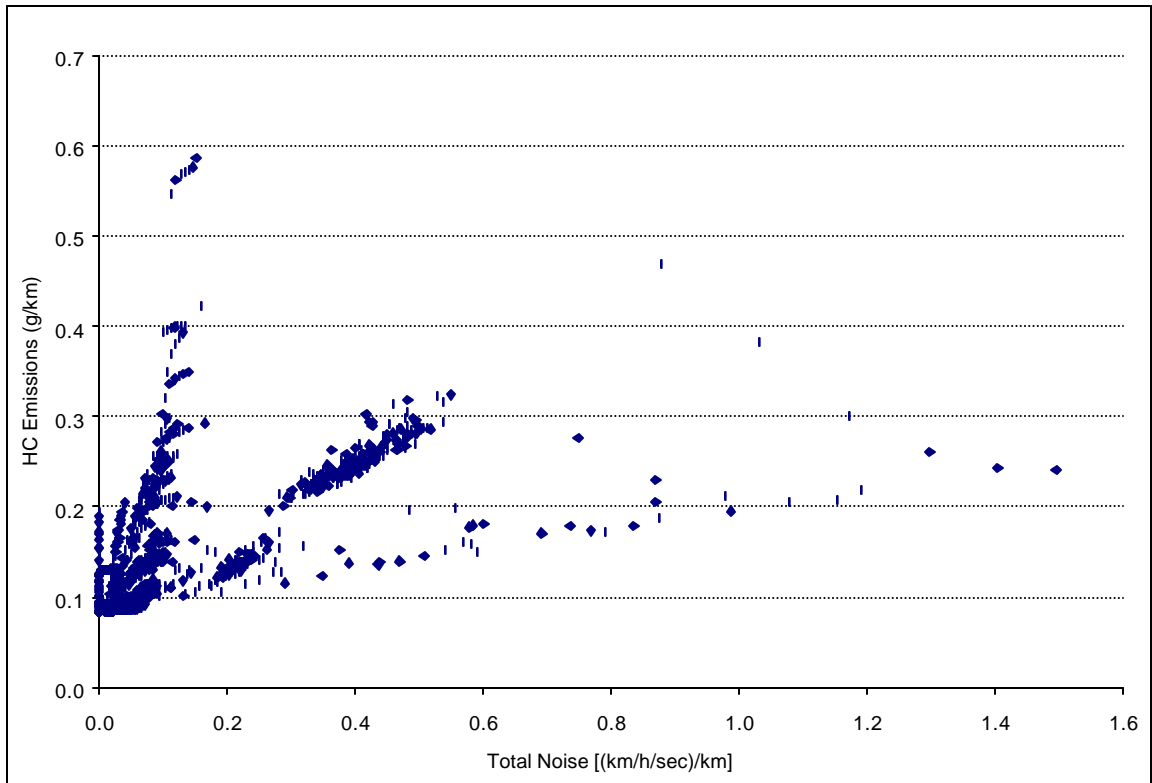


Figure B-12. HC Emissions vs. Total Noise

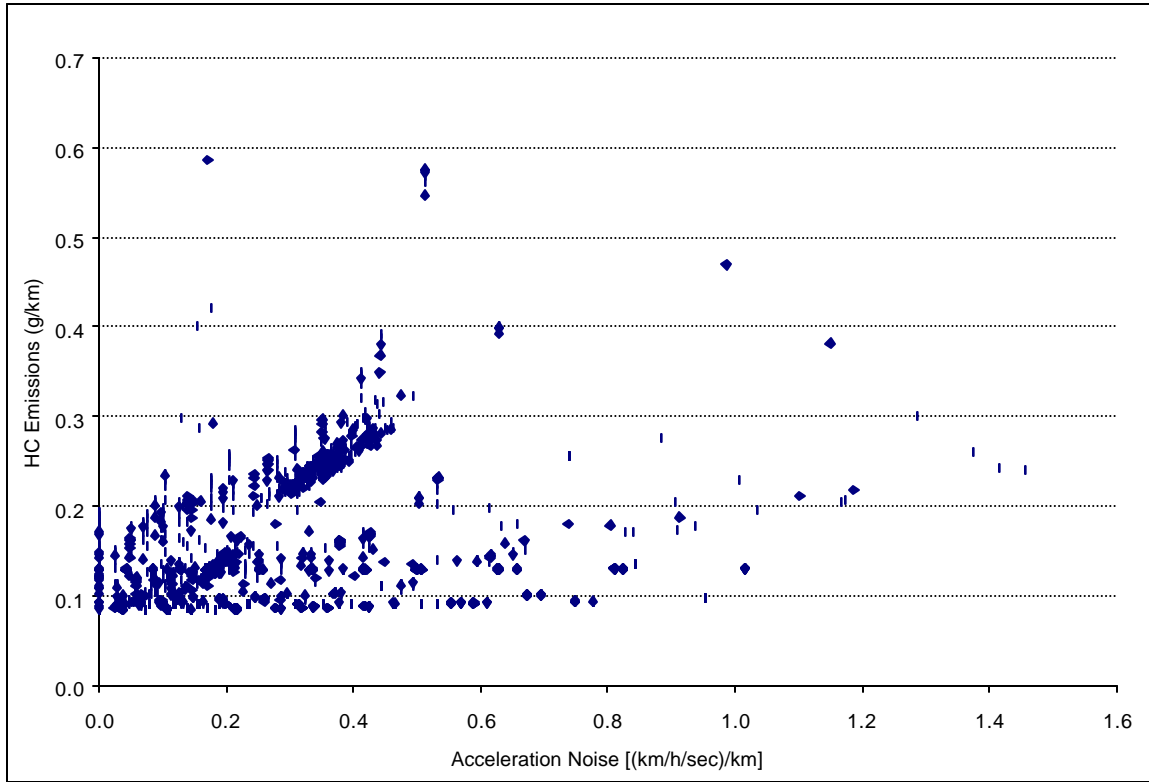


Figure B-13. HC Emissions vs. Acceleration Noise

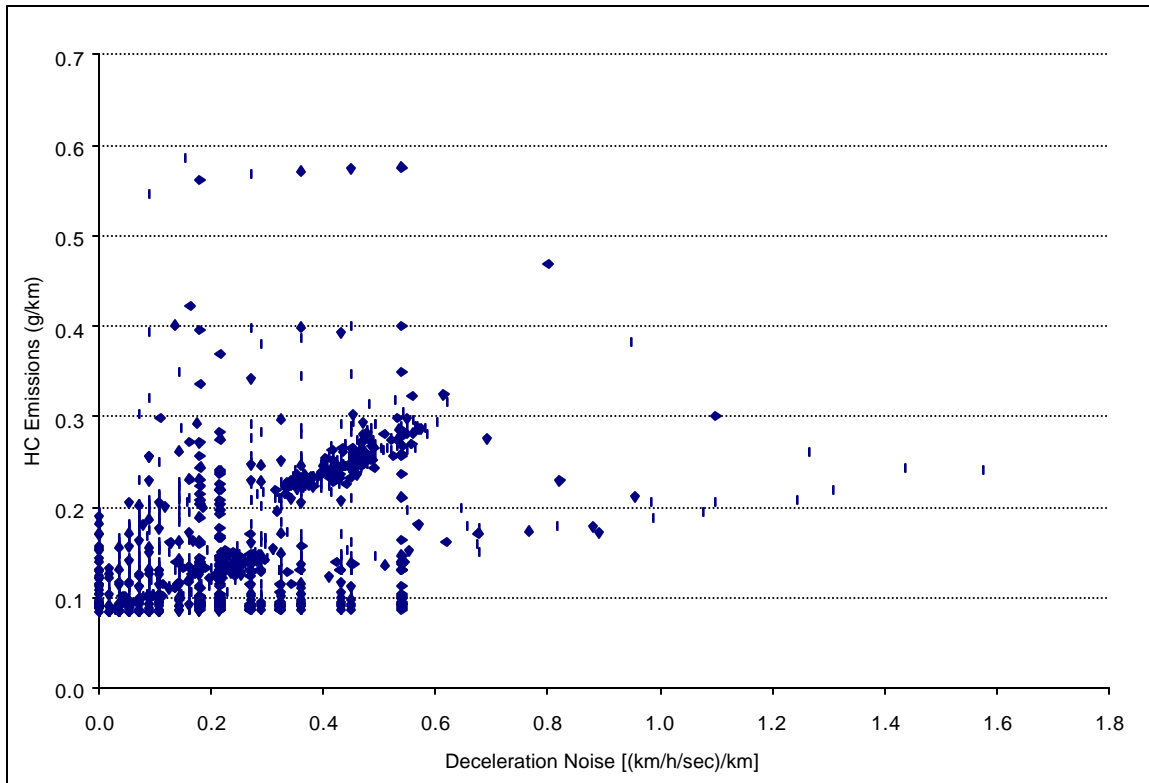


Figure B-14. HC Emissions vs. Deceleration Noise

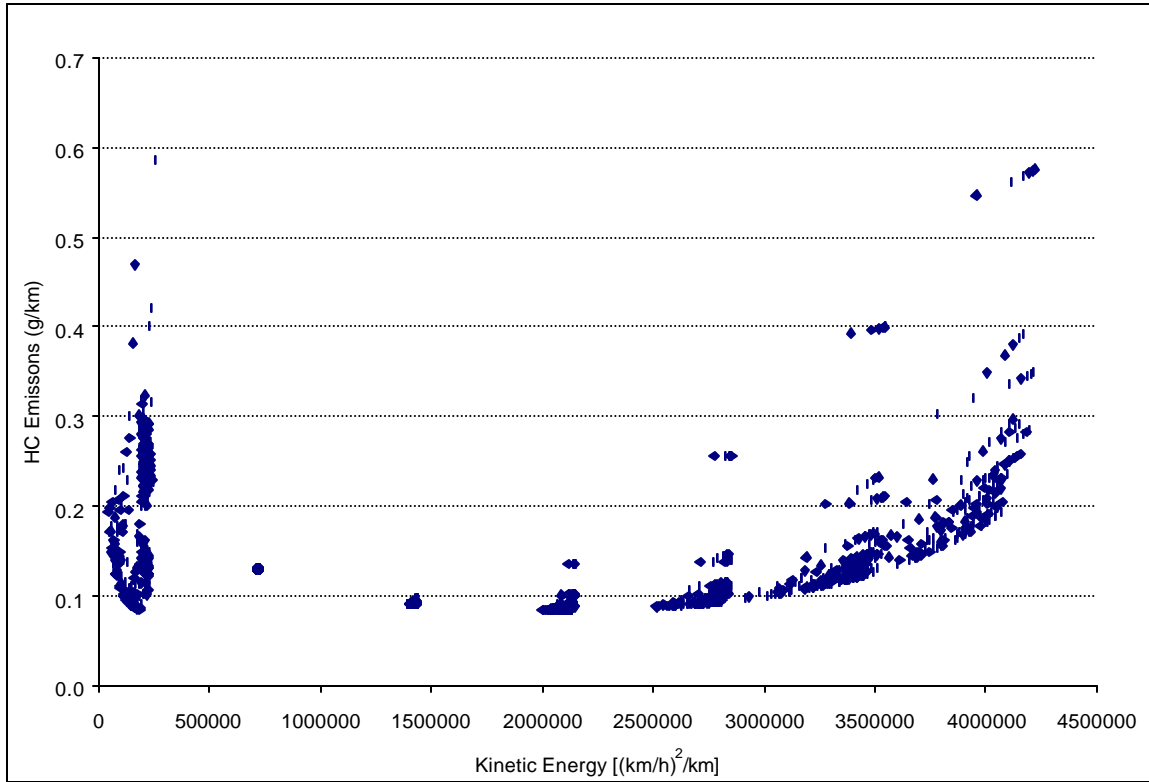


Figure B-15. HC Emissions vs. Kinetic Energy

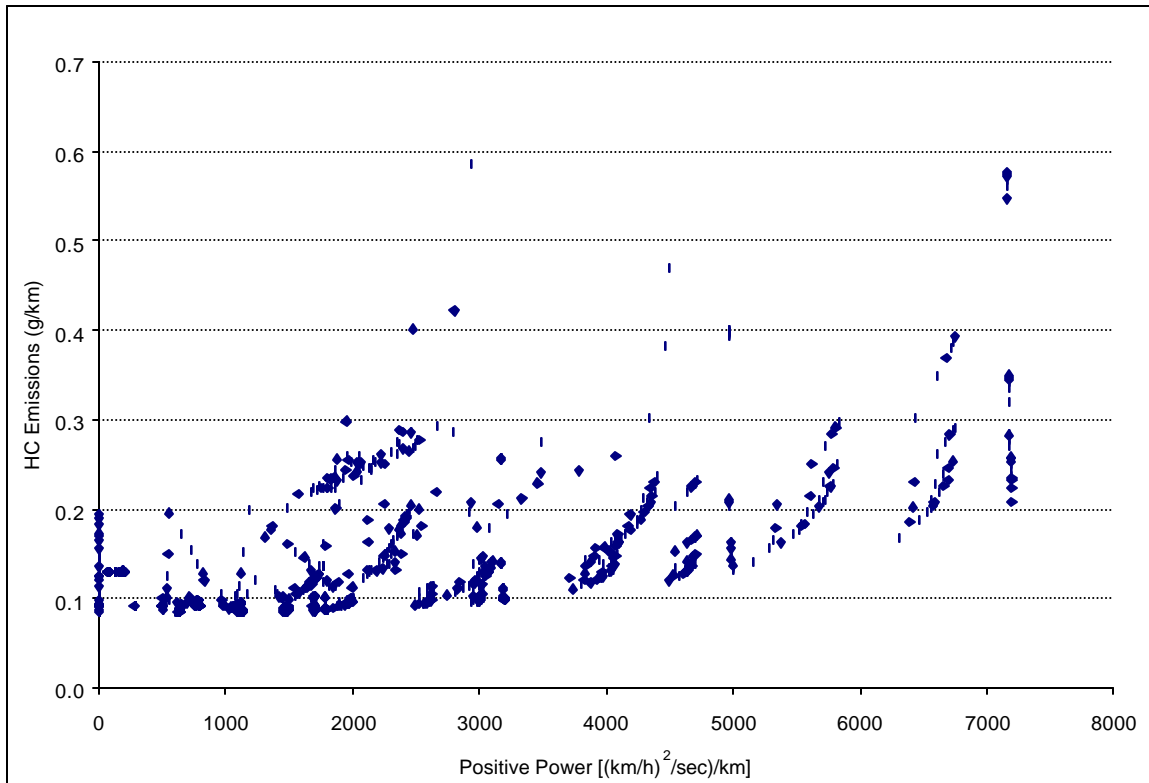


Figure B-16. HC Emissions vs. Power

### B.3 CO Emission Rates as a Function of an Independent Variable

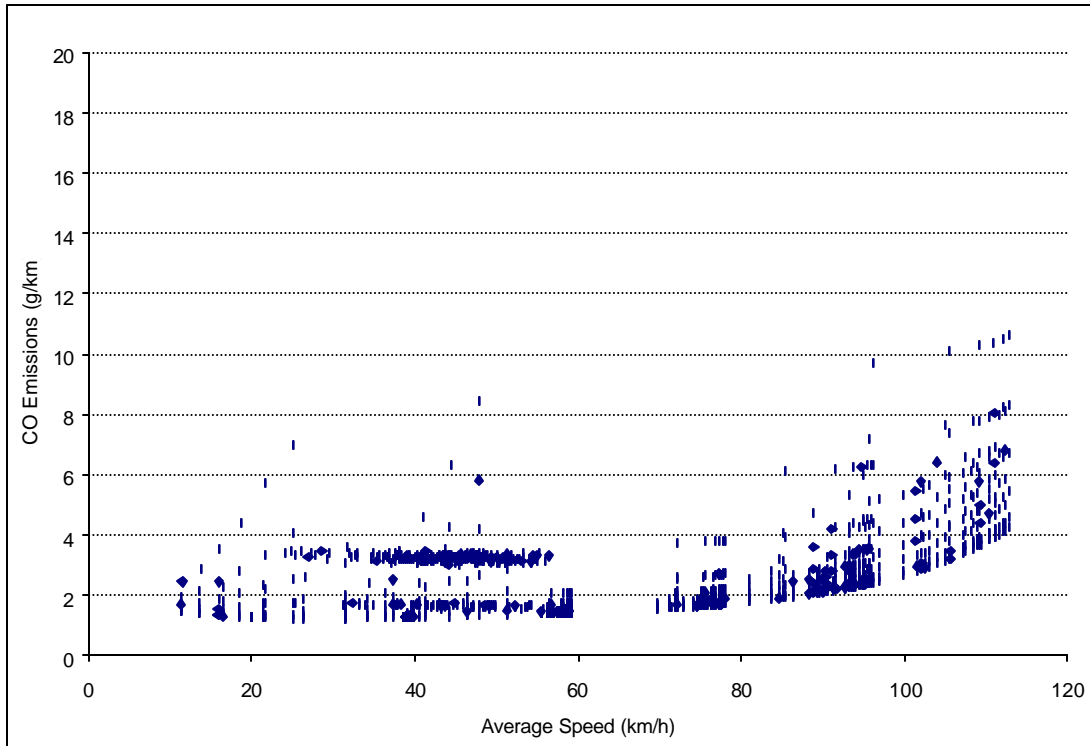


Figure B-17. CO Emissions vs. Average Speed

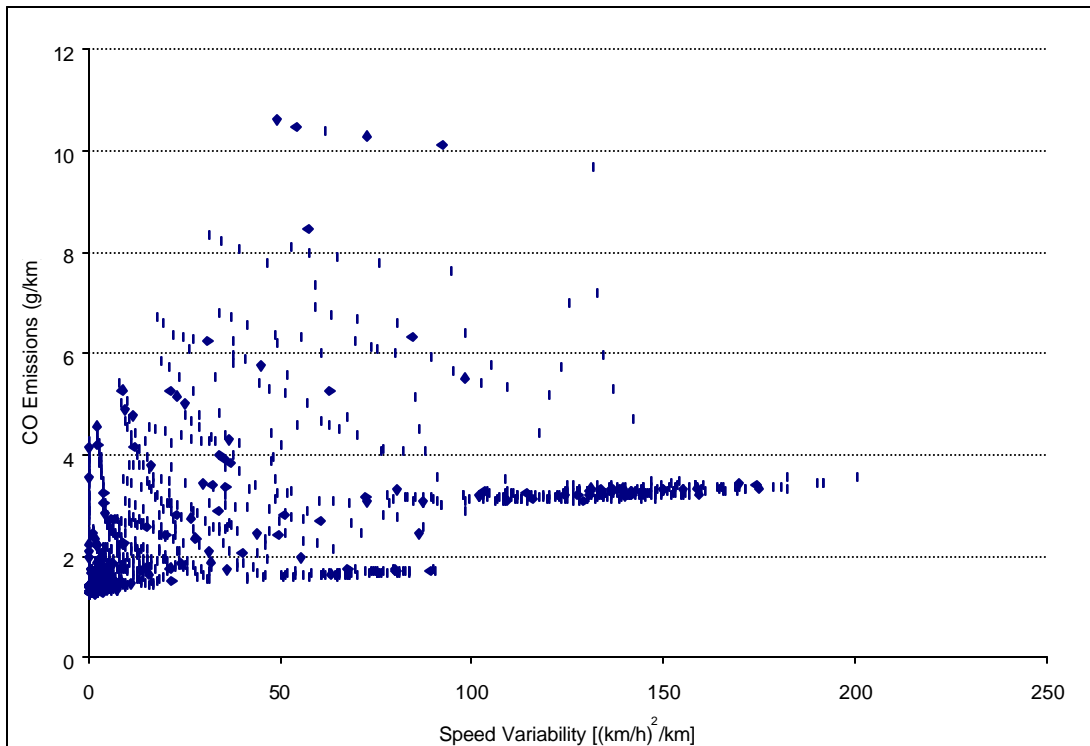


Figure B-18. CO Emissions vs. Speed Variability

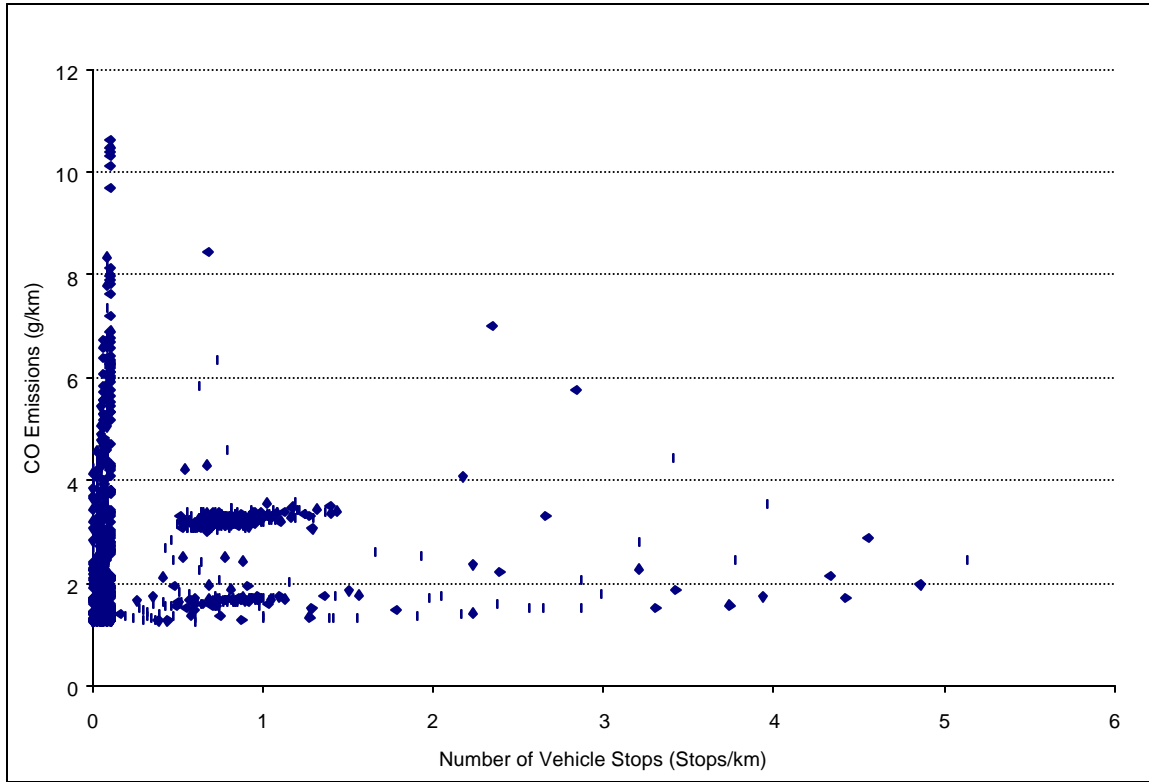


Figure B-19. CO Emissions vs. Number of Vehicle Stops

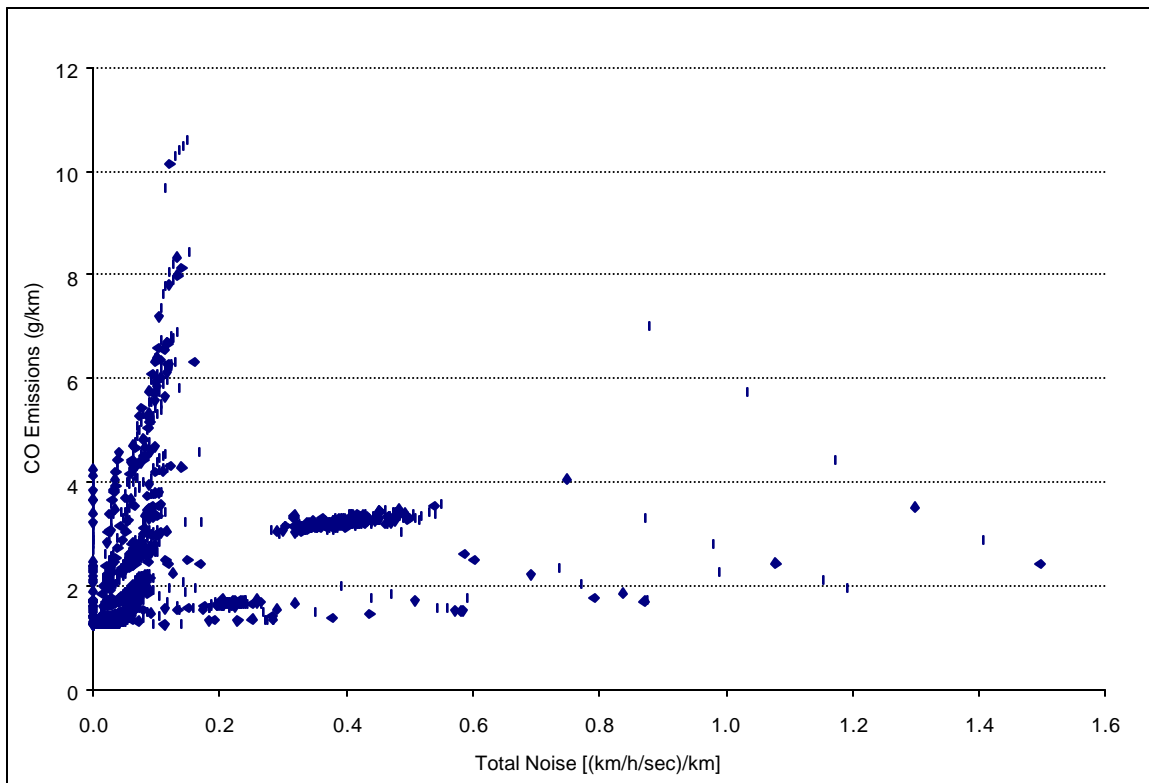


Figure B-20. CO Emissions vs. Total Noise

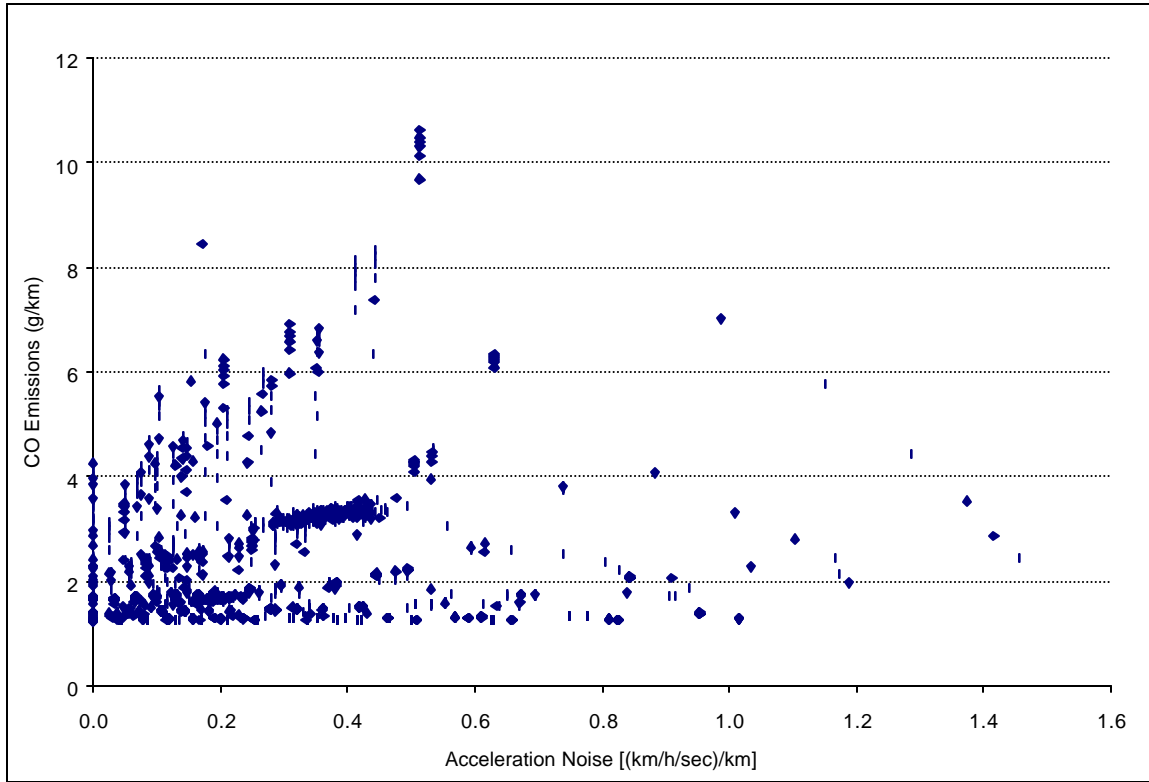


Figure B-21. CO Emissions vs. Acceleration Noise

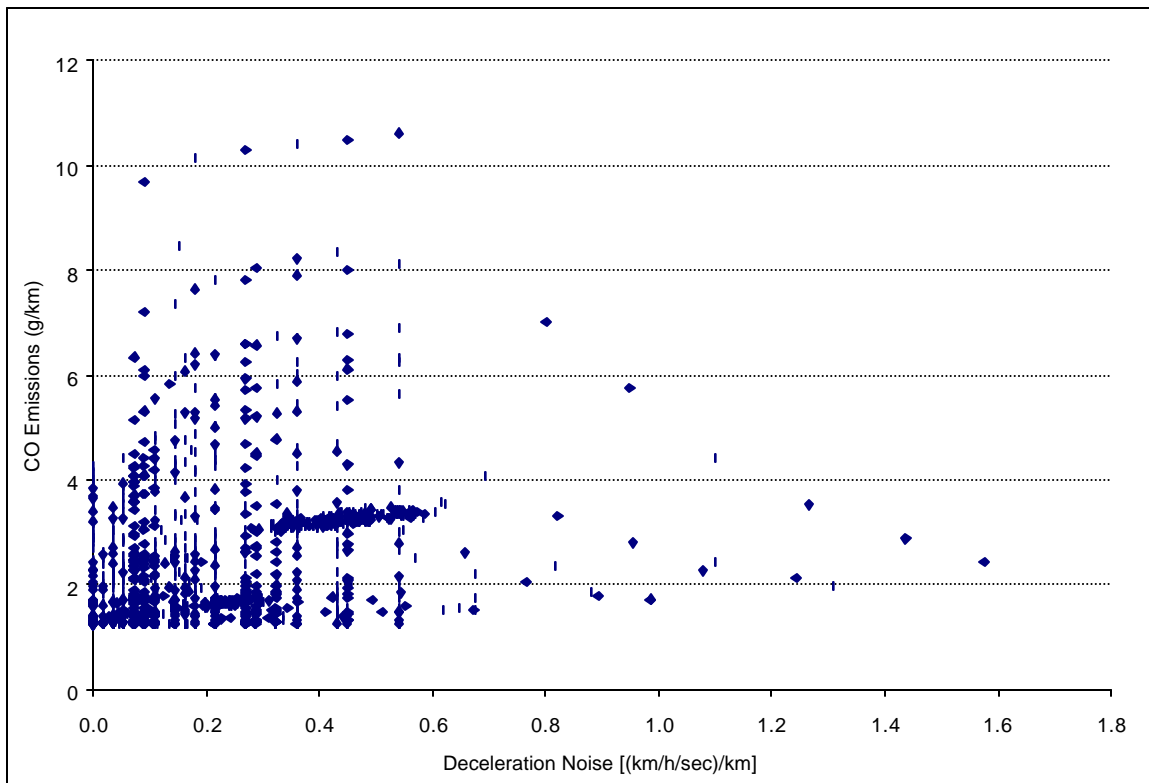


Figure B-22. CO Emissions vs. Deceleration Noise

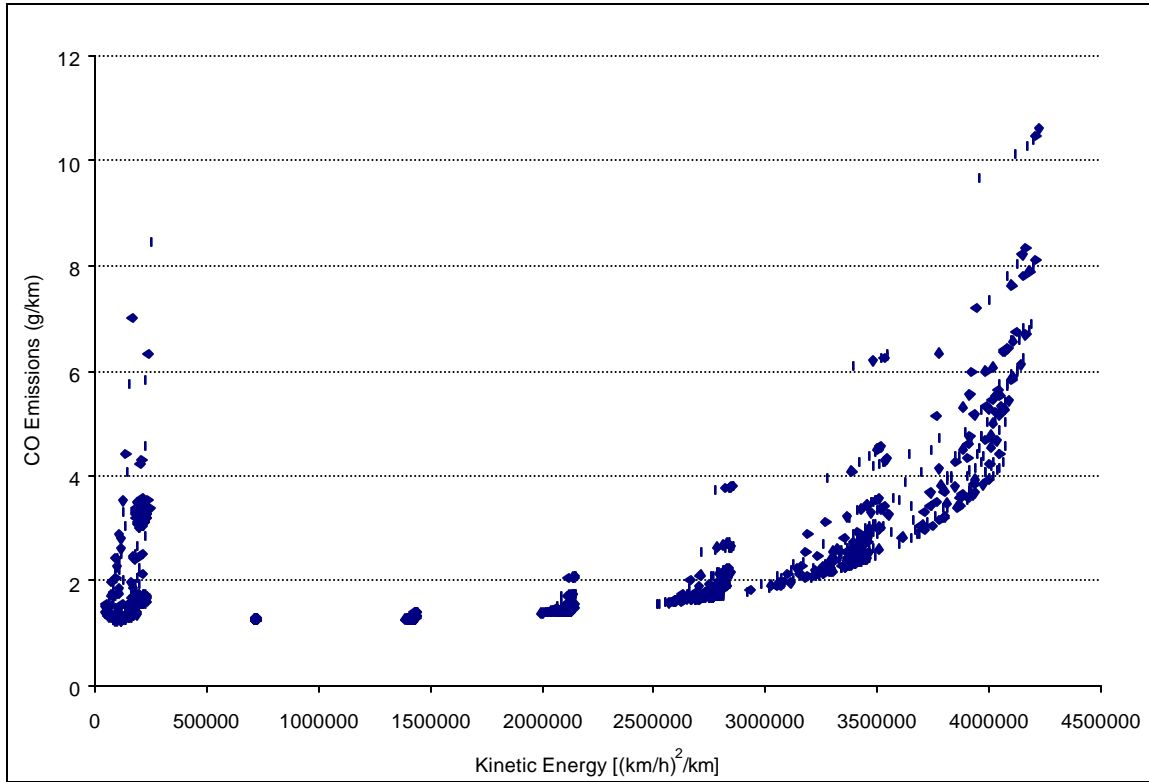


Figure B-23. CO Emissions vs. Kinetic Energy

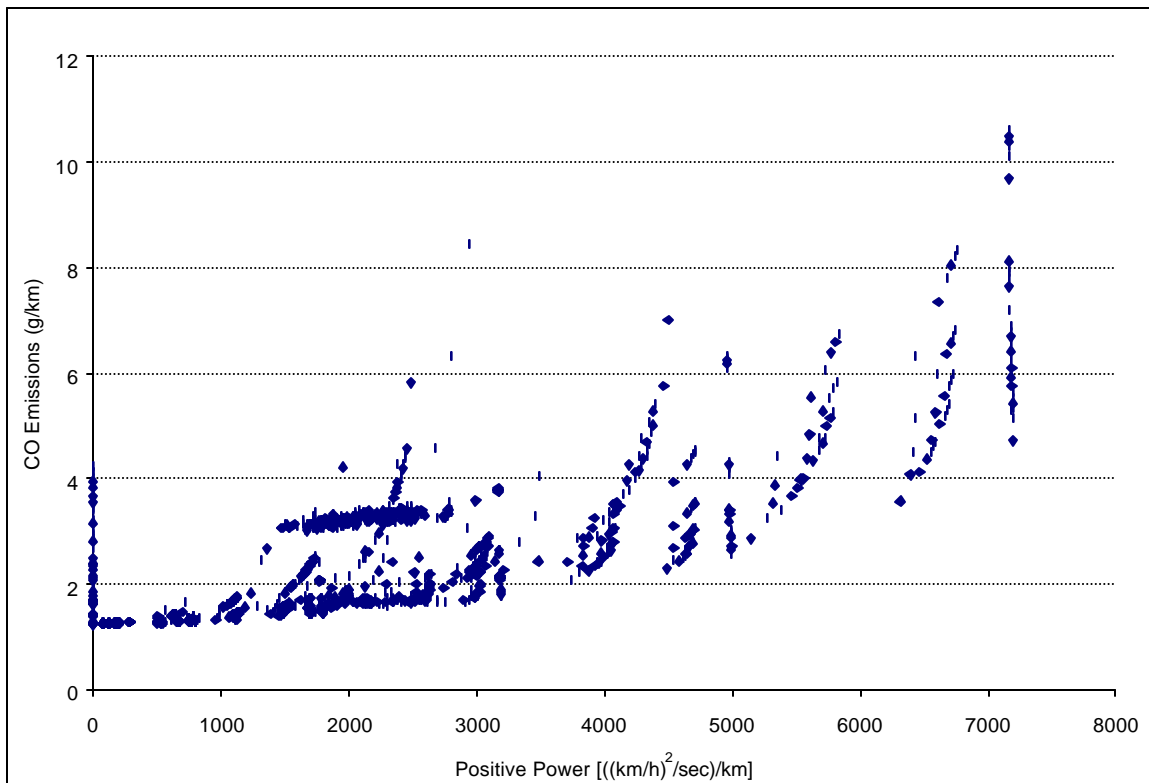


Figure B-24. CO Emissions vs. Power

#### B.4 NO<sub>x</sub> Emission Rates as a Function of an Independent Variable

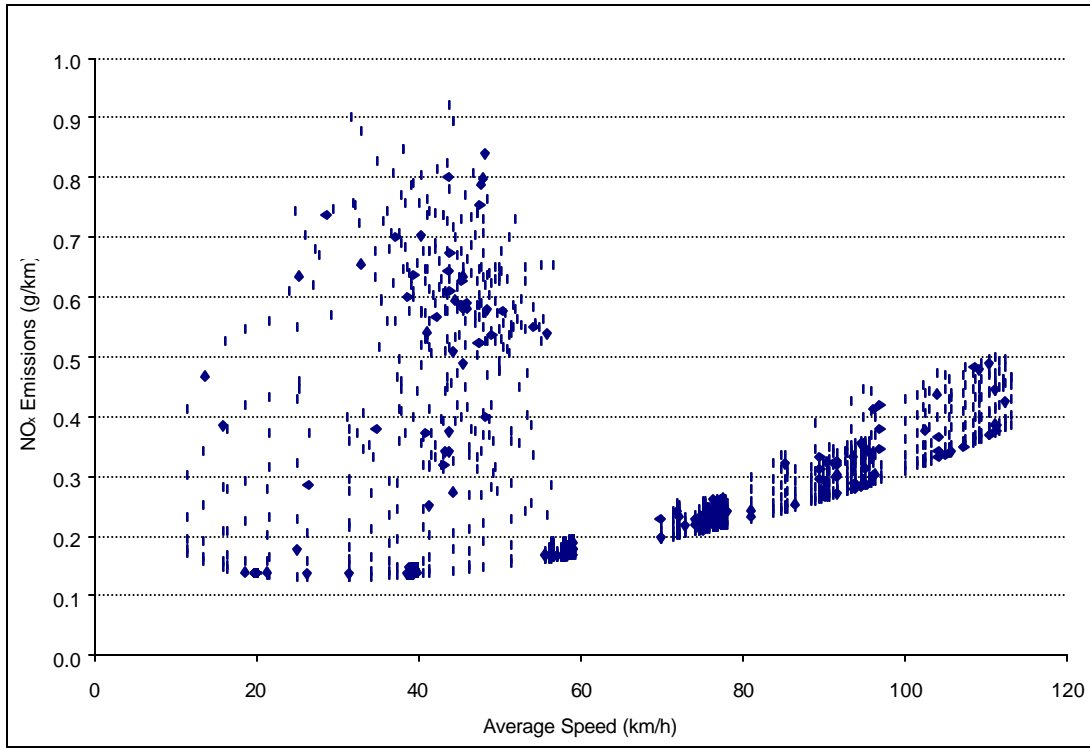


Figure B-25. NO<sub>x</sub> Emission vs. Average Speed

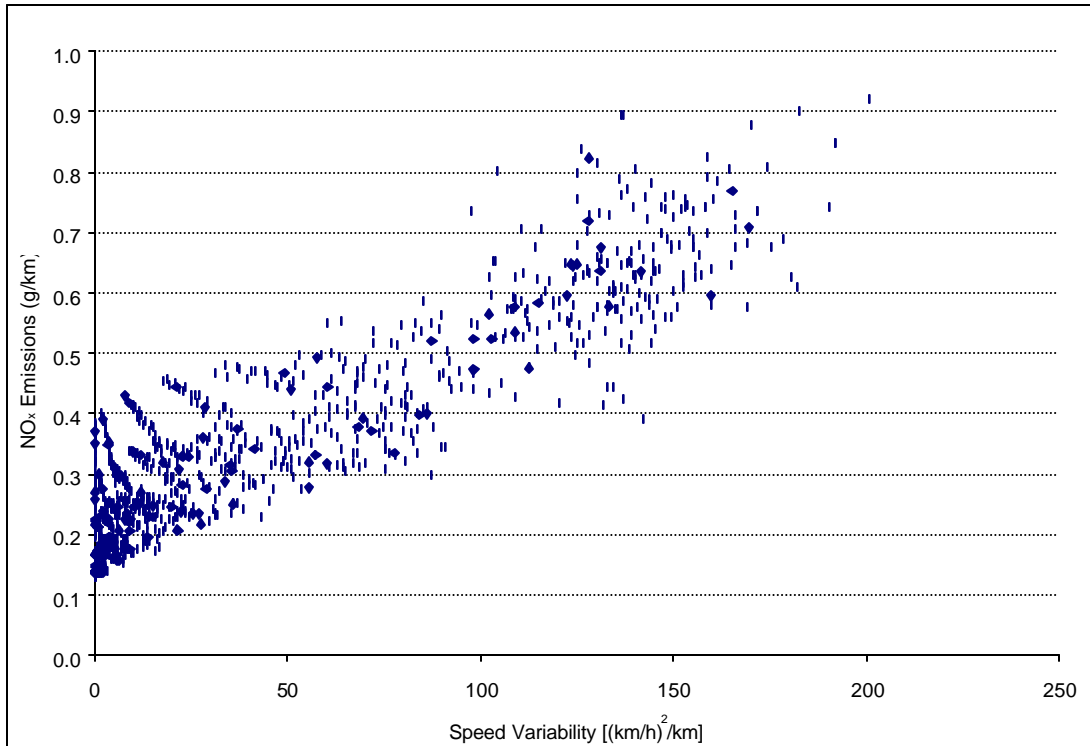


Figure B-26. NO<sub>x</sub> Emission vs. Speed Variability

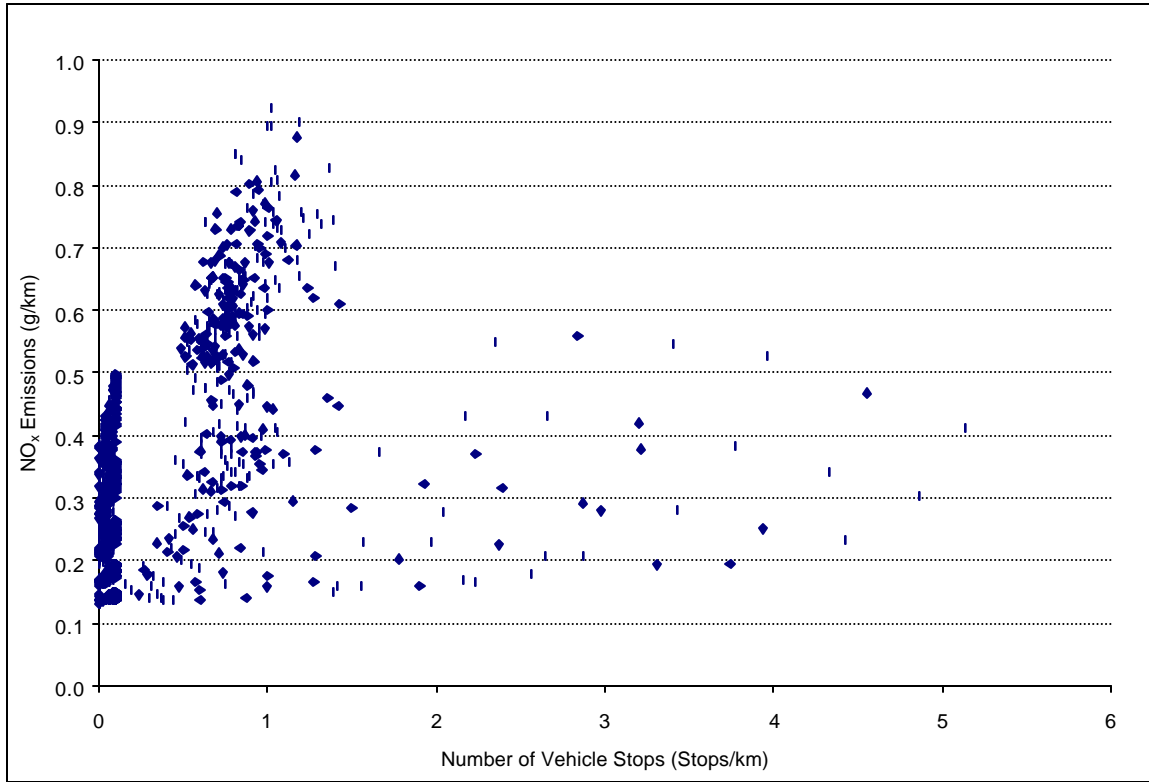


Figure B-27. NO<sub>x</sub> Emission vs. Number of Vehicle Stops

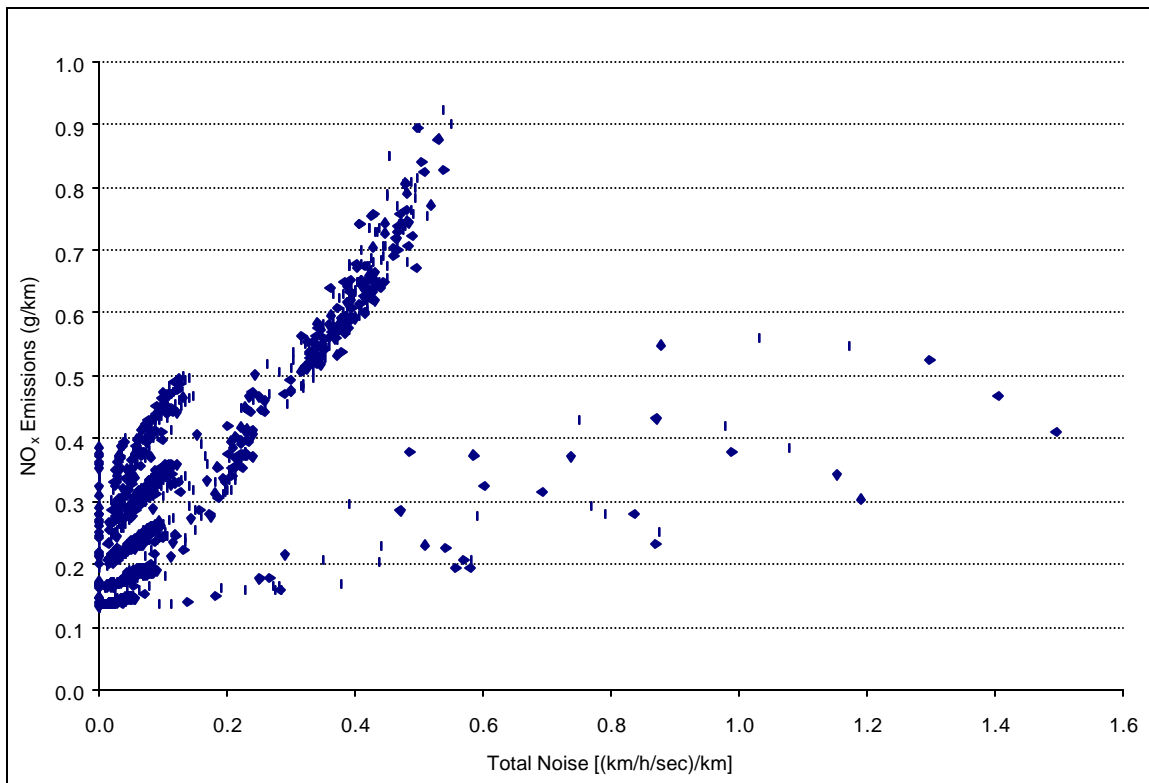


Figure B-28. NO<sub>x</sub> Emission vs. Total Noise

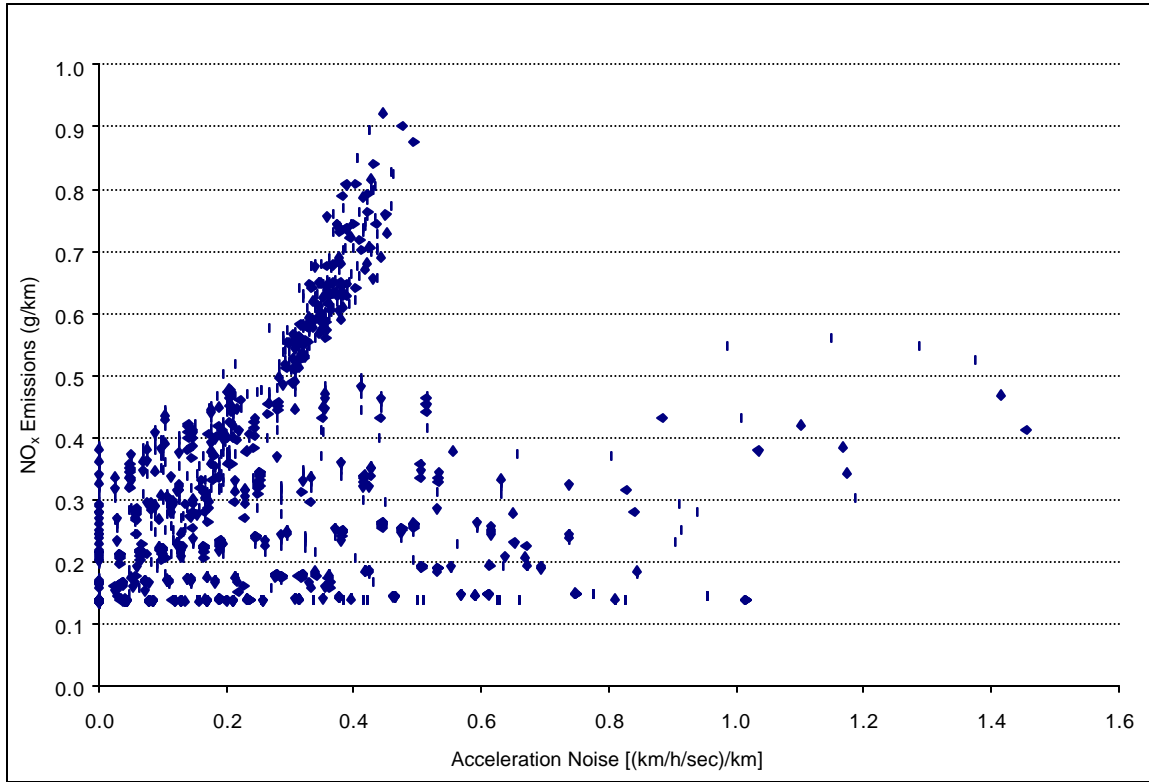


Figure B-29.  $NO_x$  Emission vs. Acceleration Noise

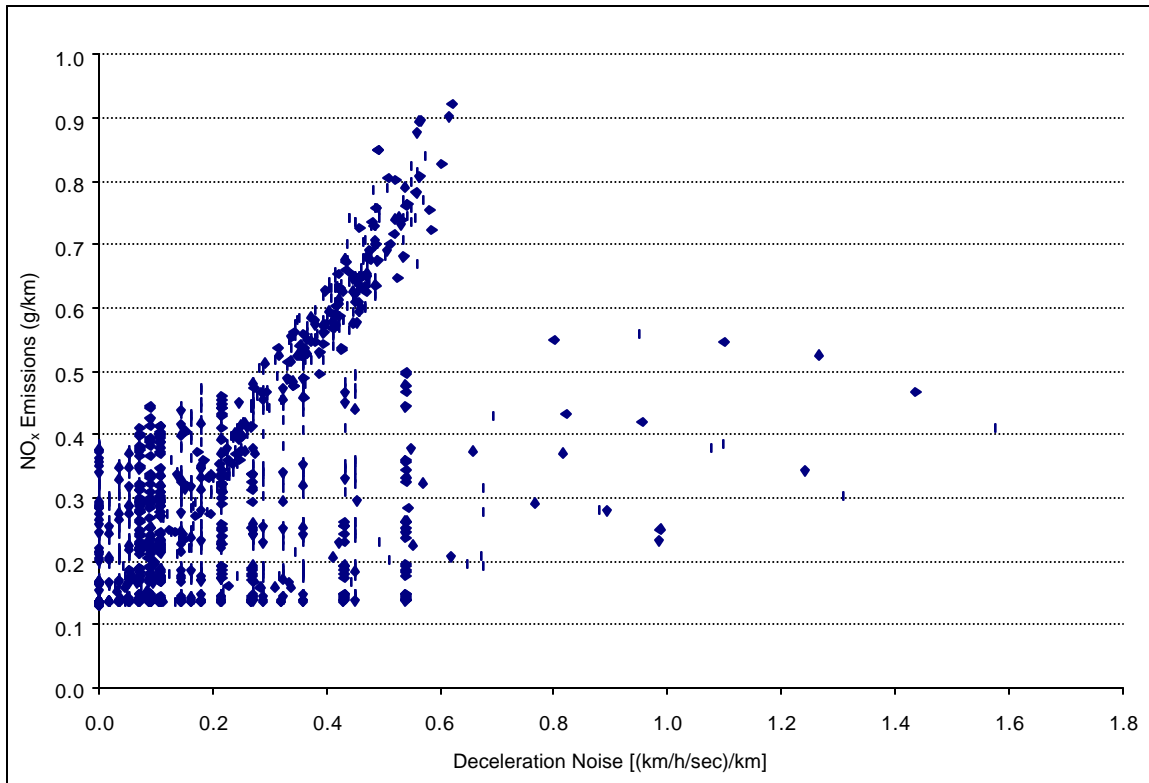


Figure B-30.  $NO_x$  Emission vs. Deceleration Noise

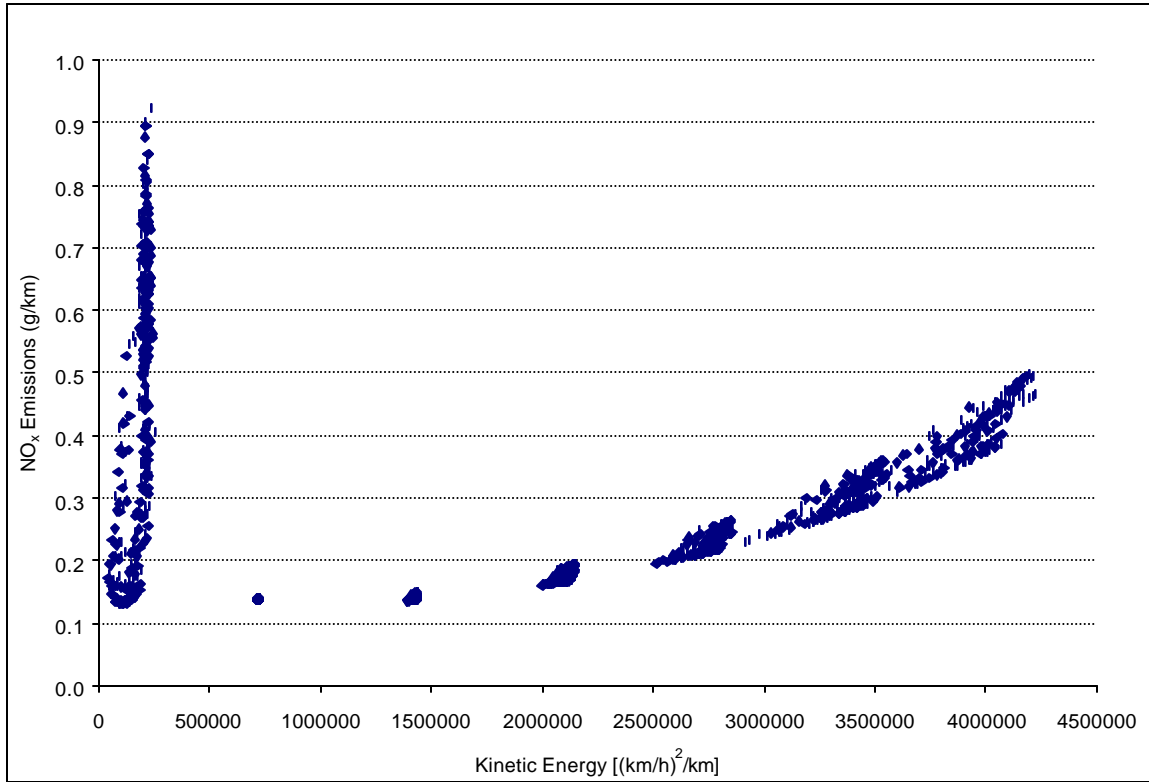


Figure B-31.  $NO_x$  Emissions vs. Kinetic Energy

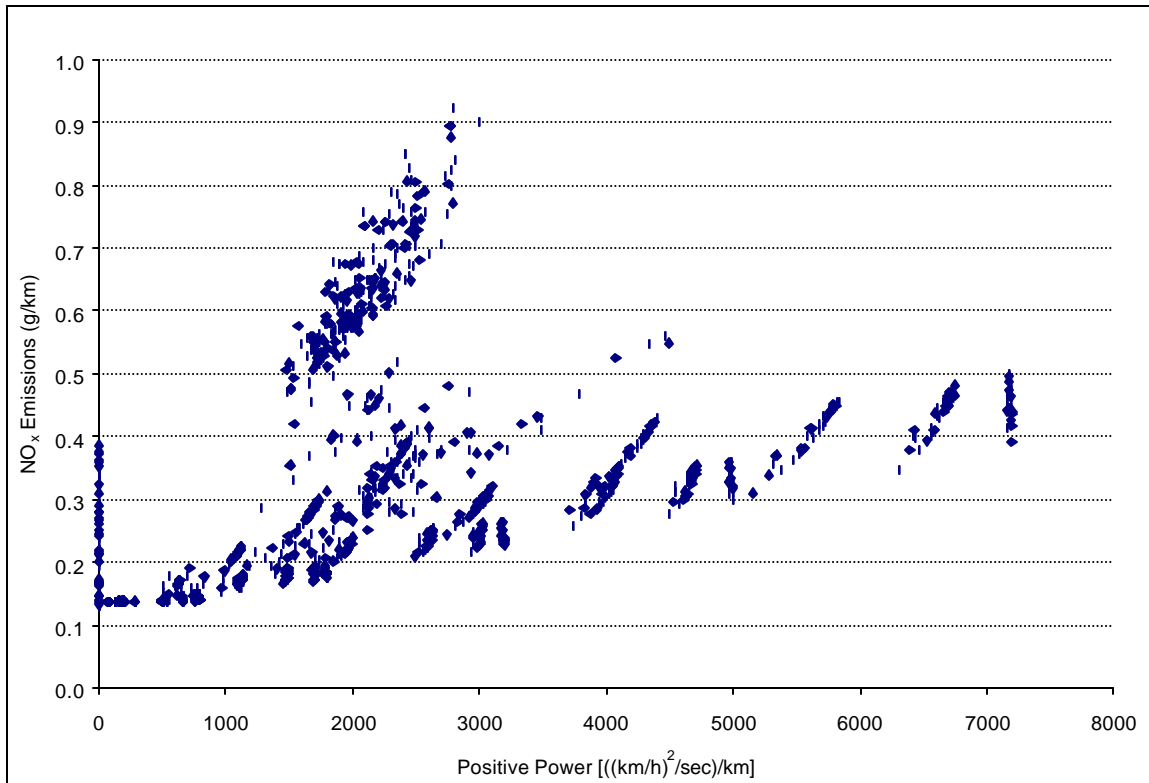


Figure B-31.  $NO_x$  Emissions vs. Power

## **APPENDIX C**

Multicollinearity is defined as a high degree of correlation among several independents in a regression model. The existence of multicollinearity is not a violation of the assumptions underlying the use of regression analysis, however, it tends to inflate the variances of predicted values and the variances of the parameter estimates (Freund and Littell, 1991). The following criterion is used to detect multicollinearity,

If a Variable Inflation Factor for a variable  $> 1/(1-R\_square)$ , then it means this variable is more closely related to the other independent variables than to the dependent variable. The conclusion is that the variable does not pass multicollinearity test.

*Table C-1. Abbreviation*

Abbreviation	Abbreviation in Equation	Description
SPD	$\hat{u}$	Average Speed
ISP	$1/\hat{u}$	Reciprocal of the Average Speed
QSP	$\hat{u}^2$	Average Speed Square
SVA	$\sigma_u^2$	Speed Variance per Kilometer
STP	S	Number of Vehicle Stops per Kilometer
NOI	A	Total Noise per Kilometer
ANOI	A <sup>+</sup>	Acceleration Noise per Kilometer
DNOI	A <sup>-</sup>	Deceleration Noise per Kilometer
KENG	E <sub>k</sub>	Kinetic Energy per Kilometer
POW	P	Positive Power per Kilometer

## C.1 Results from SAS--the Best Statistical Model Selection for Vehicle Fuel Consumption Estimate (with log-transformed data)

### C.1.1 Variables Selection

N = 1501 Regression Models for Dependent Variable: LFUEL

Number in Model	R-square	C(p)	Variables in Model
1	0.60259069	15621	SVA
1	0.56636797	17182	NOI
1	0.55806266	17539	KENG
1	0.39183837	24699	STP
1	0.35682227	26208	DNOI
1	0.33050876	27341	SPD
1	0.28213540	29425	QSP
1	0.27078885	29913	ISP
1	0.11454621	36644	ANOI
1	0.00252999	41469	POW
-----			
2	0.90813280	2462	ISP SVA
2	0.84742705	5077	SPD SVA
2	0.83165201	5757	SVA KENG
2	0.78830234	7624	QSP SVA
2	0.75224881	9177	NOI KENG
2	0.73791305	9794	SVA POW
2	0.71505331	10779	SPD NOI
2	0.69606459	11597	QSP KENG
2	0.69313058	11723	ISP NOI
2	0.69023608	11848	DNOI KENG
-----			
3	0.92110747	1905	ISP SVA POW
3	0.91729141	2070	SPD QSP SVA
3	0.91593910	2128	ISP SVA KENG
3	0.91042737	2365	ISP SVA STP
3	0.90947219	2406	SPD ISP SVA
3	0.90864546	2442	ISP QSP SVA
3	0.90851288	2448	ISP SVA ANOI
3	0.90828305	2458	ISP SVA NOI
3	0.90813545	2464	ISP SVA DNOI
3	0.85690137	4671	SPD SVA NOI
-----			
4	0.93166171	1453	SPD QSP SVA POW
4	0.92983438	1531	ISP SVA STP NOI
4	0.92904455	1565	SPD QSP SVA KENG
4	0.92834399	1596	ISP QSP SVA KENG
4	0.92545297	1720	ISP QSP SVA POW
4	0.92380144	1791	SPD ISP SVA KENG
4	0.92342285	1808	ISP SVA DNOI POW
4	0.92337716	1809	SPD ISP SVA POW
4	0.92214815	1862	ISP SVA NOI POW
4	0.92181525	1877	ISP SVA STP POW
-----			
5	0.94094809	1055	ISP SVA STP NOI POW
5	0.93876943	1148	SPD QSP SVA DNOI POW
5	0.93844180	1163	SPD QSP SVA KENG POW
5	0.93838595	1165	ISP QSP SVA KENG POW
5	0.93804372	1180	ISP SVA STP NOI KENG
5	0.93714607	1218	SPD QSP SVA NOI POW
5	0.93592852	1271	SPD QSP SVA STP NOI
5	0.93519376	1303	ISP SVA STP NOI ANOI
5	0.93469498	1324	ISP QSP SVA STP KENG
5	0.93451456	1332	SPD QSP SVA ANOI POW
-----			
6	0.95656908	383.77003	ISP QSP SVA STP NOI KENG
6	0.95301370	536.91660	SPD ISP SVA STP NOI KENG
6	0.95082941	631.00416	SPD QSP SVA STP NOI POW
6	0.94958816	684.47037	SPD QSP SVA STP NOI KENG
6	0.94553274	859.15599	ISP QSP SVA STP NOI POW
6	0.94525846	870.97066	SPD QSP SVA DNOI KENG POW
6	0.94354366	944.83485	SPD ISP SVA STP NOI POW
6	0.94315296	961.66400	SPD QSP SVA ANOI KENG POW
6	0.94263575	983.94266	ISP SVA STP NOI ANOI POW
6	0.94215807	1005	SPD ISP QSP SVA KENG POW
-----			
7	0.96339498	91.74698	ISP QSP SVA STP NOI KENG POW

7	0.95868635	294.56939	SPD ISP SVA STP NOI KENG POW
7	0.95806612	321.28559	SPD QSP SVA STP NOI KENG POW
7	0.95732927	353.02527	SPD ISP QSP SVA STP NOI KENG
7	0.95689339	371.80042	ISP QSP SVA STP NOI ANOI KENG
7	0.95661344	383.85939	ISP QSP SVA STP NOI DNOI KENG
7	0.95342310	521.28196	SPD ISP SVA STP NOI ANOI KENG
7	0.95321303	530.33042	SPD ISP QSP SVA STP NOI POW
7	0.95305655	537.07069	SPD ISP SVA STP NOI DNOI KENG
7	0.95293401	542.34918	ISP QSP SVA STP DNOI KENG POW
-----			
8	0.96476554	34.71057	SPD ISP QSP SVA STP NOI KENG POW
8	0.96414645	61.37758	ISP QSP SVA STP NOI DNOI KENG POW
8	0.96354275	87.38170	ISP QSP SVA STP NOI ANOI KENG POW
8	0.95926359	271.70493	SPD ISP SVA STP NOI DNOI KENG POW
8	0.95872526	294.89351	SPD QSP SVA STP NOI DNOI KENG POW
8	0.95872450	294.92606	SPD ISP SVA STP NOI ANOI KENG POW
8	0.95814895	319.71760	SPD QSP SVA STP NOI ANOI KENG POW
8	0.95777981	335.61809	SPD ISP QSP SVA STP NOI ANOI KENG
8	0.95741639	351.27266	SPD ISP QSP SVA STP NOI DNOI KENG
8	0.95689450	373.75259	ISP QSP SVA STP NOI ANOI DNOI KENG
-----			
9	0.96540776	9.04727	SPD ISP QSP SVA STP NOI DNOI KENG POW
9	0.96485216	32.97963	SPD ISP QSP SVA STP NOI ANOI KENG POW
9	0.96415711	62.91878	ISP QSP SVA STP NOI ANOI DNOI KENG POW
9	0.95926690	273.56251	SPD ISP SVA STP NOI ANOI DNOI KENG POW
9	0.95872577	296.87148	SPD QSP SVA STP NOI ANOI DNOI KENG POW
9	0.95778010	337.60561	SPD ISP QSP SVA STP NOI ANOI DNOI KENG
9	0.95493022	460.36336	SPD ISP QSP SVA STP ANOI DNOI KENG POW
9	0.95389379	505.00708	SPD ISP QSP SVA STP NOI ANOI DNOI POW
9	0.94820962	749.85054	SPD ISP QSP SVA NOI ANOI DNOI KENG POW
9	0.92153718	1899	SPD ISP QSP STP NOI ANOI DNOI KENG POW
-----			
10	0.96540886	11.00000	SPD ISP QSP SVA STP NOI ANOI DNOI KENG POW

### C.1.2 Candidate Models

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- ***Log(Fuel)=f(SPD ISP QSP SVA STP NOI DNOI KENG POW), All variables included initially, SAS comes out with 9 variables except ANOI. SPD QSP don't pass multicollinearity test***

Backward Elimination Procedure for Dependent Variable LFUEL

Step 0 All Variables Entered R-square = 0.96540886 C(p) = 11.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	187.07007099	18.70700710	4158.46	0.0001
Error	1490	6.70282571	0.00449854		
Total	1500	193.77289669			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.21035689	0.04560170	10.56901308	2349.43	0.0001
SPD	-0.00724215	0.00098627	0.24255585	53.92	0.0001
ISP	10.38267510	0.61194155	1.29500160	287.87	0.0001
QSP	0.00008980	0.00000552	1.19014523	264.56	0.0001
SVA	0.00402441	0.00009258	8.50114156	1889.76	0.0001
STP	-0.32654753	0.01199723	3.33274635	740.85	0.0001
NOI	1.11907117	0.05267379	2.03047648	451.36	0.0001
ANOI	0.00256351	0.01179122	0.00021263	0.05	0.8279
DNOI	0.09491557	0.01938279	0.10787333	23.98	0.0001
KENG	-0.00000012	0.00000001	2.23130808	496.01	0.0001
POW	-0.00003424	0.00000189	1.47824575	328.61	0.0001

Bounds on condition number: 251.1976, 4840.192

Step 1 Variable ANOI Removed R-square = 0.96540776 C(p) = 9.04726638

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	187.06985836	20.78553982	4623.46	0.0001
Error	1491	6.70303834	0.00449567		
Total	1500	193.77289669			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.20970951	0.04548983	10.60805381	2359.62	0.0001
SPD	-0.00725554	0.00098403	0.24440712	54.37	0.0001
ISP	10.38213413	0.61174095	1.29488806	288.03	0.0001
QSP	0.00008976	0.00000552	1.19057330	264.83	0.0001
SVA	0.00401958	0.00008983	9.00108400	2002.17	0.0001
STP	-0.32708633	0.01173472	3.49279454	776.92	0.0001
NOI	1.12202758	0.05087196	2.18697680	486.46	0.0001
DNOI	0.09629860	0.01830329	0.12444448	27.68	0.0001
KENG	-0.00000012	0.00000001	2.34977054	522.67	0.0001
POW	-0.00003414	0.00000184	1.54851198	344.45	0.0001

Bounds on condition number: 250.2177, 4283.384

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable LFUEL

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	ANOI	9	0.0000	0.9654	9.0473	0.0473	0.8279

▪ **SPD QSP don't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LFUEL

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	9	187.06986	20.78554	4623.462	0.0001
Error	1491	6.70304	0.00450		
C Total	1500	193.77290			

Root MSE	0.06705	R-square	0.9654
Dep Mean	-2.10032	Adj R-sq	0.9652
C.V.	-3.19236		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-2.209710	0.04548983	-48.576	0.0001	0.00000000
SPD	1	-0.007256	0.00098403	-7.373	0.0001	250.21773651
ISP	1	10.382134	0.61174095	16.971	0.0001	24.75269837
QSP	1	0.000089759	0.00000552	16.274	0.0001	129.15118242
SVA	1	0.004020	0.00008983	44.746	0.0001	6.48875008
STP	1	-0.327086	0.01173472	-27.873	0.0001	13.93055208
NOI	1	1.122028	0.05087196	22.056	0.0001	27.21069108
DNOI	1	0.096299	0.01830329	5.261	0.0001	4.16946775
KENG	1	-0.000000119	0.00000001	-22.862	0.0001	16.60189089
POW	1	-0.000034144	0.00000184	-18.559	0.0001	3.40855414

Collinearity Diagnostics(intercept adjusted)

Condition Number	Var Prop Eigenvalue	Var Prop Index	Var Prop SPD	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop STP	Var Prop NOI
1	4.63091	1.00000	0.0001	0.0011	0.0003	0.0016	0.0018	0.0008
2	2.91125	1.26123	0.0001	0.0008	0.0002	0.0086	0.0022	0.0020
3	0.61075	2.75361	0.0000	0.0163	0.0004	0.1033	0.0125	0.0000
4	0.36461	3.56385	0.0006	0.0122	0.0004	0.0121	0.0452	0.0101
5	0.26356	4.19174	0.0000	0.0250	0.0011	0.0268	0.0269	0.0007
6	0.14741	5.60487	0.0005	0.0664	0.0075	0.2016	0.0423	0.0003
7	0.04579	10.05610	0.0054	0.0026	0.0389	0.1057	0.0053	0.0137
8	0.02319	14.13132	0.0002	0.0043	0.0001	0.5394	0.8263	0.9723
9	0.00253	42.79390	0.9931	0.8714	0.9511	0.0009	0.0375	0.0001

Var Prop  
Number DNOI KENG POW

1	0.0038	0.0024	0.0015
2	0.0122	0.0003	0.0232
3	0.0354	0.0094	0.0097

4	0.0212	0.0003	0.3419
5	0.5264	0.0003	0.0771
6	0.0605	0.0224	0.4465
7	0.0724	0.8407	0.0034
8	0.2671	0.0053	0.0854
9	0.0009	0.1189	0.0114

•

- **Log(Fuel)=f(ISP QSP SVA STP NOI KENG POW), R\_adj=0.9632, all pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LFUEL

Step 0 All Variables Entered R-square = 0.96339498 C(p) = 8.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	186.67983616	26.66854802	5613.39	0.0001
Error	1493	7.09306053	0.00475088		
Total	1500	193.77289669			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.53599621	0.00934645	349.76598620	73621.3	0.0001
ISP	14.80476064	0.21823711	21.86348633	4601.99	0.0001
QSP	0.00004869	0.00000164	4.20004745	884.06	0.0001
SVA	0.00390634	0.00008934	9.08325666	1911.91	0.0001
STP	-0.36202052	0.01135096	4.83253499	1017.19	0.0001
NOI	1.28143663	0.04320012	4.18021176	879.88	0.0001
KENG	-0.00000013	0.00000000	3.46121779	728.54	0.0001
POW	-0.00002901	0.00000174	1.32267466	278.41	0.0001

Bounds on condition number: 18.56832, 470.315

All variables left in the model are significant at the 0.1000 level.

- **All pass multicollinearity test**

Model: MODEL2

Dependent Variable: LFUEL

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	7	186.67984	26.66855	5613.394	0.0001
Error	1493	7.09306	0.00475		
C Total	1500	193.77290			

Root MSE	0.06893	R-square	0.9634
Dep Mean	-2.10032	Adj R-sq	0.9632
C.V.	-3.28172		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-2.535996	0.00934645	-271.333	0.0001	0.00000000
ISP	1	14.804761	0.21823711	67.838	0.0001	2.98101987
QSP	1	0.000048690	0.00000164	29.733	0.0001	10.77273903
SVA	1	0.003906	0.00008934	43.725	0.0001	6.07285534
STP	1	-0.362021	0.01135096	-31.893	0.0001	12.33411400
NOI	1	1.281437	0.04320012	29.663	0.0001	18.56832257
KENG	1	-0.000000131	0.00000000	-26.992	0.0001	13.57890967
POW	1	-0.000029006	0.00000174	-16.686	0.0001	2.87989491

Collinearity Diagnostics(intercept adjusted)

Condition Number	Var Eigenvalue	Var Prop Index	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop STP	Var Prop NOI	Var Prop KENG
1	3.56116	1.00000	0.0140	0.0050	0.0034	0.0038	0.0023	0.0050
2	2.30973	1.24170	0.0124	0.0039	0.0156	0.0033	0.0042	0.0007
3	0.56744	2.50517	0.1607	0.0079	0.0927	0.0307	0.0011	0.0117

4	0.33572	3.25692	0.2580	0.0075	0.0216	0.0366	0.0129	0.0029
5	0.14936	4.88298	0.5254	0.1477	0.2572	0.0152	0.0007	0.0338
6	0.04697	8.70751	0.0050	0.7100	0.0167	0.0549	0.1162	0.7852
7	0.02963	10.96253	0.0246	0.1180	0.5929	0.8555	0.8626	0.1607

Var Prop  
Number POW

1	0.0029
2	0.0454
3	0.0267
4	0.4398

**Model 1.**

- **$\text{Log}(\text{Fuel})=f(\text{ISP QSP SVA STP NOI KENG})$ ,  $R_{\text{adj}}=0.9564$ , all pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LFUEL

Step 0 All Variables Entered R-square = 0.95656908 C(p) = 7.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	185.35716150	30.89286025	5484.24	0.0001
Error	1494	8.41573519	0.00563302		
Total	1500	193.77289669			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.50108115	0.00991891	358.15366778	63581.1	0.0001
ISP	14.42540394	0.23634302	20.98513973	3725.38	0.0001
QSP	0.00004447	0.00000176	3.58971321	637.26	0.0001
SVA	0.00332904	0.00008969	7.76092652	1377.76	0.0001
STP	-0.38201644	0.01229086	5.44177757	966.05	0.0001
NOI	1.29025950	0.04703663	4.23860760	752.46	0.0001
KENG	-0.00000015	0.00000001	5.13679650	911.91	0.0001

Bounds on condition number: 18.56554, 371.5883

All variables left in the model are significant at the 0.1000 level.

- **All pass multicollinearity test**

Model: MODEL2

Dependent Variable: LFUEL

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	6	185.35716	30.89286	5484.243	0.0001
Error	1494	8.41574	0.00563		
C Total	1500	193.77290			

Root MSE	0.07505	R-square	0.9566
Dep Mean	-2.10032	Adj R-sq	0.9564
C.V.	-3.57343		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-2.501081	0.00991891	-252.153	0.0001	0.00000000
ISP	1	14.425404	0.23634302	61.036	0.0001	2.94866617
QSP	1	0.000044474	0.00000176	25.244	0.0001	10.51632855
SVA	1	0.003329	0.00008969	37.118	0.0001	5.16203359
STP	1	-0.382016	0.01229086	-31.081	0.0001	12.19663182
NOI	1	1.290259	0.04703663	27.431	0.0001	18.56554066
KENG	1	-0.000000153	0.00000001	-30.198	0.0001	12.54219057

Collinearity Diagnostics(intercept adjusted)

Condition Number	Var Prop Eigenvalue	Var Prop Index	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop STP	Var Prop NOI	Var Prop KENG
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1	3.49733	1.00000	0.0124	0.0044	0.0057	0.0046	0.0029	0.0051
2	1.67132	1.44657	0.0443	0.0114	0.0296	0.0037	0.0060	0.0031
3	0.54860	2.52488	0.0999	0.0163	0.1019	0.0436	0.0036	0.0184
4	0.20530	4.12735	0.8083	0.0500	0.2410	0.0371	0.0029	0.0169
5	0.04736	8.59328	0.0020	0.7896	0.0137	0.0467	0.0986	0.8239
6	0.03009	10.78182	0.0331	0.1282	0.6081	0.8643	0.8861	0.1325

Var Prop	
Number POW	
5	0.4572
6	0.0103
7	0.0177

**Model 2.**

- Log(Fuel)=f(SPD ISP SVA STP NOI KENG ),  $R_{adj}=0.9528$ , all pass multicollinearity test

Backward Elimination Procedure for Dependent Variable LFUEL

Step 0 All Variables Entered R-square = 0.95301370 C(p) = 7.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	184.66822542	30.77803757	5050.42	0.0001
Error	1494	9.10467127	0.00609416		
Total	1500	193.77289669			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.82835670	0.01779909	153.88153337	25250.7	0.0001
SPD	0.00715982	0.00032817	2.90077713	475.99	0.0001
ISP	18.42759381	0.34448709	17.43833558	2861.48	0.0001
SVA	0.00345754	0.00009250	8.51444598	1397.15	0.0001
STP	-0.39152046	0.01290267	5.61130133	920.77	0.0001
NOI	1.28842086	0.04893842	4.22405260	693.13	0.0001
KENG	-0.00000015	0.00000001	4.34859377	713.57	0.0001

Bounds on condition number: 20.52965, 461.338

All variables left in the model are significant at the 0.1000 level.

- All pass multicollinearity test

Model: MODEL2

Dependent Variable: LFUEL

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	6	184.66823	30.77804	5050.417	0.0001
Error	1494	9.10467	0.00609		
C Total	1500	193.77290			

Root MSE	0.07807	R-square	0.9530
Dep Mean	-2.10032	Adj R-sq	0.9528
C.V.	-3.71682		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-2.828357	0.01779909	-158.905	0.0001	0.00000000
SPD	1	0.007160	0.00032817	21.817	0.0001	20.52964680
ISP	1	18.427594	0.34448709	53.493	0.0001	5.79046894
SVA	1	0.003458	0.00009250	37.378	0.0001	5.07543307
STP	1	-0.391520	0.01290267	-30.344	0.0001	12.42401367
NOI	1	1.288421	0.04893842	26.327	0.0001	18.57645601
KENG	1	-0.000000152	0.00000001	-26.713	0.0001	14.49365426

Collinearity Diagnostics(intercept adjusted)

Condition Number	Var Prop Index	Var Prop SPD	Var Prop ISP	Var Prop SVA	Var Prop STP	Var Prop NOI	Var Prop KENG
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1	3.53327	1.00000	0.0024	0.0068	0.0053	0.0044	0.0027	0.0043
2	1.72039	1.43310	0.0056	0.0220	0.0304	0.0036	0.0059	0.0020
3	0.51012	2.63179	0.0042	0.0319	0.1245	0.0516	0.0048	0.0225
4	0.17601	4.48041	0.0060	0.4669	0.2620	0.0278	0.0009	0.0802
5	0.03518	10.02200	0.2688	0.0652	0.1897	0.4684	0.6628	0.2372
6	0.02503	11.88182	0.7129	0.4073	0.3881	0.4442	0.3229	0.6538

**Model 3.**

- **Log(Fuel)=f(ISP SVA STP NOI KENG ), R\_adj=0.9378, NOI doesn't pass multicollinearity test**

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Backward Elimination Procedure for Dependent Variable LFUEL

Step 0 All Variables Entered R-square = 0.93804372 C(p) = 6.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	181.76744830	36.35348966	4526.98	0.0001
Error	1495	12.00544840	0.00803040		
Total	1500	193.77289669			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.51177110	0.01183220	361.88139184	45063.9	0.0001
ISP	13.01108774	0.27414608	18.08840738	2252.49	0.0001
SVA	0.00401042	0.00010212	12.38466142	1542.22	0.0001
STP	-0.33387253	0.01449733	4.25914496	530.38	0.0001
NOI	1.22097656	0.05606522	3.80859543	474.27	0.0001
KENG	-0.00000004	0.00000000	1.59074677	198.09	0.0001

Bounds on condition number: 18.50233, 203.5853

All variables left in the model are significant at the 0.1000 level.

- **NOI doesn't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LFUEL

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	181.76745	36.35349	4526.984	0.0001
Error	1495	12.00545	0.00803		
C Total	1500	193.77290			

Root MSE	0.08961	R-square	0.9380
Dep Mean	-2.10032	Adj R-sq	0.9378
C.V.	-4.26662		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob >  T	Variance Inflation
INTERCEP	1	-2.511771	0.01183220	-212.283	0.0001	0.00000000
ISP	1	13.011088	0.27414608	47.460	0.0001	2.78296911
SVA	1	0.004010	0.00010212	39.271	0.0001	4.69450866
STP	1	-0.333873	0.01449733	-23.030	0.0001	11.90297528
NOI	1	1.220977	0.05606522	21.778	0.0001	18.50233302
KENG	1	-4.056629E-8	0.00000000	-14.074	0.0001	2.83428234

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	Var Prop ISP	Var Prop SVA	Var Prop STP	Var Prop NOI	Var Prop KENG
1	3.05092	1.00000	0.0107	0.0120	0.0074	0.0049	0.0224
2	1.27680	1.54580	0.1437	0.0394	0.0004	0.0036	0.0452
3	0.47058	2.54625	0.0095	0.1296	0.0598	0.0071	0.2280
4	0.17006	4.23563	0.8117	0.2840	0.0246	0.0002	0.7027
5	0.03164	9.81891	0.0245	0.5350	0.9078	0.9842	0.0017



## C.2.Results from SAS--the Best Statistical Model Selection for HC Estimate (with log-transformed data)

### C.2.1 Variables Selection

N = 1501 Regression Models for Dependent Variable: LHC

Number in Model	R-square	C(p)	Variables in Model
1	0.58117051	4486	SVA
1	0.40817810	6957	NOI
1	0.31569991	8278	POW
1	0.29184537	8618	DNOI
1	0.20459500	9865	STP
1	0.09613726	11414	ANOI
1	0.03589062	12274	QSP
1	0.01422133	12584	SPD
1	0.01334771	12596	KENG
1	0.00013534	12785	ISP
-----			
2	0.66997708	3219	SVA POW
2	0.66781578	3250	QSP SVA
2	0.62246120	3898	SVA KENG
2	0.62191052	3906	SPD SVA
2	0.59752458	4254	SVA ANOI
2	0.59350159	4311	SVA DNOI
2	0.58728928	4400	SVA NOI
2	0.58335797	4456	SVA STP
2	0.58302079	4461	ISP SVA
2	0.58007967	4503	NOI POW
-----			
3	0.84941867	657.91719	SPD QSP SVA
3	0.82927093	945.70935	ISP QSP SVA
3	0.80446911	1300	SPD ISP SVA
3	0.72106375	2491	QSP SVA KENG
3	0.71603694	2563	ISP SVA POW
3	0.71603013	2563	ISP SVA KENG
3	0.70616441	2704	QSP SVA ANOI
3	0.69336005	2887	QSP SVA NOI
3	0.69291142	2893	QSP SVA DNOI
3	0.69093575	2922	QSP SVA STP
-----			
4	0.86458271	443.31269	SPD QSP SVA ANOI
4	0.85912139	521.32276	SPD QSP SVA KENG
4	0.85420053	591.61266	SPD QSP SVA POW
4	0.85399247	594.58462	SPD QSP SVA DNOI
4	0.85351718	601.37368	SPD QSP SVA NOI
4	0.84997146	652.02108	SPD QSP SVA STP
4	0.84955947	657.90597	SPD ISP QSP SVA
4	0.84874990	669.46995	ISP QSP SVA KENG
4	0.84035771	789.34483	ISP QSP SVA ANOI
4	0.83286804	896.32792	ISP QSP SVA POW
-----			
5	0.88241518	190.59213	SPD QSP SVA ANOI KENG
5	0.86945471	375.72060	ISP QSP SVA ANOI KENG
5	0.86818745	393.82223	SPD QSP SVA KENG POW
5	0.86499869	439.37075	SPD QSP SVA ANOI POW
5	0.86488594	440.98141	SPD QSP SVA STP ANOI
5	0.86480937	442.07511	SPD QSP SVA ANOI DNOI
5	0.86479583	442.26846	SPD QSP SVA DNOI KENG
5	0.86473663	443.11407	SPD ISP QSP SVA ANOI
5	0.86465842	444.23127	SPD QSP SVA NOI ANOI
5	0.86175965	485.63754	SPD QSP SVA STP NOI
-----			
6	0.88675547	130.59509	SPD QSP SVA STP ANOI KENG
6	0.88414318	167.90916	SPD QSP SVA NOI ANOI KENG
6	0.88411299	168.34049	SPD QSP SVA ANOI KENG POW
6	0.88355593	176.29755	ISP QSP SVA STP ANOI KENG
6	0.88334689	179.28343	SPD QSP SVA ANOI DNOI KENG
6	0.88246846	191.83105	SPD ISP QSP SVA ANOI KENG
6	0.87731049	265.50798	ISP QSP SVA NOI ANOI KENG
6	0.87195586	341.99393	ISP QSP SVA ANOI DNOI KENG
6	0.87176292	344.75001	SPD QSP SVA STP NOI KENG
6	0.87144902	349.23371	ISP QSP SVA ANOI KENG POW
-----			
7	0.88917737	98.00033	SPD QSP SVA STP ANOI KENG POW

7	0.88872162	104.51036	SPD ISP QSP SVA STP ANOI KENG
7	0.88862753	105.85436	SPD QSP SVA STP NOI ANOI KENG
7	0.88683658	131.43637	ISP QSP SVA STP ANOI KENG POW
7	0.88675607	132.58651	SPD QSP SVA STP ANOI DNOI KENG
7	0.88596152	143.93589	SPD QSP SVA NOI ANOI KENG POW
7	0.88574883	146.97391	SPD QSP SVA ANOI DNOI KENG POW
7	0.88547808	150.84139	ISP QSP SVA STP NOI ANOI KENG
7	0.88487111	159.51142	SPD ISP QSP SVA NOI ANOI KENG
7	0.88421080	168.94338	SPD QSP SVA NOI ANOI DNOI KENG
-----			
8	0.89193255	60.64516	SPD QSP SVA STP NOI ANOI KENG POW
8	0.89138827	68.41966	SPD ISP QSP SVA STP ANOI KENG POW
8	0.89081710	76.57837	SPD ISP QSP SVA STP NOI ANOI KENG
8	0.88984122	90.51782	ISP QSP SVA STP NOI ANOI KENG POW
8	0.88924955	98.96938	SPD QSP SVA STP ANOI DNOI KENG POW
8	0.88892210	103.64664	SPD QSP SVA STP NOI ANOI DNOI KENG
8	0.88872659	106.43940	SPD ISP QSP SVA STP ANOI DNOI KENG
8	0.88686947	132.96667	ISP QSP SVA STP ANOI DNOI KENG POW
8	0.88670086	135.37512	SPD ISP QSP SVA NOI ANOI KENG POW
8	0.88632559	140.73546	SPD QSP SVA NOI ANOI DNOI KENG POW
-----			
9	0.89448778	26.14594	SPD ISP QSP SVA STP NOI ANOI KENG POW
9	0.89311485	45.75708	SPD QSP SVA STP NOI ANOI DNOI KENG POW
9	0.89144302	69.63758	SPD ISP QSP SVA STP ANOI DNOI KENG POW
9	0.89109181	74.65433	SPD ISP QSP SVA STP NOI ANOI DNOI KENG
9	0.89088824	77.56224	ISP QSP SVA STP NOI ANOI DNOI KENG POW
9	0.88701784	132.84728	SPD ISP QSP SVA NOI ANOI DNOI KENG POW
9	0.88411605	174.29679	SPD ISP QSP SVA STP NOI DNOI KENG POW
9	0.87194018	348.21800	SPD ISP QSP SVA STP NOI ANOI DNOI POW
9	0.86384969	463.78317	SPD ISP SVA STP NOI ANOI DNOI KENG POW
9	0.85203764	632.50765	SPD ISP QSP STP NOI ANOI DNOI KENG POW
-----			
10	0.89568814	11.00000	SPD ISP QSP SVA STP NOI ANOI DNOI KENG POW

## C.2.2 Candidate Models



- **All variables included, SPD ISP QSP STP NOI KENG don't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LHC

Step 0 All Variables Entered R-square = 0.89568814 C(p) = 11.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	226.28441214	22.62844121	1279.41	0.0001
Error	1490	26.35308823	0.01768664		
Total	1500	252.63750037			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.10814362	0.09042069	9.61413070	543.58	0.0001
SPD	-0.01619299	0.00195562	1.21263532	68.56	0.0001
ISP	7.35643181	1.21337973	0.65010904	36.76	0.0001
QSP	0.00023346	0.00001095	8.04358459	454.78	0.0001
SVA	0.00458361	0.00018356	11.02775312	623.51	0.0001
STP	-0.26473486	0.02378855	2.19044180	123.85	0.0001
NOI	0.81330284	0.10444348	1.07247488	60.64	0.0001
ANOI	0.30059228	0.02338006	2.92354419	165.30	0.0001
DNOI	-0.15914161	0.03843289	0.30325408	17.15	0.0001
KENG	-0.00000020	0.00000001	5.99962537	339.22	0.0001
POW	0.00003034	0.00000374	1.16120425	65.65	0.0001

Bounds on condition number: 251.1976, 4840.192

All variables left in the model are significant at the 0.1000 level.

- **SPD ISP QSP STP NOI KENG don't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LHC

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	10	226.28441	22.62844	1279.409	0.0001
Error	1490	26.35309	0.01769		
C Total	1500	252.63750			

Root MSE	0.13299	R-square	0.8957
Dep Mean	-1.98469	Adj R-sq	0.8950
C.V.	-6.70086		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob >  T	Variance Inflation
INTERCEP	1	-2.108144	0.09042069	-23.315	0.0001	0.00000000
SPD	1	-0.016193	0.00195562	-8.280	0.0001	251.19760470
ISP	1	7.356432	1.21337973	6.063	0.0001	24.75310763
QSP	1	0.000233	0.00001095	21.326	0.0001	129.32397366
SVA	1	0.004584	0.00018356	24.970	0.0001	6.88689908
STP	1	-0.264735	0.02378855	-11.129	0.0001	14.55147897
NOI	1	0.813303	0.10444348	7.787	0.0001	29.15373053
ANOI	1	0.300592	0.02338006	12.857	0.0001	2.32621562
DNOI	1	-0.159142	0.03843289	-4.141	0.0001	4.67279956
KENG	1	-0.000000196	0.00000001	-18.418	0.0001	17.56344402
POW	1	0.000030343	0.00000374	8.103	0.0001	3.58990248

Collinearity Diagnostics(intercept adjusted)

Number	Condition Eigenvalue	Var Prop Index	Var Prop SPD	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop STP	Var Prop NOI
1	4.86342	1.00000	0.0001	0.0009	0.0002	0.0016	0.0018	0.0008
2	3.03315	1.26626	0.0001	0.0009	0.0002	0.0058	0.0013	0.0013
3	0.90217	2.32181	0.0000	0.0032	0.0000	0.0449	0.0001	0.0011
4	0.46495	3.23420	0.0001	0.0101	0.0011	0.0516	0.0556	0.0036
5	0.33431	3.81416	0.0004	0.0402	0.0000	0.0092	0.0048	0.0045
6	0.18821	5.08336	0.0000	0.0004	0.0002	0.0251	0.0244	0.0032
7	0.14654	5.76102	0.0005	0.0663	0.0077	0.2136	0.0352	0.0007
8	0.04300	10.63523	0.0059	0.0028	0.0434	0.1079	0.0165	0.0022
9	0.02173	14.96156	0.0006	0.0044	0.0005	0.5390	0.8270	0.9826
10	0.00253	43.87484	0.9922	0.8708	0.9466	0.0014	0.0332	0.0000

Number	Var Prop ANOI	Var Prop DNOI	Var Prop KENG	Var Prop POW
1	0.0052	0.0040	0.0019	0.0007
2	0.0064	0.0090	0.0006	0.0221
3	0.2372	0.0101	0.0043	0.0021
4	0.1535	0.0003	0.0039	0.0060
5	0.0625	0.0067	0.0001	0.4079
6	0.3846	0.8008	0.0001	0.0024
7	0.0142	0.0123	0.0228	0.4371
8	0.0629	0.0064	0.8468	0.0009
9	0.0725	0.1501	0.0021	0.1114
10	0.0009	0.0004	0.1174	0.0094

Model 1.

- LOG(HC)=f(SPD QSP SVA STP ANOI KENG), R\_adj=0.8863, SPD QSP KENG didn't pass multi analysis

Backward Elimination Procedure for Dependent Variable LHC  
 Step 0 All Variables Entered R-square = 0.88675547 C(p) = 7.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	224.02768416	37.33794736	1949.78	0.0001
Error	1494	28.60981621	0.01914981		
Total	1500	252.63750037			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-1.63613716	0.02001226	128.00042509	6684.16	0.0001
SPD	-0.02641853	0.00070153	27.15761638	1418.17	0.0001
QSP	0.00029616	0.00000543	56.99834013	2976.44	0.0001

SVA	0.00579382	0.00011411	49.37137064	2578.17	0.0001
STP	-0.07285561	0.00962802	1.09651911	57.26	0.0001
ANOI	0.36874680	0.01931318	6.98093220	364.54	0.0001
KENG	-0.00000017	0.00000001	5.52506316	288.52	0.0001

Bounds on condition number: 29.85503, 482.1515

All variables left in the model are significant at the 0.1000 level.

▪ **SPD QSP KENG don't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LHC

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	6	224.02768	37.33795	1949.782	0.0001
Error	1494	28.60982	0.01915		
C Total	1500	252.63750			

Root MSE	0.13838	R-square	0.8868
Dep Mean	-1.98469	Adj R-sq	0.8863
C.V.	-6.97253		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance	Prob >  T	Inflation
INTERCEP	1	-1.636137	0.02001226	-81.757	0.0001	0.00000000	
SPD	1	-0.026419	0.00070153	-37.659	0.0001	29.85503359	
QSP	1	0.000296	0.00000543	54.557	0.0001	29.37013451	
SVA	1	0.005794	0.00011411	50.776	0.0001	2.45782212	
STP	1	-0.072856	0.00962802	-7.567	0.0001	2.20153880	
ANOI	1	0.368747	0.01931318	19.093	0.0001	1.46604421	
KENG	1	-0.000000174	0.00000001	-16.986	0.0001	15.00800940	

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	Var Prop SPD	Var Prop QSP	Var Prop SVA	Var Prop STP	Var Prop ANOI	Var Prop KENG
1	3.39254	1.00000	0.0024	0.0024	0.0071	0.0177	0.0122	0.0052
2	1.37105	1.57302	0.0029	0.0030	0.1009	0.0752	0.0847	0.0011
3	0.79321	2.06809	0.0002	0.0000	0.1516	0.0005	0.5646	0.0035
4	0.37950	2.98990	0.0000	0.0009	0.2754	0.7509	0.1836	0.0005
5	0.04490	8.69280	0.0987	0.1020	0.4223	0.0996	0.1519	0.9895
6	0.01881	13.42996	0.8958	0.8916	0.0427	0.0560	0.0028	0.0002

**Model 2.**

- **LOG(HC)=f(SPD QSP SVA NOI ANOI KENG), R\_adj=0.8837, SPD QSP KENG didn't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LHC

Step 0 All Variables Entered R-square = 0.88414318 C(p) = 7.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	223.36772379	37.22795397	1900.20	0.0001
Error	1494	29.26977658	0.01959155		
Total	1500	252.63750037			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-1.66382284	0.01969835	139.77305352	7134.35	0.0001
SPD	-0.02578611	0.00070309	26.35243266	1345.09	0.0001
QSP	0.00029000	0.00000539	56.63476460	2890.77	0.0001
SVA	0.00596906	0.00013431	38.69442030	1975.06	0.0001
NOI	-0.19380566	0.04105627	0.43655875	22.28	0.0001
ANOI	0.36267723	0.02109956	5.78845508	295.46	0.0001
KENG	-0.00000017	0.00000001	4.92258197	251.26	0.0001

Bounds on condition number: 29.31182, 492.1319

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 All variables left in the model are significant at the 0.1000 level.

▪ **SPD QSP KENG don't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LHC

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	6	223.36772	37.22795	1900.205	0.0001
Error	1494	29.26978	0.01959		
C Total	1500	252.63750			

Root MSE	0.13997	R-square	0.8841
Dep Mean	-1.98469	Adj R-sq	0.8837
C.V.	-7.05249		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-1.663823	0.01969835	-84.465	0.0001	0.00000000
SPD	1	-0.025786	0.00070309	-36.675	0.0001	29.31182258
QSP	1	0.000290	0.00000539	53.766	0.0001	28.34084378
SVA	1	0.005969	0.00013431	44.442	0.0001	3.32857565
NOI	1	-0.193806	0.04105627	-4.720	0.0001	4.06693177
ANOI	1	0.362677	0.02109956	17.189	0.0001	1.71033774
KENG	1	-0.00000166	0.00000001	-15.851	0.0001	15.26346995

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	SPD	QSP	SVA	NOI	ANOI	KENG
1	3.36697	1.00000	0.0023	0.0024	0.0070	0.0096	0.0114	0.0052
2	1.59444	1.45317	0.0028	0.0029	0.0608	0.0443	0.0361	0.0011
3	0.80179	2.04923	0.0001	0.0000	0.0724	0.0015	0.5548	0.0032
4	0.17321	4.40898	0.0000	0.0018	0.6608	0.7795	0.2037	0.0003
5	0.04415	8.73268	0.0951	0.1189	0.1451	0.1433	0.1896	0.9894
6	0.01944	13.15886	0.8996	0.8740	0.0540	0.0218	0.0044	0.0009

**Model 3.**

▪ **LOG(HC)=f(ISP QSP SVA STP ANOI KENG), R\_adj=0.8831, QSP KENG don't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LHC

Step 0 All Variables Entered R-square = 0.88355593 C(p) = 7.00000000

DF	Sum of Squares	Mean Square	F	Prob>F	
Regression	6	223.21936142	37.20322690	1889.37	0.0001
Error	1494	29.41813895	0.01969086		
Total	1500	252.63750037			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.86476819	0.01843344	475.58781280	24152.7	0.0001
ISP	16.15153116	0.44153131	26.34929364	1338.15	0.0001
QSP	0.00015741	0.00000345	41.10176505	2087.35	0.0001
SVA	0.00600809	0.00011837	50.72878762	2576.26	0.0001
STP	-0.13663702	0.01015836	3.56249621	180.92	0.0001
ANOI	0.39211479	0.01949286	7.96782743	404.65	0.0001
KENG	-0.00000023	0.00000001	10.08089884	511.96	0.0001

Bounds on condition number: 14.0807, 209.6277  
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All variables left in the model are significant at the 0.1000 level.

▪ **QSP KENG don't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LHC

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	6	223.21936	37.20323	1889.366	0.0001
Error	1494	29.41814	0.01969		
C Total	1500	252.63750			

Root MSE	0.14032	R-square	0.8836
Dep Mean	-1.98469	Adj R-sq	0.8831
C.V.	-7.07034		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-2.864768	0.01843344	-155.411	0.0001	0.00000000
ISP	1	16.151531	0.44153131	36.581	0.0001	2.94401438
QSP	1	0.000157	0.00000345	45.688	0.0001	11.50515485
SVA	1	0.006008	0.00011837	50.757	0.0001	2.57225542
STP	1	-0.136637	0.01015836	-13.451	0.0001	2.38341100
ANOI	1	0.392115	0.01949286	20.116	0.0001	1.45241423
KENG	1	-0.00000228	0.00000001	-22.626	0.0001	14.08069903

Collinearity Diagnostics(intercept adjusted)

Number	Condition Eigenvalue	Var Prop Index	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop STP	Var Prop ANOI	Var Prop KENG
1	3.16234	1.00000	0.0207	0.0064	0.0077	0.0222	0.0173	0.0060
2	1.33034	1.54178	0.0392	0.0085	0.1207	0.0533	0.0578	0.0012
3	0.83829	1.94226	0.0179	0.0018	0.0998	0.0015	0.5141	0.0080
4	0.42802	2.71815	0.0942	0.0218	0.0580	0.4870	0.2819	0.0063
5	0.20161	3.96049	0.8269	0.0421	0.4142	0.3180	0.0013	0.0154
6	0.03940	8.95893	0.0010	0.9195	0.2995	0.1180	0.1276	0.9632

#### Model 4.

- LOG(HC)=f(SPD QSP SVA ANOI KENG),  $R_{adj}=0.8820$ , QSP SPD KENG don't pass multicollinearity test

Backward Elimination Procedure for Dependent Variable LHC

Step 0 All Variables Entered R-square = 0.88241518 C(p) = 6.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	222.93116504	44.58623301	2243.85	0.0001
Error	1495	29.70633533	0.01987046		
Total	1500	252.63750037			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-1.67590199	0.01966997	144.24398289	7259.22	0.0001
SPD	-0.02568464	0.00070774	26.16990573	1317.03	0.0001
QSP	0.00028429	0.00000529	57.30782980	2884.07	0.0001
SVA	0.00562839	0.00011408	48.36771517	2434.15	0.0001
ANOI	0.30972638	0.01799754	5.88488573	296.16	0.0001
KENG	-0.00000015	0.00000001	4.50514988	226.73	0.0001

Bounds on condition number: 29.28442, 365.6182

All variables left in the model are significant at the 0.1000 level.

- QSP SPD KENG don't pass multicollinearity test

Model: MODEL2

Dependent Variable: LHC

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	222.93117	44.58623	2243.845	0.0001

Error 1495 29.70634 0.01987  
 C Total 1500 252.63750

Root MSE 0.14096 R-square 0.8824  
 Dep Mean -1.98469 Adj R-sq 0.8820  
 C.V. -7.10251

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance	Prob >  T	Inflation
INTERCEP	1	-1.675902	0.01966997	-85.201	0.0001	0.00000000	
SPD	1	-0.025685	0.00070774	-36.291	0.0001	29.28442440	
QSP	1	0.000284	0.00000529	53.704	0.0001	26.91618190	
SVA	1	0.005628	0.00011408	49.337	0.0001	2.36759878	
ANOI	1	0.309726	0.01799754	17.209	0.0001	1.22693716	
KENG	1	-0.000000148	0.00000001	-15.057	0.0001	13.32850685	

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop	Var Prop SPD	Var Prop QSP	Var Prop SVA	Var Prop ANOI	Var Prop KENG
1	3.04053	1.00000	0.0034	0.0037	0.0055	0.0131	0.0076
2	1.09753	1.66443	0.0018	0.0018	0.2132	0.2479	0.0001
3	0.79242	1.95883	0.0002	0.0000	0.1805	0.6293	0.0041
4	0.04972	7.82004	0.0671	0.1390	0.5595	0.0765	0.9744
5	0.01980	12.39250	0.9274	0.8555	0.0413	0.0332	0.0139

Model 5.

- LOG(HC)=f(ISP QSP SVA ANOI KENG), R\_adj=0.8690, QSP KENG don't pass multicollinearity test

Backward Elimination Procedure for Dependent Variable LHC

Step 0 All Variables Entered R-square = 0.86945471 C(p) = 6.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	219.65686521	43.93137304	1991.39	0.0001
Error	1495	32.98063516	0.02206063		
Total	1500	252.63750037			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.83772349	0.01939474	472.26957694	21407.8	0.0001
ISP	14.33106768	0.44484774	22.89560589	1037.85	0.0001
QSP	0.00014208	0.00000344	37.60047939	1704.42	0.0001
SVA	0.00559078	0.00012091	47.16674826	2138.05	0.0001
ANOI	0.29521373	0.01917171	5.23081138	237.11	0.0001
KENG	-0.00000018	0.00000001	7.35099469	333.22	0.0001

Bounds on condition number: 12.61687, 145.899

All variables left in the model are significant at the 0.1000 level.

- QSP KENG don't pass multicollinearity test

Model: MODEL2

Dependent Variable: LHC

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	219.65687	43.93137	1991.393	0.0001
Error	1495	32.98064	0.02206		
C Total	1500	252.63750			

Root MSE 0.14853 R-square 0.8695  
 Dep Mean -1.98469 Adj R-sq 0.8690  
 C.V. -7.48371

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-2.837723	0.01939474	-146.314	0.0001	0.00000000
ISP	1	14.331068	0.44484774	32.216	0.0001	2.66738963
QSP	1	0.000142	0.00000344	41.285	0.0001	10.24597882
SVA	1	0.005591	0.00012091	46.239	0.0001	2.39554203
ANOI	1	0.295214	0.01917171	15.398	0.0001	1.25403024
KENG	1	-0.000000184	0.00000001	-18.254	0.0001	12.61686875

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop ANOI	Var Prop KENG
1	2.74431	1.00000	0.0343	0.0112	0.0059	0.0201	0.0094
2	1.12380	1.56269	0.0392	0.0035	0.2431	0.1330	0.0000
3	0.83541	1.81245	0.0158	0.0019	0.0781	0.6754	0.0081
4	0.25255	3.29640	0.8798	0.0868	0.1587	0.1004	0.0172
5	0.04392	7.90476	0.0309	0.8967	0.5141	0.0710	0.9653

**Model 6.**

- LOG(HC)=f(SPD QSP SVA ANOI),  $R_{adj}=0.8642$ , SPD QSP don't pass multicollinearity test

Backward Elimination Procedure for Dependent Variable LHC

Step 0 All Variables Entered R-square = 0.86458271 C(p) = 5.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	218.42601516	54.60650379	2387.83	0.0001
Error	1496	34.21148521	0.02286864		
Total	1500	252.63750037			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-1.65129553	0.02102887	141.01265013	6166.20	0.0001
SPD	-0.02957317	0.00070691	40.02240431	1750.10	0.0001
QSP	0.00026406	0.00000549	52.84607472	2310.85	0.0001
SVA	0.00688633	0.00008334	156.14133713	6827.75	0.0001
ANOI	0.24196017	0.01869423	3.83100499	167.52	0.0001

Bounds on condition number: 25.38542, 211.2656

All variables left in the model are significant at the 0.1000 level.

- SPD QSP don't pass multicollinearity test

Model: MODEL2

Dependent Variable: LHC

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	4	218.42602	54.60650	2387.833	0.0001
Error	1496	34.21149	0.02287		
C Total	1500	252.63750			

Root MSE 0.15122 R-square 0.8646  
 Dep Mean -1.98469 Adj R-sq 0.8642  
 C.V. -7.61953

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-1.651296	0.02102887	-78.525	0.0001	0.00000000
SPD	1	-0.029573	0.00070691	-41.834	0.0001	25.38542438
QSP	1	0.000264	0.00000549	48.071	0.0001	25.18289027
SVA	1	0.006886	0.00008334	82.630	0.0001	1.09787673
ANOI	1	0.241960	0.01869423	12.943	0.0001	1.15021495

Collinearity Diagnostics(intercept adjusted)

Condition Number	Var Prop Eigenvalue	Var Prop Index	Var Prop SPD	Var Prop QSP	Var Prop SVA	Var Prop ANOI
1	2.14477	1.00000	0.0078	0.0078	0.0183	0.0441
2	1.09610	1.39883	0.0025	0.0024	0.4676	0.2405
3	0.73916	1.70341	0.0003	0.0008	0.4851	0.6909
4	0.01997	10.36439	0.9895	0.9890	0.0290	0.0245

### C.3 Results from SAS--the Best Statistical Model Selection for CO Estimate (with log-transformed data)

#### C.3.1 Variables Selection

N = 1501 Regression Models for Dependent Variable: LCO

Number in Model	R-square	C(p)	Variables in Model
1	0.62592434	5978	POW
1	0.41373455	10218	QSP
1	0.37759982	10940	SPD
1	0.33378233	11816	SVA
1	0.23073175	13875	ISP
1	0.16246589	15240	NOI
1	0.13788854	15731	KENG
1	0.11938198	16100	DNOI
1	0.03643970	17758	STP
1	0.01857756	18115	ANOI
-----			
2	0.86272024	1248	QSP SVA
2	0.79631376	2575	SPD SVA
2	0.76885079	3124	QSP NOI
2	0.76123910	3276	SVA KENG
2	0.72743431	3952	SPD NOI
2	0.71802375	4140	SVA POW
2	0.69590770	4582	QSP KENG
2	0.67044756	5090	NOI POW
2	0.66219126	5255	QSP POW
2	0.65414153	5416	SPD POW
-----			
3	0.88775526	749.99588	SPD QSP SVA
3	0.88684996	768.08671	QSP SVA ANOI
3	0.88157633	873.47012	ISP QSP SVA
3	0.87854062	934.13285	QSP SVA POW
3	0.87805552	943.82662	QSP SVA NOI
3	0.87681209	968.67417	QSP SVA DNOI
3	0.87354039	1034	QSP SVA KENG
3	0.87261778	1052	QSP SVA STP
3	0.86084229	1288	SPD ISP SVA
3	0.83602280	1784	SPD SVA POW
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4	0.90468346	413.71826	QSP SVA ANOI KENG
4	0.90456320	416.12144	SPD QSP SVA ANOI
4	0.89928003	521.69559	SPD QSP SVA POW
4	0.89767713	553.72632	ISP QSP SVA ANOI
4	0.89585911	590.05600	SPD QSP SVA NOI
4	0.89525850	602.05809	QSP SVA KENG POW
4	0.89523068	602.61399	SPD QSP SVA DNOI
4	0.89283865	650.41411	ISP QSP SVA POW
4	0.89125478	682.06483	QSP SVA ANOI POW
4	0.89088597	689.43473	SPD QSP SVA KENG
-----			
5	0.91289378	251.65088	SPD QSP SVA ANOI KENG
5	0.91162185	277.06791	QSP SVA ANOI KENG POW
5	0.90933875	322.69123	ISP QSP SVA ANOI KENG
5	0.90808723	347.70057	SPD QSP SVA ANOI POW
5	0.90757847	357.86713	SPD ISP QSP SVA ANOI
5	0.90630082	383.39855	SPD QSP SVA KENG POW
5	0.90575988	394.20809	SPD QSP SVA NOI ANOI
5	0.90472494	414.88952	QSP SVA STP ANOI KENG
5	0.90471909	415.00632	SPD QSP SVA STP ANOI
5	0.90470858	415.21630	QSP SVA NOI ANOI KENG
-----			
6	0.91838781	143.86318	SPD QSP SVA ANOI KENG POW
6	0.91523022	206.96156	ISP QSP SVA ANOI KENG POW
6	0.91465378	218.48055	SPD ISP QSP SVA ANOI KENG

6	0.91326052	246.32218	SPD QSP SVA STP ANOI KENG
6	0.91293483	252.83046	SPD QSP SVA ANOI DNOI KENG
6	0.91289881	253.55037	SPD QSP SVA NOI ANOI KENG
6	0.91193174	272.87538	QSP SVA ANOI DNOI KENG POW
6	0.91192321	273.04591	QSP SVA STP ANOI KENG POW
6	0.91162557	278.99348	QSP SVA NOI ANOI KENG POW
6	0.91131647	285.17034	SPD ISP QSP SVA ANOI POW
-----			
7	0.92020830	109.48418	SPD ISP QSP SVA ANOI KENG POW
7	0.91917037	130.22517	SPD QSP SVA STP ANOI KENG POW
7	0.91891992	135.22994	SPD QSP SVA ANOI DNOI KENG POW
7	0.91838789	145.86165	SPD QSP SVA NOI ANOI KENG POW
7	0.91778993	157.81066	SPD QSP SVA STP NOI KENG POW
7	0.91659139	181.76125	ISP QSP SVA STP ANOI KENG POW
7	0.91591388	195.29989	ISP QSP SVA ANOI DNOI KENG POW
7	0.91543543	204.86081	SPD QSP SVA STP NOI ANOI KENG
7	0.91531331	207.30119	ISP QSP SVA NOI ANOI KENG POW
7	0.91512022	211.15976	SPD ISP QSP SVA NOI ANOI KENG
-----			
8	0.92285812	58.53252	SPD QSP SVA STP NOI ANOI KENG POW
8	0.92057503	104.15578	SPD ISP QSP SVA NOI ANOI KENG POW
8	0.92042268	107.20014	SPD ISP QSP SVA ANOI DNOI KENG POW
8	0.92027985	110.05431	SPD ISP QSP SVA STP ANOI KENG POW
8	0.91994457	116.75422	ISP QSP SVA STP NOI ANOI KENG POW
8	0.91930090	129.61681	SPD QSP SVA STP ANOI DNOI KENG POW
8	0.91917703	132.09221	SPD QSP SVA NOI ANOI DNOI KENG POW
8	0.91866559	142.31237	SPD ISP QSP SVA STP NOI KENG POW
8	0.91804220	154.76960	SPD QSP SVA STP NOI DNOI KENG POW
8	0.91672729	181.04545	SPD ISP QSP SVA STP NOI ANOI POW
-----			
9	0.92458437	26.03683	SPD QSP SVA STP NOI ANOI DNOI KENG POW
9	0.92372324	43.24484	SPD ISP QSP SVA STP NOI ANOI KENG POW
9	0.92149656	87.74079	SPD ISP QSP SVA NOI ANOI DNOI KENG POW
9	0.92149121	87.84761	ISP QSP SVA STP NOI ANOI DNOI KENG POW
9	0.92042884	109.07702	SPD ISP QSP SVA STP ANOI DNOI KENG POW
9	0.91892361	139.15627	SPD ISP QSP SVA STP NOI ANOI DNOI POW
9	0.91891406	139.34709	SPD ISP QSP SVA STP NOI DNOI KENG POW
9	0.91692306	179.13336	SPD ISP QSP SVA STP NOI ANOI DNOI KENG
9	0.90629599	391.49500	SPD ISP QSP STP NOI ANOI DNOI KENG POW
9	0.90068697	503.58058	SPD ISP SVA STP NOI ANOI DNOI KENG POW
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10	0.92543693	11.00000	SPD ISP QSP SVA STP NOI ANOI DNOI KENG POW

### C.3.2 Candidate Models

- 
- **All variables included, SPD ISP QSP STP NOI KENG don't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LCO

Step 0 All Variables Entered R-square = 0.92543693 C(p) = 11.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	309.76991774	30.97699177	1849.31	0.0001
Error	1490	24.95836823	0.01675058		
Total	1500	334.72828597			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.76589607	0.08799544	1.26896405	75.76	0.0001
SPD	-0.01689939	0.00190317	1.32074335	78.85	0.0001
ISP	-4.87397690	1.18083461	0.28537683	17.04	0.0001
QSP	0.00023693	0.00001065	8.28451296	494.58	0.0001
SVA	0.00349375	0.00017864	6.40701417	382.50	0.0001
STP	-0.20542823	0.02315049	1.31895411	78.74	0.0001
NOI	1.01681250	0.10164211	1.67634847	100.08	0.0001
ANOI	0.25976979	0.02275296	2.18338978	130.35	0.0001
DNOI	-0.21887338	0.03740205	0.57362102	34.24	0.0001
KENG	-0.00000012	0.00000001	2.18019341	130.16	0.0001
POW	0.00004754	0.00000364	2.84983292	170.13	0.0001

Bounds on condition number: 251.1976, 4840.192

All variables left in the model are significant at the 0.1000 level.

▪ **SPD ISP QSP STP NOI KENG don't pass Multicollinearity test**

Model: MODEL2

Dependent Variable: LCO

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	10	309.76992	30.97699	1849.308	0.0001
Error	1490	24.95837	0.01675		
C Total	1500	334.72829			

Root MSE	0.12942	R-square	0.9254
Dep Mean	0.73368	Adj R-sq	0.9249
C.V.	17.64043		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T  Inflation
INTERCEP	1	0.765896	0.08799544	8.704	0.0001 0.00000000
SPD	1	-0.016899	0.00190317	-8.880	0.0001 251.19760470
ISP	1	-4.873977	1.18083461	-4.128	0.0001 24.75310763
QSP	1	0.000237	0.00001065	22.239	0.0001 129.32397366
SVA	1	0.003494	0.00017864	19.557	0.0001 6.88689908
STP	1	-0.205428	0.02315049	-8.874	0.0001 14.55147897
NOI	1	1.016813	0.10164211	10.004	0.0001 29.15373053
ANOI	1	0.259770	0.02275296	11.417	0.0001 2.32621562
DNOI	1	-0.218873	0.03740205	-5.852	0.0001 4.67279956
KENG	1	-0.000000118	0.00000001	-11.409	0.0001 17.56344402
POW	1	0.000047536	0.00000364	13.044	0.0001 3.58990248

Collinearity Diagnostics(intercept adjusted)

Number	Condition Eigenvalue	Var Prop Index SPD	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop STP	Var Prop NOI
1	4.86342	1.00000	0.0001	0.0009	0.0002	0.0016	0.0018
2	3.03315	1.26626	0.0001	0.0009	0.0002	0.0058	0.0013
3	0.90217	2.32181	0.0000	0.0032	0.0000	0.0449	0.0001
4	0.46495	3.23420	0.0001	0.0101	0.0011	0.0516	0.0556
5	0.33431	3.81416	0.0004	0.0402	0.0000	0.0092	0.0048
6	0.18821	5.08336	0.0000	0.0004	0.0002	0.0251	0.0244
7	0.14654	5.76102	0.0005	0.0663	0.0077	0.2136	0.0352
8	0.04300	10.63523	0.0059	0.0028	0.0434	0.1079	0.0165
9	0.02173	14.96156	0.0006	0.0044	0.0005	0.5390	0.8270
10	0.00253	43.87484	0.9922	0.8708	0.9466	0.0014	0.0332

Number	Var Prop ANOI	Var Prop DNOI	Var Prop KENG	Var Prop POW
1	0.0052	0.0040	0.0019	0.0007
2	0.0064	0.0090	0.0006	0.0221
3	0.2372	0.0101	0.0043	0.0021
4	0.1535	0.0003	0.0039	0.0060
5	0.0625	0.0067	0.0001	0.4079
6	0.3846	0.8008	0.0001	0.0024
7	0.0142	0.0123	0.0228	0.4371
8	0.0629	0.0064	0.8468	0.0009
9	0.0725	0.1501	0.0021	0.1114
10	0.0009	0.0004	0.1174	0.0094

**Model 1.**

▪ **LOG(CO)=f(SPD QSP SVA ANOI KENG POW), R\_adj=0.9181, SPD QSP KENG don't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LCO

Step 0 All Variables Entered R-square = 0.91838781 C(p) = 7.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	307.41037743	51.23506291	2802.01	0.0001
Error	1494	27.31790854	0.01828508		
Total	1500	334.72828597			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.32285741	0.01890997	5.33011459	291.50	0.0001
SPD	-0.00759854	0.00068276	2.26475797	123.86	0.0001
QSP	0.00019059	0.00000526	24.03083691	1314.23	0.0001
SVA	0.00474374	0.00012696	25.52642355	1396.02	0.0001
ANOI	0.27683690	0.01861089	4.04585823	221.27	0.0001
KENG	-0.00000013	0.00000001	3.44789635	188.56	0.0001
POW	0.00003584	0.00000357	1.83900798	100.57	0.0001

Bounds on condition number: 29.61629, 479.3089

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All variables left in the model are significant at the 0.1000 level.

▪ **SPD QSP KENG don't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LCO

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	6	307.41038	51.23506	2802.015	0.0001
Error	1494	27.31791	0.01829		
C Total	1500	334.72829			

Root MSE	0.13522	R-square	0.9184
Dep Mean	0.73368	Adj R-sq	0.9181
C.V.	18.43073		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	0.322857	0.01890997	17.073	0.0001	0.00000000
SPD	1	-0.007599	0.00068276	-11.129	0.0001	29.61628951
QSP	1	0.000191	0.00000526	36.252	0.0001	28.84912567
SVA	1	0.004744	0.00012696	37.363	0.0001	3.18674551
ANOI	1	0.276837	0.01861089	14.875	0.0001	1.42574301
KENG	1	-0.000000131	0.00000001	-13.732	0.0001	13.64471027
POW	1	0.000035839	0.00000357	10.029	0.0001	3.16219617

Collinearity Diagnostics(intercept adjusted)

Condition Number	Var Eigenvalue	Var Prop Index	Var Prop SPD	Var Prop QSP	Var Prop SVA	Var Prop ANOI	Var Prop KENG	Var Prop POW
1	3.35765	1.00000	0.0029	0.0030	0.0009	0.0043	0.0058	0.0120
2	1.57163	1.46165	0.0000	0.0000	0.0866	0.1152	0.0010	0.0576
3	0.79283	2.05792	0.0002	0.0000	0.1225	0.5675	0.0041	0.0001
4	0.20937	4.00460	0.0170	0.0090	0.2552	0.2540	0.0038	0.8802
5	0.04956	8.23121	0.0593	0.1307	0.4527	0.0519	0.9617	0.0039
6	0.01896	13.30654	0.9206	0.8572	0.0820	0.0072	0.0235	0.0462

**Model 2.**

▪ **LOG(CO)=f(ISP QSP SVA ANOI KENG POW), R\_adj=0.9149, KENG doesn't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LCO

Step 0 All Variables Entered R-square = 0.91523022 C(p) = 7.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	306.35344281	51.05890714	2688.37	0.0001
Error	1494	28.37484315	0.01899253		
Total	1500	334.72828597			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.01501929	0.01858419	0.01240492	0.65	0.4191
ISP	3.30873425	0.41490781	1.20782336	63.59	0.0001
QSP	0.00014758	0.00000334	37.08363853	1952.54	0.0001
SVA	0.00461499	0.00012995	23.95349824	1261.21	0.0001

ANOI	0.28144573	0.01912531	4.11296593	216.56	0.0001
KENG	-0.00000015	0.00000001	4.66575489	245.66	0.0001
POW	0.00003710	0.00000364	1.97204060	103.83	0.0001

Bounds on condition number: 12.89326, 207.7292

All variables left in the model are significant at the 0.1000 level.

▪ **KENG doesn't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LCO

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	6	306.35344	51.05891	2688.368	0.0001
Error	1494	28.37484	0.01899		
C Total	1500	334.72829			

Root MSE	0.13781	R-square	0.9152
Dep Mean	0.73368	Adj R-sq	0.9149
C.V.	18.78389		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance	Prob >  T	Inflation
INTERCEP	1	0.015019	0.01858419	0.808	0.4191	0.00000000	
ISP	1	3.308734	0.41490781	7.975	0.0001	2.69526739	
QSP	1	0.000148	0.00000334	44.188	0.0001	11.20983142	
SVA	1	0.004615	0.00012995	35.513	0.0001	3.21416983	
ANOI	1	0.281446	0.01912531	14.716	0.0001	1.44956669	
KENG	1	-0.000000148	0.00000001	-15.674	0.0001	12.89325594	
POW	1	0.000037096	0.00000364	10.190	0.0001	3.15944101	

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop ANOI	Var Prop KENG	Var Prop POW
1	3.04122	1.00000	0.0288	0.0090	0.0007	0.0063	0.0072	0.0145
2	1.57390	1.39007	0.0004	0.0000	0.0878	0.1113	0.0012	0.0554
3	0.84885	1.89282	0.0356	0.0005	0.1074	0.4376	0.0068	0.0028
4	0.34531	2.96770	0.5959	0.0055	0.0013	0.3290	0.0004	0.2351
5	0.14681	4.55139	0.3095	0.1579	0.4286	0.0520	0.0440	0.6921
6	0.04391	8.32192	0.0298	0.8270	0.3743	0.0638	0.9404	0.0002

**Model 3.**

▪ **LOG(CO)=f(SPD QSP SVA ANOI KENG), R\_adj=0.9126, SPD QSP KENG don't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LCO

Step 0 All Variables Entered R-square = 0.91289378 C(p) = 6.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	305.57136945	61.11427389	3133.59	0.0001
Error	1495	29.15691651	0.01950295		
Total	1500	334.72828597			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.31037560	0.01948722	4.94738402	253.67	0.0001
SPD	-0.00832336	0.00070117	2.74822427	140.91	0.0001
QSP	0.00020424	0.00000524	29.57730051	1516.55	0.0001
SVA	0.00538928	0.00011302	44.34548352	2273.78	0.0001
ANOI	0.34653234	0.01783033	7.36663570	377.72	0.0001
KENG	-0.00000012	0.00000001	2.78847894	142.98	0.0001

Bounds on condition number: 29.28442, 365.6182

All variables left in the model are significant at the 0.1000 level.

▪ **SPD QSP KENG don't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LCO

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	305.57137	61.11427	3133.591	0.0001
Error	1495	29.15692	0.01950		
C Total	1500	334.72829			

Root MSE	0.13965	R-square	0.9129
Dep Mean	0.73368	Adj R-sq	0.9126
C.V.	19.03463		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	0.310376	0.01948722	15.927	0.0001	0.00000000
SPD	1	-0.008323	0.00070117	-11.871	0.0001	29.28442440
QSP	1	0.000204	0.00000524	38.943	0.0001	26.91618190
SVA	1	0.005389	0.00011302	47.684	0.0001	2.36759878
ANOI	1	0.346532	0.01783033	19.435	0.0001	1.22693716
KENG	1	-0.000000116	0.00000001	-11.957	0.0001	13.32850685

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop	Var Prop SPD	Var Prop QSP	Var Prop SVA	Var Prop ANOI	Var Prop KENG
1	3.04053	1.00000	0.0034	0.0037	0.0055	0.0131	0.0076
2	1.09753	1.66443	0.0018	0.0018	0.2132	0.2479	0.0001
3	0.79242	1.95883	0.0002	0.0000	0.1805	0.6293	0.0041
4	0.04972	7.82004	0.0671	0.1390	0.5595	0.0765	0.9744
5	0.01980	12.39250	0.9274	0.8555	0.0413	0.0332	0.0139

**Model 4.**

▪ **LOG(CO)=f(QSP SVA ANOI KENG POW), R<sub>adj</sub>=0.9113, KENG doesn't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LCO

Step 0 All Variables Entered R-square = 0.91162185 C(p) = 6.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	305.14561946	61.02912389	3084.19	0.0001
Error	1495	29.58266651	0.01978774		
Total	1500	334.72828597			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.14124660	0.00993969	3.99582482	201.93	0.0001
QSP	0.00014466	0.00000339	36.06425678	1822.56	0.0001
SVA	0.00422246	0.00012276	23.41085386	1183.10	0.0001
ANOI	0.31622860	0.01900714	5.47727617	276.80	0.0001
KENG	-0.00000017	0.00000001	6.81743562	344.53	0.0001
POW	0.00004005	0.00000370	2.32247427	117.37	0.0001

Bounds on condition number: 11.72876, 150.2893

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All variables left in the model are significant at the 0.1000 level.

▪ **KENG doesn't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LCO

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	305.14562	61.02912	3084.189	0.0001

Error 1495 29.58267 0.01979  
 C Total 1500 334.72829

Root MSE 0.14067 R-square 0.9116  
 Dep Mean 0.73368 Adj R-sq 0.9113  
 C.V. 19.17310

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	0.141247	0.00993969	14.210	0.0001	0.00000000
QSP	1	0.000145	0.00000339	42.691	0.0001	11.07513532
SVA	1	0.004222	0.00012276	34.396	0.0001	2.75302541
ANOI	1	0.316229	0.01900714	16.637	0.0001	1.37417366
KENG	1	-0.000000171	0.00000001	-18.561	0.0001	11.72876248
POW	1	0.000040049	0.00000370	10.834	0.0001	3.12676220

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	Var Prop QSP	Var Prop SVA	Var Prop ANOI	Var Prop KENG	Var Prop POW
1	2.41534	1.00000	0.0147	0.0034	0.0089	0.0134	0.0234
2	1.57028	1.24023	0.0001	0.0984	0.1175	0.0008	0.0619
3	0.78816	1.75058	0.0003	0.1392	0.6106	0.0034	0.0010
4	0.18122	3.65081	0.0744	0.4160	0.2110	0.0349	0.9113
5	0.04500	7.32590	0.9105	0.3431	0.0520	0.9475	0.0024

Model 5.

- LOG(CO)=f(ISP QSP SVA ANOI KENG), R\_adj=0.9090, KENG doesn't pass multicollinearity test

Backward Elimination Procedure for Dependent Variable LCO

Step 0 All Variables Entered R-square = 0.90933875 C(p) = 6.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	304.38140221	60.87628044	2998.99	0.0001
Error	1495	30.34688375	0.02029892		
Total	1500	334.72828597			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.03226234	0.01860422	0.06104380	3.01	0.0831
ISP	3.73871210	0.42671600	1.55825703	76.77	0.0001
QSP	0.00015756	0.00000330	46.24460080	2278.18	0.0001
SVA	0.00528327	0.00011598	42.12080734	2075.03	0.0001
ANOI	0.35302213	0.01839029	7.47996924	368.49	0.0001
KENG	-0.00000013	0.00000001	3.90347351	192.30	0.0001

Bounds on condition number: 12.61687, 145.899

All variables left in the model are significant at the 0.1000 level.

- KENG don't pass multicollinearity test

Model: MODEL2

Dependent Variable: LCO

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	304.38140	60.87628	2998.991	0.0001
Error	1495	30.34688	0.02030		
C Total	1500	334.72829			

Root MSE 0.14247 R-square 0.9093  
 Dep Mean 0.73368 Adj R-sq 0.9090  
 C.V. 19.41917

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
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INTERCEP	1	-0.032262	0.01860422	-1.734	0.0831	0.00000000
ISP	1	3.738712	0.42671600	8.762	0.0001	2.66738963
QSP	1	0.000158	0.00000330	47.730	0.0001	10.24597882
SVA	1	0.005283	0.00011598	45.552	0.0001	2.39554203
ANOI	1	0.353022	0.01839029	19.196	0.0001	1.25403024
KENG	1	-0.000000134	0.00000001	-13.867	0.0001	12.61686875

Collinearity Diagnostics(intercept adjusted)

Number	Condition Eigenvalue	Var Prop Index	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop ANOI	Var Prop KENG
1	2.74431	1.00000	0.0343	0.0112	0.0059	0.0201	0.0094
2	1.12380	1.56269	0.0392	0.0035	0.2431	0.1330	0.0000
3	0.83541	1.81245	0.0158	0.0019	0.0781	0.6754	0.0081
4	0.25255	3.29640	0.8798	0.0868	0.1587	0.1004	0.0172
5	0.04392	7.90476	0.0309	0.8967	0.5141	0.0710	0.9653

**Model 6.**

- LOG(CO)=f(QSP SVA ANOI KENG), R\_adj=0.9044, KENG doesn't pass multicollinearity test

Backward Elimination Procedure for Dependent Variable LCO

Step 0 All Variables Entered R-square = 0.90468346 C(p) = 5.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	302.82314519	75.70578630	3549.77	0.0001
Error	1496	31.90514078	0.02132697		
Total	1500	334.72828597			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.10756244	0.00980120	2.56857309	120.44	0.0001
QSP	0.00015514	0.00000337	45.14895774	2116.99	0.0001
SVA	0.00489582	0.00010990	42.32183207	1984.43	0.0001
ANOI	0.39924042	0.01805810	10.42446836	488.79	0.0001
KENG	-0.00000016	0.00000001	5.96937909	279.90	0.0001

Bounds on condition number: 11.55392, 99.70371

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All variables left in the model are significant at the 0.1000 level.

- KENG don't pass multicollinearity test

Model: MODEL2

Dependent Variable: LCO

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	4	302.82315	75.70579	3549.768	0.0001
Error	1496	31.90514	0.02133		
C Total	1500	334.72829			

Root MSE	0.14604	R-square	0.9047
Dep Mean	0.73368	Adj R-sq	0.9044
C.V.	19.90484		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	0.107562	0.00980120	10.974	0.0001	0.00000000
QSP	1	0.000155	0.00000337	46.011	0.0001	10.17385673
SVA	1	0.004896	0.00010990	44.547	0.0001	2.04730244
ANOI	1	0.399240	0.01805810	22.109	0.0001	1.15085091
KENG	1	-0.000000159	0.00000001	-16.730	0.0001	11.55391680

Collinearity Diagnostics(intercept adjusted)

Number	Condition Eigenvalue	Var Prop Index	Var Prop QSP	Var Prop SVA	Var Prop ANOI	Var Prop KENG
--------	----------------------	----------------	--------------	--------------	---------------	---------------

1	2.18191	1.00000	0.0163	0.0274	0.0404	0.0164
2	0.99139	1.48353	0.0175	0.1910	0.3279	0.0054
3	0.78161	1.67080	0.0024	0.2771	0.5802	0.0017
4	0.04509	6.95656	0.9638	0.5045	0.0516	0.9765

**Model 7.**

- LOG(CO)=f(SPD QSP SVA ANOI), R\_adj=0.9043, KENG doesn't pass multicollinearity test

Backward Elimination Procedure for Dependent Variable LCO

Step 0 All Variables Entered R-square = 0.90456320 C(p) = 5.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	302.78289051	75.69572263	3544.82	0.0001
Error	1496	31.94539546	0.02135387		
Total	1500	334.72828597			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.32973440	0.02032049	5.62259728	263.31	0.0001
SPD	-0.01138260	0.00068310	5.92912441	277.66	0.0001
QSP	0.00018832	0.00000531	26.87857425	1258.72	0.0001
SVA	0.00637895	0.00008053	133.98022375	6274.28	0.0001
ANOI	0.29321822	0.01806450	5.62609248	263.47	0.0001

Bounds on condition number: 25.38542, 211.2656

-----  
 All variables left in the model are significant at the 0.1000 level.

- KENG don't pass multicollinearity test

Model: MODEL2

Dependent Variable: LCO

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	4	302.78289	75.69572	3544.824	0.0001
Error	1496	31.94540	0.02135		
C Total	1500	334.72829			

Root MSE	0.14613	R-square	0.9046
Dep Mean	0.73368	Adj R-sq	0.9043
C.V.	19.91739		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob >  T	Variance Inflation
INTERCEP	1	0.329734	0.02032049	16.227	0.0001	0.00000000
SPD	1	-0.011383	0.00068310	-16.663	0.0001	25.38542438
QSP	1	0.000188	0.00000531	35.478	0.0001	25.18289027
SVA	1	0.006379	0.00008053	79.210	0.0001	1.09787673
ANOI	1	0.293218	0.01806450	16.232	0.0001	1.15021495

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	Var Prop SPD	Var Prop QSP	Var Prop SVA	Var Prop ANOI
1	2.14477	1.00000	0.0078	0.0078	0.0183	0.0441
2	1.09610	1.39883	0.0025	0.0024	0.4676	0.2405
3	0.73916	1.70341	0.0003	0.0008	0.4851	0.6909
4	0.01997	10.36439	0.9895	0.9890	0.0290	0.0245

## C.4 Results from SAS--the Best Statistical Model Selection for CO Estimate (with log-transformed data)

### C.4.1 Variables Selection

N = 1501 Regression Models for Dependent Variable: LNO<sub>x</sub>

Number in Model	R-square	C(p)	Variables in Model
1	0.71852167	11669	SVA
1	0.46217405	23660	NOI
1	0.35017068	28899	POW
1	0.25952518	33139	DNOI
1	0.19827764	36003	STP
1	0.13337105	39039	ISP
1	0.11506715	39896	SPD
1	0.10390729	40418	QSP
1	0.01945464	44368	ANOI
1	0.00006179	45275	KENG
-----			
2	0.91213245	2615	QSP SVA
2	0.90534872	2932	SPD SVA
2	0.84618108	5700	SVA KENG
2	0.82783579	6558	ISP SVA
2	0.80599876	7579	SVA POW
2	0.75757570	9844	SPD NOI
2	0.75044589	10178	ISP NOI
2	0.73495452	10902	QSP NOI
2	0.72334969	11445	SVA ANOI
2	0.72002906	11601	SVA NOI
-----			
3	0.94470053	1094	QSP SVA KENG
3	0.93711378	1448	QSP SVA NOI
3	0.93621860	1490	SPD SVA NOI
3	0.93175971	1699	SPD SVA KENG
3	0.93089161	1740	SPD SVA STP
3	0.93054479	1756	QSP SVA STP
3	0.91841503	2323	QSP SVA DNOI
3	0.91462995	2500	SPD SVA DNOI
3	0.91379784	2539	QSP SVA POW
3	0.91279948	2586	QSP SVA ANOI
-----			
4	0.95826771	461.02317	QSP SVA NOI KENG
4	0.95586338	573.48522	SPD SVA NOI KENG
4	0.95245170	733.06613	SPD ISP SVA KENG
4	0.95197619	755.30804	QSP SVA STP KENG
4	0.95098912	801.47817	QSP SVA DNOI KENG
4	0.95067906	815.98098	SPD SVA STP KENG
4	0.94940982	875.34961	SPD QSP SVA KENG
4	0.94813548	934.95695	QSP SVA ANOI KENG
4	0.94656081	1009	ISP QSP SVA KENG
4	0.94546467	1060	SPD SVA DNOI KENG
-----			
5	0.96611284	96.06795	SPD QSP SVA NOI KENG
5	0.96508255	144.25964	ISP QSP SVA NOI KENG
5	0.96391617	198.81697	SPD ISP SVA NOI KENG
5	0.96127507	322.35401	QSP SVA STP NOI KENG
5	0.96018613	373.28910	SPD QSP SVA STP KENG
5	0.95971731	395.21827	QSP SVA NOI KENG POW
5	0.95931936	413.83200	SPD ISP SVA DNOI KENG
5	0.95894002	431.57568	SPD QSP SVA DNOI KENG
5	0.95885093	435.74270	ISP QSP SVA STP KENG
5	0.95851766	451.33178	SPD ISP SVA STP KENG
-----			
6	0.96749779	33.28718	SPD QSP SVA STP NOI KENG
6	0.96669451	70.86018	SPD QSP SVA NOI KENG POW
6	0.96623736	92.24336	SPD QSP SVA NOI ANOI KENG
6	0.96617298	95.25474	SPD QSP SVA NOI DNOI KENG
6	0.96611877	97.79051	ISP QSP SVA STP NOI KENG
6	0.96611563	97.93732	SPD ISP QSP SVA NOI KENG
6	0.96600419	103.15014	SPD ISP SVA STP NOI KENG
6	0.96580122	112.64371	ISP QSP SVA NOI KENG POW
6	0.96512092	144.46468	ISP QSP SVA NOI ANOI KENG
6	0.96509449	145.70125	ISP QSP SVA NOI DNOI KENG
-----			
7	0.96790227	16.36772	SPD QSP SVA STP NOI KENG POW
7	0.96766073	27.66567	SPD ISP QSP SVA STP NOI KENG
7	0.96750152	35.11259	SPD QSP SVA STP NOI ANOI KENG
7	0.96749823	35.26649	SPD QSP SVA STP NOI DNOI KENG
7	0.96707548	55.04066	SPD QSP SVA NOI ANOI KENG POW
7	0.96698612	59.22028	SPD QSP SVA NOI DNOI KENG POW
7	0.96669524	72.82618	SPD ISP QSP SVA NOI KENG POW
7	0.96667296	73.86861	ISP QSP SVA STP NOI KENG POW

7	0.96624675	93.80430	SPD QSP SVA NOI ANOI DNOI KENG
7	0.96624491	93.89044	SPD ISP QSP SVA NOI ANOI KENG
-----			
8	0.96803245	12.27841	SPD ISP QSP SVA STP NOI KENG POW
8	0.96799312	14.11804	SPD QSP SVA STP NOI ANOI KENG POW
8	0.96795940	15.69553	SPD QSP SVA STP NOI DNOI KENG POW
8	0.96766587	29.42504	SPD ISP QSP SVA STP NOI ANOI KENG
8	0.96766087	29.65895	SPD ISP QSP SVA STP NOI DNOI KENG
8	0.96750414	36.99010	SPD QSP SVA STP NOI ANOI DNOI KENG
8	0.96718278	52.02165	SPD QSP SVA NOI ANOI DNOI KENG POW
8	0.96708226	56.72348	SPD ISP QSP SVA NOI ANOI KENG POW
8	0.96699094	60.99499	SPD ISP QSP SVA NOI DNOI KENG POW
8	0.96671738	73.79045	ISP QSP SVA STP NOI ANOI KENG POW
-----			
9	0.96812385	10.00312	SPD ISP QSP SVA STP NOI ANOI KENG POW
9	0.96808888	11.63878	SPD ISP QSP SVA STP NOI DNOI KENG POW
9	0.96801512	15.08920	SPD QSP SVA STP NOI ANOI DNOI KENG POW
9	0.96766799	31.32577	SPD ISP QSP SVA STP NOI ANOI DNOI KENG
9	0.96719240	53.57168	SPD ISP QSP SVA NOI ANOI DNOI KENG POW
9	0.96672881	75.25612	ISP QSP SVA STP NOI ANOI DNOI KENG POW
9	0.96625195	97.56108	SPD ISP SVA STP NOI ANOI DNOI KENG POW
9	0.96423069	192.10529	SPD ISP QSP SVA STP ANOI DNOI KENG POW
9	0.94662774	1015	SPD ISP QSP SVA STP NOI ANOI DNOI POW
9	0.92486907	2033	SPD ISP QSP STP NOI ANOI DNOI KENG POW
-----			
10	0.96814530	11.00000	SPD ISP QSP SVA STP NOI ANOI DNOI KENG POW
-----			

## C.4.2 Candidate Models

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- **All variables included initially, SAS comes out with 9 variables except DNOI, SPD QSP don't pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LNO<sub>x</sub>

Step 0 All Variables Entered R-square = 0.96814530 C(p) = 11.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	416.83223650	41.68322365	4528.49	0.0001
Error	1490	13.71495280	0.00920467		
Total	1500	430.54718930			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.22173110	0.06523027	10.67806654	1160.07	0.0001
SPD	0.01148362	0.00141080	0.60986550	66.26	0.0001
ISP	2.16002258	0.87534275	0.05604906	6.09	0.0137
QSP	0.00007432	0.00000790	0.81517514	88.56	0.0001
SVA	0.00595798	0.00013242	18.63245937	2024.24	0.0001
STP	-0.11457208	0.01716127	0.41026740	44.57	0.0001
NOI	1.01956096	0.07534644	1.68542311	183.11	0.0001
ANOI	0.02739862	0.01686658	0.02428910	2.64	0.1045
DNOI	0.02776905	0.02772582	0.00923339	1.00	0.3167
KENG	-0.00000024	0.00000001	9.26432582	1006.48	0.0001
POW	-0.00001276	0.00000270	0.20550129	22.33	0.0001

Bounds on condition number: 251.1976, 4840.192

Step 1 Variable DNOI Removed R-square = 0.96812385 C(p) = 10.00312068

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	416.82300311	46.31366701	5031.53	0.0001
Error	1491	13.72418619	0.00920469		
Total	1500	430.54718930			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.21913290	0.06517874	10.66998178	1159.19	0.0001
SPD	0.01143658	0.00141002	0.60555039	65.79	0.0001

ISP	2.16455015	0.87533199	0.05628578	6.11	0.0135
QSP	0.00007429	0.00000790	0.81451183	88.49	0.0001
SVA	0.00593768	0.00013086	18.94966656	2058.70	0.0001
STP	-0.11773715	0.01686781	0.44845467	48.72	0.0001
NOI	1.05194830	0.06805453	2.19929585	238.93	0.0001
ANOI	0.03294286	0.01593233	0.03935258	4.28	0.0388
KENG	-0.00000024	0.00000001	9.26642661	1006.71	0.0001
POW	-0.00001202	0.00000260	0.19718159	21.42	0.0001

Bounds on condition number: 250.9192, 4251.95

-----  
All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable LNO<sub>x</sub>

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	DNOI	9	0.0000	0.9681	10.0031	1.0031	0.3167

▪ **SPD QSP don't pass multicollinearity test**

Model: MODEL2

Dependent Variable: LNO<sub>x</sub>

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	9	416.82300	46.31367	5031.532	0.0001
Error	1491	13.72419	0.00920		
C Total	1500	430.54719			

Root MSE	0.09594	R-square	0.9681
Dep Mean	-1.35398	Adj R-sq	0.9679
C.V.	-7.08588		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-2.219133	0.06517874	-34.047	0.0001	0.00000000
SPD	1	0.011437	0.00141002	8.111	0.0001	250.91919012
ISP	1	2.164550	0.87533199	2.473	0.0135	24.75244747
QSP	1	0.000074291	0.00000790	9.407	0.0001	129.32201187
SVA	1	0.005938	0.00013086	45.373	0.0001	6.72554787
STP	1	-0.117737	0.01686781	-6.980	0.0001	14.05805050
NOI	1	1.051948	0.06805453	15.457	0.0001	23.78383177
ANOI	1	0.032943	0.01593233	2.068	0.0388	2.07564670
KENG	1	-0.000000243	0.00000001	-31.729	0.0001	17.48584407
POW	1	-0.000012018	0.00000260	-4.628	0.0001	3.31632332

Collinearity Diagnostics(intercept adjusted)

Condition Number	Var Prop Eigenvalue	Var Prop Index	Var Prop SPD	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop STP	Var Prop NOI
1	4.52608	1.00000	0.0002	0.0013	0.0003	0.0011	0.0016	0.0008
2	2.59874	1.31971	0.0001	0.0006	0.0001	0.0119	0.0036	0.0035
3	0.86048	2.29346	0.0000	0.0037	0.0000	0.0383	0.0001	0.0005
4	0.46467	3.12096	0.0001	0.0098	0.0011	0.0536	0.0562	0.0043
5	0.33215	3.69142	0.0004	0.0398	0.0000	0.0075	0.0069	0.0066
6	0.14703	5.54833	0.0005	0.0669	0.0079	0.2359	0.0284	0.0012
7	0.04329	10.22473	0.0060	0.0025	0.0433	0.0869	0.0067	0.0069
8	0.02504	13.44506	0.0004	0.0041	0.0000	0.5636	0.8605	0.9762
9	0.00253	42.31818	0.9924	0.8714	0.9472	0.0012	0.0360	0.0001

Var Prop  
Number ANOI KENG POW

1	0.0044	0.0025	0.0026
2	0.0131	0.0001	0.0274
3	0.3365	0.0042	0.0072
4	0.1847	0.0039	0.0078
5	0.1100	0.0000	0.4216
6	0.0411	0.0218	0.4553
7	0.1077	0.8504	0.0014
8	0.2009	0.0001	0.0652
9	0.0015	0.1170	0.0114



SVA	0.00604104	0.00009976	36.87504837	3667.00	0.0001
NOI	0.72695068	0.02581456	7.97448106	793.01	0.0001
KENG	-0.00000022	0.00000001	10.62307712	1056.40	0.0001

Bounds on condition number: 12.28159, 159.7661

-----  
 All variables left in the model are significant at the 0.1000 level.

▪ **All pass multicollinearity test**

Model: MODEL2

Dependent Variable: LNO<sub>x</sub>

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	415.51358	83.10272	8264.054	0.0001
Error	1495	15.03361	0.01006		
C Total	1500	430.54719			

Root MSE	0.10028	R-square	0.9651
Dep Mean	-1.35398	Adj R-sq	0.9650
C.V.	-7.40628		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-1.672664	0.01310854	-127.601	0.0001	0.00000000
ISP	1	-5.160117	0.30208718	-17.082	0.0001	2.69850980
QSP	1	0.000130	0.00000233	55.757	0.0001	10.26312843
SVA	1	0.006041	0.00009976	60.556	0.0001	3.57755266
NOI	1	0.726951	0.02581456	28.160	0.0001	3.13244996
KENG	1	-0.000000218	0.00000001	-32.502	0.0001	12.28158882

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	Var Prop ISP	Var Prop QSP	Var Prop SVA	Var Prop NOI	Var Prop KENG
1	2.91799	1.00000	0.0241	0.0086	0.0085	0.0164	0.0087
2	1.52090	1.38513	0.0413	0.0067	0.0796	0.0591	0.0006
3	0.35867	2.85229	0.4514	0.0441	0.0385	0.1989	0.0290
4	0.15651	4.31786	0.4828	0.0268	0.7205	0.6938	0.0049
5	0.04592	7.97127	0.0005	0.9137	0.1529	0.0317	0.9568

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop Index	Var Prop SPD	Var Prop QSP	Var Prop SVA	Var Prop NOI	Var Prop KENG
1	3.20329	1.00000	0.0028	0.0029	0.0070	0.0125	0.0071
2	1.50502	1.45891	0.0026	0.0024	0.0881	0.0769	0.0004
3	0.21907	3.82391	0.0005	0.0005	0.6004	0.8460	0.0057
4	0.05311	7.76630	0.0894	0.0931	0.2515	0.0157	0.9867
5	0.01952	12.81124	0.9047	0.9011	0.0530	0.0490	0.0001

**Model 2.**

- **$\text{Log}(NO_x) = f(QSP, SVA, NOI, KENG)$ ,  $R_{adj} = 0.9582$ , all pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LNO<sub>x</sub>

Step 0 All Variables Entered R-square = 0.95826771 C(p) = 5.00000000

DF	Sum of Squares	Mean Square	F	Prob>F	
Regression	4	412.57946738	103.14486684	8587.88	0.0001
Error	1496	17.96772193	0.01201051		
Total	1500	430.54718930			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-1.86507714	0.00732696	778.22796998	64795.6	0.0001
QSP	0.00013772	0.00000249	36.78796248	3062.98	0.0001

SVA	0.00676264	0.00009877	56.30757914	4688.19	0.0001
NOI	0.59257820	0.02687022	5.84131145	486.35	0.0001
KENG	-0.00000020	0.00000001	9.10776453	758.32	0.0001

Bounds on condition number: 11.94678, 110.2581

-----  
All variables left in the model are significant at the 0.1000 level.

▪ **all pass multicollinearity test**

Model: MODEL2

Dependent Variable: LNO<sub>x</sub>

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	4	412.57947	103.14487	8587.885	0.0001
Error	1496	17.96772	0.01201		
C Total	1500	430.54719			

Root MSE	0.10959	R-square	0.9583
Dep Mean	-1.35398	Adj R-sq	0.9582
C.V.	-8.09412		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Variance Prob >  T	Inflation
INTERCEP	1	-1.865077	0.00732696	-254.550	0.0001	0.00000000
QSP	1	0.000138	0.00000249	55.344	0.0001	9.84014605
SVA	1	0.006763	0.00009877	68.470	0.0001	2.93603204
NOI	1	0.592578	0.02687022	22.053	0.0001	2.84156540
KENG	1	-0.000000199	0.00000001	-27.538	0.0001	11.94678270

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop	Var Prop	Var Prop	Var Prop	
		Index	QSP	SVA	NOI	KENG
1	2.50707	1.00000	0.0091	0.0273	0.0352	0.0108
2	1.22885	1.42835	0.0281	0.0892	0.0592	0.0089
3	0.21813	3.39017	0.0003	0.7075	0.8672	0.0033
4	0.04594	7.38735	0.9625	0.1759	0.0384	0.9769

**Model 3.**

▪ **Log(NO<sub>x</sub>)=f(SPD SVA NOI KENG), R<sub>adj</sub>=0.9557, all pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LNO<sub>x</sub>

Step 0 All Variables Entered R-square = 0.95586338 C(p) = 5.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	411.54429178	102.88607295	8099.69	0.0001
Error	1496	19.00289752	0.01270247		
Total	1500	430.54718930			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.31998767	0.00821423	1013.27054376	79769.6	0.0001
SPD	0.01740613	0.00032809	35.75278688	2814.63	0.0001
SVA	0.00604481	0.00010788	39.88289420	3139.77	0.0001
NOI	0.78080200	0.02731700	10.37776759	816.99	0.0001
KENG	-0.00000019	0.00000001	8.45800570	665.86	0.0001

Bounds on condition number: 11.74873, 110.7272

-----  
All variables left in the model are significant at the 0.1000 level.

▪ **all pass multicollinearity test**

Model: MODEL2

Dependent Variable: LNO<sub>x</sub>

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	4	411.54429	102.88607	8099.689	0.0001
Error	1496	19.00290	0.01270		
C Total	1500	430.54719			
Root MSE	0.11271	R-square	0.9559		
Dep Mean	-1.35398	Adj R-sq	0.9557		
C.V.	-8.32402				

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob >  T	Variance Inflation
INTERCEP	1	-2.319988	0.00821423	-282.435	0.0001	0.00000000
SPD	1	0.017406	0.00032809	53.053	0.0001	9.84433692
SVA	1	0.006045	0.00010788	56.034	0.0001	3.31188122
NOI	1	0.780802	0.02731700	28.583	0.0001	2.77686378
KENG	1	-0.000000190	0.00000001	-25.804	0.0001	11.74872766

Collinearity Diagnostics(intercept adjusted)

Condition Number	Eigenvalue	Var Prop	Var Prop	Var Prop	Var Prop	
		Index	SPD	SVA	NOI	KENG
1	2.49415	1.00000	0.0090	0.0241	0.0368	0.0111
2	1.24212	1.41703	0.0283	0.0800	0.0572	0.0087
3	0.21805	3.38210	0.0002	0.5892	0.9047	0.0103
4	0.04568	7.38891	0.9625	0.3067	0.0013	0.9699

**Model 4.**

- **$\text{Log}(\text{NO}_x) = f(\text{SPD SVA KENG})$ ,  $R_{adj} = 0.9446$ , all pass multicollinearity test**

Backward Elimination Procedure for Dependent Variable LNO<sub>x</sub>

Step 0 All Variables Entered R-square = 0.94470053 C(p) = 4.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	3	406.73815593	135.57938531	8524.59	0.0001
Error	1497	23.80903338	0.01590450		
Total	1500	430.54718930			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-1.79823558	0.00767626	872.79803953	54877.4	0.0001
QSP	0.00014614	0.00000283	42.41726999	2667.00	0.0001
SVA	0.00806382	0.00009115	124.48410701	7826.97	0.0001
KENG	-0.00000024	0.00000001	14.02209386	881.64	0.0001

Bounds on condition number: 11.19379, 68.07271

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All variables left in the model are significant at the 0.1000 level.

- **all pass multicollinearity test**

Model: MODEL2

Dependent Variable: LNO<sub>x</sub>

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	406.73816	135.57939	8524.594	0.0001
Error	1497	23.80903	0.01590		
C Total	1500	430.54719			
Root MSE	0.12611	R-square	0.9447		
Dep Mean	-1.35398	Adj R-sq	0.9446		
C.V.	-9.31428				

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob >  T	Variance Inflation
INTERCEP	1	-1.798236	0.00767626	-234.259	0.0001	0.00000000
QSP	1	0.000146	0.00000283	51.643	0.0001	9.60884598
SVA	1	0.008064	0.00009115	88.470	0.0001	1.88826753
KENG	1	-0.000000239	0.00000001	-29.692	0.0001	11.19378975

Collinearity Diagnostics(intercept adjusted)

Condition Number	Condition Eigenvalue	Var Prop Index	Var Prop QSP	Var Prop SVA	Var Prop KENG
1	2.04970	1.00000	0.0209	0.0301	0.0206
2	0.90290	1.50670	0.0173	0.4932	0.0009
3	0.04740	6.57567	0.9618	0.4767	0.9786

## APPENDIX D

Table D-1. MOEs Calculated Using the Proposed Statistical Models for EPA Database

Cycle Name	Cycle #	Ave spd km/h	Spd_var ((km/h <sup>2</sup> )/km)	No_stp stops/km	Noise (km/h/s)/km	Acc_noise (km/h/s)/km	Del_noise (km/h/s)/km	Kin eng ((km/h <sup>2</sup> )/km)	Power ((km/h <sup>2</sup> /s)/km)	Observed in the EPA database			Estimated from the Statistical Model		
										HC g/km	CO g/km	NO <sub>x</sub> g/km	HC g/km	CO g/km	NO <sub>x</sub> g/km
ARTA	1	39.83	89.5214	0.8317	0.2761	0.2286	0.3231	209271.4596	2525.3018	0.0354	2.1932	0.1654	0.1818	2.2275	0.3987
ARTC	2	30.94	106.3124	1.4076	0.4879	0.4169	0.5513	178143.3061	3141.3880	0.0394	2.4028	0.1976	0.2237	2.5492	0.4673
ARTE	3	18.64	143.7940	2.4776	1.3387	0.9718	1.6877	139441.9234	3996.4415	0.1095	5.6894	0.2580	0.3804	3.7917	0.9237
FNYC	4	11.46	85.9697	5.0797	1.5562	1.4434	1.6560	92820.0784	3584.3708	0.1152	5.0442	0.1811	0.3621	3.0584	0.6963
FWAC	5	96.02	6.2900	0.1313	0.1052	0.0672	0.1353	348917.0888	1360.2324	0.0664	4.7927	0.1220	0.2193	2.7991	0.5711
FWHS	6	101.46	3.9736	0.1532	0.2529	0.0453	0.3652	367674.0589	1217.7140	0.0183	2.3347	0.1137	0.2531	3.1570	0.7088
FWYD	7	85.29	26.4792	0.1932	0.1288	0.1112	0.1466	317758.3125	1699.7086	0.0626	6.0838	0.1058	0.1896	2.5201	0.5110
FWYE	8	48.98	106.2236	0.6428	0.3273	0.2634	0.3818	224671.2929	2266.9102	0.0213	1.9885	0.1397	0.2007	2.6239	0.5131
FWYF	9	30.20	91.6647	1.2269	0.6201	0.5787	0.6754	149160.1487	3342.3295	0.0858	3.3591	0.2015	0.2188	2.4132	0.4575
FWYG	10	21.30	80.2180	1.5286	1.0261	1.1099	0.9203	107875.6475	3267.2319	0.0694	2.6541	0.0574	0.2685	2.5859	0.5098
LA92	11	39.75	63.6605	0.7814	0.1631	0.1287	0.1979	234445.8906	2789.3087	0.0591	4.6282	0.1766	0.1519	1.8436	0.3112
LOCL	12	20.66	112.5432	2.4225	1.2164	0.7455	1.5970	133348.0644	3321.5639	0.1328	4.5326	0.1136	0.2891	2.9191	0.7039
RAMP	13	56.08	181.0744	0.5821	0.7236	0.5454	0.8948	249889.1412	3558.3924	0.0759	4.4012	0.2615	0.3425	4.8033	1.1871
AREA	14	31.18	59.5863	1.1336	0.2205	0.1806	0.2603	192501.7160	2916.2487	0.0410	2.8381	0.1987	0.1591	1.7882	0.2905
US06	15	76.87	122.4536	0.3739	0.1806	0.1589	0.2091	350187.0532	2281.8098	0.1806	14.2165	0.2105	0.2768	4.0012	0.8300

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