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16. Abstract

This report details the use of a modal emissions model to estimate the relative emissions of CO due to changes in vehicle operating characteristics on urban roadways. The Davis Institute for Transportation Studies Emissions Model (DITSEM) was selected to demonstrate the emissions characteristics of different freeway operating conditions. Instrumented vehicle data collected in Houston, Texas provides a set of operating parameters for which CO emissions are estimated. These estimates are calculated for different times of the day on the same facility to determine the relative emissions levels from a representative vehicle traveling on the freeway.

The research team examined 10 samples along three roadways (two freeways, and one arterial). Implausible results were found in data exhibiting high average speeds (>60 mph) where average emissions rates were higher than those on the same roadway under congested conditions. This led to several conclusions of which the most important was that the DITSEM model not be used with samples where the percent of the driving cycle greater than 60 mph^2/sec exceeds 9%. This limit represents the highest value from which the model was derived for this variable. In addition, it is noted that the speed instrumentation was not able to provide sufficient precision for meaningful analysis with the available data.

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MODAL EMISSIONS MODELING WITH REAL TRAFFIC DATA

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IMPLEMENTATION RECOMMENDATIONS

This report documents the use of an interim, modal emission model using real-world instrumented vehicle data. Several implementation recommendations were developed from the experience gained during this investigation. The implementation recommendations proposed are:

1. The model is best applied to arterials or congested freeway segments. The model is not recommended for use on facilities with average speeds approaching 60 mph.

2. Apply the model using commonly available spreadsheet software.

3. Supporting data, such as vehicle emissions data, must be acquired prior to using the model. The EPA vehicle testing database is a good source for this data.

4. Any instrumented vehicle data must be gathered using high precision instrumentation to mitigate rounding errors from integer vehicle speeds.

This report has not been converted to metric units because the software discussed in this report relies on input to and output from the U.S. Environmental Protection Agency's MOBILE emission factor model. As of the publication of this report, English inputs are required for MOBILE, and inclusion of metric equivalents could cause errors.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation. Additionally, this report is not intended for construction, bidding, or permit purposes. George B. Dresser, Ph.D., and Carol H. Walters, P.E. (TX 51154), were the Research Supervisors for the project.

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The assistance provided by Simon Washington, Ph.D., through this research study helped bring a clearer understanding of the DITSEM model and its behavior to the analysis of its results.

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SUMMARY

Transportation improvements often involve efforts to reduce congestion, and to smooth the flow of traffic. The emissions impacts of these efforts are determined by changes in vehicle operating characteristics on the improved facility. Current thinking on emissions suggests that smoothed traffic flows will produce fewer emissions than congested traffic flows. Still, emissions factor models are required to generate the needed emissions factors for the roadway link in question.

Traditional air quality models, such as MOBILE, are not suited to the task of predicting changes in vehicle operating parameters. Therefore, the traditional emissions factor modeling approach, known as the speed factor modeling approach, will soon be replaced with a method of relating emissions estimates to vehicle operating parameters, known as the modal emissions modeling approach.

This next generation of emissions models will be used on a widespread basis after 2004. Two major efforts are currently underway by the National Cooperative Highway Research Program and the Environmental Protection Agency. In the interim, it is possible to analyze different roadway facilities and conditions using simpler methods. Three interim methods are available: PIKE PASS, VEHSIME/VEMISS, and DITSEM.

The DITSEM (Davis Institute of Transportation Studies Emissions Model) model was chosen for this research study because it offered a simple, low-cost method of analysis. The model was amenable to spreadsheet programming and a vehicle fleet could be generated from the EPA's vehicle database. These reasons made the DITSEM model the superior of the three interim methods.

The DITSEM model is comprised of two regression equations developed from a database of over 4,400 vehicles. One equation characterizes the behavior of normal emitters, and the second equation that of high emitters. This model was previously tested and showed extremely reliable results.

Real-world instrumented vehicle data was acquired from work on modal activity along roadways in Houston, Texas. The data collected included time, distance, and speed (in integer form) for creating speed-time profiles for a number of roadways.

This study examined ten samples along three roadways (Southwest Freeway, Katy Freeway, and Richmond Avenue) during the peak and off-peak periods, and also by peak and off-peak traffic flow. Implausible results were observed from the data:

(1) for the freeway samples, the off-peak period, with mostly free-flow conditions, yielded higher average emissions rates than the same facility during peak periods where congestion is more likely; and

(2) as speeds approached higher values (>60 mph) the positive kinetic energy (PKE) statistic increased dramatically.

Only the Richmond Avenue samples returned plausible results from the model where emissions rates decrease as more uniform traffic flow was established.

The instrumented vehicle data were compared against a driving cycle statistic, DPWRSUM, which characterized the roughness of a driving cycle. In most cases, the instrumented vehicle data from Houston showed much higher values than values from standard driving cycles like the IM240 or the US06.

The implausible emissions results were investigated further with a microscopic analysis of a real-world driving cycle. The results of the microscopic analysis clearly show that as average speeds increase, the PKE>60 variable, defined as the percentage of the driving cycle with PKE values greater than 60 mph^2/sec, in the DITSEM model also increases. Also increasing were the average emissions rates. Thus, the DITSEM model is sensitive to the PKE>60 variable. Several causes for this sensitivity are discussed and solutions are presented. Some solutions are to add trip starts/ends to the cycle, to increase the precision of the instrumented data, and to smooth the available data.

The conclusions of this research are not surprising. First, the DITSEM model cannot be applied to the instrumented vehicle data from Houston with confidence. The model was calibrated with PKE>60 values below 9 percent and seven of the ten samples from Houston had PKE>60 values greater than 10 percent. Second, the instrumented data has very high PKE>60 values for free-flow conditions which misrepresent the true modal activity, and the instrumentation used lacked enough precision to be of use in this exercise. Finally, there is not an objective method of smoothing the data set.

CHAPTER I. INTRODUCTION

Many different pollutants are emitted from motor vehicles, but three particular pollutants have been designated criteria pollutants by the Environmental Protection Agency (EPA): hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx). These criteria pollutants can create health hazards in many urban areas. The 1990 Clean Air Act Amendments (CAAA) mandates compliance with air quality standards for these criteria pollutants. Metropolitan planning organizations (MPOs) must demonstrate, in some cases, that a transportation improvement will not contribute to higher levels of these pollutants in urban areas. Therefore, these MPOs need methods of predicting vehicle emissions impacts from different transportation improvement alternatives.

Transportation improvements often involve efforts to reduce congestion and smooth the flow of traffic. The emissions impacts of these efforts are determined by changes in vehicle operating characteristics on the improved facility. Unfortunately, traditional air quality models used to determine emissions inventories for urban areas, such as the MOBILE model, are not suited to the task of predicting changes in vehicle operating parameters. Therefore, the traditional emissions modeling approach, known as the speed factor modeling approach, will soon be replaced with a method of relating emissions estimates to vehicle operating parameters. This method is known as the modal emissions modeling approach. To understand modal emissions, one must be aware of how and why they are produced.

IDENTIFICATION AND EFFECTS OF VEHICLE-DRIVER PARAMETERS

Many factors contribute to the production of emissions from automobiles. These factors can be segregated into two categories: vehicle and driver-behavior parameters.

Vehicle Parameters

Washington (1), in his dissertation research, identified several vehicle characteristics that affect emissions generation by a vehicle: vehicle age, fuel delivery type, engine size, control equipment type, and emissions control equipment. Typically, emissions production increases as the age of a vehicle increases. This is because the vehicle begins to operate in non-stochastic conditions through insufficient maintenance of the vehicle. Engine size relates to the available horsepower of an engine. Emissions production increases as the size of the engine increases. Of equal importance is the presence and type of emissions control equipment.

Other vehicle characteristics, identified by Washington from combustion theory, include volume and number of engine cylinders, friction and efficiency losses, engine operating temperature, and engine load. These parameters can lead to increased emissions production as they increase also. For instance, engine load is increased as the vehicle traverses a positive grade; or auxiliary systems such as air conditioners are used.

In addition to the vehicle characteristics shown above, Horowitz (2) noted that valve overlap, surface-to-volume ratio, compression ratio, and spark timing also contribute to the production of emissions. Most of these factors lend themselves to mechanical origins; however, spark timing can be controlled through regular maintenance.

Driver Behavior Parameters

The driver also controls various components of the vehicle that contribute to the rate of emissions production. These characteristics are throttle position, manifold pressure, air-fuel ratio, and engine revolutions per minute (RPMs). Each of these parameters is affected by how a driver behaves in the traffic stream. If a sufficient number of vehicles are around a driver, interaction with those vehicles may increase the variability of the identified parameters. The driver behavior parameters are directly related to the driver's use of the accelerator on the vehicle. By pressing hard on the accelerator, the driver pushes the vehicle into a non-stochastic state where the throttle position, manifold pressure, and RPMs increase and the air-fuel ratio decreases.

IDENTIFICATION OF MODAL PARAMETERS

All vehicles operate within four modes: acceleration, cruise (steady-state), deceleration, and idle. Research has identified that spikes in emissions output occur as a result of the vehicle operating outside of cruise (steady state) conditions. Work in California has shown that a single hard acceleration event can "produce emissions equivalent to 50% to 64% of the total Federal Test Procedure (FTP) emissions for HC, and 236% to 262% of the total for CO" (3, 4).

Results like this have initiated new research to find the magnitude of accelerations in the traffic stream and to begin to quantify or classify the modal characteristics of roadways. Research from California suggests that mild or normal accelerations occur in the 2 to 4 mph/sec range. Aggressive accelerations occur in the 5 to 10 mph/sec range (4). Work from Texas identified the maximum acceleration range for freeways and arterials between 2 to 3 mph/sec, and the maximum deceleration range between 4 to 5 mph/sec (3). The research in Texas also identified the modal characteristics of three functional classes: freeways, and class I and II arterials. The results of this work are shown in Table 1. The reported percentages represent the total percent time spent in each vehicle operating mode for all samples taken on a particular functional class. The cumulative percent time spent in each operating mode for the three functional classes is represented in the first column, *'freeway and arterial streets.'* As would be expected, time spent in the cruise mode decreases and time in idle, acceleration, and deceleration modes increases as the functional class of the roadway decreases.

Fuel consumption and the production of emissions can increase significantly if the frequency and magnitude of acceleration and deceleration events increase from the cruise (steady-state) condition. Driving cycles along roadways can be described by a variety of driving statistics to characterize driver performance.

TABLE 1
Percent of Time Spent in Each Vehicle Operating Mode
By Roadway Functional Class

Vehicle Operating Mode	Roadway Functional Class			
	Freeways and Arterial Streets	Freeways	Class I Arterials	Class II Arterials
Idle	6.4	0.4	9.2	12.0
Cruise (steady state)	53.6	65.7	49.1	41.9
Acceleration	21.3	17.5	22.6	24.9
Deceleration	18.7	16.4	19.1	21.2

Adapted from (3)

DRIVER PERFORMANCE CHARACTERISTICS

Positive Kinetic Energy (PKE) Statistic

Positive kinetic energy is defined by the sum of positive differences in kinetic energy. It can be normalized by the distance driven to make it possible to compare PKE values for different driving cycles. The PKE statistic proposed by Watson and Milkins (5, 6) is shown below.

$$PKE = \frac{\sum (V_f^2 - V_i^2)}{X} \quad for\ V_f > V_i \qquad (1)$$

Where:

PKE = Positive kinetic energy (mph^2/mi)
V_i = Initial speed (mph)
V_f = Final speed (mph)
X = Distance (mi)

A surrogate PKE statistic can be calculated instantaneously as the product of the velocity and acceleration at time t. The equation is shown below. The instantaneous PKE values can then be summed to generate a PKE statistic for the driving cycle under examination. Washington (1) used this variation of the PKE statistic throughout his work on a modal emissions model.

$$PKE = \sum (V_t * a_t) \quad (2)$$

Where:

PKE	=	Positive kinetic energy (mph^2/sec)
V_t	=	Speed at time t (mph)
a_t	=	Acceleration at time t (mph/sec)

Jerk Based Statistic

"Jerk" is defined as the rate of changes in acceleration. Averages and sums of positive or absolute values can be used to characterize this statistic.

$$Jerk = \frac{d^3x}{dt^3} \quad (3)$$

DPWRSUM Statistic

The variable DPWRSUM can be applied as a measure of the validity of driver behavior in prescribed driving cycles. DPWRSUM is the sum of absolute changes in vehicle power, that can be calculated from vehicle speeds alone. The variable changes significantly when speed fluctuates during a driving cycle. The magnitude of DPWRSUM can indicate whether a cycle is "smooth" or "rough" relative to a specified standard value but cannot measure adherence to the specified cycle.

Webster and Shih (6) describe the effect of different magnitudes of the variable DPWRSUM on HC, CO, and NOx emissions. This shows that CO emissions are more sensitive to variations in DPWRSUM than either total HC or NOx. DPWRSUM is calculated as follows:

$$DPWRSUM = \sum_{t=0}^{N} \frac{1}{2} \Delta P_t = \sum_{t=0}^{N} \frac{1}{2} \mid V_t^2 - 2*V_{t-1}^2 + V_{t-2}^2 \mid \quad (4)$$

Where:

DPWRSUM	=	Change in absolute specific power over the duration of a driving cycle
P_t	=	Specific power at time t (mph^2/sec)
V_t	=	Speed at time t (mph)
N	=	Duration of cycle (sec)

These researchers noted that EPA appears to omit the factor of ½ in their calculations. Webster and Shih (6) inferred that this omission would ". . . not cause any essential difference in the behavior of the DPWRSUM statistic." To provide the reader with a sense of the magnitude of this statistic, the nominal value of DPWRSUM for the IM240 cycle is 6,370 mph^2/sec.

Specified Driving Cycle Statistics

RMS Speed Error

This statistic can be used to determine errors in the performance of a specified driving cycle. The RMS speed error would yield a zero value if the specified driving cycle were followed perfectly. If the variations from the driving cycle occur, either smooth or rough, then the value of the statistic will increase; however, the statistic does not distinguish between the type of error in the driving cycle.

$$rms = \sqrt{\frac{\Sigma(V_t - C_t)^2}{N}} \quad (5)$$

Where:

rms	=	Root mean square of the speed error
V_t	=	Actual speed at time t (mph)
C_t	=	Prescribed cycle speed at time t (mph)
N	=	Duration of cycle (sec)

Accumulated Speed Error

Accumulated speed error is calculated from the sum of absolute values of the first differences in speed errors (6). The value of this statistic increases as variations, either smooth or rough driving errors, from a specified driving cycle occur. Webster and Shih (6) were not aware of any recommended limits for cycle validity.

$$ASE = \Sigma \left| (V_t - C_t) - (V_{t-1} - C_{t-1}) \right| \quad (6)$$

Where:

ASE	=	Accumulated speed error (mph)
V_t	=	Actual speed at time t (mph)
C_t	=	Prescribed cycle speed at time t (mph)

SPEED CORRECTION FACTOR MODELS

The MOBILE emissions prediction model (and the corresponding California emissions model EMFAC) is, by design, inappropriate for the comparison of emissions from vehicles on different facilities (7). MOBILE is a macroscopic model that simplifies vehicle activity by using averages of emissions over cycles. The use of the MOBILE model for estimating emissions is sometimes referred to as the speed correction factor approach.

Speed correction factor models, like MOBILE or EMFAC, are commonly used to evaluate the effects of transportation improvements. Although these models represent the current "best" available emissions factor models, they were not created to perform such tasks.

Data used to create speed correction factor models consist of emissions data collected over the course of a driving cycle. The emissions data are collected from light duty automobile tailpipe emissions which accumulate in a bag over the course of the driving cycle.

There are numerous driving cycles used by the government to certify vehicles. In fact, the driving cycles were created for the sole purpose of vehicle certification. Each driving cycle has its own unique combination of starts, stops, cruise, acceleration, and deceleration events. Washington notes that current models are not modeling acceleration rates and the models do not have realistic acceleration rates in the current testing procedures and databases. Recent work on driving cycles has produced the most aggressive driving cycle yet, the US06 driving cycle; however, this driving cycle has not yet been integrated into emissions factor models.

Another problem with current models is that emissions rates at a given speed are "corrected" based on a defined emissions rate at a prescribed speed. The MOBILE model uses the FTP Bag 2 cycle as its "base" unit of emissions for vehicles at a given average speed. "The ratio of average test results on different cycles are used to predict and multiply the 'base' emissions rate to arrive at the predicted emissions rate at speeds other than the base speed" (1). For example,

$$ER_{45\ mph} = \frac{Avg.\ ER_{45\ mph}}{Avg.\ ER_{16\ mph}} * Base\ ER_{16\ mph} \qquad (7)$$

Where:

ER = emissions rate (g/mi)

Thus, the current models become a way to use averages and ratios to develop emissions rates, whereby modal characteristics become "washed out" and watered down.

MODAL EMISSIONS MODELS

Air quality impacts of major metropolitan transportation projects must be accurately estimated in many instances. As noted by Washington, current models are not able to provide necessary accuracy in emissions reductions from transportation control measures. He also notes that the current mobile source emissions models were not designed to predict emissions rates from micro-scale transportation system changes (1).

A new emissions modeling approach is needed to make these estimations and to solve some of the deficiencies inherent in the MOBILE model. Two such models are under development today: One is being developed for the EPA by researchers at Georgia Tech, and the other is being developed with National Cooperative Highway Research Program (NCHRP) funding at the University of California at Riverside. Significant supporting research is underway at the University of Michigan, California Department of Transportation (Caltrans), and the California Air Resources Board (CARB).

EPA Modal Model

Georgia Tech is in the process of developing a modal emissions model funded by the EPA. Their goal is to create a modal emissions model within a Geographic Information System (GIS) framework that estimates emissions as a function of vehicle operating profiles. The model will likely be a stochastic model with emissions factors for different vehicle operating modes. This development requires a great deal of vehicle testing data; Georgia Tech has seven instrumented vehicles for model development.

Some components of this GIS-based working emissions model were tested in Atlanta, Georgia, during the Summer of 1996. This working model is a research-level model, since a large amount of modal activity data remains to be quantified. It is expected that a full modal emissions modeling package will be available to MPOs in 2002.

NCHRP Modal Model

The University of California Riverside (UC-Riverside) was awarded a $1.5 million contract by NCHRP in 1995 to develop a modal emissions model. The goal of the three-year project (NCHRP 25-11), Development of a Comprehensive Model Emissions Model, is to develop a physical model based on second-by-second emissions and vehicle operations data. Researchers expect to complete the project in the fall of 1998 and are performing the work in three phases. The work of the three phases is described briefly.

> Phase 1: Phase 1 consists of data collection and literature from related studies; analyzing these data and other emissions models as a starting pont for the new model design; developing a dynamometer testing protocol for the vehicle testing phase; conducting preliminary testing on a sample of vehicles with the expected dynamometer emissions testing protocol; and using the sample vehicle data supplemented by existing develop an interim working model.
>
> Phase 2: Phase 2 consists of testing a large sample of vehicles (approximately 300) using the dynamometer testing procedure; using the detailed vehicle operations and emissions data, refine the interim working modal; and validating the working model.
>
> Phase 3: Phase 3 consists of examining the interface between the developed modal emissions model and existing transportation emissions modeling frameworks; creating vehicle category mappings between EMFAC/MOBILE and the modal emissions modal; creating a vehicle category generation methodology to convert from vehicles in a local registration database to the modal emissions model categories; generating velocity/acceleration-indexed emissions/fuel lookup tables for the vehicle/technology categories; and generating roadway facility/congestion-based emissions factors for the vehicle/technology categories.

The modal emissions modal being developed in Phase 2 and the associated application procedures being developed in Phase 3 will have the most relevance to the objectives of this study. The model validation work will include comparisons between the modeled output and the measured values at the individual vehicle level and the composite vehicle level. Validation will be performed at the second-by-second resolution and the integrated "bag" level. The emissions

model will be comprehensive in that emissions characteristics will be described for each vehicle/technology group. The characteristics will also be described for composite vehicle/technology groups, for normal vehicle operation, for vehicle enrichment effects, for vehicle air conditioning effects, and for high-emitting vehicle effects. This should allow for the application for the model to "typical" vehicle fleets and for specific vehicle fleets where such data are available.

The planned integration of the modal emissions model with different transportation emissions model frameworks will provide for application of the modal emissions model with essentially the same data currently required by EMFAC and MOBILE. However, to take full advantage of the modal emissions model for analysis of the emissions impacts of specific transportation projects, more detailed vehicle and operations characteristics data will be required. The project will provide a vehicle category generation methodology to go from a vehicle registration database to the modal emissions modal categories. Vehicle/acceleration-indexed emissions/fuel lookup tables for the vehicle/technology categories will be provided for use with microscopic transportation models such as CORSIM, FRESIM, and NETSIM. This capability is expected to provide analyses procedures for evaluating the emissions impacts of operational improvement projects on freeway and arterial streets. Finally, the project will relate roadway/congestion-based emissions factors to the vehicle/technology categories using EPA facility congestion cycles to use with mesoscopic transportation models. Currently, MOBILE does not have the ability to produce facility-specific emissions inventories, that is, emissions for specific roadway facilities such as freeways, highway ramps, arterials, and local streets and roads. This is important as driving patterns vary depending on the facility type.

In summary, the modal emissions modal is expected to provide an analysis tool allowing the transportation planner to accurately and reliably estimate the emissions impacts of proposed transportation projects at the regional level, the sub-regional level, and the operational level.

University of Michigan

The University of Michigan completed several modal emissions projects. The university's Department of Physics is performing the testing and theoretical development of the modal models.

(1) The research group is working on the theoretical development of a project funded by the Oak Ridge National Laboratory. The original intention of this research was to measure second-by-second emissions from six instrumented vehicles to help improve the basis of modal emissions models.

(2) The research group is also cooperating with researchers at UC-Riverside, assisting them with plans for recruiting and testing the 300 vehicles and with the modeling of vehicles with malfunctioning emissions controls for the NCHRP Modal Model.

(3) Los Alamos National Laboratory has discussed developing a physics/chemistry-based modal emissions model for use in the TRANSIMS planning model. Los Alamos is using the VEHSIME engine map model developed by Sierra Research as an interim model, to be replaced by the physics/chemistry-based model. VEHSIME is discussed in further detail later in this chapter.

Caltrans

Caltrans is funding a research project to quantify modal activity on freeways and arterials in California. In early 1996, instrumented cars were tracked by a video camera from overhead as they passed along a six-mile section of US-101 in Marin County, California (San Francisco Bay area). Researchers at the University of California at Davis (UC-Davis) are analyzing the video and combining it with data from loop detectors along the freeway.

The researchers hoped that the operation of the instrumented vehicle itself would be a good representation of regular traffic, which would make data collection simple. It was not representative, however, and video analysis is being combined with the instrumented vehicle data and associated macroscopic flow characteristics such as average speed and flow. The researchers are using specially developed software to extract the data from the video tapes. Analysis of the video data was performed in 1996 and 1997. Caltrans began to investigate arterials in early 1997.

The goal of the research project is to provide a protocol for developing driving cycles with known modal activity that are representative of specific facility types, and conditions of the roadway, traffic, and traffic control. The research group's roadway classification may not correlate to the *Highway Capacity Manual's* (8) functional classes because there may be more stratification required to better represent or categorize modal activity on a roadway basis. These new classifications may show that traditional functional classes are not sufficient descriptors for modal emissions models. Therefore, driving cycles may be specified by number of lanes on the roadway and by area type to increase the precision of the new modal emissions models.

CARB

CARB has been an instrumental force in vehicle emissions research. CARB has investigated or is currently investigating the following three areas of modal analysis.

Acceleration/power enrichment

Using data collected by Sierra Research, Inc., in Los Angeles, California, a new unified cycle was developed. The new unified cycle is more aggressive than the presently used FTP cycle with higher acceleration and top speed (67 mph) constraints. The average speed-based results closely match the results from the FTP cycle.

UC-Riverside is using some of the data collected from a related research study on the impact of single acceleration events on emissions for its work on the NCHRP Modal Model. CARB investigated accelerations of up to 6 mph/sec in several speed ranges.

Grade Correction Factors
An instrumented vehicle was used to measure HC and CO emissions while driving up and down hills to determine the effect of various grades on emissions. CARB will use the data to develop a new Grade Correction Factor.

Starts
CARB has also investigated the emissions impacts of different start modes based on engine temperatures.

Interim Approaches
As mentioned above, the NCHRP and EPA modal emissions models are longer-term models that should be available in 2002. Less comprehensive models exist that may be useful in the interim, particularly for applications where the differences in exhaust emissions between facilities are of concern. Three approaches are described below.

PIKE PASS Project
The Clean Air Action Corporation (CAAC) paper, "Proposed General Protocol for Determination of Emission Reduction Credits Created by Implementing an Electronic 'Pike Pass' System on a Tollway," (9) was included in the Northeast States for Coordinated Air Use Management (NESCAUM) final report. The CAAC report was included in the NESCAUM final report to demonstrate a potential procedure for evaluating automotive vehicle identification (AVI) tolling technologies.

CAAC hoped that the states of New Jersey and Massachusetts would either use the techniques developed to estimate modal emissions or simply use the test results to demonstrate emissions benefits of reduced modal activity and to reveal emissions offsets. Under the CAAA rules, a transportation project is more likely to be approved if increases in emissions are offset by emissions improvements elsewhere. Neither state (nor any other agency within the states for that matter) pursued the idea any further.

This evaluation procedure is not difficult to use; the driving cycles were derived through "manual" video analysis of actual vehicle driving behavior at the toll facilities. Difficulty with this method is encountered when attempting to create a statistically sound sample with the few vehicles that can be tested on a dynamometer, given time and budget restrictions.

VEHSIME/VEMISS
VEHSIME (10) was developed for CARB by Sierra Research in 1987 and is based on two programs, VEHSIM and VSIME, that were developed by the U.S. Department of Transportation and the EPA. VEHSIME uses engine maps and other vehicle characteristics to predict light-duty vehicle emissions over any specified driving cycle. Sierra Research developed VEHSIME in response to a call for proposals by CARB to develop a computer model that would estimate emissions over virtually any driving cycle. CARB also sought to develop new representative driving cycles for urban traffic in morning-peak, afternoon-peak, and off-peak periods.

General Motors developed a vehicle simulation model called VEHSIM in the early 1970s. VEHSIM is able to determine second-by-second engine rotational speeds and torque needed to

drive a vehicle through a given speed-time profile. These data can be used in conjunction with an engine map of fuel consumption to determine a vehicle's fuel consumption over any driving cycle. The U.S. Department of Transportation and an EPA contractor modified the program to predict CO, NOx, and HC emissions in a similar manner. The new program, VSIME, could estimate instantaneous and cumulative emissions rates. In 1987, Sierra Research recreated the VSIME program. The Sierra Research program, VEHSIME, has been the subject of numerous enhancements since 1987. The VEHSIME program includes the following factors:

- torque converter data;
- engine emissions map data;
- gear ratio and inertia for a single gear;
- shift logic;
- driving cycle description; and
- losses due to fans and air conditioning.

The EPA (11) wrote a duplicate version called VEMISS. Like VEHSIME, VEMISS uses engine emissions maps to predict engine-out and tailpipe HC, CO, and NOx emissions and fuel consumption. VEHSIM can be used to predict engine activity based on a given driving profile, or based on directly input engine parameters.

A total of 29 1991-1992 light duty cars and trucks were tested using an 8.65-inch twin-roll hydrokinetic dynamometer. To develop the emissions maps, the vehicles were stabilized at one activity level for about one minute, and emissions and vehicle parameters were averaged for the stabilization period. The emissions maps were developed from several of these points; however, the emissions maps were incomplete in some areas:

- a full range of loads could not be applied at all speeds;
- the loading constraint of the dynamometer was a constraint preventing high loads from being applied at any speed with a high-performance engine; and
- the dynamometer could not generate the negative loads required to represent decelerations.

These are problems associated with the use of a twin-roll hydrokinetic dynamometer. Testing cold start conditions was problematic because the engine temperature tended to rise after the manual adjustment of loading and stabilization were complete. Therefore, limited data were obtained for cold start temperatures.

A subset of vehicles was tested over the FTP driving cycle and three other driving cycles to provide evaluation data and to assess the impacts of high speeds and accelerations. The evaluation of the model concluded that:

- engine-out HC is under predicted;
- engine-out NOx emissions are over predicted; and
- tailpipe emissions are over predicted relative to engine-out emissions.

Catalytic converter behavior is misrepresented by steady-state tailpipe emissions maps, largely because the catalytic benefits of stored oxygen are overlooked. As discussed in the test section, the engine emissions maps do not reflect the desired range of speeds and loads. Additionally, VEMISS defaults to idle emissions when deceleration events are input. Deceleration leads to a high vacuum in the engine, resulting in evaporation of fuel from the manifold walls. This increases HC and CO emissions and can reduce the efficiency of the catalytic converter. Neither of these effects is modeled when VEMISS reverts to idle emissions under deceleration.

Sierra Research, Inc., was later contracted to evaluate ways to improve parts libraries and emissions maps. The parts libraries in VEHSIM were the subject of a sensitivity analysis that showed that some parameters were more important than others were. This led Sierra Research to try to incorporate an automatic transmission shift logic in the engine simulation program. Sierra Research interpolated and extrapolated from existing data points to fill in the missing points in the emissions maps. A theoretical approach to filling in these missing points was abandoned; no relationship could be established between engine parameters and emissions using the existing data points. Sierra Research also concluded that the intake manifold vacuum is a reasonable surrogate for engine load, which is important for the model's flexibility.

Davis Institute of Transportation Studies Emissions Model (DITSEM)

DITSEM (1) was created in recognition of the potential for improving the ability of emissions models to capture the effects of small changes in modal activity. The modeling objectives were to capture the modal components of the driving cycle; to estimate parameters that were unbiased, consistent, and efficient; and to use variables that could be easily obtained in future data collection efforts and that can be included in both an interim model improvement program and in updating the vehicle fleet.

The DITSEM model is capable of predicting only CO emissions. This was a subjective decision, which ignored the results of HC and NOx, because:

- CO is the hardest pollutant to model, as it is accompanied by significant random error;
- the CAAA have mandated the determination of CO inventories and local analysis of "hotspots;" and
- CO is almost totally emitted from the tailpipe of a vehicle alone.

Table 2 shows the inputs required to use the linear regression equation in the DITSEM model. Note that four of the seven inputs reflect modal activity.

TABLE 2
DITSEM Model Inputs

Model Input	Description
ACC>3	Percentage of driving cycle spent with acceleration greater than 3 mph/sec
AVGSPD	Average speed during driving cycle in mph
B2PERCID	Federal Test Procedure Bag 2 Result, in mg CO per CID per second
CID	Engine displacement in cubic inches
MODYR	Last two digits of model year
%IDLE	Percentage of driving cycle spent at idle (V=0)
PKE>60	Percentage of driving cycle with instantaneous Positive Kinetic Energy (PKE) greater than 60 mph^2/sec

The FTP Bag 2 database can be split into two groups, low-emitters and high-emitters. The two groups were separated based on the micrograms of CO emitted per cubic inch of engine displacement. One regression equation was derived for each group.

The data set from which the equations were developed consisted of existing driving cycle measurements. CO emissions from 13 driving cycles were collected, representing the majority of data used in the MOBILE and EMFAC models. No new data were collected. Modal activity was obtained by breaking the driving cycles into components using a program called "CYCLE." Cruise components were also modeled such that the modal activity includes speed fluctuations or "noise".

To use DITSEM to forecast emissions from a fleet of vehicles and to replace existing modal emissions algorithms, the following must be known:

- model year distribution of vehicles
- Bag 2 test results for vehicles
- the vehicle database representative of the existing fleet (not the case with the present database)
- network speed/time profiles (research currently underway at UC-Davis to determine if speed/time profiles can be assumed for different facility types under different conditions)
- a method of expanding the emissions calculated from these speed profiles and individual vehicle characteristics

Washington (1) describes an investigation of the use of AVI technology to reduce congestion at tollbooths. AVI toll facilities are capable of reducing the degree to which motorists must

decelerate and accelerate by collecting tolls electronically using a communications network and in-vehicle electronic technology. The Speed Correction Factor Data Set in the MOBILE and EMFAC models was used to estimate CO emissions from a hypothetical fleet of vehicles. Different scenarios were created, each with a different level of congestion and with different proportions of aggressive and normal driver behavior. The fleet's emissions were estimated for each of these scenarios.

The DITSEM model is easy to use and designed for comparative studies involving relative, not absolute, emissions levels. Although only CO emissions are modeled in DITSEM, two similar models for HC and NOx are being developed at Georgia Tech.

Summary

The next generation of emissions models should be completed in 1999. NCHRP Project 25-11 is a $1.5 million effort by UC-Riverside to develop a modal emissions model. Georgia Tech is also developing a major modal emissions model with EPA funding. The TRANSIMS transportation-planning model will incorporate modal emissions in its environmental simulation module, but it is unclear what approach will be used. In the interim, it is possible to analyze different highway facilities and conditions using simpler models. Modal emissions models have been developed at UC-Davis (DITSEM) and Sierra Research (VEHSIME/VEMISS) that provide more insight into the emissions characteristics of vehicles' modal activity, such as accelerations, decelerations, cruising and idling. An approach to modal emissions modeling was also demonstrated in the PIKE PASS report included in the Northeast States for Coordinated Air Use Management report. These models account for only exhaust emissions of vehicles, neglecting cold start and hot soak emissions, but may prove valuable until the major models are fully developed.

PROBLEM STATEMENT

A framework for the comparison of different facilities is possible. The research will estimate the emissions characteristics of different roadway facilities under different conditions. In addition, the research will use real-world speed-time profiles on the selected roadway facilities. An interim modal emissions model will be selected and applied to the speed-time profiles. The method used in this research can be used for future studies that include estimates of traffic volumes to estimate link emissions.

ORGANIZATION OF REPORT

This report is divided into five chapters. Chapter II discusses selecting the interim modal emissions model and its application to real-world instrumented vehicle data. The results of this research are presented in Chapter III. Finally, Chapter IV provides discussion on the results from this research and identifies potential areas for improving the analysis used in this research. The recommendations derived from this research are presented in Chapter V.

CHAPTER II. STUDY METHODOLOGY

This chapter discusses the process by which this research was conducted. First, the selection of an interim modal emissions model is given. The derivation of required vehicle parameters is presented. Finally, discussion is provided on the application of the real-world instrumented vehicle data and the modal emissions model.

SELECTION OF AN INTERIM MODAL MODEL

This discussion is a summary of the inputs, modeling procedures, and databases used in the three interim modal emissions modeling approaches. An interim model was selected based on data availability and application of the models.

Inputs

Table 3 provides a summary of the models' required inputs and their availability. The driving cycle parameter data necessary for the VEHSIME/VEMISS and DITSEM models are readily available from the speed-time profiles collected for the modal activity research in Texas (3). The operating parameters of different vehicle components are available in the form of (1) output data from VEHSIM for the VEHSIME/VEMISS model, and (2) the FTP Bag 2 test results for vehicles for the DITSEM model. Actual emissions measurements are required to mimic the PIKE PASS approach.

TABLE 3
Interim Modal Emissions Model Data Requirements and Availability

Inputs	Model Requirements			Availability
	PIKE PASS	VEHSIME/ VEMISS	DITSEM	
Driving Cycle Parameters	Y	Y	Y	Y
Vehicle Component Data	Y	Y	Y	Y
Emissions Measurements	Y	N	N	N

Modeling Procedures

The three interim models share the same fundamental approach: the attributes of a driving cycle are used to determine the emissions from vehicles that have been tested on dynamometers. However, the number of vehicles that have been tested and the method of testing differs between models.

In PIKE PASS, driving cycles were obtained from video analysis of actual behavior. Ten different vehicles were then driven through three driving cycles on a dynamometer to determine their emissions.

VEMISS and VEHSIME are based on emissions measurements from 29 vehicles made at different vehicle component operating points. Emissions at operating levels outside those chosen for measurement are obtained by interpolation and extrapolation. The driving cycle of interest is input to VEHSIM, which estimates the operating levels of individual vehicle parts for one of the 29 vehicles for which data are reliable. The operating parameters of these parts are then compared with the emissions maps to estimate HC, CO, and NOx emissions.

DITSEM consists of two regression equations that were developed by extracting modal activity from 13 driving cycles on which over 4,400 vehicles were tested as part of the EPA emissions test programs. The DITSEM equations require driving cycle variables, vehicle characteristics, and FTP Bag 2 emissions measurements to predict CO emissions. The vehicle characteristics and FTP Bag 2 emissions measurements are available for 4,431 vehicles.

Vehicle Component Databases

All three interim models require driving cycle parameters as inputs. To replicate the PIKE PASS approach, vehicles must be tested on a dynamometer over a driving cycle representative of vehicle behavior for the facility in question. VEHSIME/VEMISS was calibrated for 29 vehicles. Testing additional vehicles with this method is difficult because operating parameters for driving cycles and emissions levels at different operating points must be evaluated for each new vehicle. DITSEM relies on the validity of a breakdown of existing driving cycles into modal activity. The necessary input is available for 4,431 vehicles. This model represents the largest vehicle emissions database presently available.

Final Selection

PIKE PASS is a resource- and labor-intensive approach. Vehicles that are representative of the vehicle fleet using the facility in question must be tested on a dynamometer using the driving cycle of interest. Therefore, this interim method was discarded for use in this study.

VEMISS/VEHSIME is ideal for comparing the changes in emissions of individual vehicles, not for fleets that are representative of regional vehicle distributions, since there are only 29 vehicles from which to draw. Estimates generated from this model were recognized to be inaccurate for the purposes of this research.

DITSEM is specifically designed for comparative analysis. It offers a simple, low cost method of analysis. The approach is amenable to spreadsheet-type programming. A vehicle fleet could easily be selected from the 4,431 available vehicles using a random sampling technique. This model can be applied to an appropriate set of data quickly and easily. Therefore, this model is the superior of the three interim models and was used for this study.

Anticipated Data

The ultimate goal of this study was to compare highway facilities in Houston based on modal emissions. Three items are required to make such a comparison:

(1) a representative estimate of the velocity profile must be made
(2) an accurate estimate of the emissions produced by such a profile must be made
(3) a method of expanding this estimate to represent the volume of traffic on the facility must be acquired

The inputs for the DITSEM model were derived from existing databases; ACC>3, AVGSPD, percent IDLE, and PKE>60 were calculated from data collected from the Texas modal activity research. The goal of that research effort was to establish and analyze the acceleration characteristics of freeways and arterials in the Houston, Texas area. Vehicles were outfitted with electronic distance measuring instruments (DMI). Velocity profile data were fed from this instrument to a laptop computer in the vehicle. These data consist of distance, time, and speed measurements at approximately half-second intervals over the driving cycle. The variables ACC>3, AVGSPD, percent IDLE, and PKE>60 were derived from this velocity profile data. Thus, an accurate estimate of the emissions produced by a vehicle profile was attempted.

VEHICLE PARAMETERS

The FTP database includes emissions-related data from over 4,400 vehicles on which the EPA has performed dynamometer tests. This database was acquired and then separated into six groups based on the database vehicle's model year. The model year groups were taken from the national distribution of vehicle-miles traveled (VMT) by vehicle age (12). Table 4 shows the distribution of vehicles as grouped by model year for this research. Data from this database used in the DITSEM regression equations is model year (MODYR), carbon monoxide emissions production in micrograms per second (CO), and the cubic inch displacement (CID) of the database vehicle.

TABLE 4
Model Year Distribution of FTP Vehicle Database

Model Year Group	Number of Vehicle Tests
1977-1979	349
1980-1982	1,349
1983-1985	1,143
1986-1988	955
1989-1991	211
1992-1995	5
TOTAL	4,012

APPLICATION OF INSTRUMENTED VEHICLE DATA

Instrumented vehicle data were acquired from the Texas Transportation Institute (TTI). Probe vehicles were outfitted with electronic distance measuring instruments (DMI). Velocity profile data were transmitted to a laptop computer inside the probe vehicle. These data consist of distance, time, and speed measurements at approximately half-second intervals over the course of the driving cycle. The DMI has an accuracy of ± 1 foot per 1,000 feet driven, which relates to ± 0.06 mph at 60 mph, and ± 0.03 mph at 30 mph, or ± 0.01 mph per mph driven (3). Unfortunately, the speeds are reported as integer values due to limitations in the instrumentation.

Several speed-time profiles that are representative of extreme traffic conditions and different roadways were chosen to demonstrate the emissions calculations. Two freeways and one arterial were analyzed in Houston. The two freeways were the Katy Freeway (IH-10) outside of IH-610 and the Southwest Freeway (US 59) inside of IH-610. Richmond Avenue was selected as the sample arterial. Richmond Avenue is a parallel route for travelers along the Southwest Freeway. Figure 1 shows the major transportation facilities in the Houston area.

The peak and off-peak periods were compared for the Southwest Freeway and Richmond Avenue samples. The Katy Freeway sample was examined in the peak period but against the peak and off-peak directions of traffic flow.

The DPWRSUM statistic was used in this particular study to show the relationship between the instrumented vehicle data and existing EPA driving cycle data. A comparison of the DPWRSUM calculated from these data can show how rough or smooth the velocity profile is relative to the standard driving cycles such as the FTP BAG 2 cycle, the IM240 cycle, or the new aggressive US06 cycle.

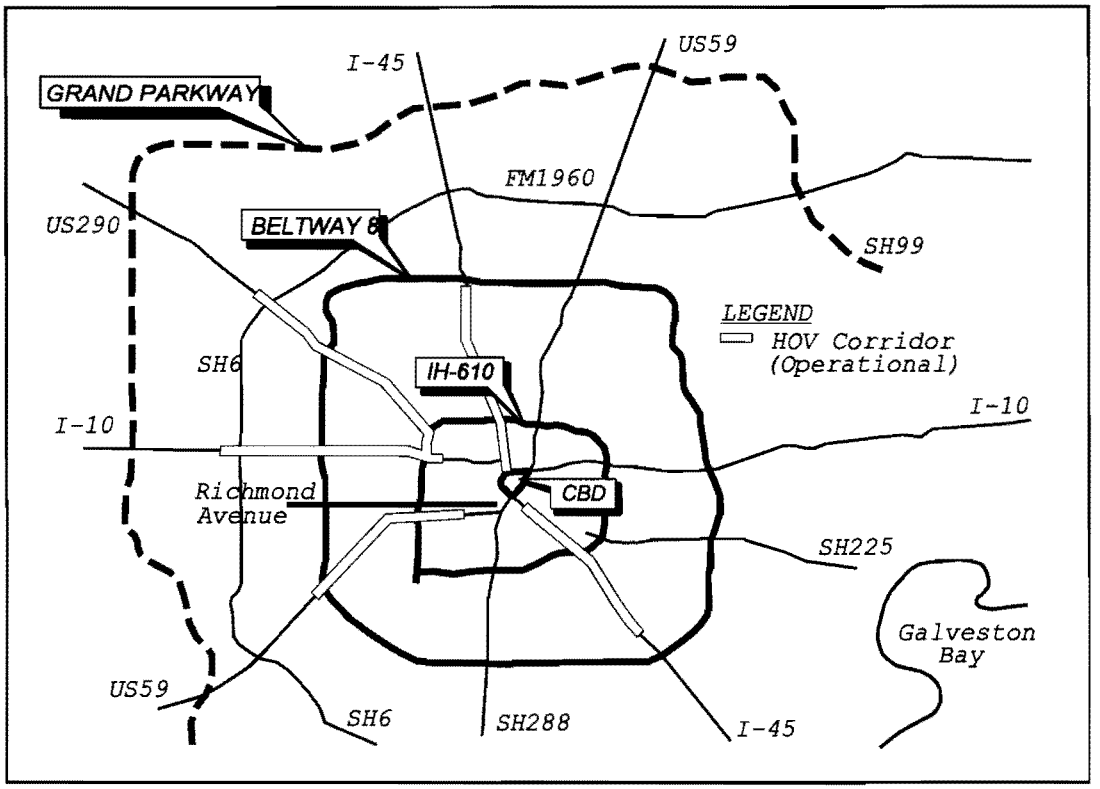


FIGURE 1 Major Transportation Facilities in Houston, Texas

Several DITSEM inputs were derived from the instrumented vehicle data. These data are the average cycle speed, cycle duration, and percent of the driving cycle spent with accelerations greater than 3 mph/sec, PKE greater than 60 mph^2/sec, and vehicle in idle (V=0 mph).

APPLICATION OF DITSEM

DITSEM is defined by two regression equations: a normal and high emitter model. These two regression equations represent the different emissions-producing behaviors of vehicles that have been tampered with, or the age of the vehicle. To estimate CO emissions for a sample of vehicles, the necessary inputs are placed in the appropriate DITSEM regression equation:

For HIGH Emitters (COPERCID > 2.5):

$$LOG_{10}\left[\left(\frac{CO}{CID}\right) + 1\right] = 1.5720 - 0.5503(BAG2) + .1775(BAG2^2) + 0.0128(MODYR) + 0.0112(\%IDLE) + 0.0104(AVGSPD) \quad \textbf{(8)}$$

For NORMAL Emitters (COPERCID <= 2.5)

$$LOG_{10}\left[\left(\frac{CO}{CID}\right) + 1\right] = 2.2360 + 0.5132(BAG2) + 0.0835(PKE{>}60) - 0.0107(MODYR) - 0.0067(\%IDLE) + 0.04093(ACC{>}3) \quad \textbf{(9)}$$

Where:

ACC>3	=	Percent of cycle spent with acceleration rate greater than 3 mph/sec
AVGSPD	=	Average speed of cycle in mph
BAG2	=	LOG_{10} (B2PERCID + 1), the transformed B2PERCID variable
BAG2PERCID	=	CO emissions in micrograms per cubic inch displacement per second on the Federal Test Procedure, Bag 2
CO	=	Micrograms per second of CO emissions
CID	=	Cubic inches of engine displacement
MODYR	=	Last 2 digits of model year of vehicle
PERCENT IDLE	=	Percent of cycle spent at idle, V = 0 mph
COPERCID*	=	LOG_{10} [(CO/CID) + 1], the transformed ratio of CO/CID
PKE>60	=	Percent of cycle spent with instantaneous positive kinetic energy (velocity x acceleration) greater than 60 mph^2/sec

SPREADSHEET CALCULATION TABLES

Several spreadsheets were created to develop the required DITSEM data and to perform the actual emissions calculations. Two FTP variables were converted to support the DITSEM model from distance-based measures to time-based measures.

Conversions

The two FTP variables that require conversions are the CO and FTPBAG2 variables. To calculate COPERCID*, the CO variable must be converted from a per distance measure to a per time measure.

$$CO\left(\frac{\mu g}{\text{sec}}\right) = CO\left(\frac{g}{mi}\right) \; x \; AVGSPD\left(\frac{mi}{hr}\right) \; x \; \frac{1 \; hr}{3600 \text{ sec}} \; x \; \frac{1 \; x \; 10^6 \; \mu g}{1 \; g} \qquad \textbf{(10)}$$

$$COPERCID^* = \log_{10}\left(\frac{CO(\mu g/\text{sec})}{CID} + 1\right) \qquad \textbf{(11)}$$

To calculate the BAG2 variable, the FTPBAG2 variable must be converted from a per distance measure to a per time measure.

$$FTPBAG2(\mu g/\text{sec}) = FTPBAG2(g/mi) \; x \; AVGFTPSPD(mi/hr) \; x \; \frac{1 \; hr}{3600 \text{ sec}} \; x \; \frac{1 \; x \; 10^6 \; \mu g}{1 \; g} \qquad \textbf{(12)}$$

$$B2PERCID(\mu g/CID\text{-sec}) = \frac{FTPBAG2(\mu g/\text{sec})}{CID} \quad \textbf{(13)}$$

$$BAG2 = \log_{10}(B2PERCID + 1) \quad \textbf{(14)}$$

Internal Calculations

Each instrumented driving cycle was analyzed to determine the magnitude of accelerations, and positive kinetic energy. From these data, calculations were then made to determine the percent of the driving cycle where: (1) accelerations exceeded 3 mph/sec, (2) PKE exceeded 60 mph^2/sec, and (3) the vehicle was in idle (V = 0 mph). Accelerations were calculated using a 3-data point (or 2 time-interval) average to approximate accelerations on a per second basis (2 x 0.42276 sec = 0.84 sec). Table 5 shows an example of how accelerations were computed. PKE values were calculated instantaneously. To compare instrumented driving cycles from the roadway samples, DPWRSUM was calculated and then normalized against the cycle's duration in seconds and the distance in miles.

Each instrumented driving cycle underwent analysis to determine which regression equation to use, either the normal or high emitter model, for each vehicle in the vehicle parameter database. The emissions generated over the instrumented driving cycle were then averaged from each vehicle's emissions in the vehicle parameter database. Additional detail on the internal calculations is provided in Appendix A, Detailed Calculations.

TABLE 5
Acceleration Calculation Method Sample

Observation	Speed (mph)	Time (sec)	Acceleration (mph/sec)
V_1	18	0.42	0
V_2	18	0.84	2.38
V_3	20	1.26	2.38
V_4	20	1.68	2.38
V_5	22	2.10	–

CHAPTER III. RESULTS

DEMONSTRATION OF INSTRUMENTED VEHICLE DATA

This section presents the results of driving cycle and emissions analysis for 10 roadway samples in Houston, Texas. Appendix B contains the speed-time, acceleration-time, and PKE-time profiles for each roadway sample used in this research. Each of the roadways is discussed in detail below.

Southwest Freeway

The Southwest Freeway sample was 1.64 miles long, and the results are shown in Table 6 for the peak and off-peak periods. The samples were taken in the outbound (souhtbound) direction. This table also shows the differences in emissions results from different model year groupings.

TABLE 6
Driving Cycle and Emissions Results From the Southwest Freeway (Southbound)

Statistic	Units	Southwest Freeway	
Period	Peak/Off-peak	Peak	Off-peak
Cycle Distance	miles	1.64	1.64
Average Speed	mph	29.95	49.67
ACC>3	% of cycle	12.96	2.89
PKE>60	% of cycle	21.60	30.32
Idle	% of cycle	8.64	0.00
Cycle Duration	sec	195	117
Average Emissions Rate			
1992-1995 Model Years	g/mi	111.53	156.35
1986-1995 Model Years	g/mi	104.00	138.34

From Table 6, the driving statistic results do not seem plausible between the peak and off-peak periods. Current thinking suggests that vehicles with uniform and higher speeds produce fewer emissions than vehicles with less uniform and lower speeds. Though the hard accelerations and idling are reduced, and the average speed increases in the off-peak, emissions rates are higher. This may be due to the increase in the PKE value in the off-peak. The higher PKE values may be the result of higher speeds coupled with additional moderate accelerations.

Katy Freeway

The Katy Freeway roadway sample was 19.5 miles long and the samples were taken in the outbound (westbound) lanes during the morning and afternoon peak periods. The six particular

samples were chosen because of the variability of driving patterns they exhibited. The results of these samples are shown in Table 7.

TABLE 7
Driving Cycle and Emissions Results From the Katy Freeway in the PM Peak

Section	Direction	Average Speed (mph)	% of Cycle with			Cycle Duration (sec)	Average Emissions (g/mile)
			ACC>3 mph/sec	PKE>60 mph^2/sec	Speed at 0 mph		
Katy Fwy 1	Off-peak	58.3	0.00	14.33	0.00	1,200	7.96
Katy Fwy 2		49.0	0.47	11.33	0.09	1,439	6.42
Katy Fwy 3		59.9	0.00	14.95	0.00	1,176	8.44
Katy Fwy 4	Peak	50.1	0.00	10.74	0.00	1,396	5.90
Katy Fwy 5		39.6	1.10	8.70	1.48	1,769	5.77
Katy Fwy 6		49.0	0.24	11.98	0.00	1,429	6.77

The off-peak direction, which exhibits free-flow conditions, has higher emissions rates than those in the peak direction as shown in Figure 2. Again, these results are not consistent with current thinking regarding vehicle and emissions activity in free-flow conditions. What is most interesting is that the lowest emissions rate is associated with the hardest accelerations, lowest average speed and PKE values, and the most idling. From these samples, it appears that DITSEM is very sensitive to PKE. Additionally, the DITSEM calculation can result in high PKE values coupled with low accelerations at higher speeds. This relationship misrepresents the amount of modal activity at higher average speeds.

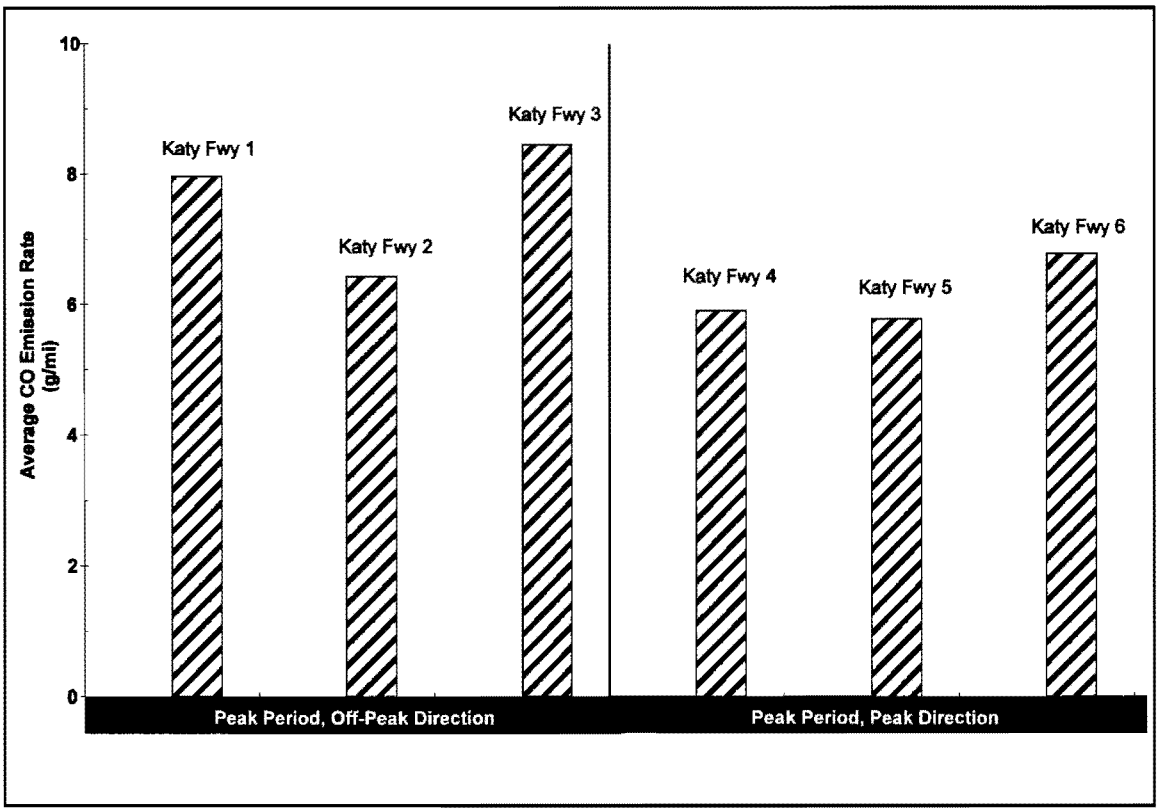


FIGURE 2. Average CO Emissions Rates for Katy Freeway Samples

Richmond Avenue

The Richmond Avenue sample was 2.10 miles in length and the two profile samples were taken in the inbound direction (eastbound) during the peak and off-peak periods. The driving cycle and emissions results are shown in Table 8.

The off-peak period shows a decrease in idling, which is expected as congestion decreases on an arterial. In addition, the off-peak period showed a greater percentage of the driving time with hard accelerations and high PKE values. This may be because as a vehicle traverses an arterial section in the off-peak period, there are greater distances to allow for high accelerations and fewer vehicles with which to interact. The newer model year group has higher peak emissions rates because there are no or few high emitters, which are somewhat cleaner in idle conditions than normal emitting vehicles (1). The two Richmond Avenue samples are the only samples of the ten presented here that produced plausible driving statistic and emissions results.

TABLE 8
Driving Cycle and Emissions Results From Richmond Avenue (Eastbound)

Statistic	Units	Richmond Avenue	
Period	Peak/Off-peak	Peak	Off-peak
Cycle Distance	miles	2.10	2.10
Average Speed	mph	21.20	31.66
ACC>3	% of Cycle	2.83	6.03
PKE>60	% of Cycle	2.71	6.38
Idle	% of Cycle	19.81	3.90
Cycle Duration	sec	358	238
Average Emissions Rate			
1992-1995 Model Years	g/mi	7.65	1.23
1986-1995 Model Years	g/mi	6.34	2.94

DRIVING CYCLE COMPARISONS

Comparisons can be made between the driving cycles of the 10 sample sectionA with the DPWRSUM statistic. As a refresher, the DPWRSUM statistic can best be described as a measure of the 'roughness' of the cycle. Webster and Shih (6) reported that more than 60 percent of trips generated a time-normalized DPWRSUM greater than 20 and that approximately 30 percent of trips generated a time-normalized DPWRSUM greater than 30. Table 9 compares standard driving cycles and the driving cycles of the instrumented vehicles. DPWRSUM is normalized by cycle duration and distance for comparisons between the different cycles presented.

The instrumented data yielded higher DPWRSUM values (12,506 to 155,230 mph^2/sec) than most of the standard driving cycles. Only the US06, an aggressive cycle, and the UDDS cycles fall within the range of the instrumented data, though these cycles fall toward the lower end of the range of values. The FTP Bag 2 cycle used in the DITSEM model approaches the low values of the instrumented data. Also interesting here is that the value of DPWRSUM decreases as PKE values from the instrumented samples increase.

TABLE 9
Comparison of Standard Driving Cycles to the Instrumented Vehicle Data

Speed Cycle		Cycle Duration	Cycle Distance	Average Speed	DPWRSUM	DPWRSUM Normalized by	
						Cycle Duration	Cycle Distance
		(sec)	(miles)	(mph)	(mph^2/sec)	(mph^2/sec^2)	(mph^2/sec-mi)
Standard Driving Cycles	FTP Bag 1	505	3.59	25.60	9,383	18.58	2,613.65
	FTP Bag 2	867	3.86	16.03	10,987	12.67	2,846.37
	UDDS	1,372	7.45	19.56	20,371	14.85	2,734.36
	HFET	776	10.26	48.20	9,886	12.91	963.55
	NYCC	600	1.18	7.10	9,909	16.52	8,397.46
	US06	600	8.01	48.04	39,831	66.39	4,972.66
	IM240	240	1.96	29.38	6,370	26.54	3,250.00
Real-World Samples	Richmond Ave Off-peak	238	2.10	31.66	16,806	70.61	8,079.81
	Richmond Ave Peak	358	2.10	21.20	19,330	53.99	9,204.76
	Southwest Fwy Off-peak	117	1.62	49.67	12,506	106.89	7,719.75
	Southwest Fwy Peak	195	1.62	29.95	25,790	132.26	15,919.75
	Katy Freeway 1	1,200	19.54	58.58	98,580	82.15	5,045.55
	Katy Freeway 2	1,439	19.58	48.96	119,388	82.97	6,097.45
	Katy Freeway 3	1,176	19.59	59.93	100,633	85.57	5,136.96
	Katy Freeway 4	1,396	19.41	50.11	125,612	89.98	6,471.51
	Katy Freeway 5	1,769	19.46	39.60	155,230	87.75	7,976.88
	Katy Freeway 6	1,429	19.44	48.96	135,774	95.01	6,984.26

Adapted from (6)

The instrumented data, when normalized, range from 53.99 to 132.26 mph^2/sec^2 by cycle duration, and 5,045 to 15,920 mph^2/sec-mi by cycle distance. Figure 3 shows how each of the cycles compare to one another when the DPWRSUM statistic is normalized over cycle duration and distance.

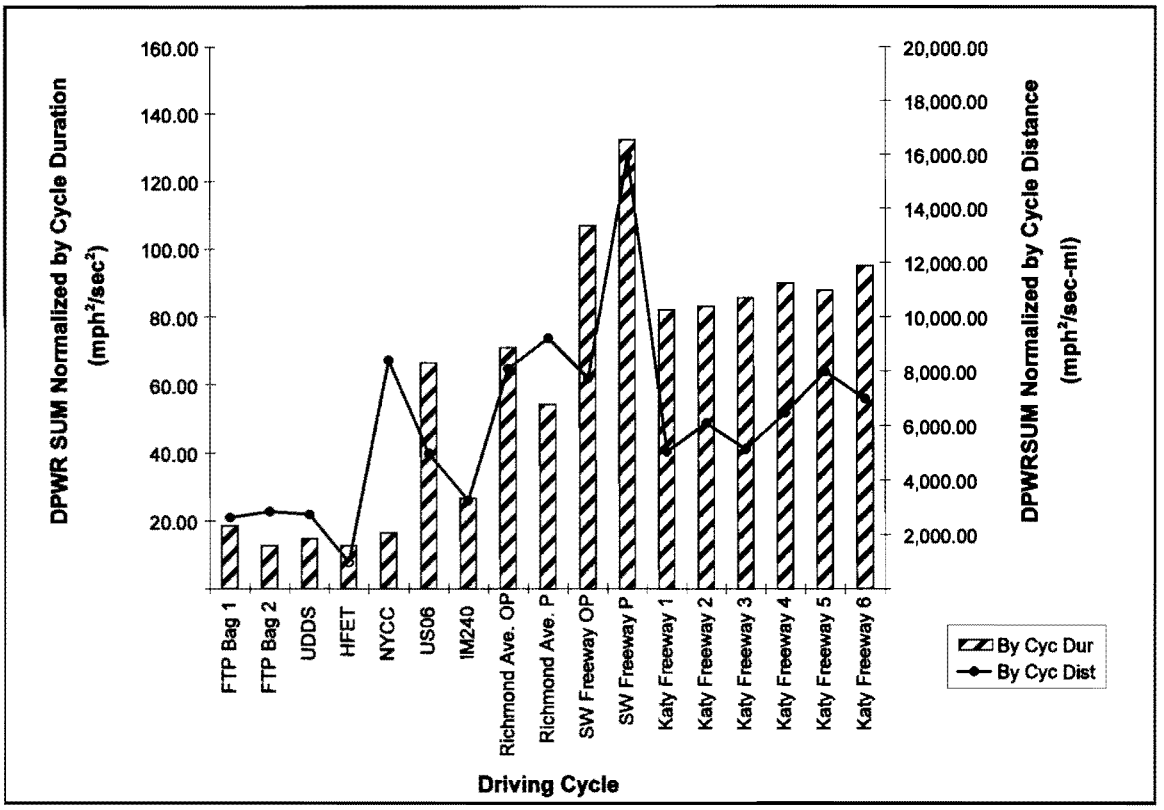


FIGURE 3. Normalized DPWRSUM Values for Standard and Instrumented Driving Cycles

From the above figure, it can be seen that the US06 cycle best represents the instrumented data. All instrumented driving cycles are greater than the standard IM240 driving cycle.

Figure 4 shows how the instrumented data compare to the US06 driving cycle. There is a lot of variation between the samples. The Richmond Avenue off-peak sample provides the best match to the US06 cycle when DPWRSUM is normalized by cycle duration. The Katy Freeway 1 cycle is the best match to the US06 cycle when the DPWRSUM statistic is normalized by cycle distance.

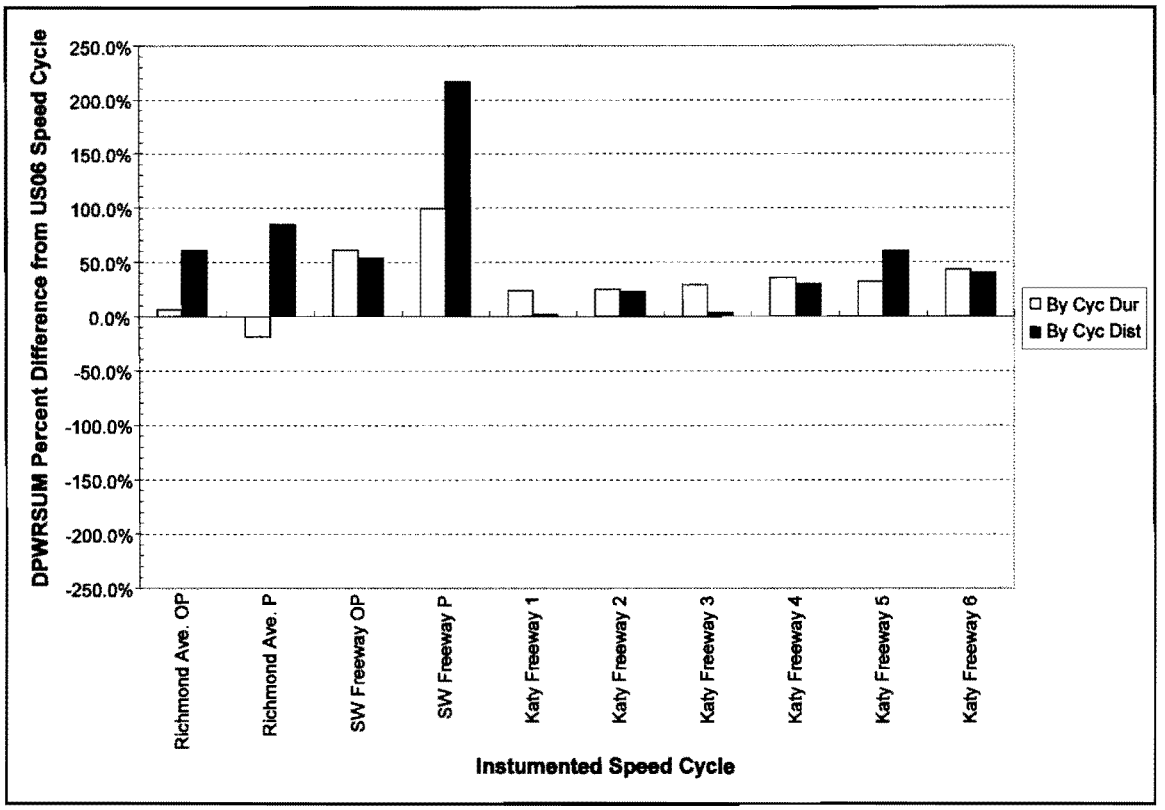


FIGURE 4. Comparison Between the Instrumented Speed Cycles and the US06 Driving Cycle with the DPWRSUM Statistic

KATY FREEWAY MICRO-ANALYSIS

The emissions estimates from above are very revealing and contradict prior assumptions and findings regarding emissions due to modal behavior. The emissions estimates are higher for small fluctuations in speed at high speeds than for large fluctuations in speed at low speeds. This appears to be due to the high values for the variable PKE>60 that are calculated for each cycle.

Three sections of one Katy Freeway sample were separated for further analysis. Figure 5 shows each of the three sections on the speed-time profile of the Katy Freeway sample. One section, labeled Section A on the velocity profile, features a lot of acceleration and deceleration at relatively low speeds. Section B includes high accelerations and decelerations at a higher average speed. Finally, Section C is representative of free-flow driving at high speeds, and includes slight accelerations and decelerations at a high average speed. The sections' cycle parameters are shown in Table 10 below.

The emissions estimates generated by the DITSEM model for these sections are 0.97 g/mile for Section A, 4.6 g/mile for Section B, and 6.3 g/mile for Section C. It is possible that small fluctuations in vehicle speed at high speeds could increase emissions significantly, since throttle position is a very important determinant of emissions. However, the high values of the variable PKE>60 appear to determine the magnitude of the emissions in each case. The emissions estimates show an inverse relationship to the amount of hard accelerations in this micro-analysis.

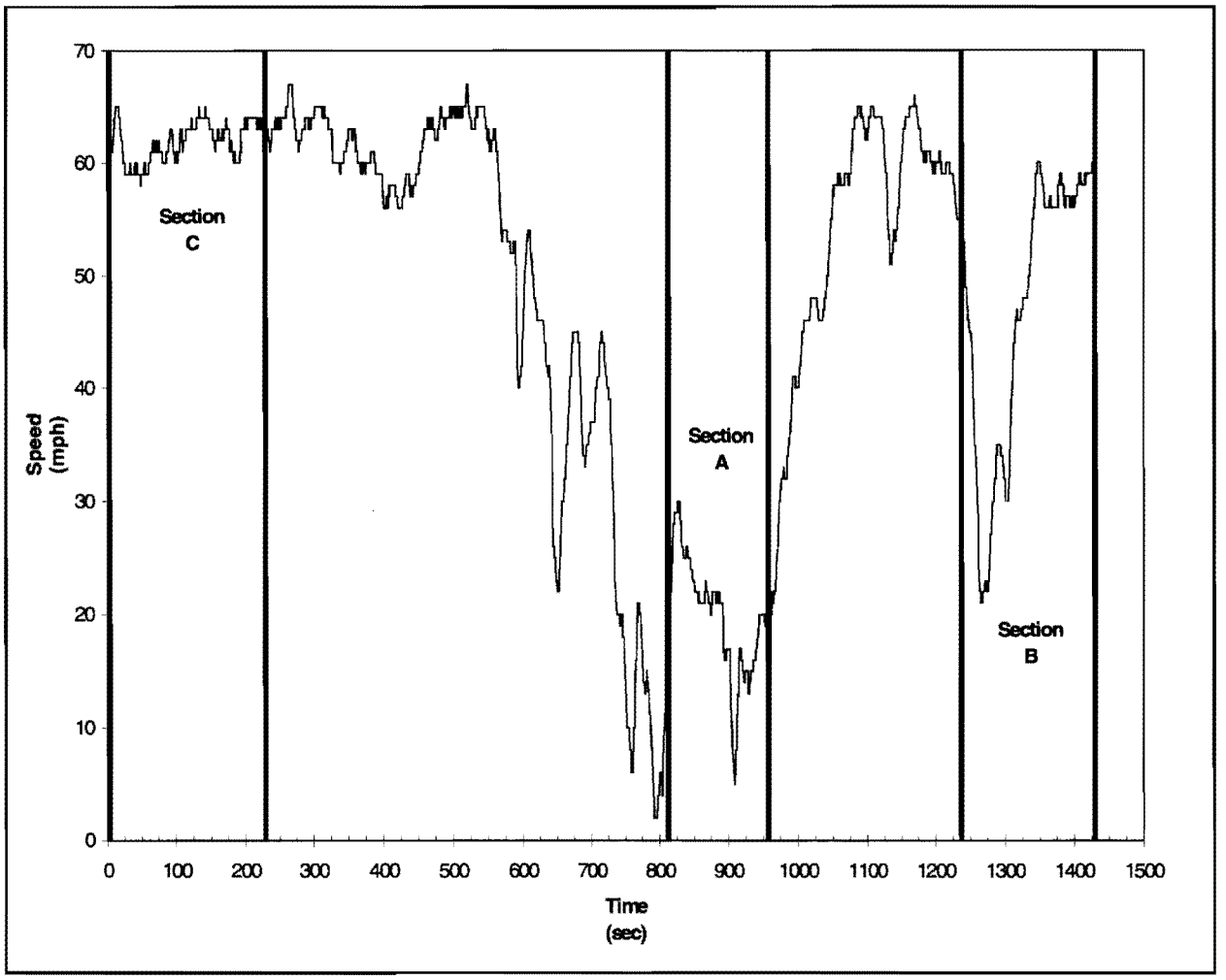


FIGURE 5. Speed-Time Profile for Sample Katy Freeway Section Used in Micro-Analysis

TABLE 10
Results of Katy Freeway Micro-Analysis

Section	Average Speed (mph)	% of Cycle with			Cycle Duration (sec)	Average Emissions (g/mile)
		ACC>3 mph/s	PKE>60 mph^2/s	Speed at 0 mph		
A	19.80	0.61	0.61	0.00	138	0.97
B	47.14	0.43	13.17	0.00	195	4.57
C	61.91	0.00	16.48	0.00	225	6.33

CHAPTER IV. DISCUSSION

This chapter provides the necessary discussion of the implausible driving statistic and emissions results presented in the previous chapter. The primary discussion focuses on the effect of the PKE statistic in the DITSEM model. Methods for reducing its impact are presented. Additionally, a brief discussion is provided on the differences between the two model year groups used. Finally, the use of traffic volumes with the results of this method is presented.

PROBLEMS WITH THE PKE STATISTIC

Some implausible emissions results were presented in the previous chapter. In summary, as PKE values and average speeds increased and hard accelerations decreased, the average emissions rate was shown to increase. There are three possible explanations for this anomaly.

First, the PKE statistic may not have been calculated correctly. The variable is defined as the product of positive acceleration and velocity resulting in a value with the units of mph^2/sec (1). A slight acceleration of 1 mph/sec multiplied by a high speed of over 60 mph results in a PKE value of greater than 60. Thus, a cycle that includes many slight accelerations at high speeds will have a high percentage of PKE>60. After review, the PKE values were calculated correctly, so this explanation can be discounted. Thus, the PKE statistic is sensitive to both speed and acceleration. As can be seen in Figure 6, mild or normal accelerations at high speeds can result in PKE values exceeding the allowable limit of 60 mph^2/sec as specified by Washington in the DITSEM model.

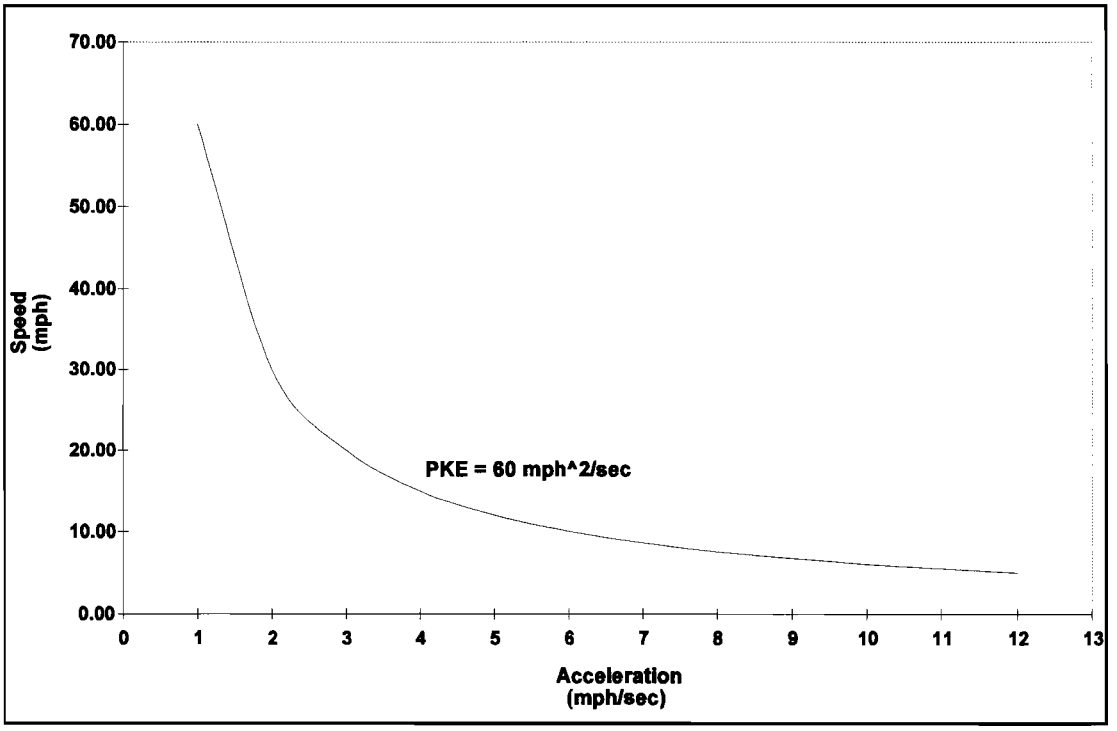


FIGURE 6. Velocity-Acceleration Relationship to Positive Kinetic Energy (PKE)

Second, the fluctuation in speeds that results in accelerations of 1 mph/sec is not indicative of the actual vehicle operation. In other words, the instrument readings may not accurately represent the actual vehicle behavior. This explanation is supported by the fact that the test cycles used to calibrate the DITSEM model have PKE>60 values of less than 10 percent. The highest value of PKE>60 used in deriving the DITSEM model was 8.9 percent from the Unified Cycle. The toll road example used by Washington (1) assumed a maximum PKE>60 value of 5.3 percent. With these PKE>60 values as benchmarks, it is reasonable to assert that the PKE>60 values calculated using high-speed sections of the instrumented vehicle data from Houston are too high. The ACC>3 values may be reasonable even if there are too many accelerations of 1 mph/sec or more indicated by the device. The slope coefficient used to create the DITSEM model should not be interpolated out beyond this value with any confidence. There are two solutions that can then be used: (1) assume a value of 9% for all PKE>60 and assume that the analysis is conservative in its estimate of emissions; and (2) smooth the profile at accelerations < 1.0 mph/sec so that the proportion of cycle where PKE>60 is reduced.

A third possibility is that the PKE>60 values are accurate, but the DITSEM regression equation is inaccurate for high-speed cycles. Since the model is only calibrated with a maximum PKE>60 value of 8.9%, it should not be applied to most of the roadway profiles in this study. In fact only three of the ten samples had PKE>60 values less than 10%. Of those three samples, two samples were on Richmond Avenue that did not show implausible results.

Thus, the emissions estimates appear implausible for two reasons. First, the measurement device does not possess the degree of precision to adequately characterize vehicle activity for modal emissions estimates. Second, the model itself is not calibrated with PKE>60 values in the range determined from the instrumented vehicle data. The following discussions present methods for reducing the effect the PKE statistic has in DITSEM.

Addition of Trip Start/Ends

One possible method to lower the PKE>60 values without changing the characteristics of the different sample driving cycles is to add equal segments to all profiles to represent a start and end to the trip. These start/end segments might have no accelerations greater than 3 mph/sec and no PKE values greater than 60 mph^2/sec. This exercise would effectively increase the cycle duration thereby reducing the percent of the driving cycle spent with PKE values greater than 60 mph^2/sec. Because they are applied consistently to all of the velocity profiles, they would not conceivably change the relative emissions benefits of one profile over another.

However, determining the appropriate segment length to add is a subjective matter. A segment approximately 1 mile long must be added to each end of a freeflow section with an average speed of 60 mph and a length of 18 miles to reduce the PKE>60 value from 14% to 10%. Even with these trip ends added, the model still predicts the free flow section to have approximately three times the emissions of a congested section with low average speeds and high accelerations. There are two questions that remain: (1) How long a section should be added?; and (2) Why should it make a difference, in the model, what length of trip start/end is added?

Strong reservations about using this method exist because Washington's case study (1) included no such trip starts/ends. In examining the emissions characteristics of a 10-mile

roadway with a tollbooth and the same roadway with Electronic Toll Collection networks, Washington assumed PKE>60 values of between 0% and 5.3%. More importantly, he also assumed that vehicles start and end their 10-mile velocity profile at 45 mph or 55 mph, not at 0 mph.

Insufficient Precision From the Distance Measuring Instrument (DMI)
The measuring device returns only integer speed values. Acceleration estimates during slight fluctuations in speed may be artificially inflated because of this speed precision. Consider the velocity profile excerpt shown in the table below.

TABLE 11
Current DMI Precision

Time	Speed	Acceleration	PKE
0.0000	60 mph	–	–
0.4227	60 mph	-1.18 mph/sec	0
0.8454	59 mph	-1.18 mph/sec	0
1.2681	59 mph	1.18 mph/sec	69 mph^2/sec
1.6908	60 mph	1.18 mph/sec	69 mph^2/sec
2.1135	60 mph	0	0
2.5362	60 mph	0	0

This excerpt shows how a slight fluctuation at high speed can result in a high PKE value. Again, the DMI returns speeds only in integer form. In other words, the speed might be 60.2 mph, but the instrument's precision limits the output speed to 60 mph. As an example, the velocity profile might actually look like this:

TABLE 12
Improved DMI Precision

Time	Speed	Acceleration	PKE
0.0000	60.2 mph	–	–
0.4227	60.0 mph	-0.35 mph/sec	0
0.8454	59.9 mph	-0.24 mph/sec	0
1.2681	59.8 mph	0.35 mph/sec	21 mph^2/sec
1.6908	60.2 mph	0.83 mph/sec	50 mph^2/sec
2.1135	60.5 mph	0.35 mph/sec	21 mph^2/sec
2.5362	60.5 mph	–	–

If this is the case, few of the calculated PKE values in the instrumented data are above 60 mph^2/sec. Of course, there is no reason to assume that the accelerations should be slight.

Data Smoothing

The only reason to justify smoothing the instrumented vehicle data is that the behavior is not what was anticipated and does not contain the range of values from which the DITSEM model has been calibrated. Figures 7 through 9 show the effects of data smoothing from one time interval to three time intervals. The existing calculations are based on calculating the accelerations over two time intervals (0.845 seconds), or three data points, where the measuring device returns values every 0.42276 seconds. By adopting this method of calculating accelerations, data smoothing was performed to some extent.

PROBLEMS WITH VEHICLE GROUPS

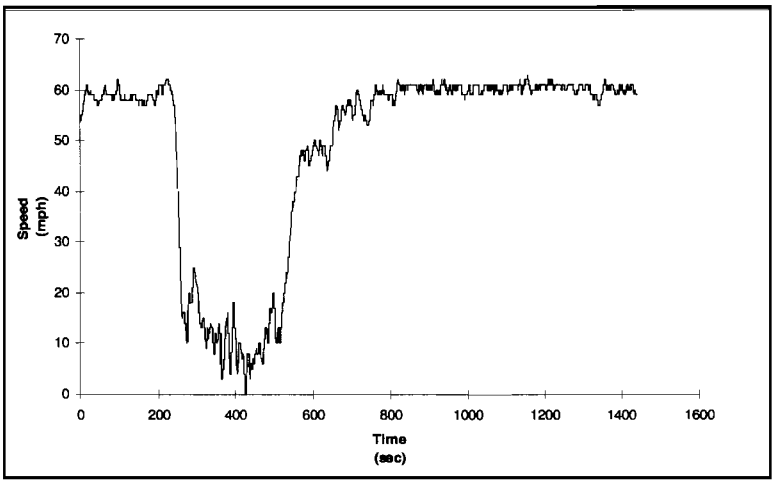
As mentioned previously, the newest model year group, 1992-1995, produced higher emissions than the group containing model year 1986-1995. These results may be due to the small vehicle sample in the 1992-1995 group. Figure 10 shows the relative increase in emissions from the 1992-1995 vehicle group on the Southwest Freeway and Richmond Avenue samples.

COLLECTION AND USE OF TRAFFIC VOLUMES

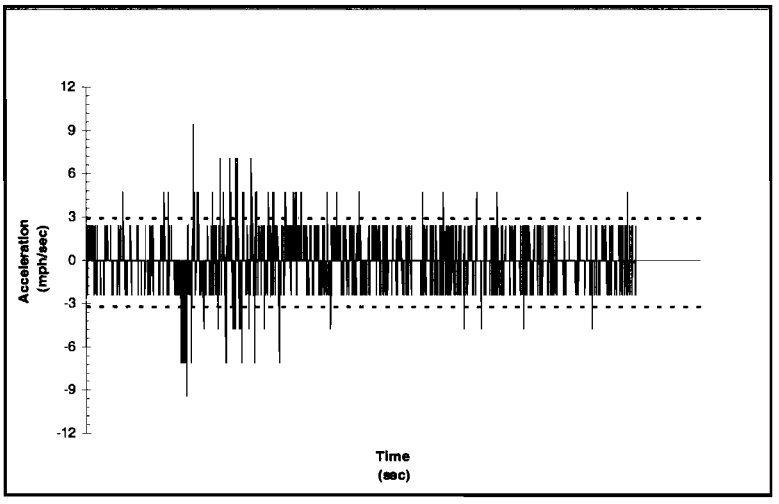
Traffic volumes were not collected with the modal activity data in Houston. This poses a problem: There is no way to relate the velocity profile to actual traffic conditions on the road. Speed profiles may be similar for roads with two different traffic volumes; no conclusion about the specific traffic volume can be drawn by examining the speed profile. Speed profiles are sensitive to congestion events that involve high levels of interaction with surrounding vehicles.

FIGURE 7. 2-Point Average of ACC and PKE

Speed



Acceleration



PKE

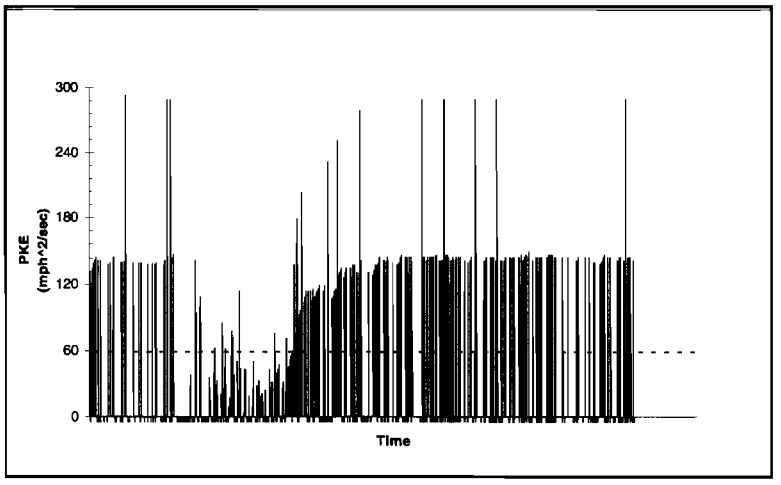
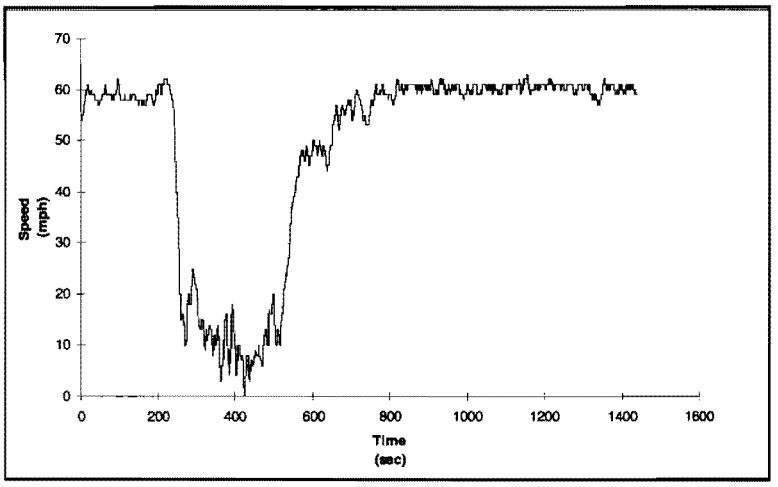
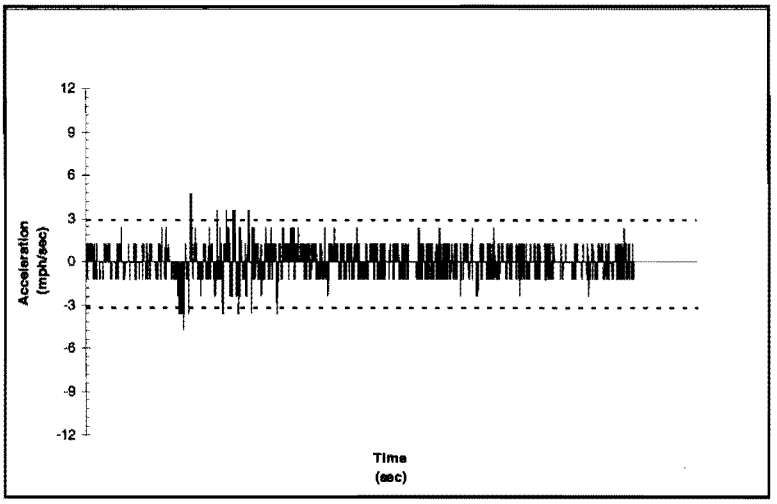


FIGURE 8. 3-Point Average of ACC and PKE

Speed



Acceleration



PKE

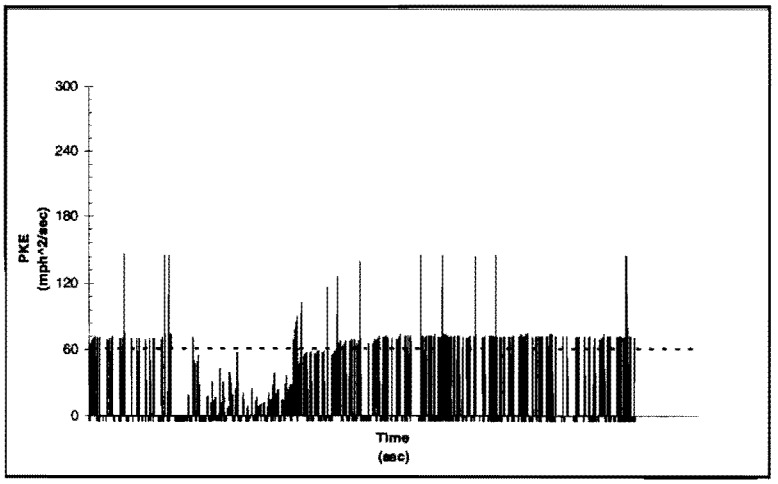
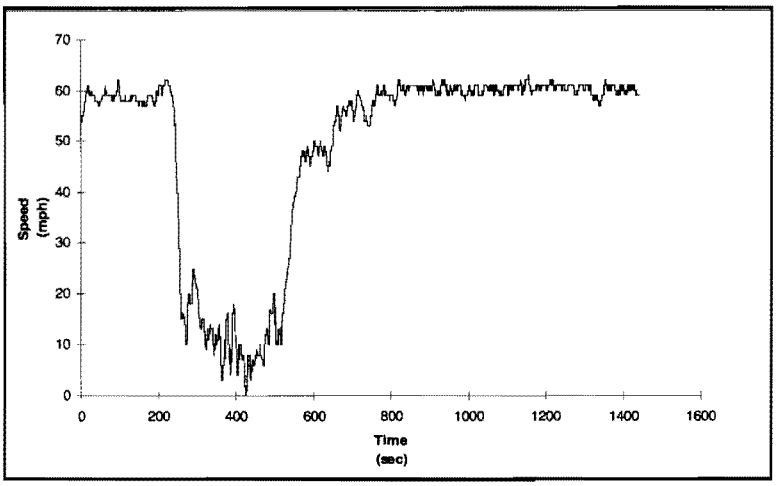
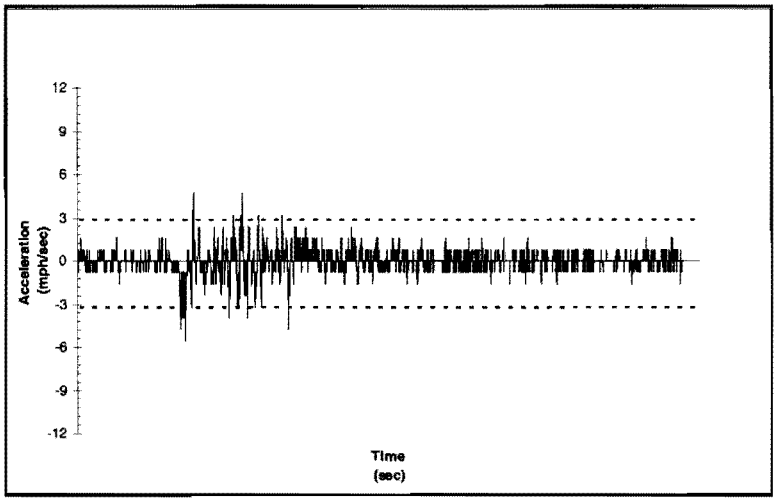


FIGURE 9. 4-Point Average of ACC and PKE

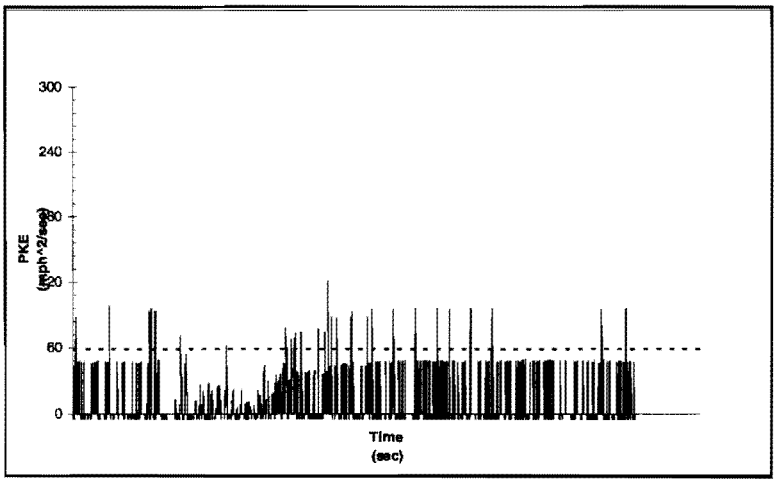
Speed



Acceleration



PKE



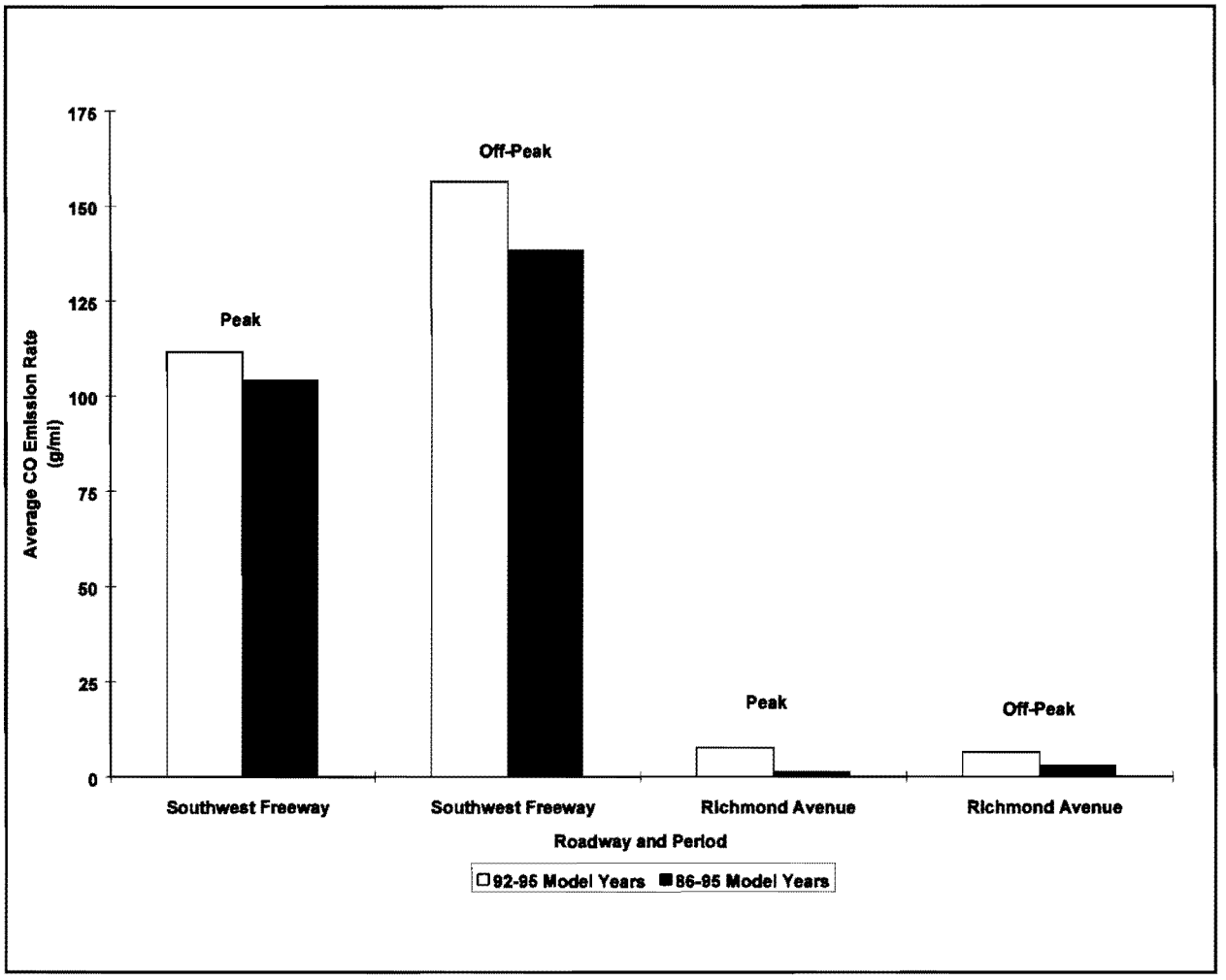


FIGURE 10. Comparison of Vehicle Model Year Group Effects on Average CO Emissions Rates

CHAPTER V. RECOMMENDATIONS

This report has documented the use of an interim, modal emissions model (DITSEM) using real-world instrumented vehicle data that was collected in Houston, Texas. Several recommendation for implementing this interim model for use in air quality analyses were developed from the experience gained during this investigation. Each recommendation is numbered below and supplemented with a brief discussion of issues and conclusions raised in the proceeding chapters.

1. **The model is best applied to arterials or congested freeway segments. The model is not recommended for use on facilities with average speeds approaching 60 mph.**

   This is a very important recommendation for model implementation. The recommendation is based on a couple of conclusions found through testing the DITSEM interim modal emissions model. Those two conclusions are:

   (a) The DITSEM model cannot be applied to the Houston instrumented vehicle data with confidence because the PKE>60 values are beyond the range for which the model was developed. The model should not be used with PKE>60 values of more than 9%.
   (b) The Houston instrumented vehicle data have very high PKE>60 values because many slight accelerations at high speeds are calculated within the data set. Most of the free-flow and congested velocity profiles have PKE>60 values of higher than 10%.

2. **Apply the model using typical spreadsheets.**

   The model is easy to use with commonly used spreadsheet software. Modal vehicle data is used on the page with simple formulas described in this report. Modal vehicle characteristics can then be easily calculated and used to determine an estimate of modal activity and vehicle emissions.

3. **Supporting data, such as vehicle emissions data, must be acquired prior to using the model. The EPA vehicle testing database is a good source for this data.**

   As with the application of any model, network, travel demand, or sketch-planning, data must be gathered to use as input to the model. Data used in this investigation was taken from two sources: (1) the EPA vehicle testing database, and (2) locally collected modal vehicular data from Houston. Good planning is required when using each source to ensure that the data collected will be useful and needed, and that the data collected meets certain quality guidelines.

4. **Any instrumented vehicle data must be gathered using high precision instrumentation.**

   A major conclusion dealing with instrumented data which was formulated during this investigation was that the PKE>60 values appear to be too high because of the lack of precision provided by the speed profile measuring device, or DMI. Any measure of roughness (PKE>60 or DPWRSUM) applied to the instrumented vehicle data results in very high values compared to standard driving cycles.

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APPENDIX A

GLOSSARY

Accumulated Speed Error - A statistic that is calculated from the sum of absolute values of the first differences in speed errors. This statistic increases as variations, either smooth or rough driving errors, from a specified driving cycle occur.

AVI Toll Facilities - A toll collection communications network and in-vehicle electronic technology that reduces the degree to which motorists must decelerate and accelerate. This facility uses technology that allows a driver to pass through a toll area without stopping.

CO (Carbon Monoxide) - A colorless, odorless, highly toxic gas that is a normal by-product of incomplete fossil fuel consumption. This is one of the pollutants measured in emissions modeling, and it is the hardest pollutant to model.

Cold Start Emissions - The emissions produced by a vehicle after a long engine-off period (one hour for vehicles equipped with a catalytic converter, four hours for vehicles not equipped with a catalytic converter).

Compression Ratio - The volume of the combustion chamber and the cylinder when the piston is at the bottom of its stroke, divided by the volume of the combustion chamber when the piston is at the top of its stroke.

DITSEM (Davis Institute of Transportation Studies Emission Model) - A model emissions model that can predict CO emissions using seven inputs, four that reflect modal activity. This model requires the inputs of driving cycle parameters and is the largest vehicle emissions database presently available.

DMI (Distance Measurement Instrument) - An instrument that electronically collects data on the distance that a vehicle has traveled. The data collected with this instrument can be downloaded to a computer.

DPWRSUM - A measure of the validity of driver behavior in prescribed driving cycles; the sum of absolute changes in vehicle power. The magnitude of DPWRSUM can indicate whether a cycle is "smooth" or "rough" relative to a specified standard value, but it cannot measure adherence to the specified cycle.

Driving Cycle - A combination of starts, stops, cruise, acceleration, and deceleration events that is used to certify vehicles for emissions factoring modeling.

Dynamometer - A device with large rollers on which the drive wheels of a vehicle are placed. The dynamometer simulates the load that the weight of the vehicle and the frictional resistance to the vehicle's movement place on the engine in actual driving.

EPA Modal Model - A model being developed for the EPA that uses a Geographic Information System (GIS) to estimate emissions as a function of vehicle operating profiles.

Freeflow Driving - These are the optimal driving conditions where the user has the freedom to select a desired speed and maneuver without any interference.

FTP (Federal Test Procedure) - A test that determines the amount of CO, NOx, HC, and other emissions produced by a vehicle during a standard driving schedule. The default values for this test are often used in emissions models.

HC (Hydrocarbons) - A compound that contains only hydrogen and carbon. The simplest and lightest forms of HC are gaseous. This is one of the pollutants measured in emissions modeling.

Hot Start Emissions - The emissions produced by a vehicle after a short engine-off period (less than one hour for vehicles equipped with a catalytic converter and less than four hours for vehicles nor equipped with a catalytic converter).

IM240 - A standard driving cycle that is often used in models such as DPWRSUM.

Manifold Pressure - Absolute pressure as measured at the appropriate point in the induction system and usually expressed in inches of mercury. The manifold pressure contributes to the rate of emissions production.

MOBILE - A macroscopic emissions prediction model that simplifies vehicle activity by using averages of emissions over cycles. This is often referred to as the speed correction factor approach.

Modal Activity - The activity that a vehicle is going through; for example, acceleration, deceleration, cruising, and idling.

Modal Emissions Modeling Approach - The new emissions factor modeling approach that relates emissions estimates to vehicle operating parameters.

NCHRP Modal Model - A physical model being developed for the NCHRP based on second-by-second emissions and vehicle operation data.

NOx - A product of fossil fuel combustion whose production increases with the temperature. This is one of the pollutants measured in emissions modeling.

Off-Peak Period - The period outside the peak period. This demand for transportation is not as heavy as it is in the peak period.

Peak Period - The period during which the maximum amount of travel occurs. This is the period when the demand for transportation is the heaviest.

PIKE PASS - A modal emissions model that requires the inputs of driving cycle parameters, vehicle component data, and emissions measurements.

PKE (Positive Kinetic Energy) - The sum of positive differences in kinetic energy. This statistic is sensitive to both speed and acceleration.

RMS Speed Error (Root Mean Square of the Speed Error) - A statistic used to determine errors in performance of a specified driving cycle.

Speed Correction Factor Model - The traditional emissions factor modeling approach that is commonly used to evaluate transportation improvements. Emissions data is collected over the course of a driving cycle. Examples of this are MOBILE and EMFAC.

Stochastic - An assignment technique that allocates point-to-point travel to more than one path by using a set of probabilities to estimate the expected number of trips on each relevant path. These probabilities are computed as a function of path characteristics.

TRANSIMS - A transportation-planning model that is being developed that will incorporate modal emissions in its environment simulation module.

US06 - The most aggressive driving cycle to date. This has not been integrated into emissions factor models.

VEHSIME/VEMISS - A modal emissions model that uses engine maps and other vehicle characteristics to predict light-duty vehicle emissions over any specified driving cycle. It predicts engine-out tailpipe HC, CO, and NOx emissions and fuel consumption. This model requires the inputs of driving cycle parameters, vehicle component data, and emissions measurements.

Velocity - The distance passes per unit of time or the rate of change in location relative to time.

VMT (Vehicle Miles Traveled) - A measurement of the total miles traveled by all vehicles in an area for a specific period. It is calculated by multiplying the number of vehicles and the number of miles traveled in a given area over a specific period.

APPENDIX B

DETAILED CALCULATIONS

VELOCITY PROFILE VARIABLES

Given the velocity profile over a specific roadway section, the variables ACC>3, AVGSPD, %IDLE, and PKE>60 can be calculated. The following is an excerpt from the instrumented vehicle database:

```
# CUM  DIST SPD  DATE   TIME
   DIST
.
.
31. 0.222 0.008 63 @ Tue Mar 14 06:05:20 1995
32. 0.229 0.008 63 @ Tue Mar 14 06:05:20 1995
33. 0.236 0.008 63 @ Tue Mar 14 06:05:20 1995
34. 0.244 0.008 63 @ Tue Mar 14 06:05:21 1995
.
.
```

(Data measurements were taken each 0.42276 seconds instead of 0.5 seconds. Therefore, an additional cumulative time column must be added for each driving cycle.)

DITSEM parameters would be calculated as follows:

$ACC_t = (SPD_a - SPD_b)/(t_a - t_b)$
$ACC_t(31\text{-}33) = (63-63)/(0.42*2) = 0$ mph/sec

ACC>3 mph/sec = number of entries with ACC>3 / number of entries
ACC>3 = 0/4 = 0

PKE>60 mph = number of entries with SPD * ACT > 60 / number of entries
PKE>60 = 0/4 = 0

%IDLE = number of entries with SPD=0 / number of entries
%IDLE = 0/4 = 0

AVGSPD = CUM DIST / CUM TIME
AVGSPD= (0.244-0.222)/(0.42276*3)

VEHICLE PARAMETER VARIABLES

The parameters of an individual vehicle can then be read from the FTP database, that consists of a number of different parameters with the same data entry for each vehicle. For instance, the entry for a specific vehicle includes:

COPERCID B2PERCID BAG2 FINJ MODYR CID

These variables can be read from this entry and used directly in the DITSEM equation.

APPLICATION OF THE DITSEM REGRESSION EQUATIONS

To estimate CO emissions for the vehicle in question, the values for the above variable are placed in the DITSEM regression equations:

For HIGH Emitters (COPERCID > 2.5):

LOG10[(CO/CID)+1] = 1.5720 - 0.5503(BAG2) +0.1775(BAG2^2) + 0.0128(MODYR) + 0.0112(%IDLE) + 0.0104(AVGSPD)

For NORMAL Emitters (COPERCID <= 2.5)

LOG10[(CO/CID)+1] = 2.2360 + 0.5132(BAG2) + 0.0835(PKE>60) - 0.0107(MODYR)- 0.0067(%IDLE) + 0.04093(ACC>3)

DETERMINATION OF OVERALL EMISSIONS FOR HYPOTHETICAL TRAFFIC VOLUMES

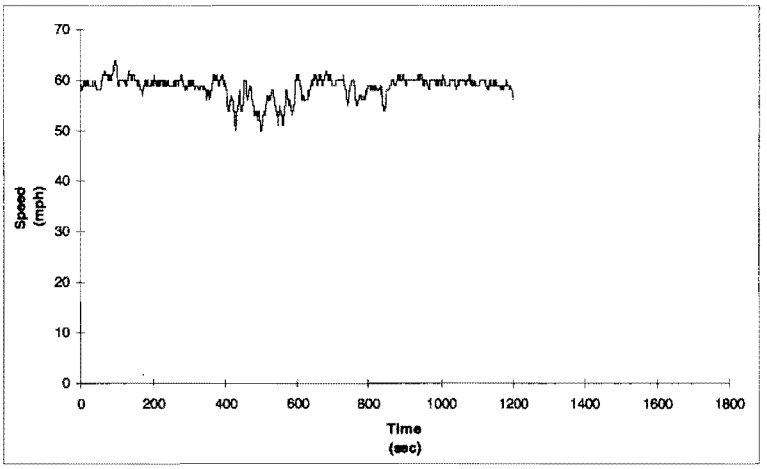
It may be desirable to sum these emission results over a representative traffic volume in order to determine the overall emissions contribution of the traffic on the roadway. In this case, a series of calculations may be performed with a random sample of vehicles that might make up this traffic volume. As an extreme example, emissions might be calculated for a selection of 1,300 light-duty gas vehicles, 800 light-duty gas trucks, 400 heavy-duty diesel trucks, 100 heavy-duty gas trucks, 300 light-duty diesel trucks, and 50 motorcycles, representative of traffic passing a point in one hour in one direction on a four-lane arterial during peak periods. Given the hypothetical nature of the scenario, this approach may be more intensive than needed.

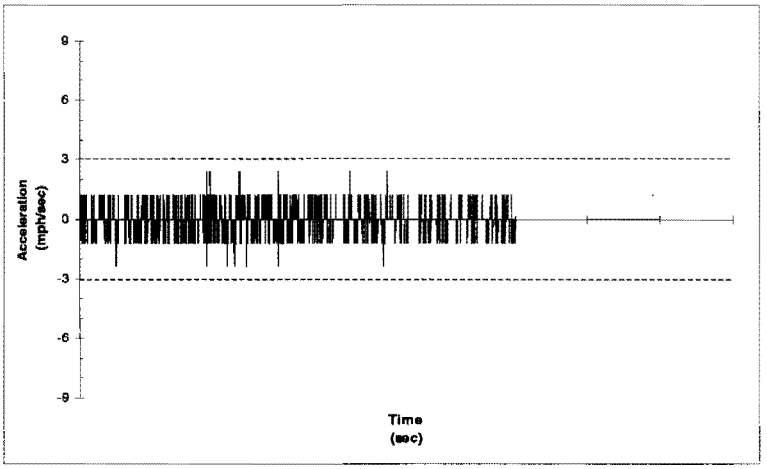
Alternatively, the emission result for a composite of vehicles could be multiplied by the traffic volume to obtain an overall emission estimate. For example, the emissions of a smaller sample of light-duty gas vehicles, heavy-duty diesel trucks, and so on could be averaged, with weightings corresponding to the representative distribution of vehicle types. This single emission value could then be multiplied by the traffic volume on the facility.

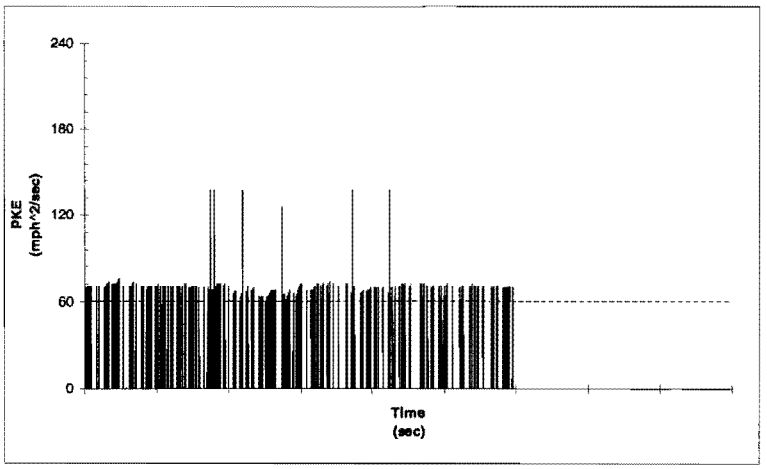
APPENDIX C

SPEED, ACCELERATION, AND PKE PROFILES VERSUS TIME

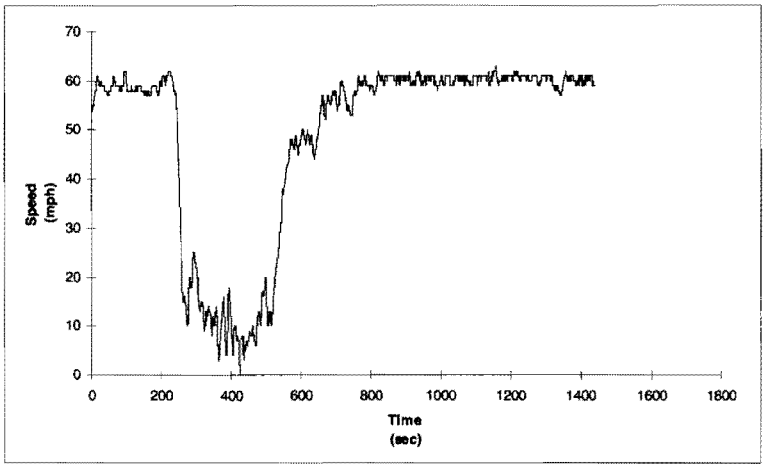
Sample: Katy Freeway 1 – AM Peak Period, Non-Peak Direction

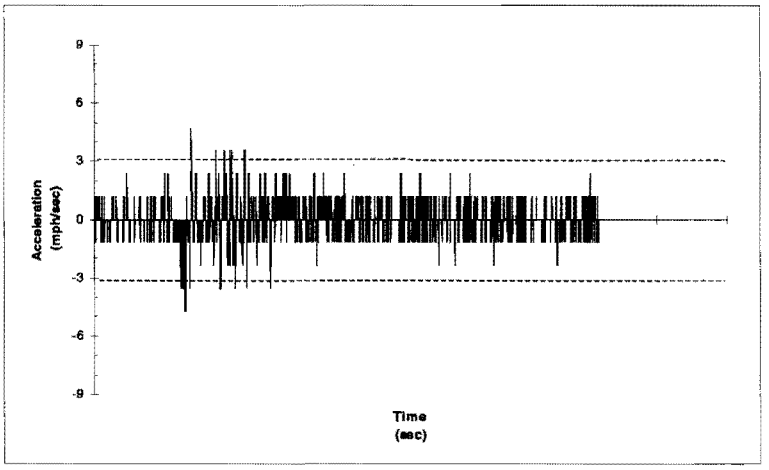


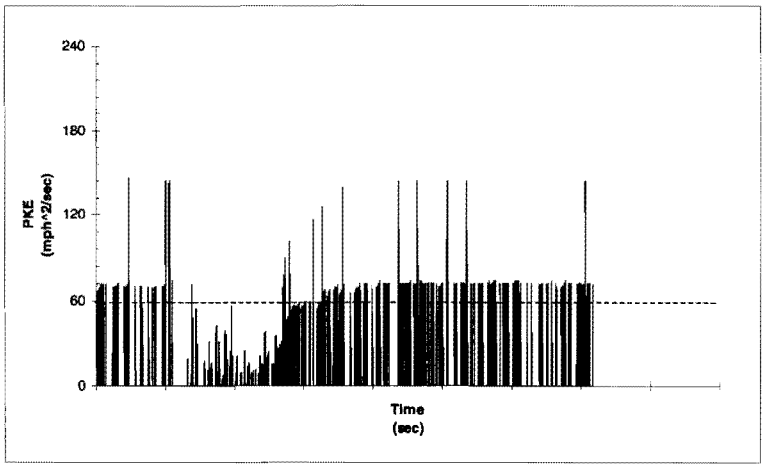




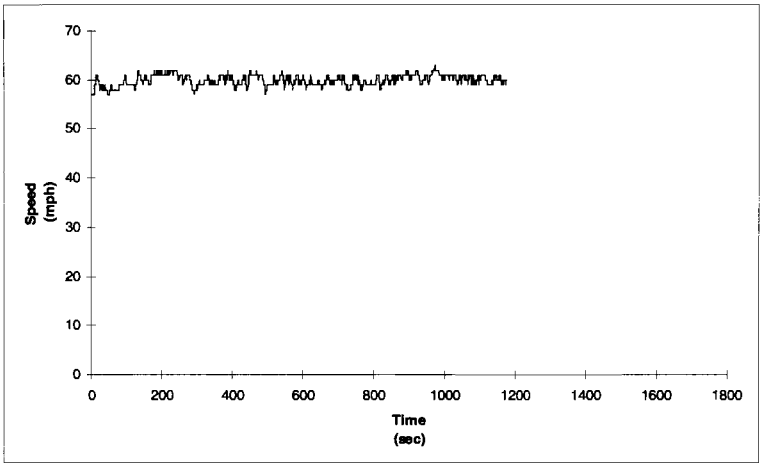
Sample: Katy Freeway 2 – AM Peak Period, Non-Peak Direction

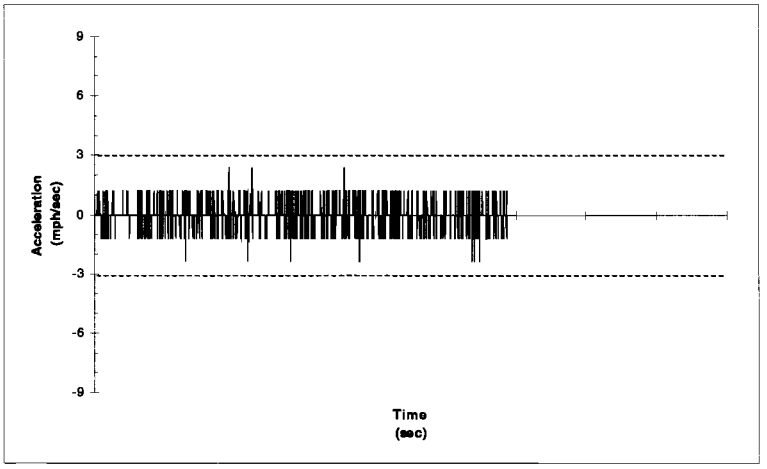


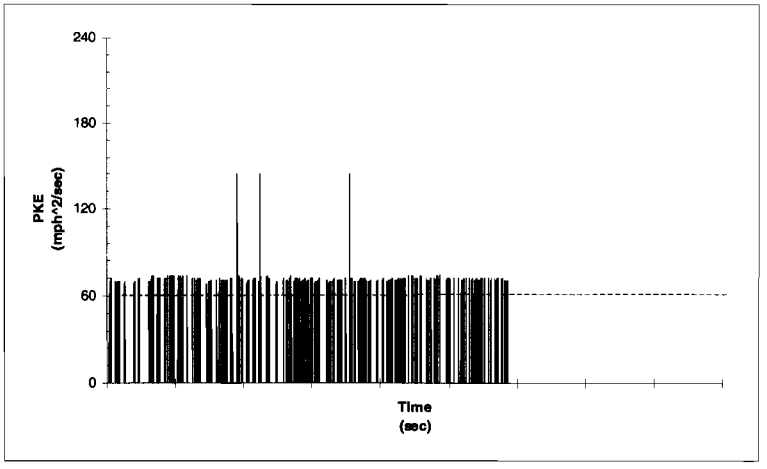




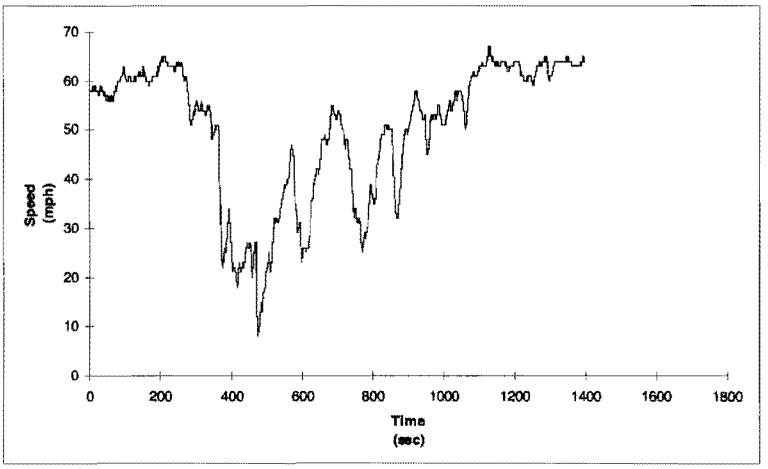
Sample: Katy Freeway 3 – AM Peak Period, Non-Peak Direction

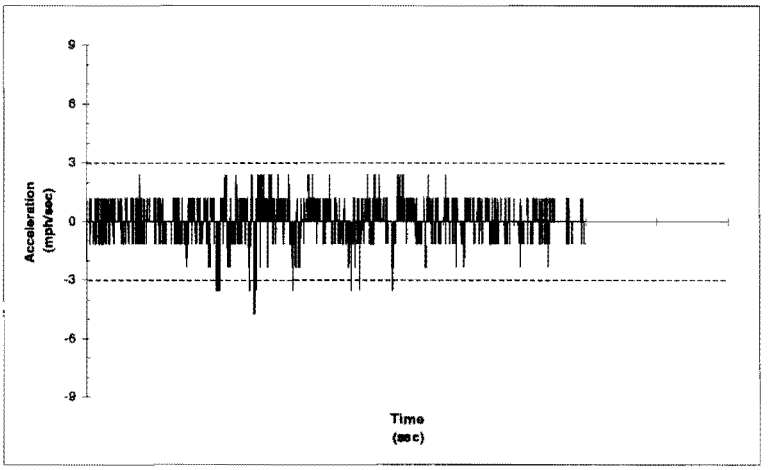


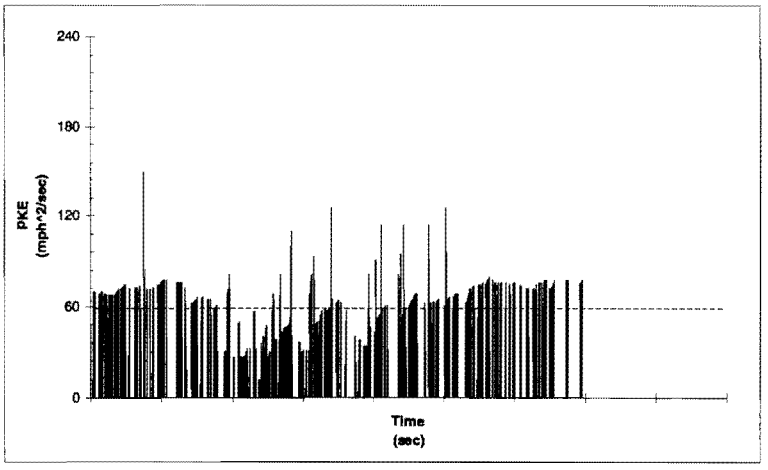




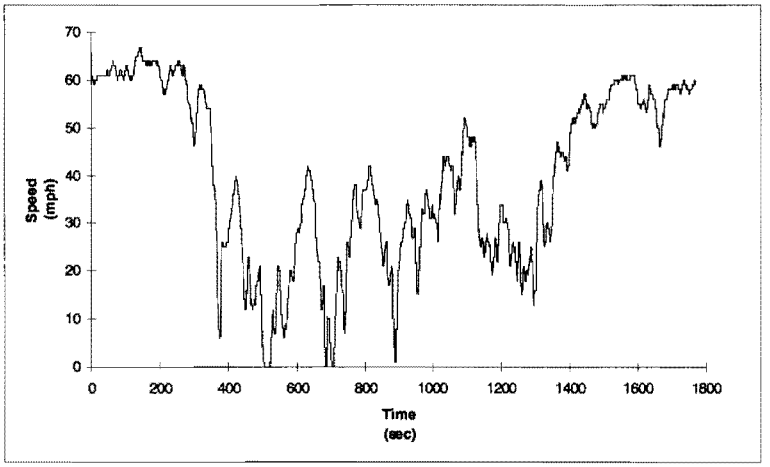
Sample: Katy Freeway 4 – PM Peak Period, Peak Direction

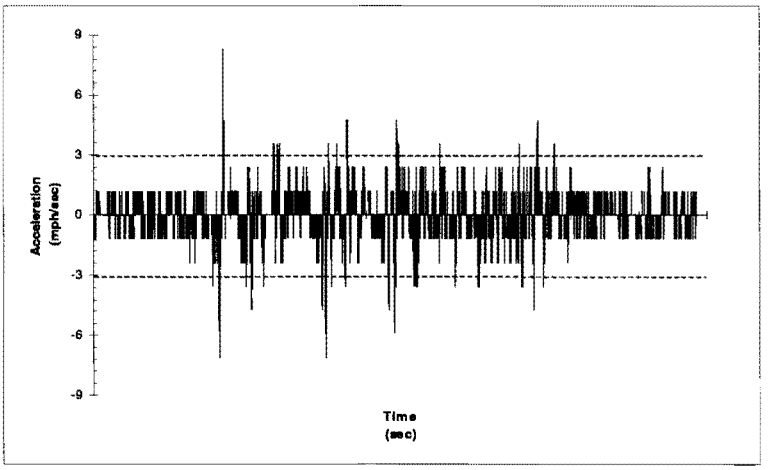


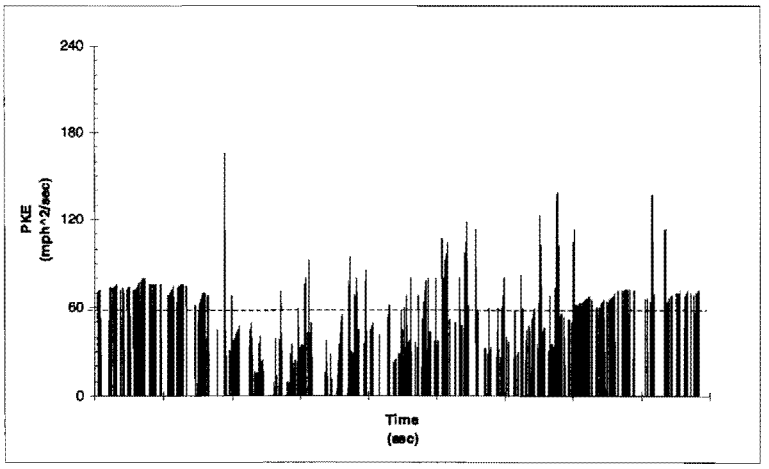




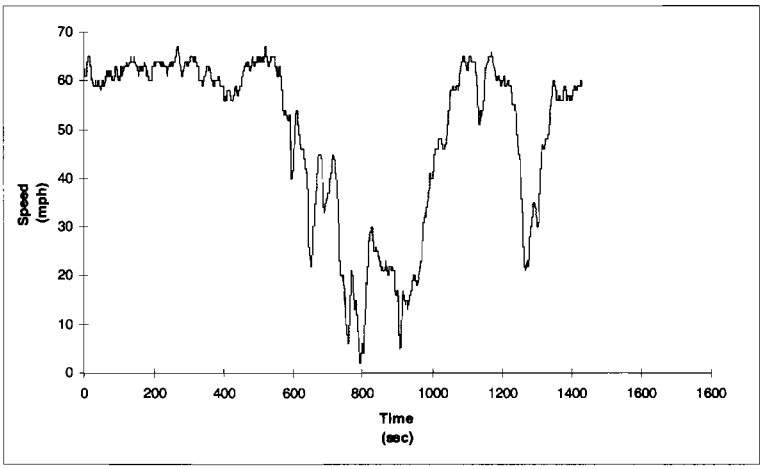
Sample: Katy Freeway 5 – PM Peak Period, Peak Direction

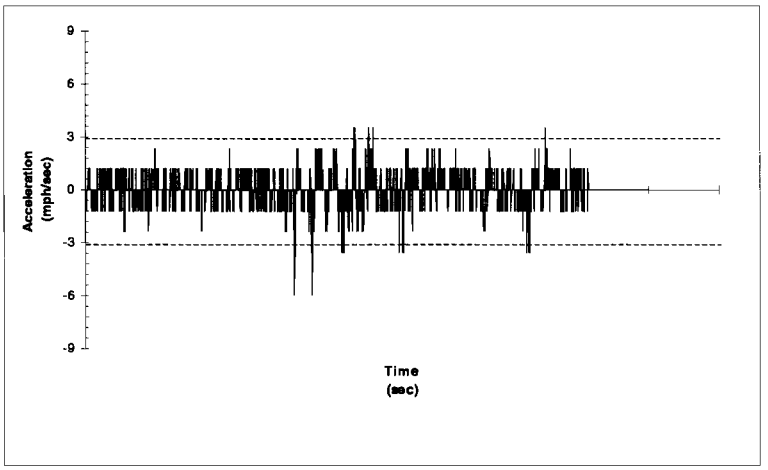


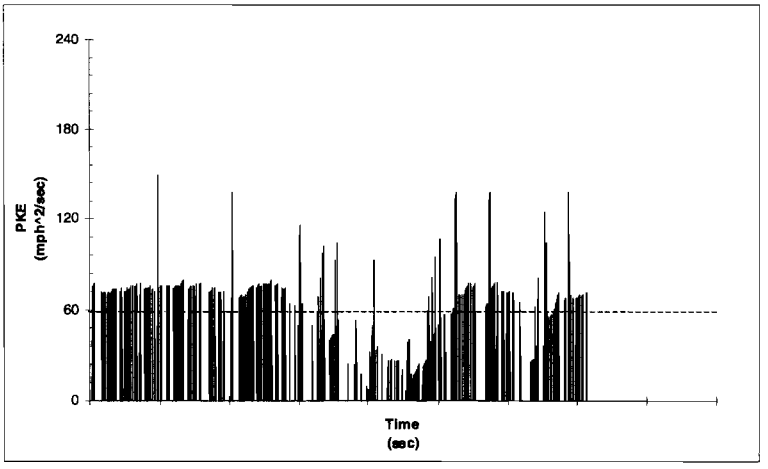




Sample: Katy Freeway 6 – PM Peak Period, Peak Direction







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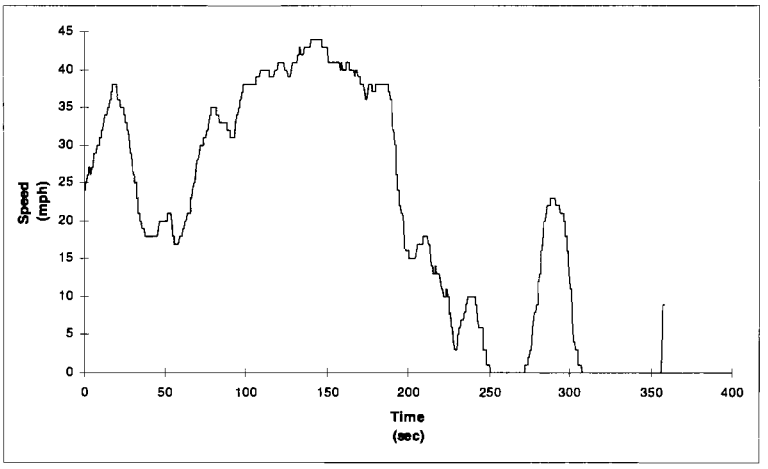
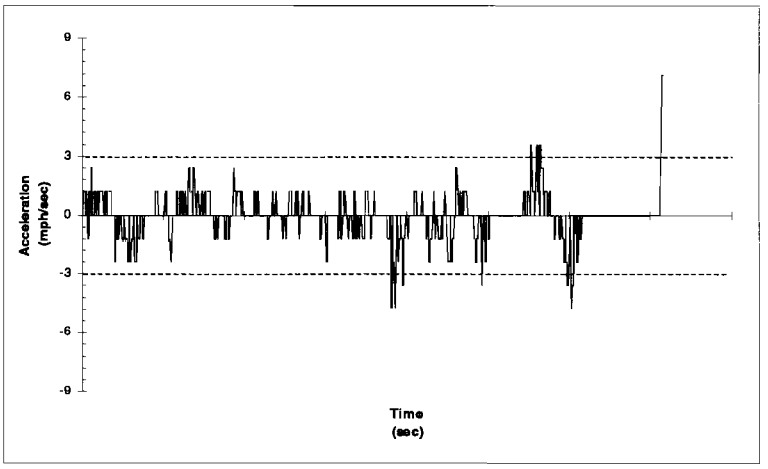
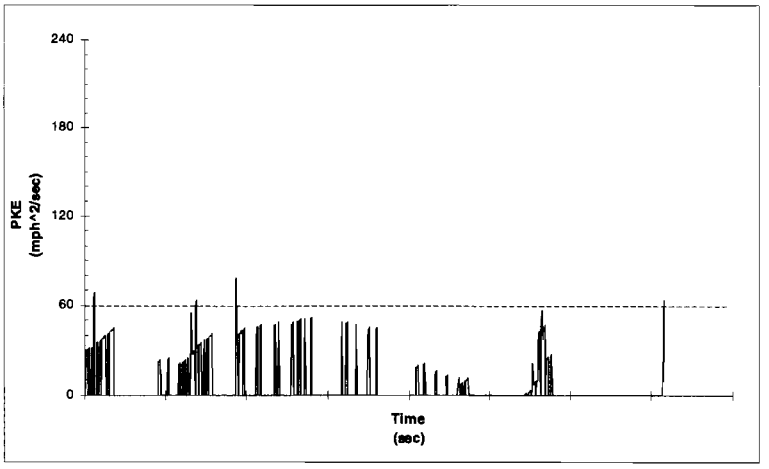
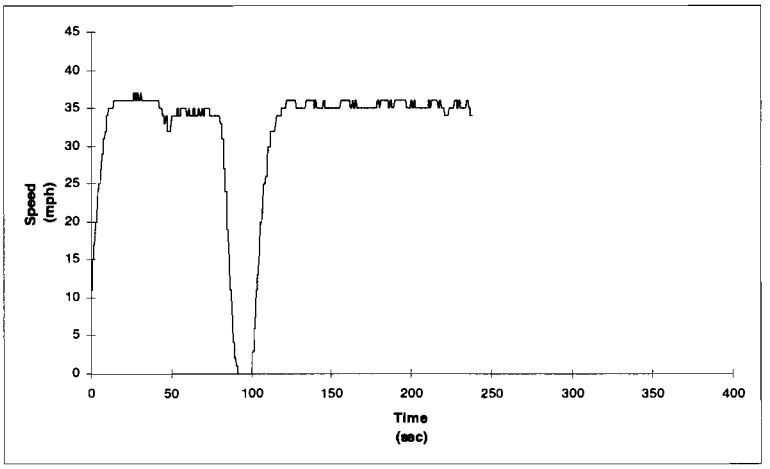
Sample: Richmond Avenue – AM Peak Period, Peak Direction

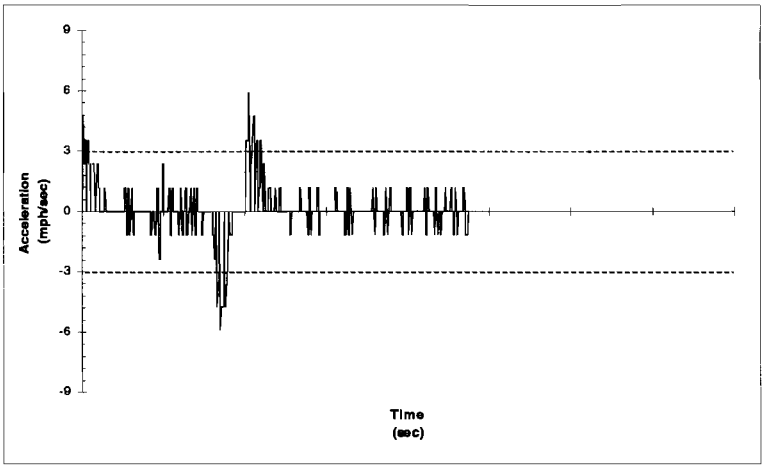


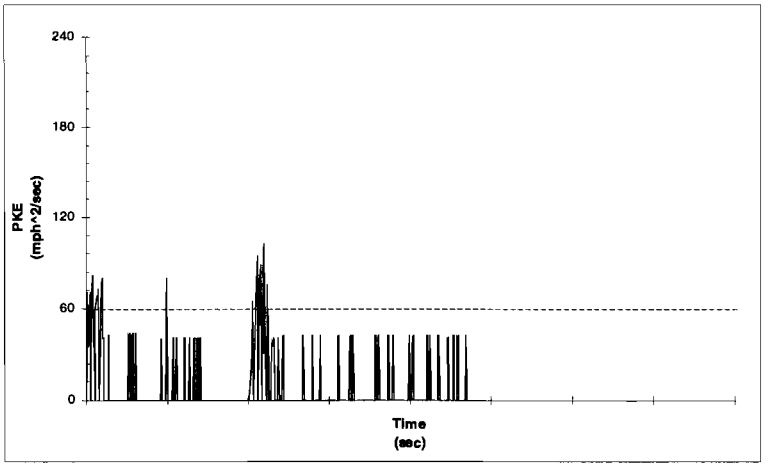




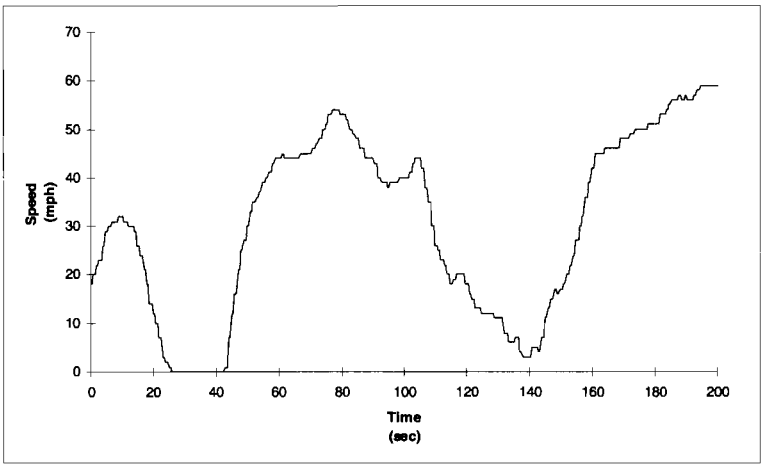
Sample: Richmond Avenue – PM Off-Peak Period, AM Peak Direction

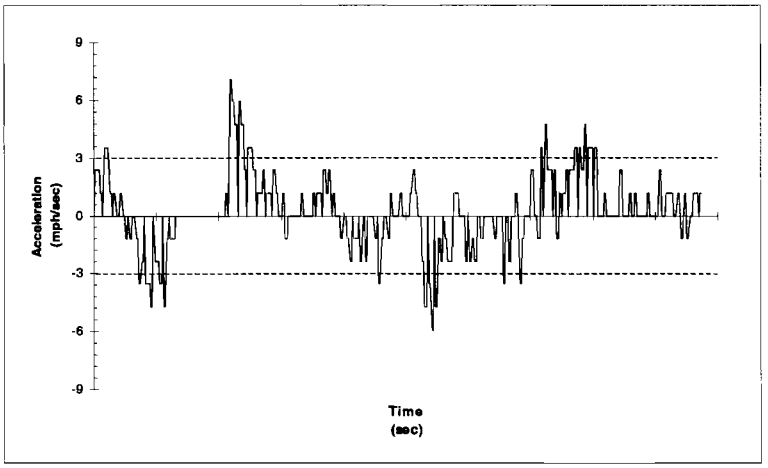


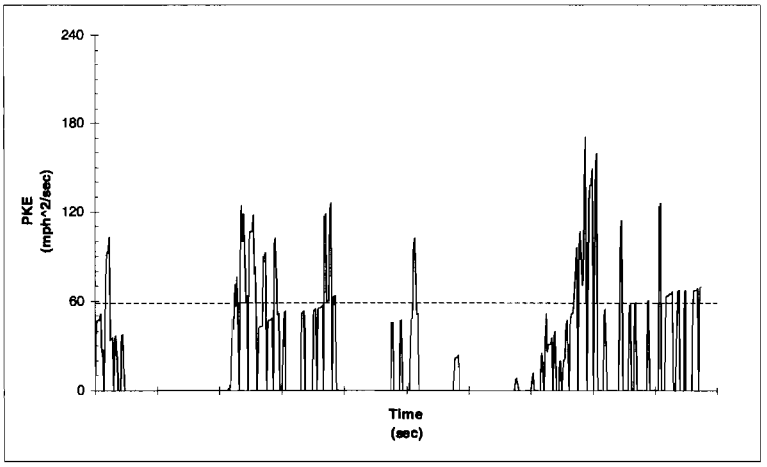




Sample: Southwest Freeway – PM Peak Period, Peak Direction







Sample: Southwest Freeway – PM Off-Peak Period, PM Peak Direction