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**16.** Abstract
This report presents a research effort for collecting the on-road vehicle emission data, developing the ONROAD emission estimation model and evaluating existing emission estimation models including the emission factor models MOBILE and EMFAC. The on-road emission data were collected from five highway locations in Houston using a Remote Emission Sensor (RES) called Smog Dog, which was developed by the Santa Barbara Research Center (SBRC). The SMOG DOG is used to collect the emission concentrations of CO, HC, and NOx, as well as to simultaneously record a vehicle's instantaneous speed value and **acceleration/deceleration** rates while its emission is detected. During the emission data collection, the ambient temperature and humidrty were periodically recorded. The collected emission data are used to develop the ONROAD emission estimation model, which consists of a series of emission estimation equations. In these emission estimation equations, the emission rates are made functions of a vehicle's instantaneous speed, **acceleration/deceleration** rate, ambient temperature and humidrty. It can be used to estimate the emission reductions that may be obtained through the operational improvements of traffic control and management strategies. The emission factors that are derived from MOBILE and EMFAC are compared with the collected on-road emission data by emulating the standard FTP driving cycles using the ONROAD emission rates. In general, both MOBILE and EMFAC are found to underestimate on-road vehicle emissions. However, these two models are the only EPA approved models for establishing mobile source emission inventories. Efforts are also made to compare the emission estimations in traffic simulation models with the on-road emission data. It is found that traffic simulation models considerably underestimate the on-road emissions, and thus these models are not recommended for use in performing any field vehicle emission analysis.

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# COLLECTION AND EVALUATION OF MODAL TRAFFIC DATA FOR DETERMINATION OF VEHICLE EMISSION RATES UNDER CERTAIN DRIVING CONDITIONS

by

Dr. Lei Yu, Associate Professor

Research Report Number 1485-1
Research Project Number 0-1485
Project Title: Collection and Evaluation of Modal Traffic Data for Determination of Vehicle Emission Rates Under Certain Driving Conditions

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# IMPLEMENTATION STATEMENT

This research collected on-road vehicle tailpipe emission data at five highway locations in the city of Houston. The remote emission sensor SMOG DOG was used to collect emission concentrations of CO, HC and NOx, as well as a vehicle's instantaneous speeds and acceleration rates for a combination of on-road vehicle types, ages and technologies. The ONROAD emission estimation model is developed which establishes relationships between the emission rates and vehicles' instantaneous speed, acceleration rate and ambient temperature. The existing emission estimation models including MOBILE and EMFAC emission factor models are compared and evaluated with the ONROAD emissions. The following recommendations for implementation of the research findings are provided:

1. The emission factor model MOBILE should continuously be used for the purpose of establishing mobile source emission inventories and performing various air quality planning functions. However, cautions should be given in selecting the input parameters to the model, such as the mix of vehicle types, ages and accumulated mileage, as it is found that using the national averages of these parameters underestimates the on-road emissions.

2. TxDOT should use the ONROAD emission estimation model in conjunction with a traffic simulation or a dynamic traffic assignment model in the evaluation of emission implications of .various traffic control and management strategies, as this model provides an effective means to determine how an alternative traffic network demand and control scenario will affect a vehicle's on-road instantaneous speed profile and thus the on-road vehicle emissions.

3. The emission estimation by existing traffic simulation models considerably underestimate emissions for on-road driving vehicles. Therefore, these models are not recommended for use in performing any field vehicle emission analysis.

4. On-road vehicle emission data should be collected routinely using the advanced infrared remote emission sensing equipment from various highway locations in Texas so as to establish more consistent and reliable on-road vehicle emission inventories and database.

5. A traffic simulation or dynamic traffic assignment model should be selected for incorporating the ONROAD emission model so that the evaluation of emission implications of alternative traffic network control and management strategies and various ITS applications can be consistently conducted.

## DISCLAIMER

The contents of this report reflect the views of the author, who is responsible for the facts **and** the accuracy of the **data** presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration ***(FHWA)*** or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

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# LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| BER | Basic Emission Rate |
| CAAA | Clean Air Act Amendment |
| CARB | California Air Resources Board |
| CFR | Code of Federal Regulation |
| CNG | Compressed Natural Gas |
| CO | Carbon Monoxide |
| EPA | Environmental Protection Agency |
| FTP | Federal Test Procedure |
| GIT | Georgia Institute of Technology |
| HC | Hydrocarbon |
| HDDV | Heavy Duty Diesel Vehicle |
| HDGV | Heavy Duty Gasoline Vehicle |
| HDT | Heavy Duty Trucks |
| HDV | Heavy Duty Vehicles |
| HESI | Huges Environmental Systems, Inc. |
| HEV | High Emitter Vehicle |
| HOV | High Occupancy Vehicle |
| I/M | Inspection and Maintenance |
| ISTEA | Intermodal Surface Transportation Efficiency Act |
| ITS | Intelligent Transportation System |
| LDDT | Light Duty Diesel Truck |
| LDDV | Light Duty Diesel Vehicle |
| LDGT | Light Duty Gasoline Truck |
| LDGV | Light Duty Gasoline Vehicle |
| LDT | Light Duty Trucks |
| LDV | Light Duty Vehicles |
| LEV | Low Emitter Vehicle |
| LNG | Liquefied Natural Gas |
| MDT | Medium Duty Trucks |
| MY | Model Year |
| NCHRP | National Cooperative Highway Research Program |
| NMHC | Non-Methane Hydrocarbon |
| NMOG | Non-Methane Organic Gases |
| NOx | Oxides of Nitrogen |
| OMS | Office of Mobile Sources |
| ppm | Parts Per Million |
| RES | Remote Emission Sensor |
| RPM | Rotes Per Minute |
| SBRC | Santa Barbara Research Center |
| SCAQMD | South Coast Air Quality Management District |
| UC | University of California |

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| VMT | Vehicle Miles of Travel |

## SUMMARY

In order to achieve the air quality goals and deadlines set in The Clean Air Act Amendments (CAAA) of 1990 and The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, transportation professionals have actively been searching for effective measures aimed at reducing vehicle emissions. Some of the existing measures, for example, include Employee Trip Reduction Programs, Ridersharing Programs with Vanpools or Carpools, and the use of Alternative Fuels such as Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG). In addition to these measures, which should be further evaluated in terms of their cost and effectiveness in reducing vehicle emissions, the use of traffic control and management strategies is an alternative that has the potential to significantly reduce the on-road vehicle exhaust emissions.

Traffic control and management strategies have been traditionally used to relieve traffic congestion and reduce vehicles' travel times. For a long time, there has been a perception in the transportation community that suggests that a traffic control and management strategy that can minimize travel times will automatically result in the minimization of vehicle exhaust emissions. Many recent research findings, however, have indicated that this perception is not accurate. In fact, the travel time is a function of only the average speed, while a vehicle's exhaust emission factor is found to be more related to its instantaneous speed profile. Therefore, an optimal traffic control and management strategy can minimize either travel times or emissions but not both concurrently.

The accurate modeling and estimation of vehicle exhaust emissions are very important in evaluation or optimization of traffic control and management strategies with vehicle emissions as the primary objectives, as opposed to the travel times. Three major vehicle exhaust emission species that affect the air quality the most considerably are identified as Carbon Monoxide (CO), Hydrocarbon (HC), and Oxides of Nitrogen (NOx). For a long time, these emissions have been estimated by using various emission models which include the Environmental Protection Agency (EPA) approved mobile source emission factor models MOBILE and EMFAC (in California only) and emission estimation in various traffic simulation models. MOBILE and EMFAC emission factor models are widely used to evaluate numerous air quality planning functions but require the average speed as the sole descriptor of a vehicle's modal events and driving conditions. This input requirement of average speed corresponds to a specific series of defined driving cycles, such as Federal Test Procedure (FTP) urban driving cycle and highway driving cycle. An emission factor model is used to produce the emission factors of CO, HC, and NOx for various vehicle classifications based on more specific inputs of ambient temperature, model and calendar year, fuel volatility and operating mode:

Since both MOBILE and EMFAC emission factor models are insensitive to a vehicle's modal events, such as acceleration/deceleration, cruise speed and idling, they cannot be used to effectively evaluate the traffic control and management strategies that are aimed at reducing vehicle emissions. These models offer little help for evaluating operational improvements that smooth traffic flow through better ramp metering, signal

coordination, incident management, High Occupancy Vehicle (HOV) lane operation, and various Intelligent Transportation Systems (ITS) applications. In addition, the emission factors in MOBILE and EMFAC are derived from the FTP driving cycles of in-laboratory emission testing. Their capability in representing the vehicle emissions for the on-road driving conditions was not extensively investigated.

Some of the traffic simulation and optimization models, such as TRANSYT-7F, INTEGRATION, NETSIM, and MTRAS, have incorporated their own emission estimation methods, but none of these methods was tested or validated based on the on-road driving vehicles. There are some on-going research efforts with respect to the development of new generation of modal emission models in University of California at Riverside (UC Riverside) and George Institute of Technology (GIT). However, when the new models will become fully operational and how effective these models can be used for the microscopic emission analysis of advanced traffic networks are still unknown.

The development of advanced infrared remote emission sensing technology brings us a cost-effective and convenient instrument for collecting on-road vehicle exhaust emissions. Although initially, the Remote Emission Sensor (RES) was proven to be useful and highly effective in screening for the High Emitter Vehicles (HEV) on the road, there are also advantages in using RES in emission model evaluation and emission model development. The emission data collected by RES naturally reflect the on-road vehicle fleet combinations and current vehicular technologies. It is inexpensive and easy to use comparing with the in-laboratory emission testing.

The on-road emission data were collected from five highway sites in Houston using a RES called Smog Dog developed by the Santa Barbara Research Center (SBRC), which is an application of space technology in vehicle emission sensing. The Smog Dog can collect the emission concentrations of CO, HC, and NOx. It can also simultaneously record a vehicle's instantaneous speed value and acceleration/deceleration rates while its emission is detected. The five locations selected for the emission data collection include two on-ramps, two off-ramps, and one signalized arterial. In order to collect the emission data for both acceleration and deceleration events, one of the two on- and off-ramp locations was selected at a slight uphill grade, while the other ones were on a slight downhill grade. During the emission data collection, the ambient temperature and humidity were periodically recorded.

The collected emission data were used to develop an emission estimation model called ONROAD, which consists of a series of emission estimation equations, using the standard regression technique. These emission estimation equations were designed to be sensitive to a vehicle's instantaneous speed profile. Specifically, the emission rates were made functions of a vehicle's instantaneous speed, acceleration/deceleration rate, ambient temperature and humidity. The ONROAD model represents a combination of on-road vehicle ages, mileage, model years, technologies and driving conditions. It can be used to estimate the emission reductions that may be obtained through the operational improvements of traffic control and management strategies, which usually can alter the on-road vehicles' speed profiles. If the ONROAD emission model is incorporated into a traffic simulation or dynamic traffic assignment model that can accurately predict the vehicles' modal activities in the traffic network, the emission implications of different traffic control and management strategies can then be evaluated and an alternative traffic control and management strategy with a vehicle emission as the objective can be optimized.

The emission factors that are derived from MOBILE and EMFAC are compared with the collected on-road emission data by emulating the standard FTP driving cycles using the ONROAD emission model. Generally, both MOBILE and EMFAC underestimate on-road vehicle emissions. Efforts are also made to compare the emission estimations of traffic simulation models TRANSYT-7F and INTEGRSTION with the on-road emission data. It is found that traffic simulation models estimate much lower emissions than the ONROAD emissions.

# CHAPTER 1: INTRODUCTION

## *Background of Research*

In order to achieve the air quality goals and deadlines set in The Clean Air Act Amendments (CAAA) of 1990 and The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, transportation professionals have actively been searching for effective measures aimed at reducing on-road vehicle emissions. Some of the existing measures, for example, include Employee Trip Reduction Programs, Ridersharing Programs with Vanpools or Carpools, and the use of Alternative Fuels such as Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG). In addition to these measures which need to be further evaluated in terms of their cost and effectiveness in reducing vehicle emissions, the use of traffic control and management strategies is an alternative that has the potential to significantly reduce the on-road vehicle exhaust emissions.

For a long time, travel time related factors have been the major concerns in both traffic management and transportation planning. For example, most of existing traffic assignment techniques (Yu and Van Aerde, 1996), which are central components to transportation planning and traffic network modeling, have used either the user travel time or the system travel time as the objective. On the other hand, the optimization of traffic signal timing plans (Courage and Wallace, 1991) has predominantly attempted to minimize either the delays or the number of stops. In all of these scenarios, the vehicle emission factors have always played implicit roles. In fact, the vehicle emission factors are not explicitly and quantitatively considered in selecting traffic control and management strategies primarily due to the limitations of existing emission modeling capabilities.

Traffic control and management strategies have been traditionally used to relieve traffic congestion and reduce vehicles' travel times. Many people in the transportation community have perceived that a traffic control and management strategy that minimizes travel times will automatically result in the minimization of vehicle exhaust emissions. The research by Yu and Stewart (1995), however, has indicated that this perception is not accurate. In fact, the travel time is a function of only the average speed, while a vehicle's exhaust emission factor is found to be more related to its instantaneous speed and acceleration/deceleration events. The research by Cicero-Ferandez and Long (1993, 1994) further indicated that the acceleration events contribute significant portions of emissions for the on-road vehicles. Therefore, travel times and emissions respond differently to vehicles' modal events such as acceleration/deceleration, cruise speed and idling, and thus they must also be considered differently in setting up a traffic control and management strategy.

The accurate modeling and estimation of vehicle exhaust emissions are very important in the evaluation or optimization of traffic control and management strategies with the emissions as the primary objectives, as opposed to the travel times. Three major vehicle exhaust emission species that directly contribute to the air pollution are Carbon

Monoxide (CO), Hydrocarbon (HC), and Oxides of Nitrogen (NOx). For a long time, the estimation of these emissions has relied heavily on various emission estimation models which include the Environmental Protection Agency (EPA) approved mobile source emission factor models MOBILE (US EPA, 1991) and EMFAC (CARB, 1996). EMFAC is used in California only because the state has stricter environmental standards than other states. MOBILE and EMFAC emission factor models are widely used to evaluate numerous air quality planning functions but require the average speed as the sole descriptor of a vehicle's modal events and driving conditions. This input requirement of average speed corresponds to a specific series of defined driving cycles, such as the Federal Test Procedure (FTP) urban driving cycle and highway economy driving cycle. An emission factor model is used to produce the emission factors of CO, HC, and NOx for various vehicle classifications based on more specific inputs of ambient temperature, model and calendar year, fuel volatility and operating mode.

Since both MOBILE and EMFAC are insensitive to a vehicle's modal events, such as acceleration/deceleration, cruise and idling, they cannot be used to effectively evaluate the traffic control and management strategies that are aimed at reducing vehicle emissions. These models offer little help for evaluating operational improvements that smooth traffic flow through better ramp metering, signal coordination, incident management, High Occupancy Vehicle (HOV) lane operation, and various Intelligent Transportation Systems (ITS) applications. In addition, the emission factors in MOBILE and EMFAC are derived from the FTP driving cycles of in-laboratory emission testing. Their capabilities in representing the vehicle emissions for the on-road driving conditions were not extensively investigated.

Some of the traffic simulation and optimization models, such as TRANSYT-7F (Penic and Upchurch, 1992), INTEGRATION (Van Aerde, 1994), FREQ(Imada and May), NETSIM (Rathi and Santiago, 1989), and INTRAS (Wicks and Liebermann, 1980), have incorporated their own emission estimation methods, but none of these methods were tested or validated for the on-road driving vehicles and conditions. There are on going research efforts with respect to the development of new generation of modal emission models in University of California at Riverside (An et al, 1997, Barth et al, 1997) and George Institute of Technology (Bachman et al, 1997). But when the new modal emission models will become fully operational and how effective these models can be used for performing the microscopic emission analysis of advanced traffic networks are still unknown.

The development of advanced infrared remote emission sensing technology brings us a cost-effective and convenient instrument for collecting on-road vehicle exhaust emissions. Although initially the Remote Emission Sensor (RES) was proven to be useful in screening for the High Emitter Vehicles (HEV) on the road (Bishop et al, 1994, Sorbe, 1995, Jack et al, 1995), there are many advantages to use RES in emission model evaluation and emission model development. This is because the emission data collected by RES will naturally reflect the on-road vehicle fleet combinations and current vehicular technologies. It is also inexpensive and easy to use comparing with the in-laboratory emission testing.

### *Objectives of Research*

The primary objectives of this research are to use a RES to collect on-road emission data, evaluate various existing emission estimation models with on-road emissions, and develop an emission estimation model that can be used to evaluate emission implications of alternative traffic control and management strategies. The emission data collection uses the Smog Dog (SBRC, 1995), a RES which was developed by the Santa Barbara Research Center (SBRC), which is an application of space technology in vehicle emission sensing. The Smog Dog can collect the emission concentrations of CO, HC, and NOx. It can also simultaneously record a vehicle's instantaneous speed value and acceleration/deceleration rates while its emission is detected. The new developed emission model will establish relationships between the on-road vehicle exhaust emissions and a vehicle's instantaneous speed and acceleration rate. This emission model can be used to evaluate emission implications of alternative traffic control and management strategies.

### *Outline of This Report*

The next chapter of this report will present the extensive review of the state-of-the-art emission estimation models including emission factor models, emission estimation methods in traffic simulation models, and on-going development of new generation modal emission models. Chapter 3 will then describe the emission data collection effort in this research including the description of the emission collection equipment, emission collection design and the actual emission collection activities. Chapter 4 will subsequently use the collected on-road emission data to develop an emission model, ONROAD, using the regression technique and describe the significance for using the ONROAD emission estimation model. Chapter 5 will evaluate the existing emission models based on the collected emission data for the on-road driving conditions. Finally, Chapter *6* will summarize various findings from this research and provide recommendations to TxDOT as how the research results should be implemented and what additional research effort. need to be made.

# CHAPTER 2: REVIEW OF STATE-OF-THE-ART EMISSION MODELS

This chapter intends to explore the existing emission modeling capabilities so as to establish the context for collecting on-road emission data and evaluate existing emission models in the following chapters. Over the past decades, many emission models have been developed for performing various air quality analysis functions. In general, emission estimation models can be roughly classified into three types. The first type is called the emission factor models, the second type is the emission estimation in traffic simulation models, and the third type is the new generation of modal emission models.

## *Emission Factor Models*

Emission factor models are used to generate emission factors for each emission species, which will be interfaced with travel demand models to calculate the mobile source emissions estimates. Specifically, an emission factor model calculates the emissions of HC, CO and NOx in grams per mile, a travel demand model supplies an estimate of Vehicle Miles of Travel (VMT), and the total grams of pollutants emitted by vehicles can be produced by multiplying the emission factors by the VMT. At present, there are two EPA approved emission factor models, MOBILE which is required by EPA to be used by all states but California and EMFAC which is used in California only.

### MOBILE Emission Factor Model

MOBILE is a computer program developed by EPA that estimates HC, CO and NOx emission factors for gasoline-fueled and diesel highway motor vehicles. While the version of MOBILE5a is used for writing this research report, the new version MOBILE6 is released and available from the summer of 1997.

MOBILE calculates emission factors for eight individual vehicle types in two regions (low and high altitude) of the country. Its emission factor estimates depend on various conditions such as ambient temperatures, average travel speed, operating modes, fuel volatility, and mileage accrual rates. MOBILE will estimate emission factors for any calendar year between 1960 and 2020, inclusive. The 25 most recent model years are considered to be in operation in each calendar year.

The eight vehicle types used in MOBILE include lightduty gasoline vehicles (LDGV), lightduty gasoline truck 1 (LDGT1), light-duty gasoline truck 2 (LDGT2), heavy-duty gasoline vehicles (HDGV), light-duty diesel vehicles (LDDV), light-duty diesel trucks (LDDT), heavy-duty diesel vehicles (HDDV), and motorcycles (MC). The MOBILE derives its emission factors by multiplying the Basic Emission Rate (BER) by a series of correction factors that account for various variables. All of the BER equations for light duty vehicles describing emissions as a function of accumulated mileage are based on the 19.6 mph (31.5 km/hr) average trip speed, which corresponds to the FTP urban driving cycle for light-duty vehicles (40 CFR Part 86).

The speed correction factors are derived from analysis of emission data taken from tests over driving cycles of different average speeds. The range of average speeds for which MOBILE contains speed correction factors is 2.5 to 65 mph (4.0 to 105 km/hr). The speed correction factors are divided into ranges of average speeds: low speeds, consisting of speeds from 2.5 mph to 19.6 mph; mid-range speeds, from 19.6 mph to 48 mph (77km/hr); and high speeds, from 48 mph to 65 mph. The general shape of the curves describing HC and CO emission as functions of average speed exhibits high g/mi emissions at very low speeds, with emission factors dropping rapidly as average speed increases up to 19.6 mph, then emissions dropping more slowly as average trip speed increases from 19.6 to 48 mph, no change in emissions in the rage 48 to 55 mph (88 km/hr), and finally emissions rising again as average speed increases.

The MOBILE uses the average speed as the sole descriptor of a vehicle's modal activities and all the effects of acceleration, deceleration, idling and cruise are aggregated into a single emission factor which represents the emissions for a complete trip of a vehicle. In order to more clearly demonstrate how the MOBILE emission factors are derived in association with the instantaneous modal activities, three standard FTP driving cycles are presented through Figure 2-1 to Figure 2-3. Figure 2-1 to Figure 2-3 illustrate the FTP urban driving cycle for light-duty vehicles, FTP highway fuel economy driving cycle, and FTP driving cycle for heavyduty vehicles. Consider Figure 2-1 as an example to show how the emission factors are derived. The vertical axis represents the instantaneous speed and the horizontal axis represents the time. The dots show the acceleration/deceleration rates.

The FTP urban driving cycle for light-duty vehicles consists of a cold start segment, a hot stabilized segment, and a hot start segment. Initially, the vehicle is stored for a minimum of 12 hours before testing to simulate a 12-hour overnight soak period. The vehicle is then driven over the start segment which lasts 505 seconds and the emissions collected are defined as Bag 1, cold start emissions. Once the vehicle is in a hot stabilized mode (engine and catalyst at normal operating temperature), Bag 2 emissions are collected over the remaining 867 seconds of driving. After a ten minute soak, the 505 seconds of the start segment is repeated and the emissions collected are defined as Bag 3, hot *start* emissions. The final emission factor is derived based on the weighted sum of the emissions from three bags divided by the total miles traveled.

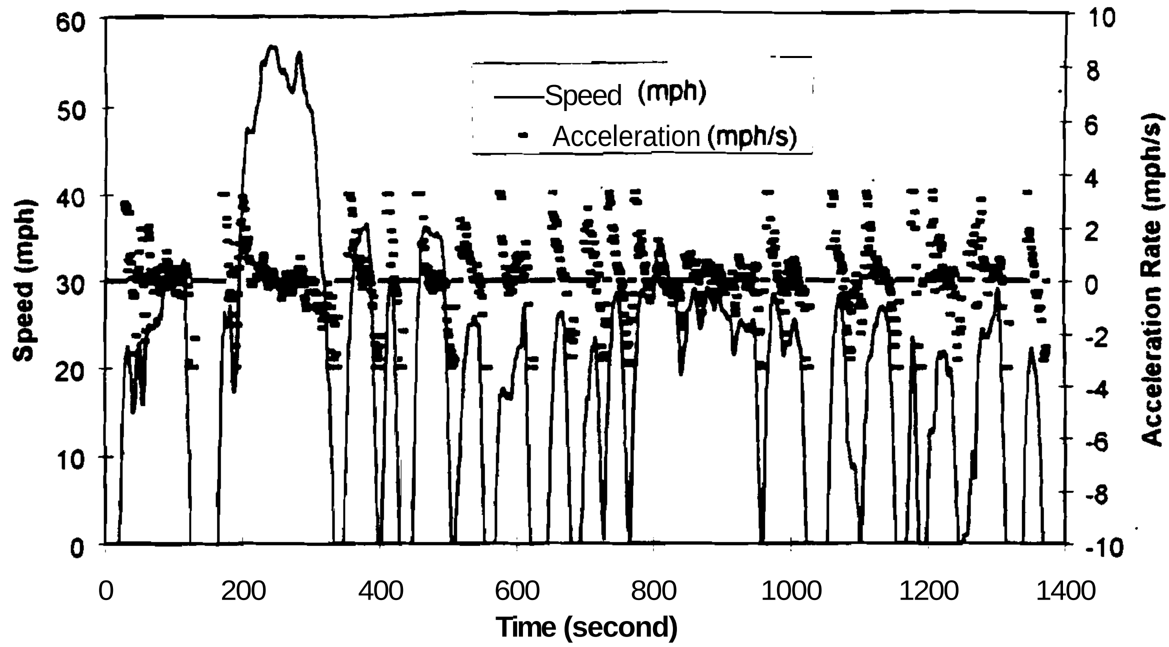


Figure 2-1: Time versus instantaneous speed and acceleration rate for FTP urban driving cycle for light-duty vehicles

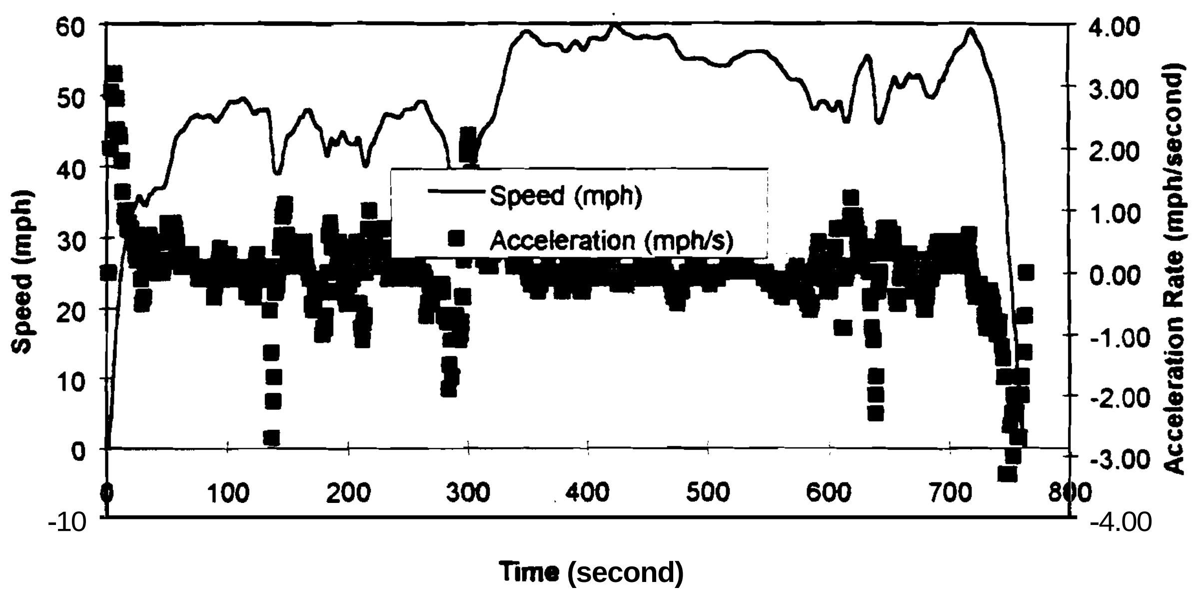


Figure 2-2: Time versus instantaneous speed and acceleration rate for FTP highway fuel economy driving cycle

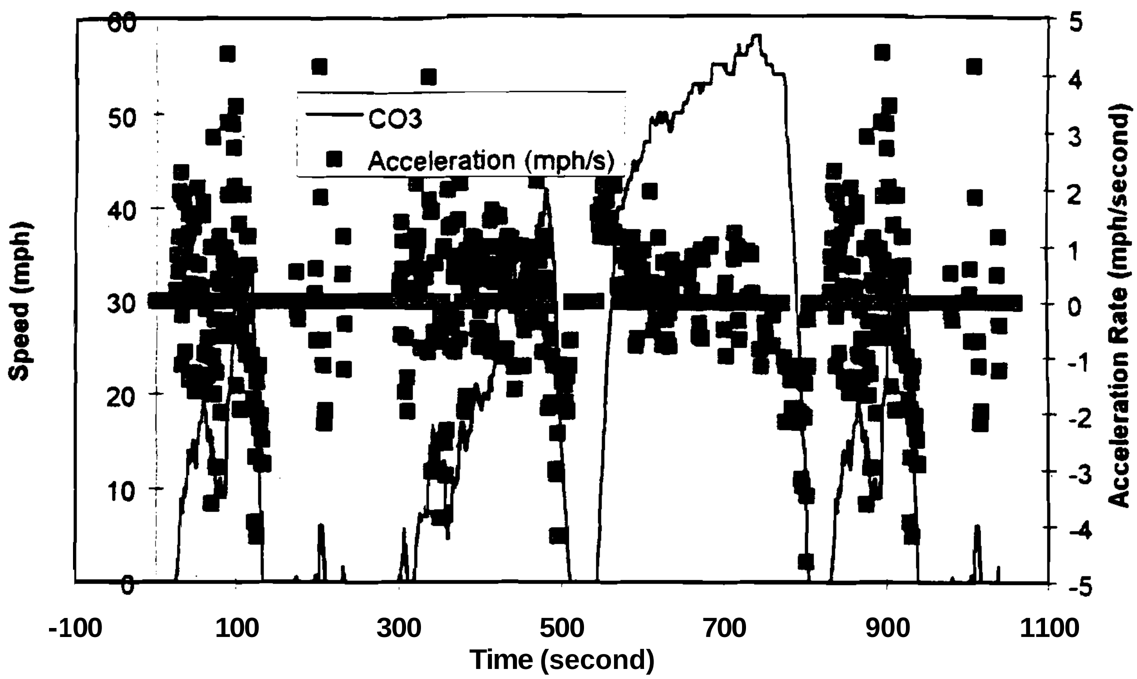


Figure 2-3: Time versus instantaneous speed and acceleration rate for FTP driving cycle for heavy-duty vehicles

MOBILE utilizes an input file that provides program control information and the data describing the scenarios for which emission factors are to be estimated. The input information consists of three distinct sections: the Control section, the One-time Data section, and the Scenario section. The Control section is the portion of the input file that controls the input, output, and execution of the program. For example, the Control section indicates whether MOBILE will require the user to supply additional input data, or analyze a scenario that includes an inspection and maintenance program, or output the emission factors in a format suitable for visual inspection or in a format suitable as input to another program.

Some parameters used in the emission factor calculations have internal values built into MOBILE. The One-time Data section is the portion of the input that allows the user to define parameter values different from those internal to MOBILE, which will be used in the calculations for all of the scenarios within a given run. For example, in the One-time Data section the user can specify alternate annual mileage accumulation rates or registration distributions by age for each vehicle type. In addition, the One-time Data section allows the user to specify further control program parameters, such as descriptions of inspection and maintenance programs.

The Scenario section is the portion of the MOBILE input that details the individual scenarios for which emission factors are to be calculated. For example, in the Scenario section the user specifies the calendar year of evaluation and the average speed(s) to be assumed. Each MOBILE run can include many scenarios, and each scenario can have different scenario parameters. Appendix A provides an example input file of MOBILE which shows where the Control section, One-time Data section and Scenario section locate. .

MOBILE generates four outputs, the interactive user dialog, which includes all input format specifications, prompting messages, diagnostic messages (errors and warnings), and formatted emission factor report. The formatted emission factor report includes the emission factor information for all the scenarios that were provided in the input file. The resulting emission factors include total HC, exhaust HC, evaporative HC, refueling HC, running HC, resting HC, exhaust CO and exhaust $NO_x$, for each of eight vehicle types as described earlier. These resulting emission factors can be combined with the total vehicle miles of travel, which can be derived from a travel demand model, to produce the final emission estimate for a target traffic network. Appendix B provides an example of the MOBILE output file.

## EMFAC Emission Factor Model

EMFAC emission factor model was developed by the California Air Resources Board (CARB) and the California Department of Transportation (CALDOT). California is allowed to use EMFAC instead of MOBILE because it has stricter environmental standard than the national standards and EMFAC produces slightly different results. It can generate exhaust and evaporative emission' factors of HC, CO, and $NO_x$. It can also estimate emissions for particulate matter from tire wear to exhaust. Its emission factors can be input into the BURDEN model to produce emission inventories.

Two companion models CALIMFAC and WEIGHT provide input to EMFAC in order to generate emission factors. CALIMFAC model produces base emission rates for each model year when a vehicle is new and as it accumulates mileage and the emission controls deteriorate. The WEIGHT model calculates the relative weighting each model year should be given in the total inventory, and each model year's accumulated mileage. The EMFAC uses these pieces of information, along with correction factors and other data, to produce fleet composite emissions factors.

The emission testing procedure for EMFAC emission factors is similar to that for MOBILE emission factors except that emission characteristics of California were considered and incorporated. The EMFAC uses a series of correction factors to simulate non-standard conditions of in-laboratory emission testing. The correction factors that are used to adjust the basic emission rates in EMFAC include fuel correction factors, speed correction factors, cycle correction factors, high emitter correction factors, bag correction factors, and composite emission factors.

The major difference between EMFAC and MOBILE is that EMFAC employs 13 combinations of vehicle classes and technology groups as opposed to only eight vehicle types in MOBILE. The 13 combinations of vehicle classes and technology groups include non-catalyst light-duty autos, catalyst light-duty autos, diesel light-duty autos, non-catalyst lightduty trucks, catalyst light-duty trucks, diesel light-duty trucks, non-catalyst medium-duty trucks, catalyst medium-duty trucks, non-catalyst heavy-duty trucks, catalyst heavy-duty trucks, diesel heavy trucks, diesel urban buses, and motorcycles.

The input data to EMFAC include the calendar year (any year between 1970 and 2020), model year, model year groups, either summer or winter inventory, speed range (3-65 mph), temperature range (30 - 110 F), I/M program on or off and type of output. The results of the EMFAC calculation can be formulated into one of the two types of output files. The report output file summarizes the data in a tabular format and the impact rates file summarizes the data for each possible combination of inputted parameters. The Appendix C provides an example input to EMFAC while Appendix D ill'ustrates an example of the report output file from the EMFAC.

### *Emission Estimation in Traffic Simulation Models*

Many traffic simulation models have incorporated emission estimation equations to enhance their capabilities in performing vehicle emission analysis of various traffic network scenarios and controls. Different from the EPA approved emission factor models, which require supplemental travel demand models for generating the final emission estimates, a traffic simulation model can produce a complete emission estimation of traffic networks with a single modeling package. The emission estimation in traffic simulation models is primarily designed and incorporated for evaluating the emission implications of traffic network demands and control strategies. Most of them are not approved by EPA for use in establishment of vehicle emission inventories.

The examples of traffic simulation models with the emission estimation capabilities include the TRANSYT-7F, INTEGRATION, FREQ, NETSIM, and INTRAS. The current version of TRANSYT-7F model (Courage and Wallace, 1991) does not have the emission estimation capabiities. Enhancements to the existing model have been suggested by Penic and Upchurch (1992), which would estimate emissions based on microscopic measures, mainly the four modes of a vehicle's motion: acceleration, deceleration, cruise and idle. The emission estimation in INTRGRATION (Baker, 1994) was based on a series of emission equations, which were developed based on the MOBILE emission outputs. The FREQ model (May, 1990) predicts vehicle emissions during a given time slice for a given subsection of the network based on results from the EMFAC emission factor model. The microscopic simulation model NETSIM (Rathi and Santiago, 1989) computes emissions on a link level based on a table of emission rates. INTRAS (Wicks and Liebermann, 1980), a microscopic model for freeway corridors, is also capable of providing link-specific values of vehicle emissions.

In the following subsections, the emission estimations in TRANSYT-7F and INTEGRATION will be described as representations to illustrate the difference between the emission factor models and the emission estimation in traffic simulation models.

## Emission Estimation Model for TRANSY-7F

TRANSYT-7F is a traffic signal simulation and optimization computer program, which uses a macroscopic deterministic platoon dispersion model to simulate the flow of traffic through a street network. It is used extensively through the United States to optimize the performance of urban signal systems with respect to delays and number of intersection stops. As indicated previously, the current version of TRANSYT-7F does not have the emission estimation capabilities. Penic and Upchurch suggested an enhancement to TRANSYT-7F for estimating emissions, which would involve modifying the TRANSYT-7F input routines to accept new data cards and adding pollution equations as subroutines.

The suggested TRANSYT-7F emission equations were developed based on the emissions data summarized by McGill (1985). The test procedure used combined laboratory and on-road tests using six vehicles. Data were collected in tabular form as a function of both acceleration and velocity. These six vehicles were tested for emissions of CO, HC and NOx. Upon completion of the tests, the consumption and emission values from all of the vehicles tested were averaged in proportion to each vehicle's contribution to the January, 1986, U.S. vehicle fleet.

For each emission species of CO, HC and NOx, the emission estimation is performed for four distinguished modes of travel, namely delay emissions, acceleration speed change emissions, deceleration speed change emissions, and constant speed emissions. The delay emission is a fixed value in the unit of grams per second, which is considered to represent the idling emission rate. The acceleration and deceleration emissions were made functions of initial and final speed values and the road grades. The constant speed emissions were made functions of a vehicle's instantaneous speed value and the road grades, which are considered to represent the emission rates for cruising.

The TRANSYT-7F emission estimation equations are virtually a modal emission model that captures each vehicle's modal activities, such that the emission effects of a traffic signal timing plan can be effectively evaluated. It should be noted that the sample size of test vehicles for TRANSYT-7F emission equations is very small and is not approved by EPA for use to provide the accurate estimation of emissions for attainment or non-attainment areas. However, these equations are still useful for evaluating how the vehicle emissions are affected by different traffic signal control plans.

## Emission Estimation Model for INTEGRATION

The INTEGRATION is a microscopic traffic simulation model, which was developed to analyze a number of specialized problems related to the operation, and optimization of integrated freeway/arterial traffic networks, of real-time controls and of route guidance systems. Its emission estimation capabilities were enhanced by incorporating the emission estimation model developed by Baker (1994). This emission model estimates the emissions of a specific vehicle as it experiences travel along a specified route, influenced by the traffic flow characteristics and the countless traffic management strategies associated with the driven network.

Baker initially developed a fuel consumption model for TravTek vehicles (Rillings and Lewis, 1991) in Orlando based on the fuel consumption data, which were collected over a five-month period. This fuel consumption model was later expanded to account for various driving environments, operating conditions and vehicle types by using the data provided in publicly available fuel consumption guides. Then a vehicle emission estimation model was developed based on strategically selected MOBILE output. The output from the MOBILE was generated by carefully selecting the inputs to the model such that results could be directly linked to the developed fuel consumption models. Using emissions and fuel consumption data, which correspond to similar driving cycles, operating environments, and vehicle types, a series of regression equations were calibrated which predict the quantity of HC, CO and NO that result from consuming a given volume of fuel.

The emission estimation model in INTEGRATION was designed as polynomial functions of the independent variables such as the instantaneous speed value and the ambient temperature. It can predict emissions for three vehicle classes, light-duty gasoline vehicles, light-duty gasoline trucks 1 and lightduty gasoline trucks 2. It can also predict the idling emission rate and cold start impact on emissions.

### *Other Emission Estimation Models*

As indicated previously, MOBILE and EMFAC predict vehicle emissions based in part on average trip speeds and were built upon regression analysis based on FTP defined driving cycles. Since these models are intended to predict emission inventories for large regional areas, they offer little help for evaluating operational improvements that are more microscopic in nature, such as ramp metering, signal coordination, and many ITS applications. What is needed is an emissions model that considers at a more fundamental level the modal operation of a vehicle such as idle, cruise, and various levels of acceleration/deceleration rates. While some of existing emission models in traffic simulation models provides some degrees of help, most of these models have not been extensively tested. In this context, research efforts are being made in University of California (UC) at Riverside and Georgia Institute of Technology (GIT) to develop new generation of comprehensive modal emission models.

### UC Riverside Modal Emission Model

UC Riverside is currently developing a comprehensive modal emissions model under sponsorship of the National Cooperative Highway Research Program (NCGRP Project 25-11). While the final model has not been ready yet at the time of writing this report, some preliminary results have been published (An et al, 1997, Barth et al, 1997). The overall objective of this project is to develop and verify a comprehensive modal emission model that accurately reflects the impacts of a vehicle's operating mode. The model is comprehensive in the sense that it will be able to predict emissions for a wide variety of Light Duty Vehicles (LDV) in various states of conditions (properly functioning, deteriorated, and malfunctioning).

The UC Riverside emission model is being designed so that it can interface with a wide variety of transportation models and transportation data sets. As part of the modal emission model development, 28 different vehicle/technology categories have been identified and are being implemented in the model. These vehicle/technology categories have been chosen based on vehicle class (car or truck), emission control technology (non-catalyst, 3-way catalyst, etc.), emission standard levels, power-to-weight ratio, and emitter level categories (normal emitter, high emitter).

The conventional emission factor models are based on bag emissions data of FTP driving cycles collected fiom certification tests of new cars, surveillance programs, and inspection/maintenance programs. These large sets of emissions data provide the basis for the conventional emission inventory models and are indexed primarily by model year. The emission data for the UC Riverside emission model were collected second-by-second fiom a sample of vehicles to build emissions for the national fleet. The choice of vehicles for this sample is crucial, since only a small sample (300+ vehicles) will be the basis for the model.

The input operating variables in the model include second-by-second speed (fiom which acceleration can be derived), grade, and accessory use (such as air conditioning). In many cases, grade and accessory use may be specified as static inputs or parameters. In addition, the vehicle soak time and special loads are specified as static input variables.

Since this model is not fully operational yet, the final input and output formats, and the actual mathematical equations for calculating the emissions are not available at this time. It is too early to judge what improvements could be made in this model over the existing emission models, how accurately the model can predict the on-road vehicle emissions, and how extensively the model can be used in practice.

### GIT Emission Model

There is an on-going research effort in Georgia Tech in conjunction with the EPA to develop a next generation modal emissions model within a Geographic Information System (GIS) framework (Bachman et al, 1997). Georgia Tech's modal emissions model is designed to improve emission estimates by considering a variety of vehicle activities, environmental factors, vehicle and driver characteristics, and the spatial and temporal distributions of these characteristics. The framework for this model is a modal basis, where emissions rates are employed for specific modes of vehicle operation. Important vehicle operating modes include engine starts, idle, hot stabilized operation, enrichment conditions (influenced by high acceleration and power demand), hot soak evaporation, etc.

The technology group definitions and corresponding emission rates for the model were developed through regression analyses of vehicle emissions test data (more than 700 vehicles and 4000 vehicle test). The emission data were derived based on real world driving with real-world fleets experiencing real-world driving environments. This means a research program based on remote sensing, on-road studies, instrumented vehicles, rather than simply supplements laboratory analysis.

The model employs on-network and off-network components. On-network estimates include activities, which are attributed to a transportation system on a link by link basis. On-network data used in emissions modeling may include temporally modeled and/or monitored traffic volumes, speeds, and fleet characteristics. Local roads, however, are included in an off-network database by aggregating their characteristics into mini-transportation analysis zones (analogous to the methods typically employed in travel demand forecasting models). Other off-network activity is handled on a zonal basis derived from socioeconomic and environmental data.

The activities for various vehicle technology groups are tracked within the model so that separate base emissions rates can be employed. Emission rate algorithms are based upon statistical analysis of emissions data and designed to reflect state of the practical emissions modeling. Emission rates will be determined for all the modes, which are modeled.

The Georgia Tech GIs-based emission model does not generate aggregate emission rates or emission factors like emission factor models. Instead, it predicts spatial and temporal allocation of motor vehicle emissions in an urban area. It requires the development and integration of new data and requires a large amount of time and effort to produce the data required. Costs associated with developing GIs-based emissions models are likely to be large primarily associated with model development, standardization, and integration of new data sources.

### *Summary of Emission Models*

As indicated in the proceeding sections, there exist three types of emission estimation models at present, emission factor models, traffic simulation emission estimation, and the new generation of modal emission models. Both emission factor models MOBILE and EMFAC use the average speed as the sole indicator of a vehicle's modal activities, and thus they cannot be used to evaluate the emission implications of operational improvements of traffic control and management strategies. While emission estimations in traffic simulation models are designed more sensitive to vehicles' modal events, their emission databases are very limited and they were not extensively tested and validated for their accuracy in representing the on-road vehicle emissions. The new generation of modal emission models are being developed at UC Riverside and Georgia Tech. The UC Riverside model relies more on the conventional in-laboratory testing of sample vehicles, while the Georgia Tech emission model is GIS based and is developed based more on remote sensing programs. Since both UC Riverside and George Tech

**models are not fully operational yet, no concrete conclusions can be drawn at this point with respect to the accuracy and capabilities of these models.**

# CHAPTER 3: ON-ROAD EMISSION DATA COLLECTION

In order to evaluate the emission estimation models reviewed in Chapter 2, the on-road vehicle emission data are collected. The remote vehicle emission sensing equipment is used as a tool in data collection. The major advantage of using a Remote Emission Sensor (RES) is that extensive emission data can be collected for the on-road driving vehicles and conditions in a cost-effective manner. The following sections in this chapter will briefly describe the RES that is used in this research, present the design of the data collection, and illustrate a summary of the emission data that are collected.

## *Data Collection Equipment: Remote Emission Sensor*

The RES that is used in the vehicle emission data collection is called SMOG DOG (SBRC, 1995 and Jack et al, 1995), which was developed by the Santa Barbara Research Center (SBRC), a wholly owned subsidiary of Hughes Aircraft Company. It is an application of advanced technology developed for environmental monitoring from space to accurate measurement of automotive emissions on earth. It was initially developed for providing a cost-effective tool for screening for high emitter vehicles and has experienced many successful applications in Arizona, California, North Carolina, Alaska, Georgia, and New Mexico. Some other states are also starting the use of RES to reduce automobile pollution.

The SMOG DOG, which consists of a sensor head, source, video camera, and state-of-the-art electronics for capture, display, and storage of both image data (automobile license plates) and vehicle emission data, uses a remote sensing technique that has been used for many years for satellite monitoring of ecological and environmental points of interest like earth's atmosphere and forest. In its vehicle emission sensing, infrared "light" is passed through a vehicle's exhaust plume and is absorbed by the different gases in the plume. The sensor determines changes in the selective absorption of infrared radiation by molecular vibrational modes at wavelengths specific to the pollutant; i.e., HC, CO, NOx, and $CO_2$. Changes are measured using chemically specific detectors, which sense radiation only at these wavelengths. The motion of a vehicle through the beam triggers the simultaneous measurement of CO, HC, NOx, and $CO_2$ in the dispersing exhaust cloud for a user-selectable period (typically one-second). The data from all four pollutants are analyzed in a real time and the results, expressed as a percentage of the exhaust, are stored on computer disk. The image data is stored on a VCR tape, which can be read by an operator and the license plate information is entered into the same file as the emission data.

The SMOG DOG can identify the high-emitting vehicles, and owners of these cars can then be notified that their cars are polluting and are encouraged to repair the cars. Because the SMOG DOG continuously samples the emission from vehicles on the road, a high-emitting vehicle will likely be identified and repaired. In this way, a dirty vehicle will have less of a chance of being driven and polluting the air. The SMOG DOG is non-obtrusive to drivers. The test is performed unknown to the driver in a fraction of a second as the vehicle passes by the sensor without having to slow down and increase traffic. Thus, it is a very cost-effective means of reducing air pollution. It can screen thousands of vehicles per day at low cost.

A special feature of the SMOG DOG system is its enhancement of the capability in detecting a vehicle's speed and acceleration rate. The instantaneous speed value and acceleration rate of a vehicle passing through the test site are monitored utilizing piezo strips and a computer. Speed and acceleration data are then transferred to the main system computer and stored with the vehicle records. The simultaneous measurements of emissions, speed and acceleration rate provide an opportunity to establish a relationship between the emissions and a vehicle's instantaneous speed profile.

### *Data Collection Site Selection*

A number of factors are considered in determining where the emission data should be collected. First, emission data should be collected for a wide range of speeds and acceleration rates in order to more accurately establish the relationship between the emission rate and a vehicle's speed profile. In this consideration, freeways can be used to collect emission data for high speeds, while the signal controlled streets can be used to collect emissions of vehicles at lower speeds. An on-ramp location is ideal for collecting emissions at acceleration mode while an off-ramp location suited to collect emission of vehicles that decelerate. Second, emission data should be collected for diverse geometric conditions in order to determine how geometric conditions influence the vehicle exhaust emissions. To this end, various highway sites of at-grade, up-hill grade, and downhill grade should be included. Finally, the safety of the equipment operator of the SMOG DOG should be considered. The current version. of the SMOG DOG requires the equipment operator to walk cross the highway several times in setting up the emission sensor, laying out the piezo strips across the pavement, and calibrating the entire emission sensing system before the actual emission collection can be conducted. Therefore, setting up the system onto a multiple lane freeway or major arterial location places the equipment and operator at a high safety risk.

With all of the above considerations in mind, many locations in the city of Houston were evaluated and finally five highway locations were earmarked for the emission data collection. Of the five locations, two are on-ramps, two are off-ramps and one is on a signalized street. For the on-ramp and off-ramp locations, one of each is on a slight uphill grade while the another one of each is on a slight downhill grade. While the vehicle emission data for an idling mode should also be collected for the completeness of the emission data set, the operation of SMOG DOG requires that the vehicle must be in motion. Hence, the on-road emission data for the idling mode can not be collected in this research. The selection of only five locations for emission data collection may not be ideal, because many traffic and geometric conditions are not included. For example, it would be ideal to include highways with various uphill and downhill slopes, as opposed to only two uphill and downhill distinctions. Also, various traffic conditions such as vehicles in front of a traffic signal, vehicles after a traffic signal, platoon dispersion vehicles, free driving vehicles, vehicles at merging areas, vehicles at diverging areas, etc., should all be included. However, the scope of this research project in terms of the funding has limited the emission collection designs to five highway locations. In fact, considering the cost in using the SMOG DOG, the scope of this research can only support the emission collection for five days.

Considering the time for setting up the SMOG DOG equipment and the need for collecting sufficient emission data for each location, it is not practical to collect emissions from more than one location on each day. Therefore, five highway locations were selected for collecting emissions and each location was collected for an entire day. The actual emission data collection work was conducted during the period of April 29 to May 3, 1996. Table 3-1 illustrates the list of locations that were selected for the data collection as well as the actual date that each collection exercise was conducted.

Table 3-1: List of emission data collection locations in the city of Houston

| # | Location | Characteristics | Collection Data |
|---|---|---|---|
| 1 | Holcombe & Yellowstone Blvd. Onto the I-288 Southbound | On-ramp with approximately 150 meters long and a 3 4 percent downhill grade | April 29, 1996 |
| 2 | Reed Rd. Onto I-288 Northbound | on-ramp with approximately 250 meters long and a slight uphill grade | April 30,1996 |
| 3 | I-288 Southbound off to Reed Rd. | Off-ramp with approximately 250 meters long and a slight downhill grade | May 1,1996 |
| 4 | I-288 Northbound off to Yellowstone & Holcombe Blvd | Off-ramp with approximately 150 meters long and a 3 4 percent uphill grade | May 2, 1996 |
| | between Holly Hall Rd. and El | Signal controlled surface street with a level grade | May 3, 19% |

It should be noted that all the emission data collection using the SMOG DOG did not consider the effect of cold start and hot start conditions of vehicles, although it is equally important to consider these factors in evaluating the existing emission estimation capabilities, as all the emission factor models have considered these conditions as proportional contributors to the entire emissions. The emission data collected in this research are considered to represent the emissions under hot stabilized mode of vehicles.

### *On-Road Emission data Collection*

The on-road emission data were collected from the five locations selected above with the assistance of a technician from the SBRC. The final products of this emission collection efforts include standard ASCII files which include emission concentration percentages and speed and acceleration data, hourly updates on ambient temperature and humidity, license plate TIF files, and video tapes of the rear of vehicles with emission data superimposed.

As an illustration of the remote emission sensor SMOG DOG, three photos were taken during the emission data collection. In the following Figure 3-1, the equipment on this side of the on-ramp pavement is the source, the other side has the sensor head, and the piezo strips are shown on the pavement surface. Figure 3-2 shows the video camera, which was set on the back of the SMOG DOG system. Figure 3-3 illustrates the van within which the entire computer system is built and connected with other equipment.

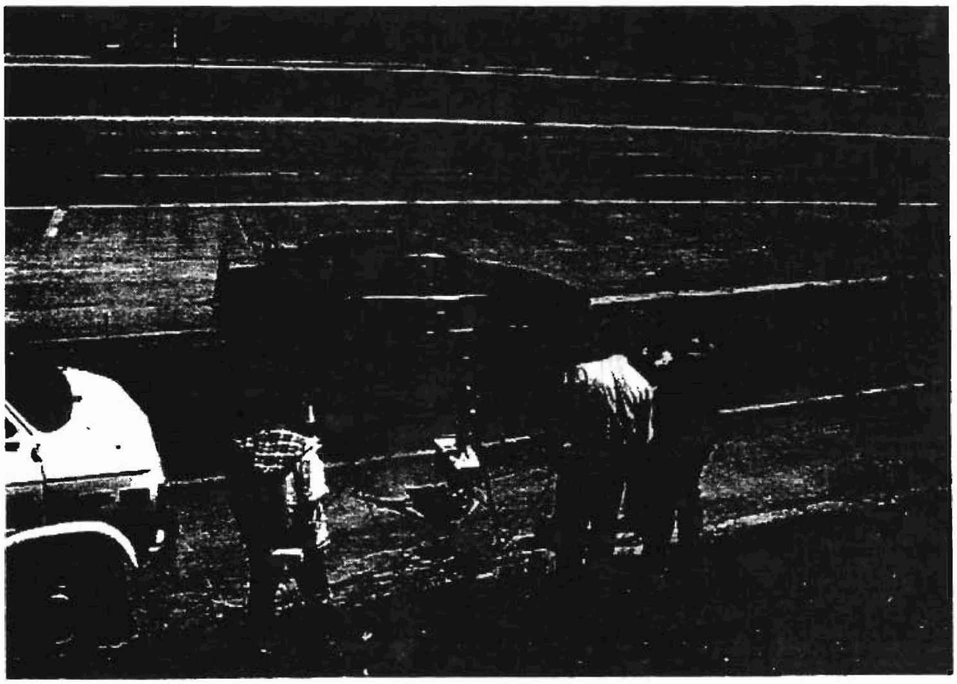

**Figure 3-1: Illustration of source, sensor head and piezo strips during emission data collection**

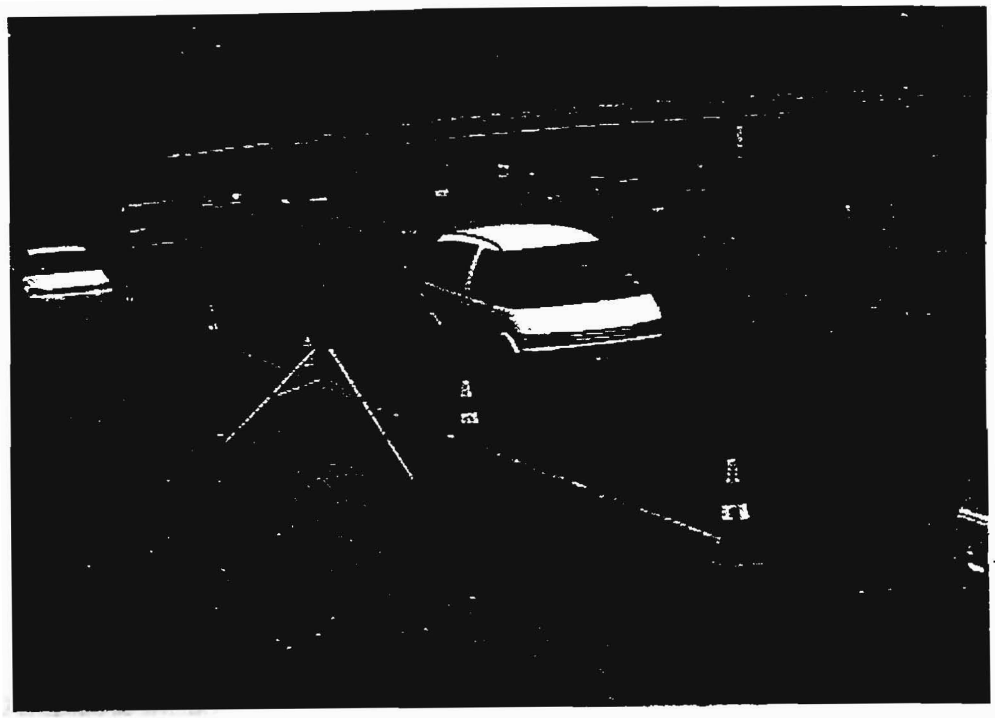

Figure 3-2: Illustration of video camera location during emission data collection

Figure 3-3: Illustration of the van, which includes the entire computer system during emission data collection

In the end, the on-road emission data collection resulted in a total of 1062 data samples for Location 1, **828** data samples for Location 2. 1000 data samples for Locations 3 and 4, and **738** data samples for Location 5. Appendix E illustrates a sample of the collected emission data, while a complete documentation of collected emission data can be found in a separate TxDOT Report **1485-2.** The following Table **3-2** interprets the meaning of each column in the collected emission data file in Appendix E.

Table **3-2:** Collected emission **data** file header

| Column | Interpretation | Column | Interpretation | Column | Interpretation |
|---|---|---|---|---|---|
| 1 | Vehicle No. | 8 | HC% | 15 | Speed 2 |
| 2 | Date | 9 | Slope CO | 16 | Acceleration Rate |
| 3 | Time | 10 | Slope HC | 17 | NOx% |
| 4 | Sensor No. | 11 | Max $CO_2$ | 18 | Slope NOx |
| 5 | License Plate No. | 12 | Max CO | 19 | Max NOx |
| 6 | CO% | 13 | Max HC | | |
| 7 | $CO_2$% | 14 | Speed 1 | | |

In this research, the emission concentrations of CO, HC, and NOx in Columns 6, **8,** and 17, and the speed and acceleration data in Columns 14-16 will be used. Columns 9-13 and 18-19 are useful in the derivation of emission concentrations within the SMOG DOG computer processing and will not be directly used in this research. Interested readers can find more detailed description about these columns from the reference SBRC (1**985).**

# CHAPTER 4: DEVELOPMENT OF ONROAD EMISSION MODEL

Chapter 2 reviewed the existing methodologies for estimating vehicle emissions. Chapter 3 presented an effort for collecting on-road vehicle emission data using the remote emission sensor at five selected locations in the city of Houston. This chapter attempts to develop an emission model, consisting of a series of emission estimation equations, based on the on-road collected emission data. This new emission model, which is named ONROAD, will be compared with the existing emission models in next chapter so that the accuracy of existing emission models in representing on-road emissions can be evaluated. Since the ONROAD emission model is made sensitive to a vehicle's instantaneous operating modes such as the instantaneous speed and acceleration, it can be incorporated into a dynamic traffic assignment or traffic simulation model so that the emission implications of traffic network operations and various traffic scenarios can be evaluated.

## *Emission Data Conversion and Reduction*

As illustrated in Appendix E, the collected on-road emission data for CO, HC, and NOx are concentrations in the unit of percentage or parts per million (ppm). Obviously these emission data cannot be successfully compared with the emission factors or emission rates that are generated by the existing emission models such as MOBILE and EMFAC. Usually, emission factors and emission rates in the units of grams per mile and grams per second are more useful units in practice. Therefore, the first step in processing the collected emission data will be to convert these data from the unit of concentration to the unit of emission factors or emission rates. While the author did not find, in the literature, any differences in using the terms of an emission factor and an emission rate, the following definitions of emission factors and emission rates will be used in the rest of this report in order to clarify which unit, grams per mile or grams per second, is implicated each time a term is mentioned: an emission factor represents the emissions in grams per mile while an emission rate represents emissions in grams per second. The lack of the capability for directly collecting emission factor/rate is a drawback of the remote emission sensor SMOG DOG at its current design.

### Conversion of Emission Concentrations to Emission Rates

Conversion of emission concentrations to emission rates is a very difficult task. While most of the time emission concentration can be directly related to emission rates, in some cases emission concentration is not related to the emission rate at all. In a research report prepared by the South Coast Air Quality Management District (SCAQMD), the linear correlation relationships were developed between the emission concentrations from the smog check data and IM240 emissions in *grams* per mile readings (Huges, 1995). While this conversion method is not perfect, it is the only one that exists at this time.

The smog check test and IM240 test are two tests that are implemented in California to enhance the Inspection and Maintenance (I/M) program. The smog test detects the emission concentrations of the exhaust of vehicles at idle and at a fast idle speed of approximately 2500 RPM. If the emission concentrations exceed the emission thresholds which are specific for each vehicle type and model year, the vehicle will be sent to conduct the IM240 test which can identify the emissions in grams per mile to confirm if the vehicle is a High Emitter Vehicle. The IM240 test lasts for 240 seconds, which was developed as a time efficient substitute for the more involved Federal Test Procedure (FTP) test.

Recognizing the problem that the Smog Check Test cannot provide the mass emission data needed to quantify emissions, the SCAQMD developed correlations between smog check data and IM240 mass emissions readings. These correlations were based on data from AQMD's Orange County remote sensing program, the City of Los Angeles Remote Sensor Program, and Hughes remote emission sensing data. The equations based on these data were developed so that CO and HC values in grams per mile based on measured Smog Check Test concentration data for these pollutants could be estimated. The correlations are as follows:

**Equation 4-1**

$$\text{CO (gm / mi)} = 11.1 \times \text{CO (\%)} + 21.3, \; R^2 = 052$$

**Equation 4-2**

$$\text{HC (gm / mi)} = 63.3 \times \text{HC (\%)} + 1.7, \; R^2 = 0.42$$

It was not possible to develop a similar relationship for NOx because it was not measured in the smog check test. Therefore, in the rest of this report, emission modeling for only CO and HC are conducted, while any further research on NOx will not be included in this report. Equations 4-1 and 4-2 are used to convert the collected emission concentrations of CO and HC into the emissions in grams per mile. The emissions in grams per mile are further converted into the emission rates in grams per second based on the instantaneous speed of each vehicle when the respective emission data was recorded. The Equation 4-3 is used for this purpose.

**Equation 4-3**

$$\text{CO / HC Rate (gm / s)} = \frac{\text{CO / HC (gm / mile)} \times \text{Speed (mile / hr)}}{3600}$$

## Emission Data Reduction and Vehicle Type Definition

After all the emission data are converted from the original concentrations to the grams per mile to the final grams per second, any invalid data is deleted from the database. The invalid data represent the instances when SMOG DOG was unable to detect or identify certain types of emissions. In these circumstances, the data were recorded as 99999. Thus, the initial data reduction process screened for the valid data for CO and HC emissions and resulted in two groups of a database. One group contains the valid CO emission data and the other one lists the valid HC emission data.

Recalling that MOBILE and EMFAC emission factor models can produce emission factors or emission rates for more detailed classified vehicle types as indicated in Chapter 2, it is felt that the collected emission data should also be classified into different vehicle types. Since the scope of this research does not generate detailed information about each vehicle that was detected in terms of what vehicle type it belongs to, MOBILE or EMFAC like classifications of vehicle types are impossible. It is noted that the emission data collected using SMOG DOG has generated videotapes, which recorded the image of each detected vehicle. Using these videotapes, the vehicles can be visually classified into different types. Due to the limitation of the video, it is not possible to classify vehicles into the detailed categories as in MOBILE and EMFAC. In the end, three vehicle types were classified in this research as follows:

- Vehicle Type 1 (W-I): passenger cars,
- Vehicle Type 2 (W-2): van and pick-up trucks,
- Vehicle Type 3 (W-3): other trucks, and
- Aggregate (W): all vehicles.

While the above classification of vehicle types seems coarse, it is not expected to affect the accuracy of the final modeling of the on-road emission data. As a matter of fact, the objective of any emission estimation is to produce the aggregate emissions from all vehicles in the network instead of calculate emissions for each vehicle type. If the coarse classification of vehicle types and the relatively aggregate modeling of emissions can represent the emissions of on-road vehicle fleet combinations, more detailed emission estimation of each specific vehicle type will not be necessary. Nonetheless, readers should note the difference between the vehicle classifications in this research and in conventional emission factor models.

For traffic engineering analysis purposes, the simpler classification of vehicle types should be more meaningful. For example, if a traffic engineer intends to use a traffic simulation model or a dynamic traffic assignment model (Yu and Van Aerde, 1996) to estimate the emission implications of traffic network scenario and controls, the available input information to the model usually does not include the information on detailed vehicle types. In this application, an aggregate emission model of a coarse classification of vehicle types is more useful.

After the conversion and reduction of the collected on-road emission data as described above, the CO emissions and HC emissions are organized into the following data groups, namely the VT, VT-1 emissions group, W-2 emissions group and VT-3 emissions group. Figure 4-1 illustrates the scattered CO emission data for the aggregate emissions for the instantaneous speed versus CO emission rate. It can be noted from this graph that the data are heavily concentrated around the lower portion of the scattered points, while some emission data are spread over the higher portion of the data area. The emission data falling into the higher portion of the graph can be considered a representation of the high emitter vehicles. The bottom line formed by the congested emission data points can be considered to represent the emission rates of the new vehicles. It can be seen from this graph that no vehicles will emit emissions that fall beiow this tidy bottom line. Graphs 4-2 to 4-4 represent the similar graphs for CO emissions for VT-I, W-2, and VT-3, while Graphs 4-5 through 4-8 represent similar graphs for HC emissions for W , VT-I, VT-2 and W-3.

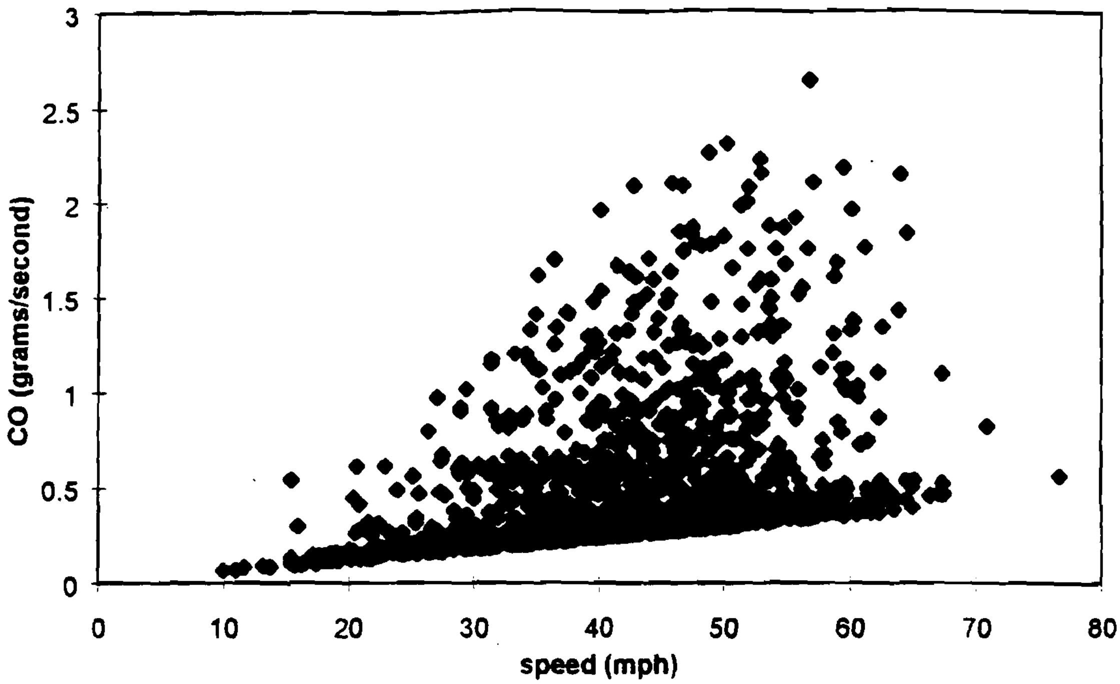


Figure 4-1: Aggregate CO emission rates versus **instantaneous speed values**

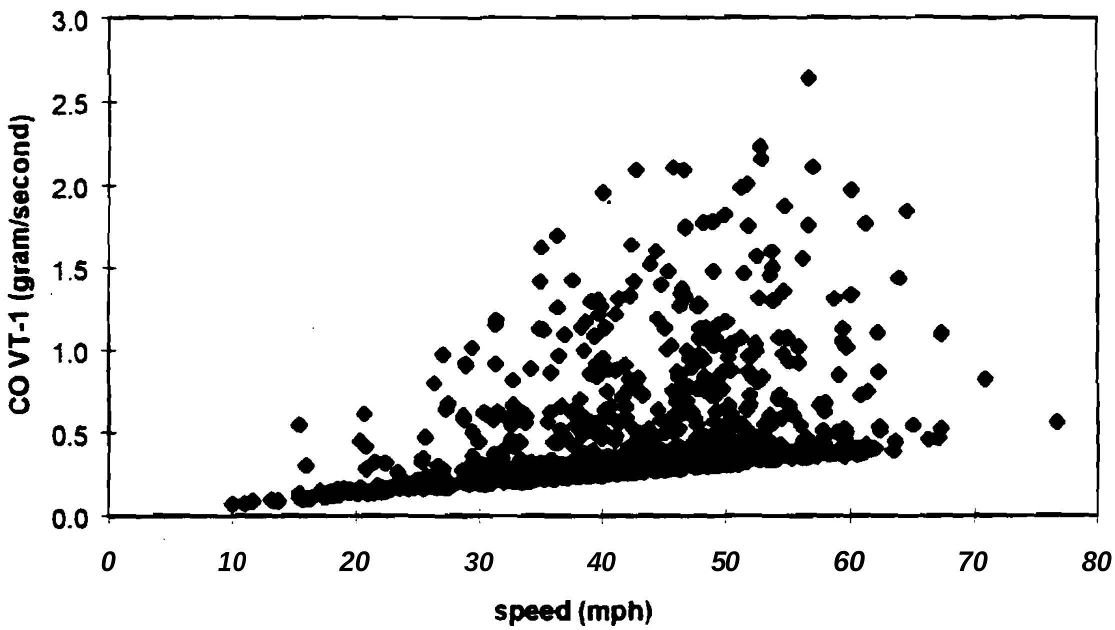


Figure 4-2: CO emissions rates versus **instantaneous speed values** for **vehicle** type 1

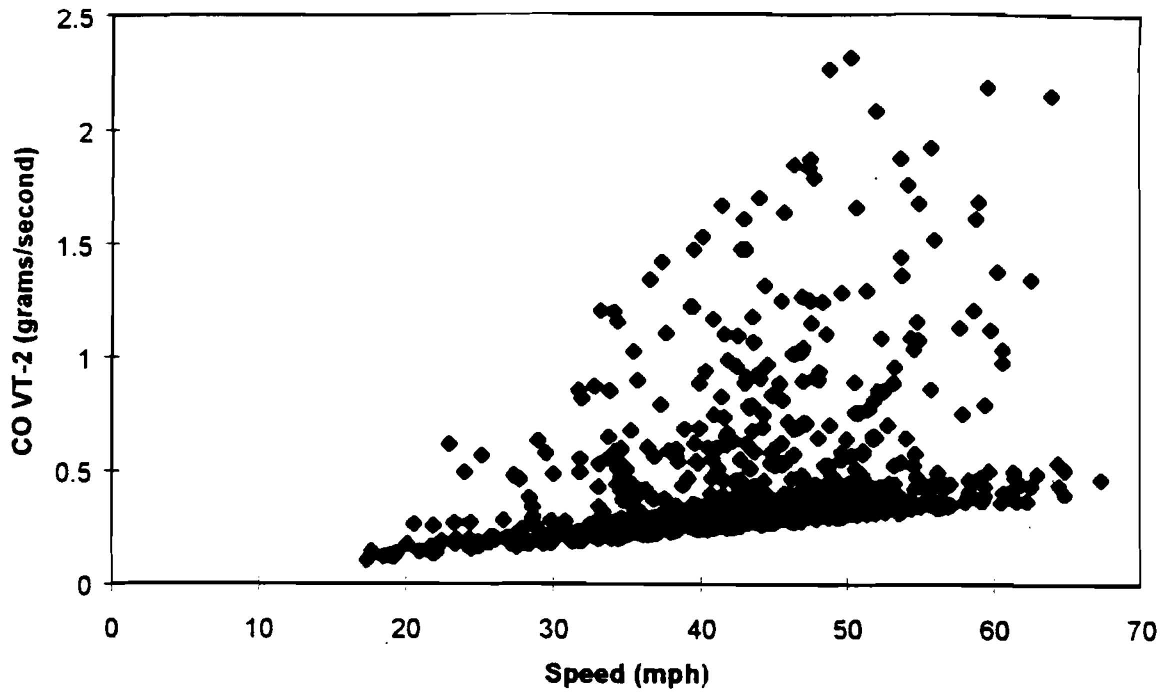


Figure 4-3: CO emissions rates versus instantaneous speed values for vehicle type 2

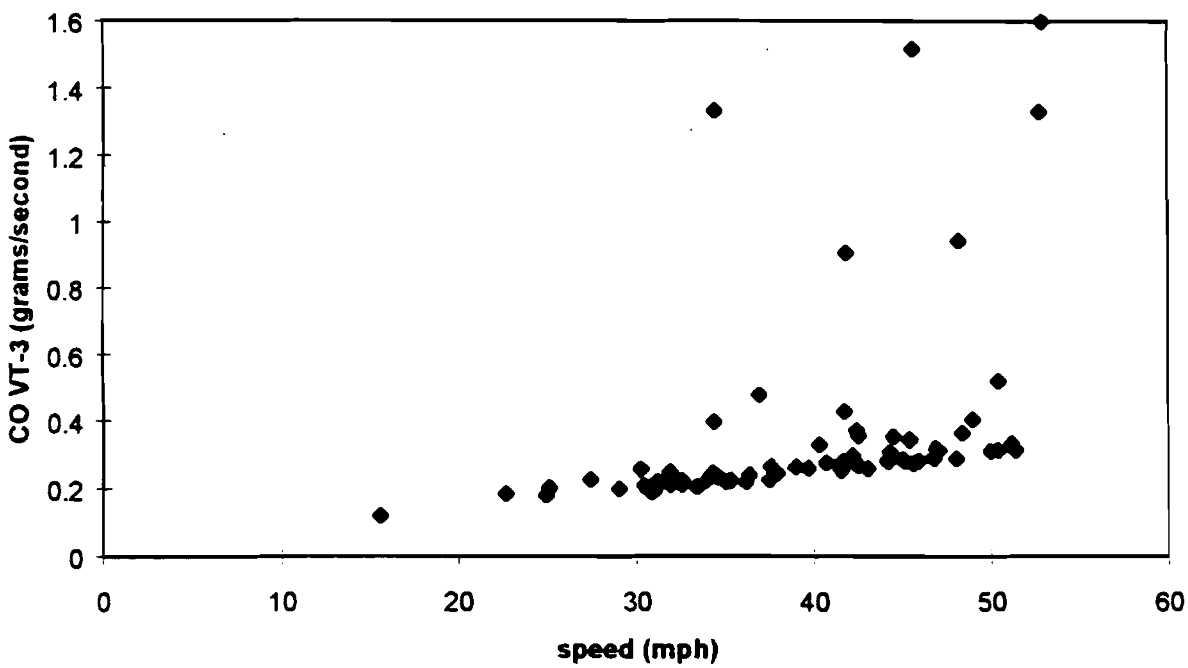


Figure 4-4: CO emissions rates versus instantaneous speed values for vehicle type 3

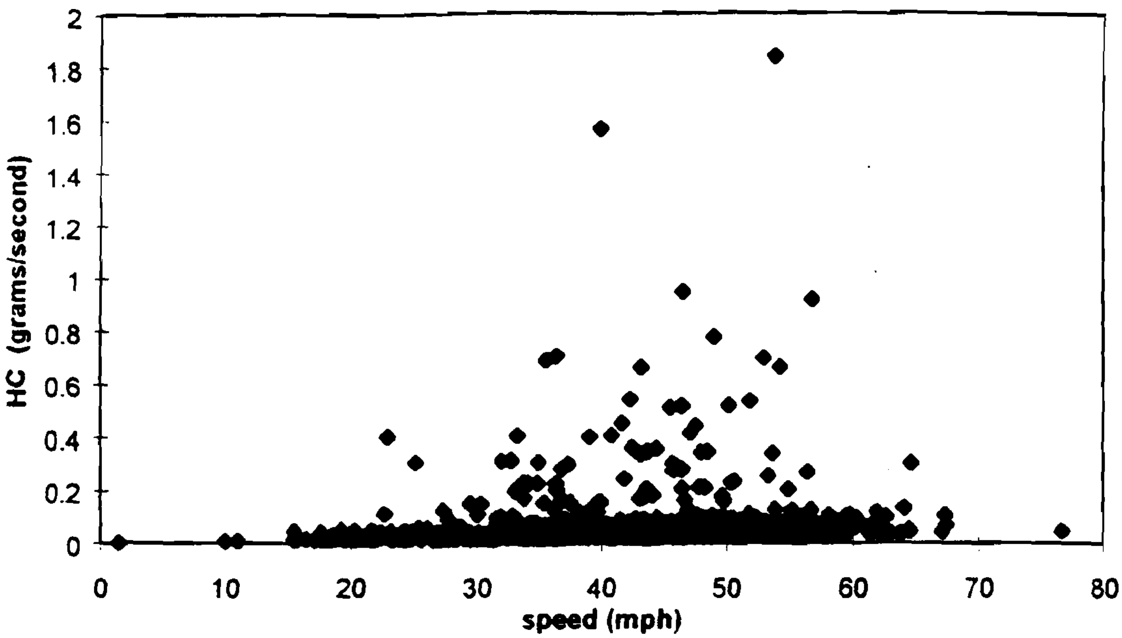


Figure 4-5: Aggregate HC emissions rates venus instantaneous speed values

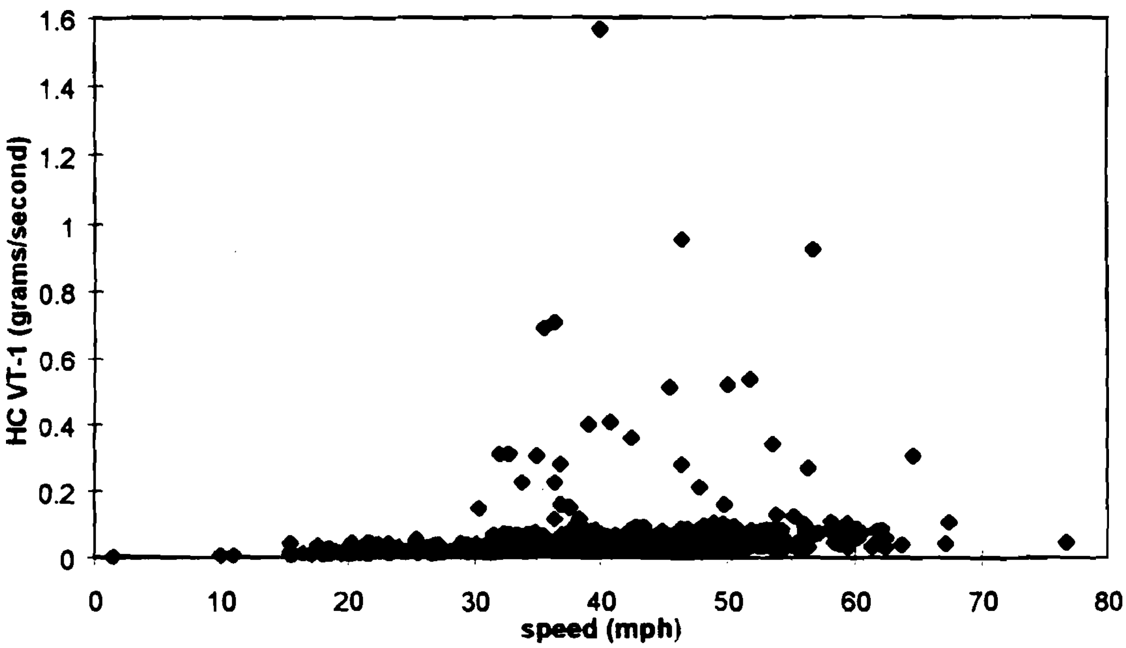


Figure 4-6: HC emissions rates versus instantaneous speed values for vehicle type 1

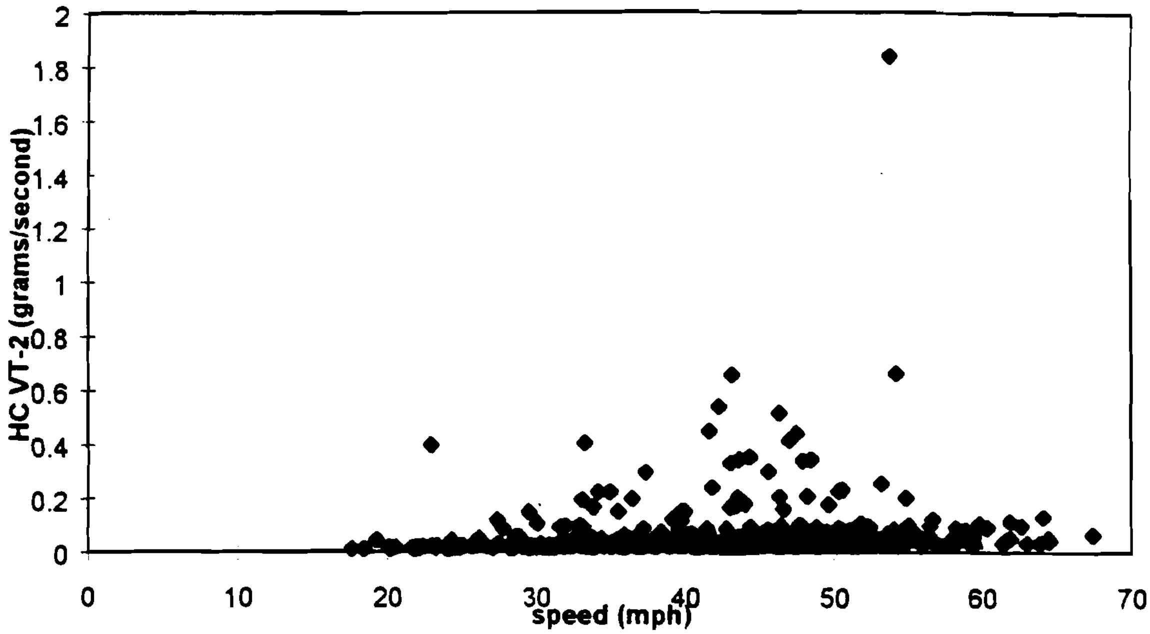


Figure 4-7: HC emissions rates versus instantaneous speed values for vehicle type 2

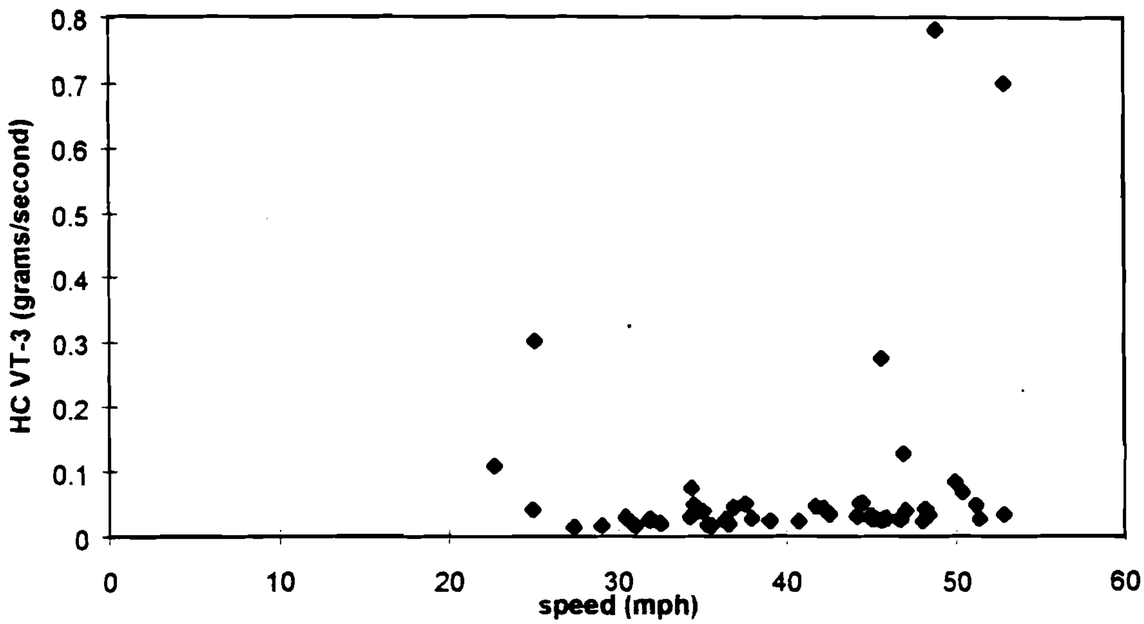


Figure 4-8: HC emissions rates versus instantaneous speed values for vehicle type 3

## *Regression Analysis of Emission Data*

The on-road emission data that were collected, converted, and reduced can be used to develop the ONROAD emission estimation model, which consist of a series of emission estimation equations. The data sets resulted From processing the raw emission data include emission rates in grams per second, instantaneous speed value, acceleratioddeceleration rates, ambient temperature, and humidity. While the geometric grades are very important information that affect the emissions, the on-road emission data collection could only use five sample locations with two of them in uphill grades, two of them in downhill grades, and one of them in at-grade. These data are not sufficient to successfully incorporate the grade data into the development of the ONROAD emission model. Therefore, this study will not separately consider the geometric grade data. Instead, all emissions for five days for each emission species are aggregated into a single data set.

## Definition of Variables

The dependent variables in the regression analysis are the emission rates of CO and HC for each vehicle type. The potential independent variables are the instantaneous speed, acceleration rate, ambient temperature, and humidity. These variables are expressed by the following notations:

| | |
|---|---|
| $EMIs_x$ | emission rate in grams per second for emission species E M and vehicle type x, |
| EM | emission species CO or HC, |
| x | vehicle type, VT, V-1, VT-2, and VT-3, |
| u | a vehicle's instantaneous speed in miles per hour (mph), |
| a | a vehicle's acceleration rate in mph per second, |
| t | ambient temperature in Fahrenheit degree, |
| h | ambient humidity in percentage (%), and |
| $c_0$, $c_1$, ... | constant values (regression model coefficients). |

## Regression Analysis Design

The first step in any regression analysis will be the selection of mathematical equations that may best fit the field-collected data. The research by Penic and Upchurch (1992) has indicated that the exponential equations would result in the best goodness-of-fit between field emission data and the ,regression curves. However, Baker (1994) used multiple variable polynomial equations in a similar modeling effort. Further statistical test and examination of the emission data collected for this research have found that the exponential equations are more suitable for establishing relationships between emission rates and various independent variables.

Having decided to use the exponential equations in formulating the ONROAD emission model, we should then determine how many independent variable terms should be included in each emission equation. Considering all of the possible independent variable terms, the following six are selected for the regression analysis: speed, speed square, acceleration, acceleration square, ambient temperature, and humidity. Technically, there exist unlimited potential combinations of various independent variable terms that can be tested. However, testing all of them is not feasible. In addition, most of them are not statistically suitable as that can also be easily judged fiom the regression analysis results in the later portion of this chapter. The format of the exponential emission equation is illustrated by the following equation:

**Equation 4-4**

$$LN(EMIs_x) = c_0 + c_1u + c_2u^2 + c_3a + c_4a^2 + c_5t + c_6h$$

Selecting six independent variable terms as the initial inputs for the regression analysis does not secure the inclusion of any of these variable terms in the final regression formula, as they may not satisfy the statistical requirements for the regression analysis. In other words, any of the six independent variable terms can be deleted fiom the consideration so long as they are not statistically satisfactory. The statistical examination about the quality of the regression equation will primarily go through the following three steps:

Step 1: Check the coefficient of correlation or the R-square of the regression analysis. This will indicate the amount of the total variability in the values of the response variable that is accounted for by the fitted regression model. The closer the correlation coefficient is to either 1 or -1 the stronger is the linear association between the dependent and independent variables. However, it should be cautious if the correlation coefficient is closer to 1 for the very large sample size, as indicated by Hayter (1996).

Step 2: The F-test is used to determine the general acceptance of the regression model. A large pvalue in F-test indicates that there is no evidence that any of the input variables affects the distribution of the response variable. A small p-value, on the other hand, indicates that the response variable is related to at least one of the independent variables.

Step 3: The t-test is used to determine the acceptance of each individual independent variable. Hayter (1996) suggests that p-values larger than 10% in a t-test indicate that the corresponding input independent variable can be dropped from the model, while p-values smaller than 1% indicate that the corresponding independent variable should be kept in the model. However, p-value between 1% and 10% do not provide a clear indication, and how the corresponding independent variables are dealt with is left to the experimenter's judgment.

Step 4: **If the finally** remained variables include both u and $u^2$, only one of them will be necessary, as both of them are exponents of an exponential function. Which one is retained will be dependent on which one results in a higher correlation coefficient.

The above four steps will serve as the main guideline in the following selection of independent variable terms in the regression analysis.

## Regression Analysis

Following the steps described above, the regression analysis is conducted. The following tables present the details in deleting variable terms that are found not appropriate statistically for inclusion in the regression equation. Take Table 4 1 as an example. In the Step 1 of Table 41, the regression analysis that involves all of the six independent variable terms results in a correlation coefficient of ***0.5209.*** While this value is not very high, it is a realistic number considering the quantity of the emission data set. The p-value in the F-test is 0, which indicates that at one of the selected six independent variable terms is statistically related to the dependent variable CO emission rate. The p-values of t-test for six independent variable terms indicate that the variable $a^2$ (acceleration square) should be removed fiom the regression equations since its p-value ***0.9567*** is the highest and higher than 10% threshold value as described previously. In the Step 2, the regression analysis is re-conducted by excluding the variable $a^2$. Similar analysis requires that the variable t, which is the ambient temperature, should be removed fiom inclusion. Then Step 3 removes the variable h, which is the humidity. In the Step 4, the p-values for F-test and for all independent variables in t-test fall into the acceptable range and thus all of the rest variables are kept in the regression equation. In the Step 5, the Speed Square is removed and the speed is retained as the former results in lower correlation coefficient than the latter one. Therefore, eventually the emission equation for the aggregate CO emissions include speed and acceleration rate. In addition, only one of the speed related variable tenns is kept in the final equation based on which one results in a higher coefficient correlation.

In Table 41, although six independent variable terms are initially considered in the regression analysis, the ambient temperature and the humidity have to be deleted fiom the inclusion considering the statistical requirement. This means that either these two variables are not related to the aggregate CO emission rates or the collected emission data are not sufficient for establishing reliable relationships between the CO emissions and the temperature and humidity. Tables *4-2* through 4 8 illustrate the process in performing the regression analysis for the other emission species and vehicle types. It is shown that, statistically, CO and HC emission rates for vehicle type 1 are related to speed and acceleration, CO emission rate for vehicle type 2 is related to speed only, while CO and HC emission rates for vehicle type 3 are related to the variable speed square only. The aggregate HC emission rate is related to speed, acceleration, and temperature, and the HC emission rate for vehicle 2 is related to speed and temperature.

**Table** 4-1: Summary of regression analysis **for** aggregate CO emissions

| LN (CO) = $c_0+c_1s+c_2s^2+c_3a+c_4a^2+c_5t+c_6h$, Total Number of Data = 1786<br>u = Speed, a = Acceleration Rate, t = Temperature, h = Humidity, $c_0,c_1,c_2,c_3,c_4,c_5,c_6$ = **Constants** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Step 1 | | **Step** 2 | | Step 3 | | **Step** 4 | | **Step** 5 | |
| | **Coefficients** | t-test | Coefficients | t-test | **Coefficients** | t-tent | Coefficients | t-test | Cocfficients | **t-test** |
| $c_0$ | -2.9099 | 0.0000 | -2.9090 | 0.0000 | -2.8346 | 0.0000 | -2.9046 | 0.0000 | -2.2182 | 0.0000 |
| $c_1$ | 0.0664 | **0.0000** | 0.0664 | 0.0000 | 0.0656 | 0.0000 | 0.0656 | 0.0000 | 0.0300 | 0.0000 |
| $c_2$ | -0.0004 | **0.0000** | -0.0004 | 0.0000 | -0.0004 | 0.0000 | -0.0004 | 0.0000 | | |
| $c_3$ | -0.0178 | 0.0055 | -0.0178 | 0.0055 | -0.0177 | 0.0056 | -0.0181 | 0.0044 | -0.0184 | 0.0042 |
| $c_4$ | 0.0001 | 0.9567 | | | | | | | | |
| $c_5$ | 0.0006 | 0.6704 | 0.0006 | 0.6692 | | | | | | |
| $c_6$ | -0.1233 | 0.3020 | -0.1228 | 0.3025 | -0.1484 | 0.1497 | | | | |
| **Coef**. Corrl. **R** | 0.5209 | | 0.5209 | | 0.5208 · | | 0.5200 | | 0.5100 | |
| F-test | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | |

**Table** 4-2: Summary of regression analysis foi CO emissions for vehicle type 1

| LN **(CO1)** = $c_0+c_1s+c_2s^2+c_3a+c_4a^2+c_5t+c_6h$, Total Number of Data = 946<br>u = Speed, a = **Acceleration** Rate, t = Temperature, h = Humidity, $c_0,c_1,c_2,c_3,c_4,c_5,c_6$ = Constants | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Step **1** | | Step 2 | | Step 3 | | Step 4 | | **Step** 5 | |
| | **Coefficients** | t-test | Coefficients | t-test | Coefficients | t-tent | Coefficients | t-test | Coefficients | t-test |
| $c_0$ | -2.7415 | 0.0000 | -2.7735 | 0.0000 | -2.7673 | 0.0000 | -2.893427 | 0.0000 | -2.2493 | 0.0000 |
| $c_1$ | 0.0653 | 0.0000 | 0.0656 | 0.0000 | 0.0653 | 0.0000 | 0.065474 | 0.0000 | 0.0312 | 0.0000 |
| $c_2$ | -0.0004 | 0.0002 | -0.0004 | 0.0001 | -0.0004 | 0.0001 | -0.000425 | 0.0002 | | |
| $c_3$ | -0.0271 | 0.0028 | -0.0271 | 0.0028 | -0.0271 | 0.0028 | -0.027166 | 0.0027 | -0.0270 | 0.0030 |
| $c_4$ | **0.0005** | 0.7983 | 0.0005 | 0.7996 | | | | | | |
| $c_5$ | -0.0003 | 0.8938 | | | | | | | | |
| $c_6$ | -0.2782 | 0.0930 | -0.2673 | 0.0636 | -0.2658 | 0.0648 | | | | |
| **Coef. Corrl**. R | 0.5510 | | 0.5510 | | 0.5510 | | 0.5487 | | 0.5388 | |
| F-test | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | | **0.0000** | |

## Table 4-3: Summary of regression analysis for CO emissions for vehicle type 2

| LN (CO2) = $c_0+c_1s+c_2s^2+c_3a+c_4a^2+c_5t+c_6h$, Total Number of Data = 770<br>u = Speed, a = Acceleration Rate, t = Temperature, h = Humidity, $c_0,c_1,c_2,c_3,c_4,c_5,c_6$ = Constants | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Step 1 | | Step 2 | | Step 3 | | Step 4 | | Step 5 | | Step 6 | |
| | Coeff. | t-test | Coeff. | t-test | Coeff. | t-test | Coeff. | t-test | Coeff. | t-teat | Coeff. | t-test |
| $c_0$ | -3.3608 | 0.0000 | -3.3727 | 0.0000 | -3.2219 | 0.0000 | -3.2233 | 0.0000 | -2.9814 | 0.0000 | -2.1076 | 0.0000 |
| $c_1$ | 0.0749 | 0.0000 | 0.0756 | 0.0000 | 0.0743 | 0.0000 | 0.0743 | 0.0000 | 0.0708 | 0.0000 | 0.0270 | 0.0000 |
| $c_2$ | -0.0006 | 0.0003 | -0.0006 | 0.0002 | -0.0006 | 0.0003 | -0.0006 | 0.0003 | -0.0005 | 0.0005 | | |
| $c_3$ | -0.0082 | 0.3760 | -0.0082 | 0.3793 | -0.0073 | **0.4266** | | | | | | |
| $c_4$ | -0.0006 | **0.7381** | | | | | | | | | | |
| $c_5$ | 0.0030 | 0.1481 | 0.0030 | 0.1519 | 0.0022 | 0.2184 | 0.0022 | **0.2160** | | | | |
| $c_6$ | 0.1369 | 0.4437 | 0.1306 | **0.4622** | | | | | | | | |
| Coef. Corrl. R | 0.4726 | | 0.4725 | | 0.4719 | | 0.4712 | | 0.4696 | | 0.4563 | |
| F-test | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | |

## Table 4-4: Summary of regression analysis for CO emissions for vehicle type 3

| **LN (CO3) = $c_0+c_1s+c_2s^2+c_3a+c_4a^2+c_5t+c_6h$, Total Number of Data = 70**<br>**u = Speed, a = Acceleration Rate, t = Temperature, h = Humidity, $c_0,c_1,c_2,c_3,c_4,c_5,c_6$ = Constants** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Step 1** | | **Step 2** | | **Step 3** | | **Step 4** | | **Step 5** | | **Step 6** | |
| | **Coeff.** | **t-test** | **Coeff.** | **t-test** | **Coeff.** | **t-test** | **Coeff.** | **t-test** | **Coeff.** | **t-test** | **Coeff.** | **t-test** |
| $c_0$ | -1.8908 | 0.1390 | -1.8762 | 0.0507 | -1.7902 | 0.0000 | -1.7601 | 0.0000 | -1.9736 | 0.0000 | -1.97976 | 0.0000 |
| $c_1$ | 0.0048 | 0.9216 | 0.0047 | **0.9215** | | | | | | | | |
| $c_2$ | 0.0004 | 0.4876 | 0.0004 | 0.4841 | 0.0005 | 0.0000 | 0.0005 | 0.0000 | 0.0005 | 0.0000 | 0.00049 | 0.0000 |
| $c_3$ | 0.0204 | 0.6860 | 0.0204 | 0.6815 | 0.0204 | **0.6797** | | | | | | |
| $c_4$ | -0.0315 | 0.3070 | -0.0316 | 0.2997 | -0.0315 | 0.2971 | -0.0245 | 0.3239 | -0.0254 | **0.3038** | | |
| $c_5$ | 0.0001 | **0.9861** | | | | | | | | | | |
| $c_6$ | -0.3996 | 0.6063 | -0.4062 | 0.5461 | -0.4043 | 0.5447 | -0.4362 | **0.5080** | | | | |
| Coef. Corrl. R | 0.6004 | | 0.6004 | | 0.6003 | | 0.5989 | | 0.5953 | | 0.5865 | |
| F-test | 0.0001 | | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | |

Table 4-5: Summary of regression analysis for aggregate HC emissions

| LN (HC) = $c_0+c_1s+c_2s^2+c_3a+c_4a^2+c_5t+c_6h$, Total Number of Data = 1117<br>u = Speed, a = Acceleration Rate, t = Temperature, h = Humidity, $c_0,c_1,c_2,c_3,c_4,c_5,c_6$ = Constants | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Step 1 | | Step 2 | | Step 3 | | Step 4 | | Step 5 | |
| | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test |
| $c_0$ | -6.2404 | 0.0000 | -6.2405 | 0.0000 | -6.380152 | 0.0000 | -4.9619 | 0.0000 | | |
| $c_1$ | 0.0945 | 0.0000 | 0.0945 | 0.0000 | 0.095265 | 0.0000 | 0.0288 | 0.0000 | | |
| $c_2$ | -0.0008 | 0.0000 | -0.0008 | 0.0000 | -0.000820 | 0.0000 | | | | |
| $c_3$ | -0.0418 | 0.0002 | -0.0418 | 0.0002 | -0.042268 | 0.0001 | -0.0445 | 0.0001 | | |
| $c_4$ | 0.0000 | **0.9949** | | | | | | | | |
| $c_5$ | 0.0087 | 0.0003 | 0.0087 | 0.0003 | 0.009458 | 0.0000 | 0.0075 | 0.0003 | | |
| $c_6$ | -0.1314 | 0.5108 | -0.1316 | **0.5083** | | | | | | |
| Coef. Corrl. R | 0.4258 | | 0.4258 | | 0.4254 | | 0.3967 | | | |
| F-test | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | | | |

Table 4-6: Summary of regression analysis for HC emissions for vehicle type 1

| LN (HC1) = $c_0+c_1s+c_2s^2+c_3a+c_4a^2+c_5t+c_6h$, Total Number of Data = 554<br>u = Speed, a = Acceleration Rate, t = Temperature, h = Humidity, $c_0,c_1,c_2,c_3,c_4,c_5,c_6$ = Constants | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Step 1 | | Step 2 | | Step 3 | | Step 4 | | Step 5 | |
| | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test |
| $c_0$ | -6.1099 | 0.0000 | -6.1109 | 0.0000 | -6.3541 | 0.0000 | -5.717824 | 0.0000 | -4.4435 | 0.0000 |
| $c_1$ | 0.1043 | 0.0000 | 0.1044 | 0.0000 | 0.1055 | 0.0000 | 0.099976 | 0.0000 | 0.0303 | 0.0000 |
| $c_2$ | -0.0009 | 0.0000 | -0.0009 | 0.0000 | -0.0009 | 0.0000 | -0.000882 | 0.0000 | | |
| $c_3$ | -0.0405 | 0.0091 | -0.0404 | 0.0090 | -0.0403 | 0.0093 | -0.040554 | 0.0091 | -0.0430 | 0.0069 |
| $c_4$ | -0.0002 | **0.9477** | | | | | | | | |
| $c_5$ | 0.0052 | 0.1070 | 0.0052 | 0.1068 | 0.0066 | **0.0178** | | | | |
| $c_6$ | -0.2299 | 0.3911 | -0.2306 | **0.3888** | | | | | | |
| Coef. Corrl. R | 0.4965 | | 0.4965 | | 0.4954 | | 0.4875 | | 0.4470 | |
| F-test | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | |

## Table 4-7: Summary of regression analysis for HC emissions for vehicle type 2

| LN (HC2) = $c_0+c_1s+c_2s^2+c_3a+c_4a^2+c_5t+c_6h$, Total Number of Data = 512<br>u = Speed, a = Acceleration Rate, t = Temperature, h = Humidity, $c_0,c_1,c_2,c_3,c_4,c_5,c_6$ = Constants | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Step 1 | | Step 2 | | Step 3 | | Step 4 | | Step 5 | |
| | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test | Coefficients | t-test |
| $c_0$ | -6.4256 | 0.0000 | -6.4214 | 0.0000 | -6.5449 | 0.0000 | -6.593385 | 0.0000 | -5.1106 | 0.0000 |
| $c_1$ | 0.0893 | 0.0001 | 0.0890 | 0.0001 | 0.0899 | 0.0001 | 0.091394 | 0.0001 | 0.0250 | 0.0000 |
| $c_2$ | -0.0008 | 0.0055 | -0.0008 | 0.0052 | -0.0008 | 0.0045 | -0.000793 | 0.0036 | | |
| $c_3$ | -0.0388 | 0.0198 | -0.0391 | 0.0155 | -0.0400 | **0.0123** | | | | |
| $c_4$ | 0.0003 | **0.9234** | | | | | | | | |
| $c_5$ | 0.0124 | 0.0009 | 0.0124 | 0.0009 | 0.0131 | 0.0001 | 0.013294 | 0.0000 | 0.0111 | 0.0005 |
| $c_6$ | -0.1146 | 0.7062 | -0.1097 | **0.7140** | | | | | | |
| Coef. Corrl. R | 0.3745 | | 0.3745 | | 0.3742 | | 0.3596 | | 0.3386 | |
| F-test | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | | 0.0000 | |

## Table 4-8: Summary of regression analysis for HC emissions for vehicle type 3

| LN (HC3) = $c_0+c_1s+c_2s^2+c_3a+c_4a^2+c_5t+c_6h$, Total Number of Data = 51<br>u = Speed, a = Acceleration Rate, t = Temperature, h = Humidity, $c_0,c_1,c_2,c_3,c_4,c_5,c_6$ = Constants | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Step 1 | | Step 2 | | Step 3 | | Step 4 | | Step 5 | | Step 6 | |
| | Coeff. | t-test | Coeff. | t-test | Coeff. | t-test | Coeff. | t-test | Coeff. | t-test | Coeff. | t-test |
| $c_0$ | 1.6412 | 0.6260 | 1.3565 | 0.6835 | 3.0987 | 0.2610 | 3.6304 | 0.1710 | 3.8704 | 0.1444 | -3.859321 | 3.07E-15 |
| $c_1$ | -0.3864 | 0.0088 | -0.3784 | 0.0096 | -0.3924 | 0.0069 | -0.3921 | 0.0067 | -0.4103 | 0.0044 | | |
| $c_2$ | 0.0053 | 0.0052 | 0.0053 | 0.0053 | 0.0054 | 0.0041 | 0.0053 | 0.0042 | 0.0056 | 0.0025 | 0.000384 | 0.048343 |
| $c_3$ | -0.1277 | 0.2422 | -0.0872 | 0.3525 | -0.0918 | 0.3264 | -0.1006 | **0.2762** | | | | |
| $c_4$ | 0.0456 | **0.4563** | | | | | | | | | | |
| $c_5$ | 0.0132 | 0.3701 | 0.0135 | **0.3565** | | | | | | | | |
| $c_6$ | 1.5471 | 0.3327 | 1.7013 | 0.2808 | 0.9984 | **0.4672** | | | | | | |
| Coef. Corrl. R | 0.5231 | | 0.5141 | | 0.5001 | | 0.4913 | | 0.4709 | | 0.2778 | |
| F-test | 0.0229 | | 0.0141 | | 0.0090 | | 0.0044 | | 0.0024 | | 0.0483 | |

### Summary of Regression Analysis

The results of regression analysis above can be summarized into the following mathematical equations, which can be used to calculate the emission rates of CO and HC for each vehicle type at each instantaneous speed value and acceleration rate.

**Table 4-9: Summary of regression analysis**

| |
|---|
| CO Aggregate Emission Rate: |
| $LN(CO) = -2.2182+0.0300u-0.0184a$ |
| CO Emission Rate for Vehicle Type 1: |
| $LN(CO1) = -2.2493+0.0312u-0.0270a$ |
| CO Emission Rate for Vehicle Type 2: |
| $LN(CO2) = -2.1076+0.0270u$ |
| CO Emission Rate for Vehicle Type 3: |
| $LN(CO3) = -1.9798+0.0005u^2$ |
| HC Aggregate Emission Rate: |
| $LN(HC) = -4.9619+0.0288u-0.0445a+0.0075t$ |
| HC Emission Rate for Vehicle Type 1: |
| $LN(HC1) = -4.4435+0.0303u-0.0430a$ |
| HC Emission Rate for Vehicle Type 2: |
| $LN(HC2) = -5.1106+0.0250u+0.0111t$ |
| HC Emission Rate for Vehicle Type 3: |
| $LN(HC3) = -3.859321+0.0004u^2$ |

It should be noted that the emission rate was defined as the emissions in the unit of grams per second. If the derivation of an emission factor, which represents the emissions in grams per mile, is required, the following equation should be used where the **$EMIm_x$** represents the emission factor in grams per mile for the emission species EMI and vehicle type **x.**

**Equation 4-5**

$$EM\,\mathrm{Im}_x = \frac{EMIs_x}{u}$$

### *Implications of the ONROAD Emission Model*

The Figures 4-9 to 4-16 illustrate the emission factor and emission rate versus instantaneous speed for all emission species and vehicle types. It is shown in these graphs that all of emission rates are monotonically increasing functions of the speed. In other words, the higher the vehicle's speed the more emissions the vehicle will emit per unit time. On the other hand, the emission factor reaches a minimum value at a speed between 30 and 40 mph. For speeds higher than this minimum point, the emission factors increase slightly but are almost flat for all vehicle types except for vehicle type 3 which observes more significant increase in emission factors.

The ONROAD emission model developed in this chapter represents the on-road emissions, which are based on specific emission data collected from five locations in the city of Houston. It represents the emission data for a combination of vehicle types and vehicular technologies of all vehicles forming the emission database. These emission data reflect neither certain types of vehicles nor the national average conditions of vehicle types. It only represents five locations in Houston. However, they provide very useful information for evaluating the emission estimation capabilities of existing emission models.

Since the ONROAD emission model is made sensitive to each vehicle's instantaneous speed and acceleration, it can be used to calculate the on-road vehicle emissions for various traffic scenarios in a traffic network. For example, if it is incorporated into a dynamic traffic assignment or traffic simulation model which can generate vehicles' speed profiles in the traffic networks, the emission implications of various traffic control and management plans in the network as well as the demand scenarios can then be easily evaluated.

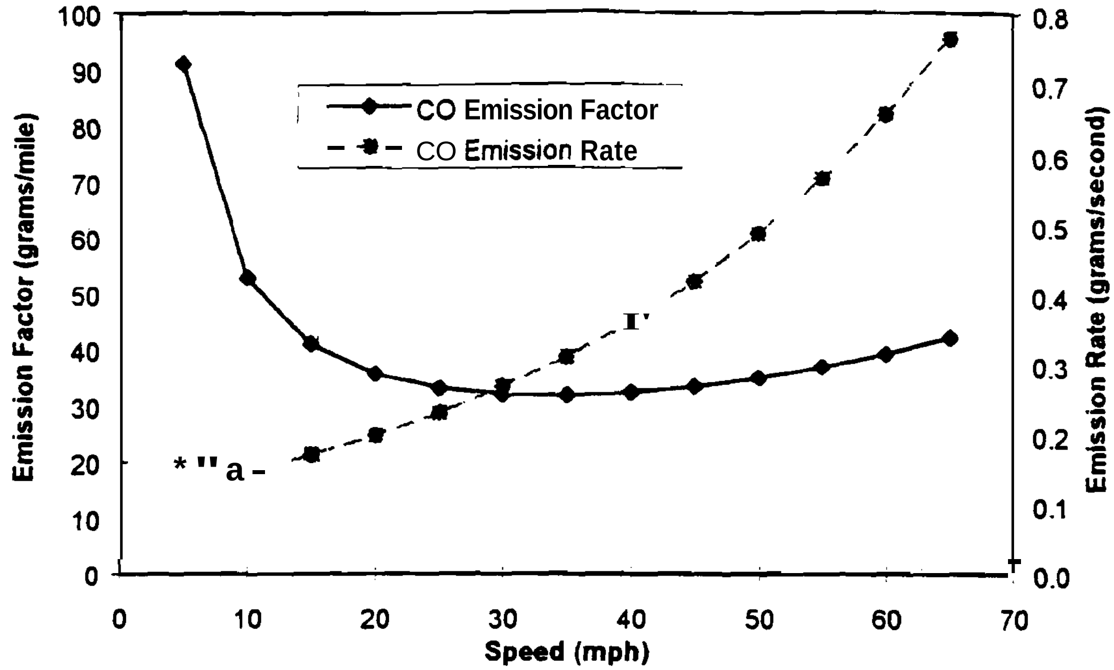


**Figure 4-9:** Emission factor and emission rate versus instantaneous speed for the aggregate CO emissions

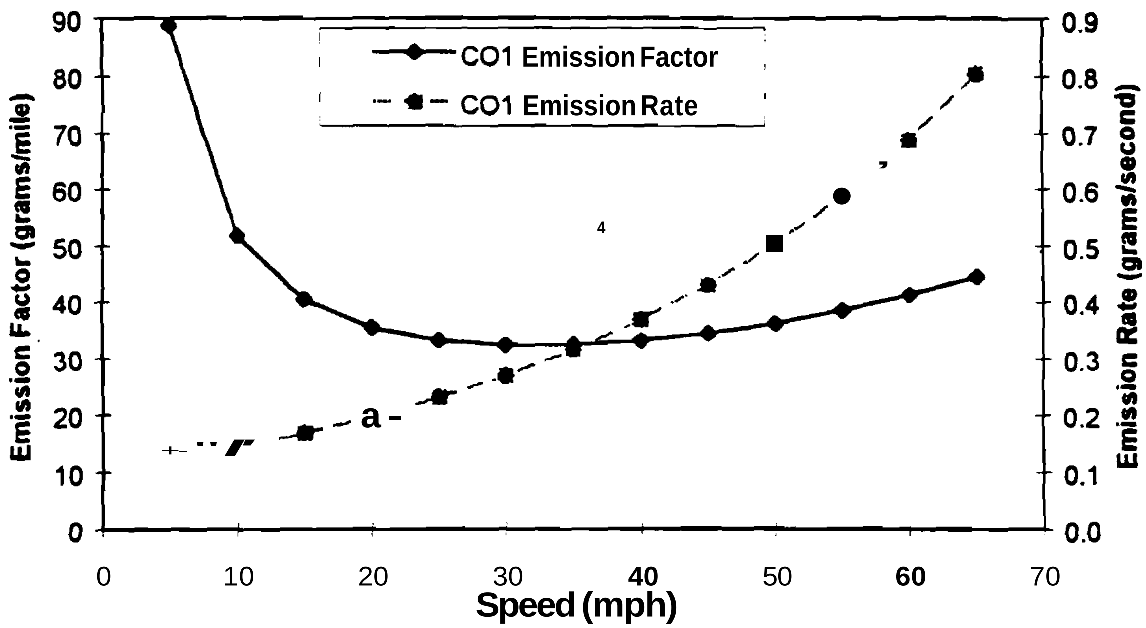


**Figure 4-10:** Emission factor and emission rate versus instantaneous speed for the CO emissions for vehicle type 1

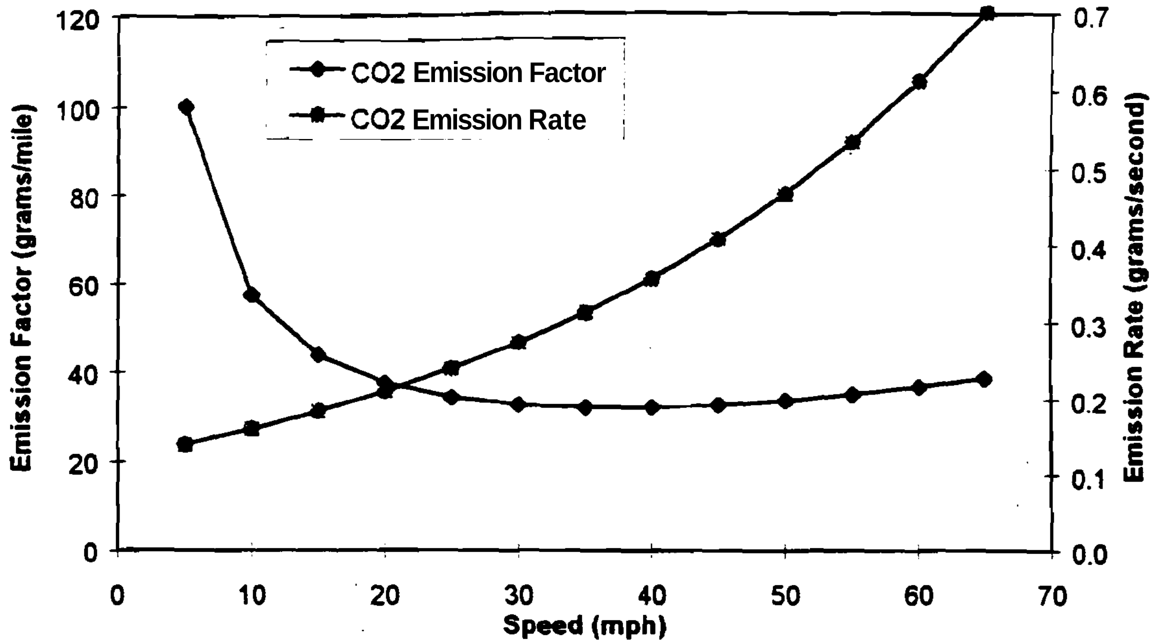


Figure 4-11: Emission factor and emission rate **versus** instantaneous speed for the CO emissions for vehicle type 2

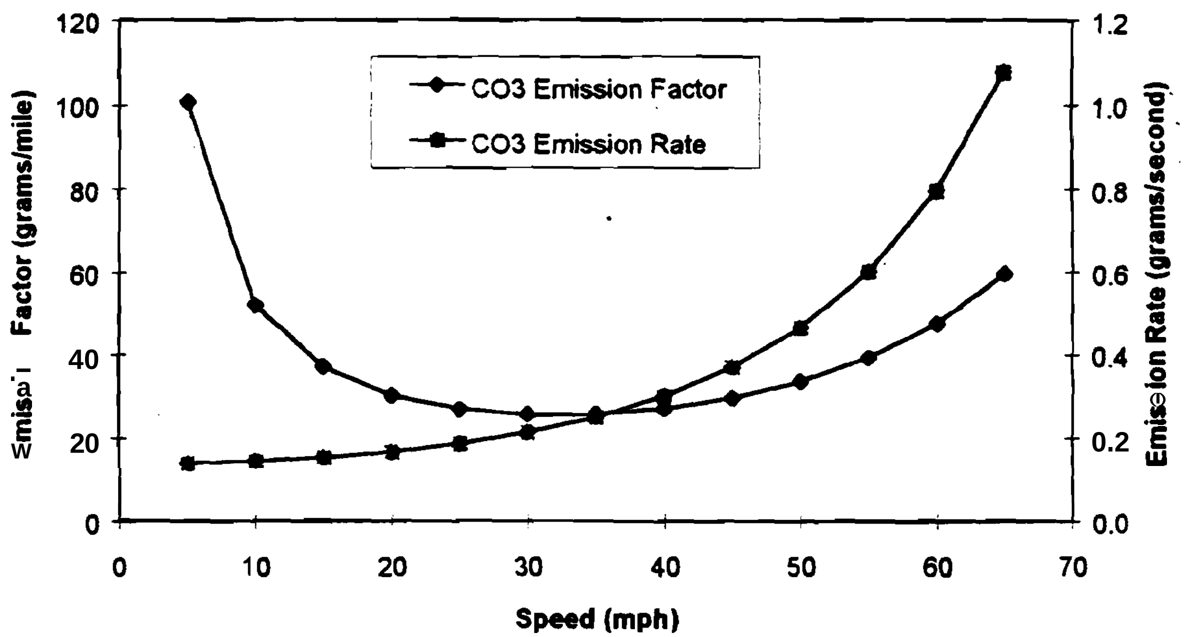


Figure 4-12: Emission factor and emission rate **versus** instantaneous **speed** for the CO emissions for vehicle type 3

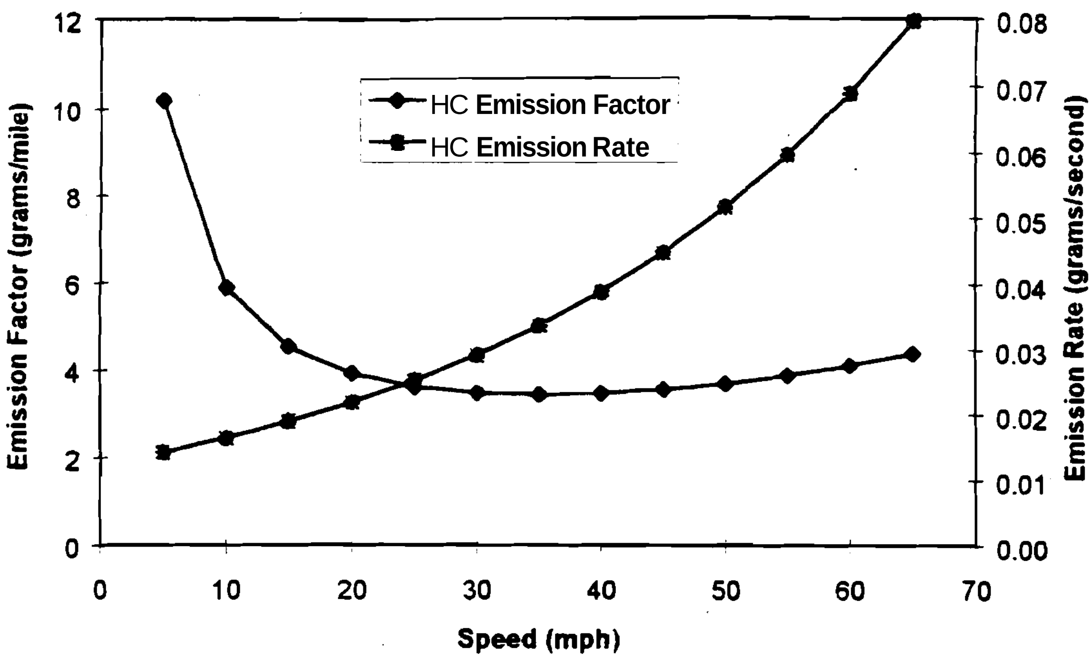


**Figure 4-13: Emission factor and emission rate versus instantaneous speed for the aggregate HC emissions**

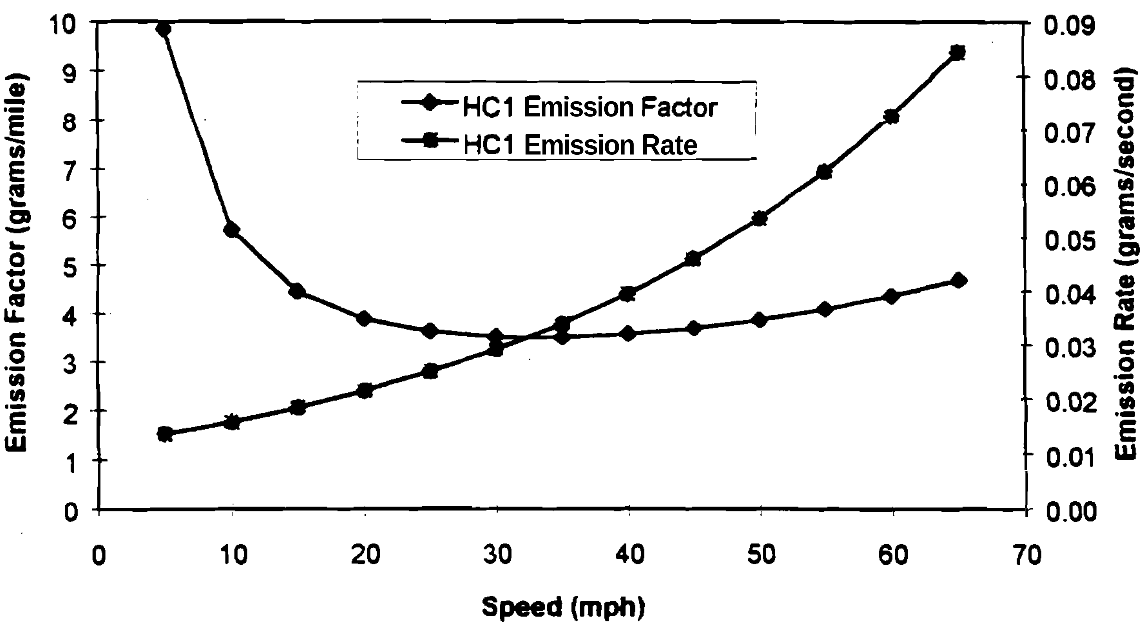


**Figure 4-14: Emission factor and emission rate versus instantaneous speed for the HC emissions for vehicle type 1**

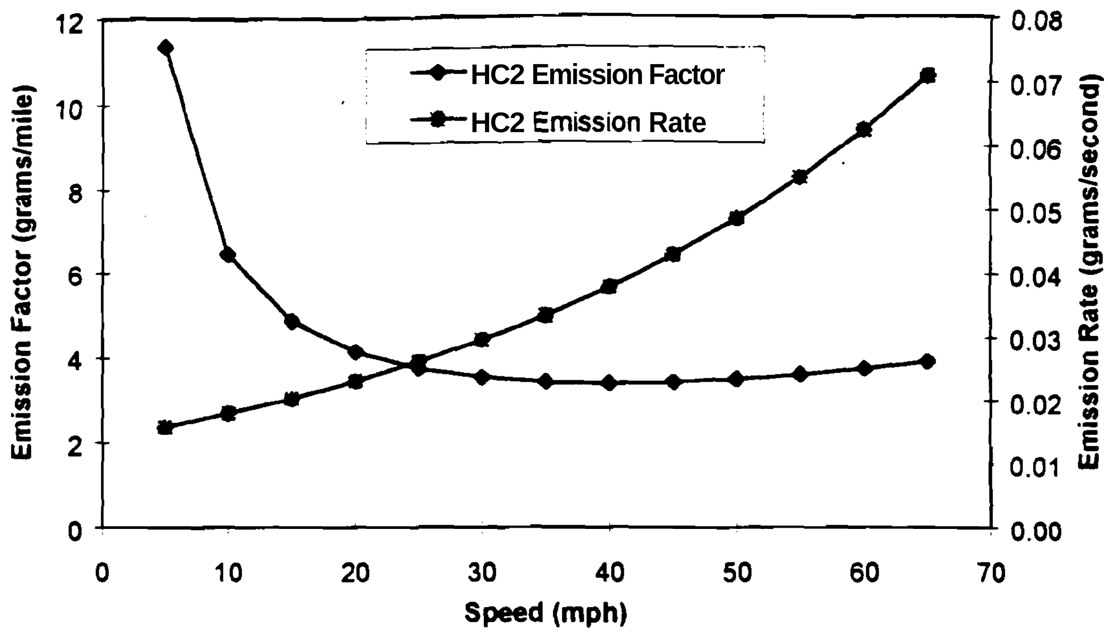


**Figure 4-15: Emission factor and emission rate versus instantaneous speed for the HC emissions for vehicle type 2**

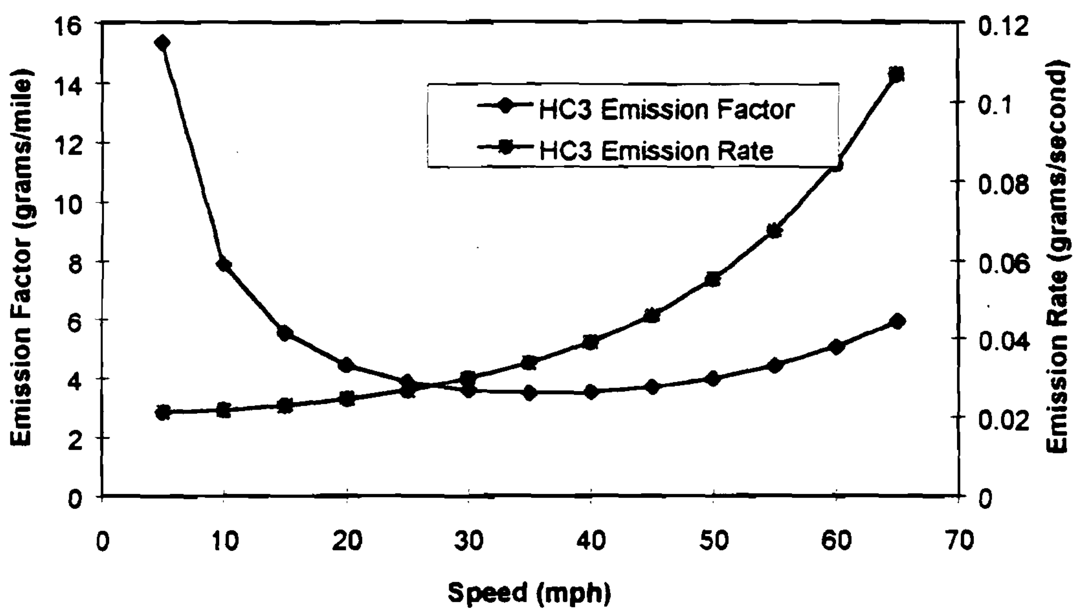


**Figure 4-16: Emission factor and emission rate versus instantaneous speed for the HC emissions for vehicle type 3**

As indicated previously, the emission factors reach a minimum point at a speed value. This minimum point can be mathematically calculated using Equations 4-4 and 4-5. By substituting the emission rate in Equation 4-4 into the Equation 4-5 and setting the derivative of Equation 4-5 to zero, the optimal point of the emission factor can be solved. The resulting speed value for the minimum emission factor is found to take the following form.

**Equation 4-6**

$$u_{optimal} = \frac{1}{c_1} \quad \text{for VT, V-1 and V-2}$$

**Equation 4-7**

$$u_{optimal} = \sqrt{\frac{1}{2c_2}} \quad \text{for VT-3}$$

Equations 4-6 and 4-7 illustrate that a speed value that minimizes the vehicle exhaust emissions in grams per mile can be theoretically calculated if the coefficients of c, and $c_2$ are known. Using the coefficient summary in Table 4-9, the optimal speed values for various combinations of emission species and vehicle types are calculated and presented in the following table.

**Table 4-10: Optimal speed values for minimizing the emissions in grams per mile**

| | CO | CO1 | C02 | C03 | HC | HC1 | HC2 | HC3 |
|---|---|---|---|---|---|---|---|---|
| Coefficient c, or $c_2$ | 0.0300 | 0.0312 | 0.0270 | 0.0005 | 0.0288 | 0.0303 | 0.0250 | 0.0004 |
| Optimum Speed (mph) | 33.39 | 32.01 | 37.07 | 32.07 | 34.73 | 32.98 | 39.97 | 36.07 |
| Minimum Emission Factor (grams/mile) | 32.4914 | 32.7724 | 25.6252 | 25.6608 | 3.6321 | 3.7168 | 3.6340 | 3.4678 |

The Table 4-10 indicates that by influencing drivers to drive at optimal speed values in an advanced traffic management scheme can help reduce the overall emission amounts. Driving at speeds that are either higher or lower than the optimal speed values are not desired for purely considering the vehicle emission benefits. While it is still unrealistic to consider influencing drivers' driving behavior just for the benefits of reducing vehicle emissions, the rapid development of Intelligent Transportation Systems (ITS) technologies is increasing the potentials for influencing drivers' driving behavior in the foreseen future.

# CHAPTER 5: EVALUATION OF EMISSION MODELS

This chapter attempts to evaluate the existing emission estimation models based on the collected on-road emission data, which is represented, by the ONROAD emission model developed in Chapter 4. Since the emission factor models MOBILE and EMFAC can only generate emission factors/rates based on the standard FTP driving cycles of in-laboratory emission testing as indicated by Figures 2-1 to 2-3, the on-road emissions must be converted into emission factors similar to the MOBILE and EMFAC emission factors in order for the comparisons to be feasible.

### *Derivation of Emission Factors for Driving Cycles*

The MOBILE emission factors were derived based on the FTP defined driving cycles. The standard urban driving cycle for the light duty vehicles and light duty trucks is characterized by a total of 1371 seconds in traveling a distance of 7.5 miles at an average speed of 19.6 mph. The correction factors for vehicles driving at other average speed values are derived based on the test of other driving cycles, but essentially the emission factors for the average speed of 19.6 mph are the basis. On the other hand, the urban driving cycle for the heavy-duty vehicles consumes a total of 1060 seconds in traveling 5.5 miles at an average speed of 18.8 mph.

The standard FTP driving cycles assume that a vehicle completes it entire trip through a trafiic network at various speeds and acceleration rates that are specified in the cycles. The emission informations that can be derived from the ONROAD emission models are the instantaneous emission factors or rates. In order to compare the existing emission factors with the on-road collected emissions, the ONROAD emission model is used to emulate the FTP driving cycles. In other words, the emission rate at each of the FTP driving cycle incremental step is calculated based on the instantaneous speed value and acceleration rate. While the original description of the FTP driving cycles in the Code of Federal Regulation (1986) does not include the acceleration rate, it can be easily derived by figuring the differential speed for any two consecutive seconds.

In the emulation of FTP driving cycles, the temperature and humidity are fixed at 75°F (24°C) and 50% respectively as would also be used in implementing emission factor models. Figure 5-1 through Figure 5-6 illustrate emulated CO and HC emission rates for various vehicle types other than vehicle type 3, while Figure 5-7 and Figure 5-8 illustrate emulated CO and HC emission rates for heavy-duty vehicles. It is shown from these graphs that, without exception, the ONROAD emission estimation model can catch the speed trends in the FTP driving cycles. It should be noted that at the speed of zero, all the emission rates have non-zero values. This value can be interpreted as the idling emission rate in grams per second, although this number was virtually extrapolated from the on-road emission data.

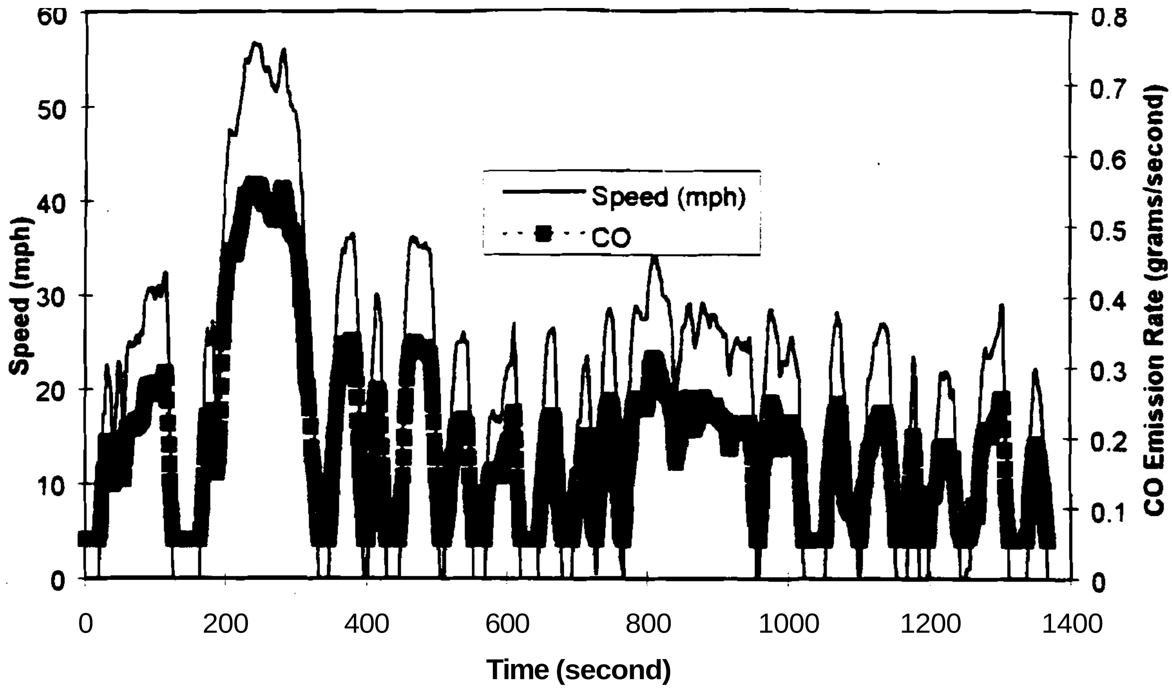


Figure 5-1: Emulated CO emission rate for FTP urban driving cycle for light duty vehicles and light duty trucks

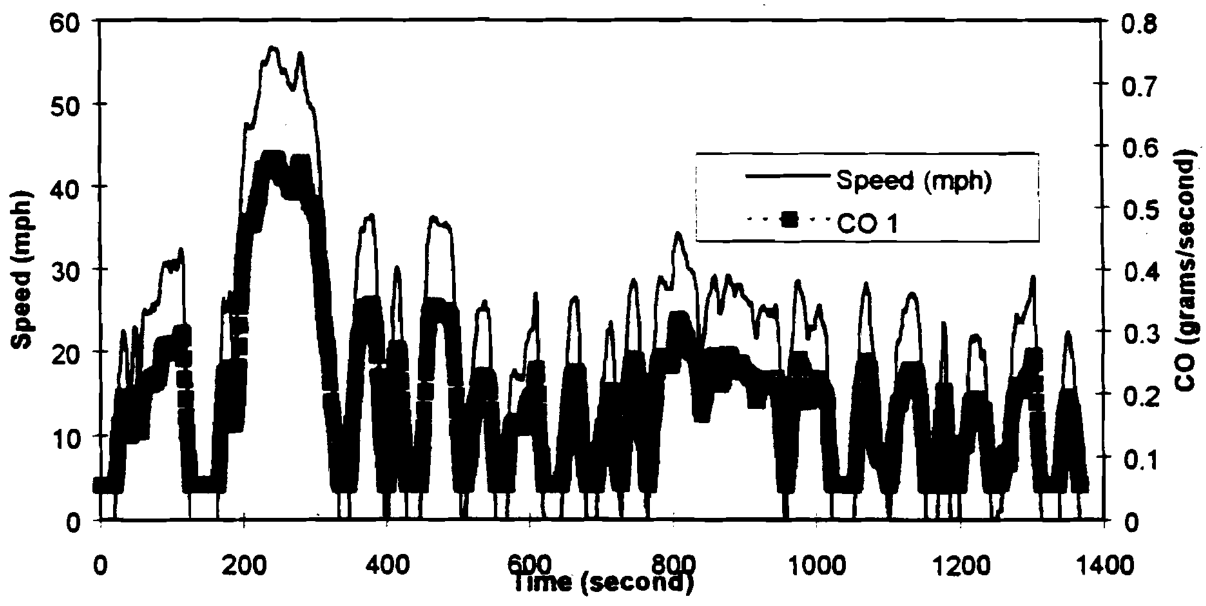


Figure 5-2: Emulated CO emission rate for vehicle type 1 for FTP urban driving cycle for light duty vehicles and light duty trucks

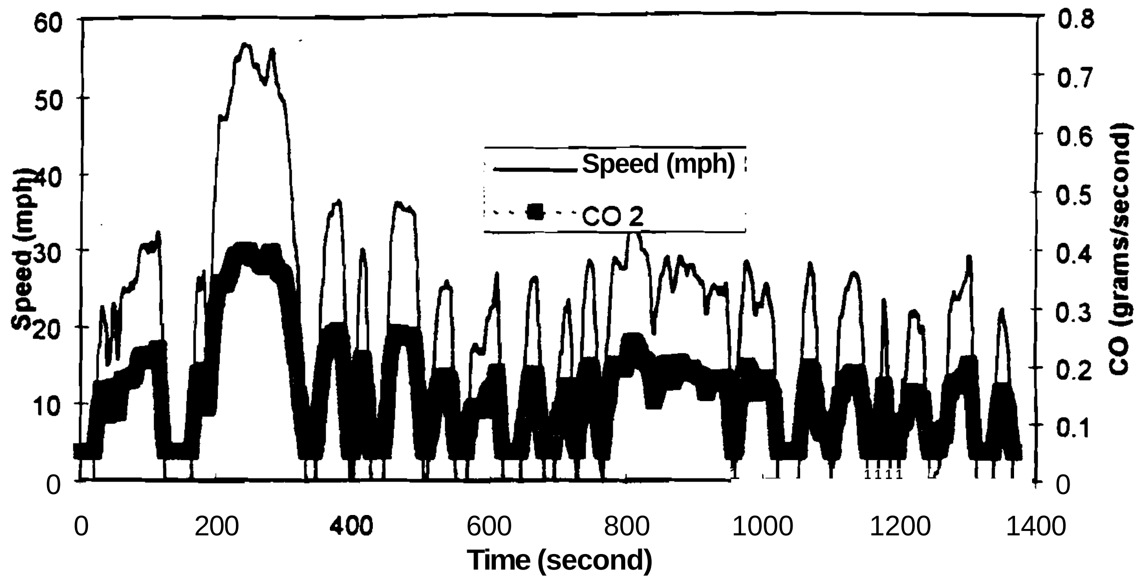


**Figure 5-3: Emulated CO emission rate for vehicle type 2 for FTP urban driving cycle for light duty vehicles and light duty trucks**

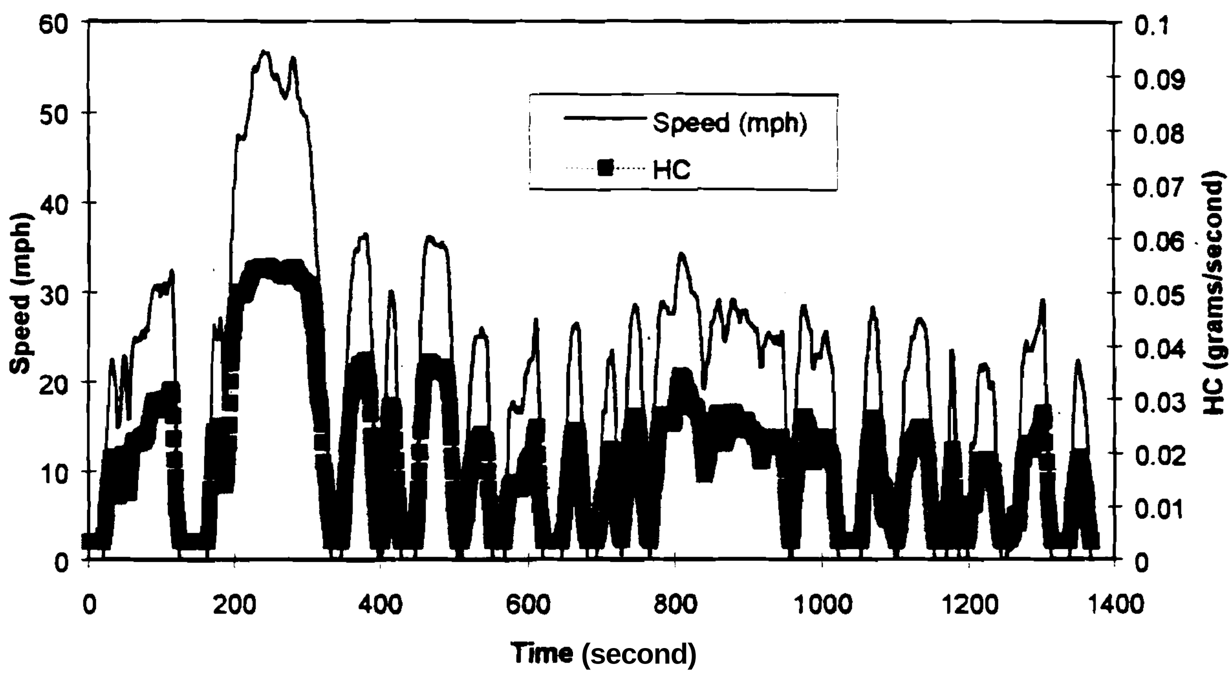


**Figure 5-4: Emulated HC emission rate for FTP urban driving cycle for light duty vehicles and tight duty trucks**

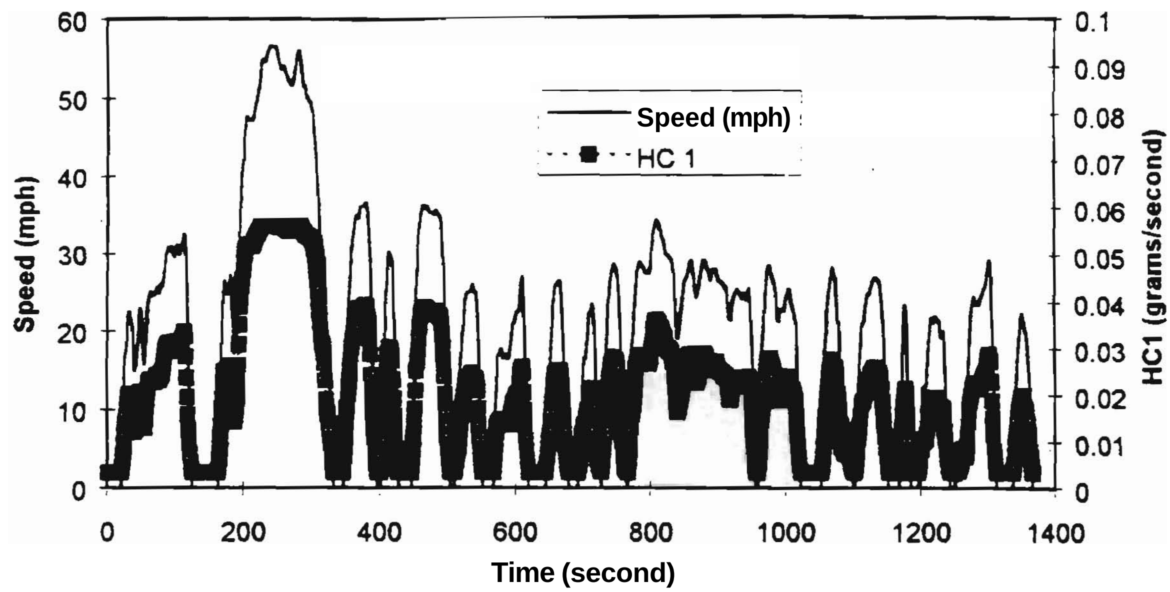


**Figure 5-5: Emulated HC emission rate for vehicle type 1 for FTP urban driving cycle for light duty vehicles and light duty trucks**

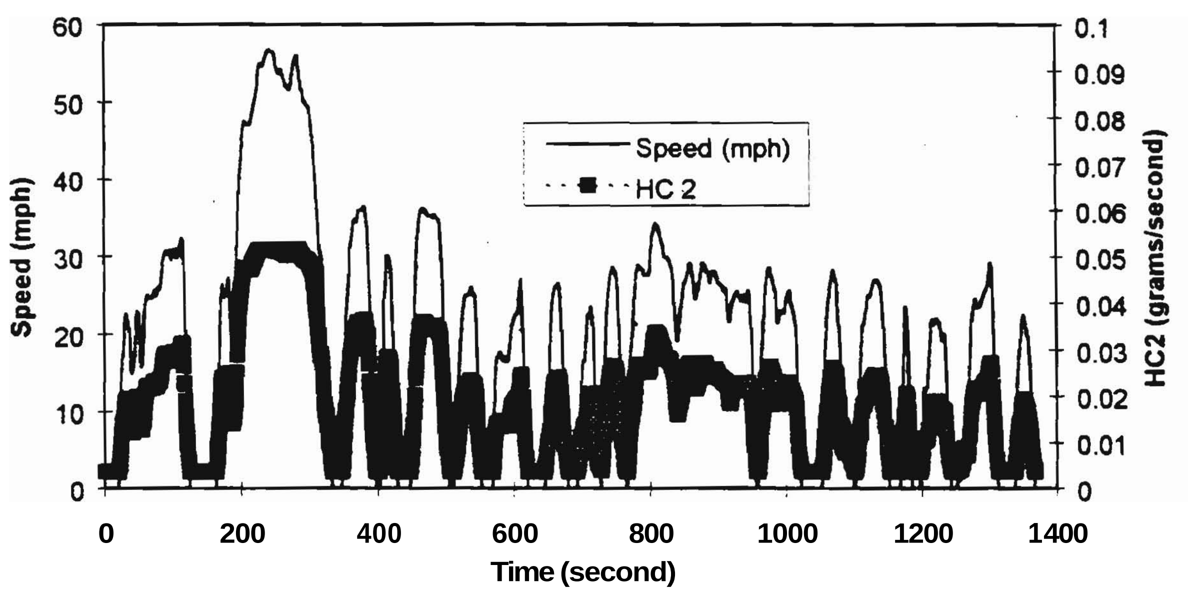


**Figure 5-6: Emulated HC emission rate for vehicle type 2 for FTP urban driving cycle for light duty vehicles and light duty trucks**

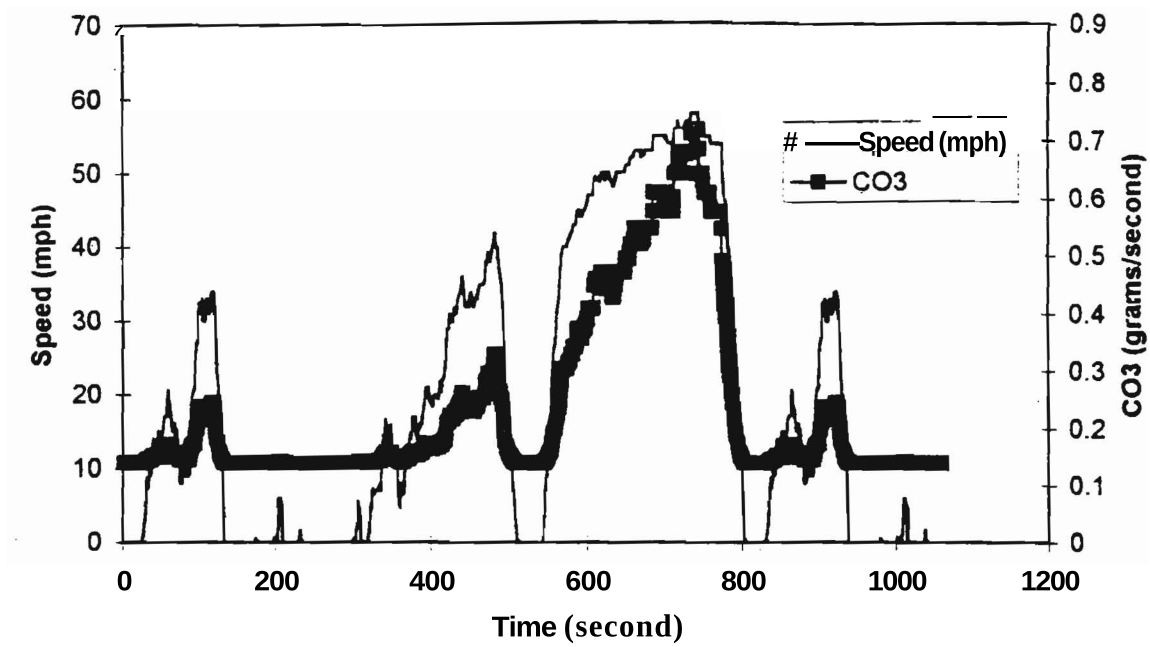


**Figure 5-7: Emulated CO emission rate for vehicle type 3 for FTP urban driving cycle for heavy-duty vehicles**

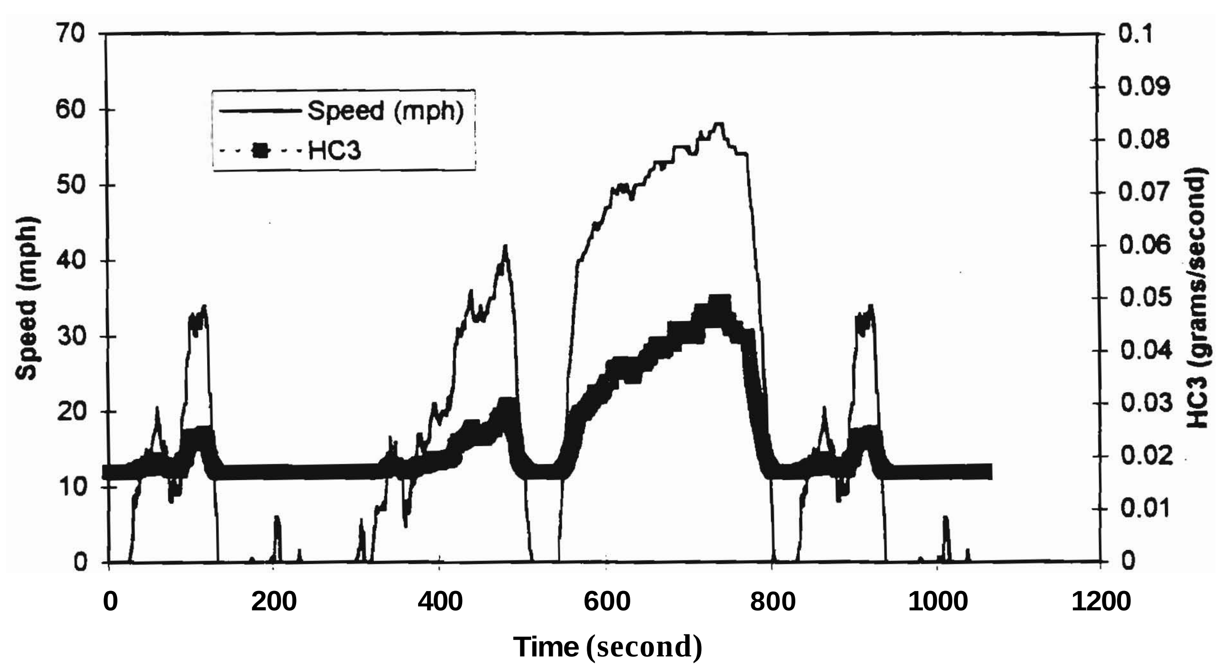


**Figure 5-8: Emulated HC emission rate for vehicle type 3 for FTP urban driving cycle for heavy duty vehicles**

The emission rates at each incremental step that were emulated in the above graphs are summarized for the entire driving cycle. Then the emission factors can be calculated by dividing the total emissions for the entire driving cycle by the total distance traveled for each specific driving cycle. This final emission factor is comparable with the similar emission factors in MOBLLE and EMFAC.

### *Emission Factor Comparisons for Driving Cycles*

The MOBILE emission factor model is implemented by inputting an average speed of 19.6 mph for the light duty vehicles and light duty trucks, and an average speed of 18.8 mph for the heavy-duty vehicles. The ambient temperature was fixed to 75°F (24°C), as was also used in emulation of driving cycles using the ONROAD emission model. Most of the other required parameters in MOBILE are set to the model default values, which generally represent the national average conditions. For the implementation of EMFAC, the 19.6-mph of speed is not a valid input to the model, as an integer value of speed is required. Thus, 20 mph of speed is used as an approximation to the standard FTP average speed for light duty vehicles and trucks.

The major problem in proceeding the emission factor comparison effort is the inconsistency of definitions of vehicle types among the ONROAD, MOBILE and EMFAC. The ONROAD emission model classifies all vehicles into only three types due to the scope of this research, MOBILE incorporates eight vehicle types, and EMFAC uses 13 vehicle types. Therefore, there should be a way in converting all the emission factors for various vehicle types into a commonly defined vehicle type scheme, so that the emission factors derived from three different models can be appropriately compared.

It is assumed that the definition of vehicle types in this research is used for the emission factor comparison purpose. In other words, three vehicle types are used, which are named passenger cars, van and pick-up trucks and other trucks. The emission factors from MOBILE and EMFAC will be combined into the same three vehicle types. For this purpose, the Houston Galveston Area Council (HGAC) 1993 vehicle's registration report is used as a reference for vehicle type information. Although this report is four years old and may not exactly represent the on-road vehicle information for our emission data collections, it is felt that actual vehicle types should not deviate too much from this report. The actual conversion of emission factors for MOBILE and EMFAC is described as follows.

For the MOBILE, the LDGV will match the VT-1 and LDDV takes no account in the emission factor calculation. A combination of 75% of LDGT1 and 25% of LDDT will match the VT-2. A combination of 54% of LDT2 which includes 70% LDGT2 and 30% LDDT, and 46% of HDV which includes 60% HDGV and 40% HDDV will match VT-3. The aggregate emission factor will exclude the effect of motor cycles since no motor cycle emission data were collected during the data collection.

For the EMFAC, the emission factor that matches VT-1 is considered a combination of 50% catalyst and 50% non-catalyst gasoline vehicles without the effect of diesel vehicles. For W-2, a combination of 50% catalyst and 50% non-catalyst, and 75% gasoline and 25% diesel vehicles are considered. For VT-3, again, catalyst and non-catalyst trucks are each counted 50%, gasoline trucks account 60% and diesel trucks account 40%, and MDTs account 54% and HDTs account 46%.

Based on what have been described, the emission factors are derived for VT, VT-1, VT-2 and VT-3, which are comparable to emission factors from the ONROAD emission model. Figures 5-9 and 5-10 are the resulting comparisons of CO and HC emissions for the ONROAD, EMFAC and MOBILE. Generally saying, the ONROAD emission model, which represents the on-road emissions at selected locations in Houston, resulted the highest emission factors for all vehicle types. In other words, both MOBILE EMFAC underestimate on-road emissions. It is noted that the FTP driving cycles for the emission testing take into account the various operating conditions of vehicles such as cold start, hot start and hot stabilized. However, the on-road emission data collected for this research are considered to only represent the hot stabilized mode of vehicles. As such, the emission factors derived from the on-road emission data should be lower than the emission factors fiom emission factor models, as the hot stabilized condition is considered the most emission efficient. Nonetheless, the emission factors fiom the ONROAD emission model are the highest.

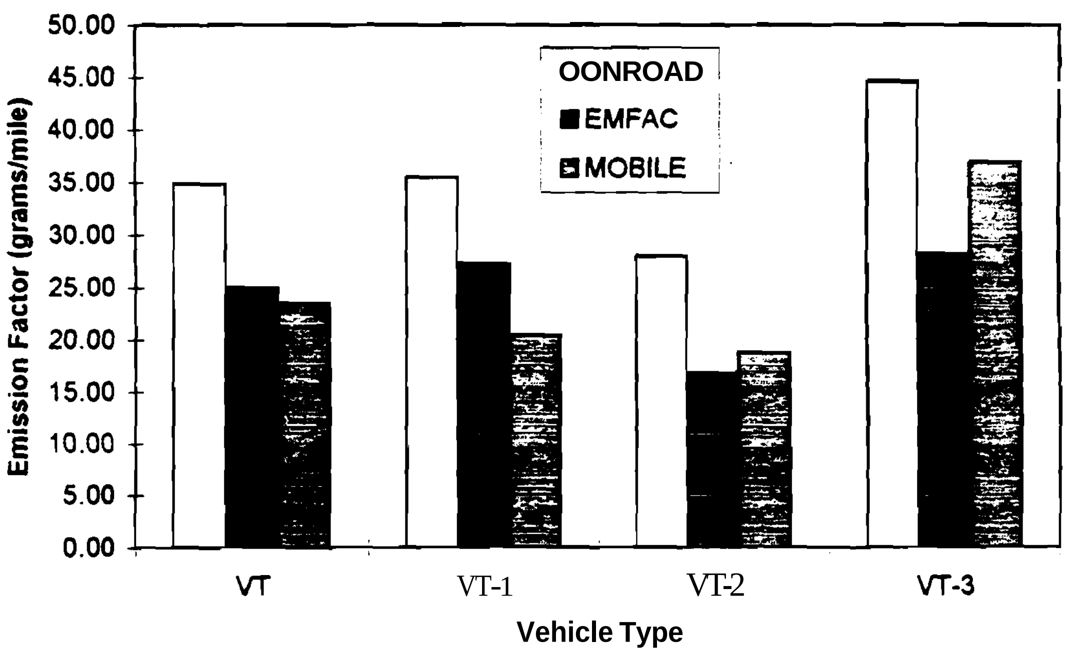


**Figure 5-9: Comparisons of CO emissions for ONROAD, EMFAC and MOBILE**

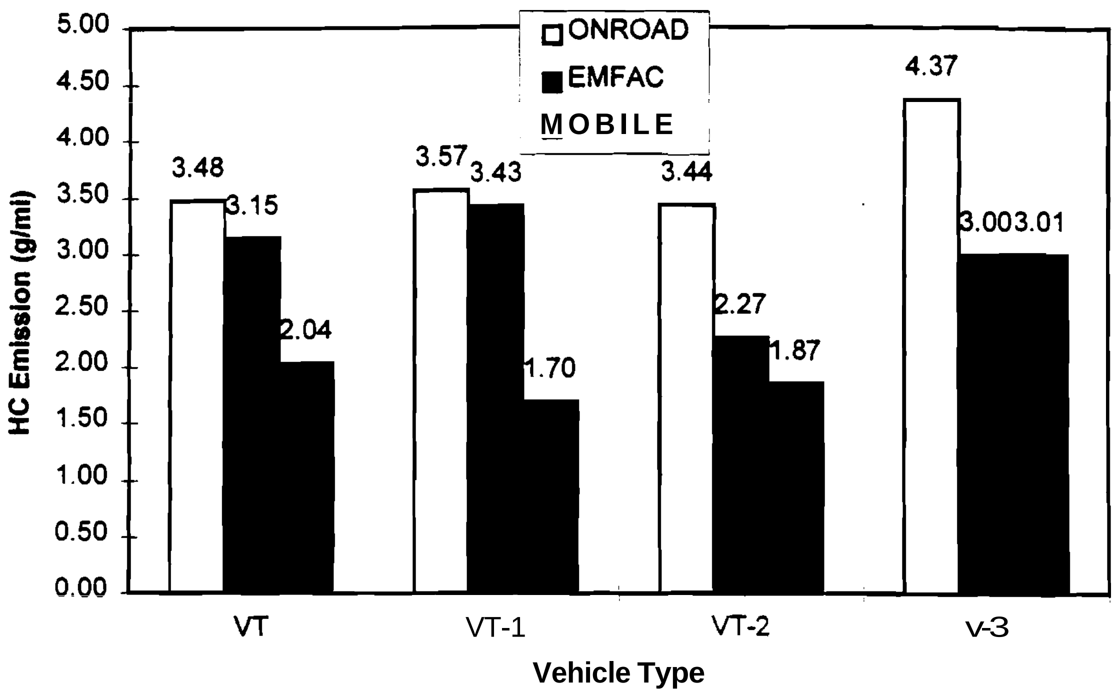


**Figure 5-10: Comparisons of HC emissions for ONROAD, EMFAC and MOBILE**

### *Instantaneous Emission Factor/Rate Comparisons*

The comparisons of CO and HC emissions described above were based on the FTP driving cycles. In other words, a vehicle is assumed to complete its entire trip through an urban traffic network at various FTP defined instantaneous speeds and acceleration rates. The emission factors derived in this way are called the average emission factors for short. It is an average emission factor that is required in the calculation of the network wide vehicle emissions and in the establishment of mobile source emission inventories.

Nonetheless, the average emission factors are not sufficient for use in performing various traffic-engineering tasks. For example, if a traffic engineer attempts to determine the traffic signal timings for a series of coordinated traffic signals with an objective to minimize the vehicle exhaust emissions, the calculation of the average emission factors will not help in determining which signal timing plan is the best. Instead, emission estimation based on the instantaneous speed profile for more aggregate vehicle types will be more useful. In other words, a traffic engineer will be more concerned with how each traffic control strategy will likely affect the change, either increase or decrease, of emissions for vehicles on road, rather than concerned with the estimation of emissions for each of more detailed vehicle type and operating classifications.

This is also the case for other traffic control and management strategies such as freeway ramp metering, HOV lane operation, variable message signs, and even various

ITS applications. For a traffic engineer, a traffic simulation or optimization model is often used in the analysis of various network scenarios and in the determination of traffic management strategies. Usually, the detailed vehicle types and other parameters that are required for emission factor models are not required for a standard traffic simulation model. Thus, the emission factor models such as MOBILE and EMFAC are widely used for establishing mobile source emission inventories, but are not useful to a traffic engineer who wants to determine traffic management strategies with a consideration of vehicle emissions.

As indicated in Chapter 4, the ONROAD emission model, which represents the on-road emissions at selected locations in Houston, is designed in a more aggregate manner for vehicle types and in a simple format that can be easily incorporated into a traffic simulation model. If the said traffic simulation model can produce the instantaneous speed profile of vehicles in its simulation process, the vehicle emissions can then be easily tracked throughout the network. Then the emission effect of any change in either traffic control or the traffic demand scenarios can be explicitly evaluated. While the format of the ONROAD emission model is rather simple, it is very useful in performing traffic engineering oriented emission analysis functions.

The ONROAD emission model developed in this research can generate instantaneous emission rates or emission factors. The instantaneous emission factor can be defined as the emissions in grams per mile at an instantaneous speed value. This section will compare the instantaneous emission factorlrate for the selected emission models including ONROAD, emission factor models MOBILE and EMFAC, and emission estimation in traffic simulation models INTEGRATION and TRANSYT. The INTEGRATION and TRANSYT emission models, which were initially designed for traffic simulation purposes, can calculate the instantaneous emission rates, and thus they can be compared with the emission rates from the ONROAD. However, MOBILE and EMFAC cannot generate instantaneous emission factorslrates. For the purpose of comparisons, the emission factors at various average speeds derived from MOBILE and EMFAC are used to compare with the instantaneous emission factorslrates of other models. It seems that the two sets of values are totally different and incomparable. However it is felt that this comparison does provide some interesting implications and observations of the emission factors in different models.

All the emission factors that are derived from the implementation of MOBILE and EMFAC at each average speed value can be combined into emission factors for the vehicle types VT, VT-1, VT-2 and VT-3, which are defined in this research. The method to do this was described in the emission factor comparison for driving cycles. The resulting emission factors can then be converted into emission rates using the speed values and Equation 4-5. INTEGRATION can only calculate emission rate for LDGV, LDGTl and LDGT2. Its emission rates for LDGV matches VT-1, for LDGTl are used to match VT-2 (not exactly the same as the diesel vehicles are excluded), and for LDGT2 do not match any defined vehicle types. On the other hand, TRANSYT only generates one single emission rate for CO or HC, and thus it is used in the comparisons of VT, VT-1 and V-2. It should be kept in mind the potential discrepancy in this comparison that may be caused by the different representations of vehicle types in different models. Both INTEGRATION and TRANSYT do not have representation of heavy-duty vehicles in calculating emission rates, and thus they will not be included in the comparison of instantaneous emission factors/rates for VT-3.

Figure 5-11 illustrates the CO emission factors for the aggregate vehicle types for the ONROAD, TRANSYT, MOBILE and EMFAC. It is shown that TRANSYT estimates much lower emissions than other models. This is because the development of TRANSYT emission formulas used only six test vehicles, which were insufficient in representing real world vehicles. It is interesting to note that MOBILE and EMFAC generate almost identical trends of CO emissions for the aggregate vehicle types, which implicates the similar testing procedures that were used in developing emission factor models. The curve for the ONROAD demonstrates a deviation fiom MOBILE and EMFAC. At lower speeds, the estimation of CO emission factors fiom the ONROAD is rather consistent with that of MOBILE and EMFAC. However, with the increase of speeds, the deviation increases. Specifically, MOBILE and EMFAC predicts rapid decrease of emission factors with the increase of speeds until the speed reaches 55 mph and then increase sharply after this speed. The ONROAD predicts rapid decrease of emission factors before the speed of 33 mph and increase rather moderately after this speed. While the change of emission factors on the two sides of the minimum point is smooth and continuous for the ONROAD, it is discontinuous for MOBILE and EMFAC. It is noted that at lower speeds, emission estimation by the ONROAD overlaps the emission estimation by EMFAC.

Figure 5-12 illustrates the CO emission rates for the aggregate vehicle types. The new emission model demonstrates a continuously increasing emission rates with the increase of the speeds, while emission rates for MOBILE and EMFAC at speeds lower than 55 mph are rather flat with a significant increase with speeds higher than 55 mph. It is felt that the discontinuous point at the speed 55-mph occurred because of the design of the emission testing for the development of MOBILE and EMFAC. The emission rates for TRANSYT are much lower than other models but the curve is an increasing function of speed, which is similar to the ONROAD.

Since the emission results fiom MOBILE and EMFAC represent the average speeds and the emission results fiom the ONROAD represent the instantaneous speeds, emissions fiom MOBILE and EMFAC should be higher than those fiom the ONROAD. This is because average emission factors/rates mean that vehicles drive at various acceleration/deceleration rates in addition to various instantaneous cruise values and thus the emitted pollutants should be higher than just driving at a single cruise speed value. However, Figures 5-11 and 5-12 demonstrate a different trend.

Figure 5-13 illustrates the emission factors at instantaneous speeds for emission models that are selected for comparison for vehicle type 1. Similar to TRANSYT, INTEGRATION predicts much lower CO emission factors than other models, which means that the emission database for developing INTEGRATION emission estimation model is very limited. In fact, the INTEGRATION emission estimation equations were developed based on the selected MOBILE outputs for certain vehicle types. The trends of curves for the ONROAD and MOBILE and EMFAC are very similar to Figure 5-11 except for that MOBILE predicts lower emission factors than EMFAC for vehicle type 1. Again, both MOBILE and EMFAC expect the lowest emission factor at the speed value of 55 mph, while the ONROAD expects the lowest emission factor at a speed of 32 mph and a moderate increase of emission factors beyond this speed. Figure 5-14 illustrates the emission rates for the same scenario for vehicle type 1. INTEGRATION and TRANSYT predict much lower CO emission rates for the vehicle type 1 than other models. MOBILE estimates lower CO emission rate for vehicle type 1 than does EMFAC. It is much easier to identify the turning point of curves for MOBILE and EMFAC at the speed 55 mph. Obviously, MOBILE and EMFAC assume a rather flat emission rates for speeds below 55 mph while a sharp increase in emission rates for speeds higher than 55 mph. On the other hand, the ONROAD predicts a smooth increase in emission rates over speeds.

Figures 5-15 and 5-16 illustrate CO emission factors and CO emission rates respectively at various instantaneous speeds for vehicle type 2. It should be noted that INTEGRATION can only estimate LDGT1 emissions, while other models excluding TRANSYT can estimate LDT emissions which include both gasoline and diesel based. The most important difference between Figure 5-15 and Figure 5-13 is that MOBILE predicts higher CO emission factors than EMFAC in Figure 5-15 while lower CO emission factors than EMFAC in Figure 5-13. This also explains while the aggregate CO emission factors predicted by MOBILE and EMFAC are identical in Figure 11. The emission estimations by MOBILE and EMFAC are even further deviated from the ONROAD for vehicle type 2.

Figures 5-17 and 5-18 illustrate CO emission factors/rates versus instantaneous speeds for the vehicle type 3, which are virtually the heavy-duty vehicles. While the estimates by MOBILE and EMFAC still demonstrate some deviations from the ONROAD, the difference is much smaller than the previous graphs. In other words, MOBILE and EMFAC estimate CO emissions more accurately for the heavy-duty vehicles. Especially, at lower speed portion of the graphs, CO emission estimates from three models almost overlap. Since both INTEGRATION and TRANSYT emission equations did not consider the heavy-duty vehicles at all, they are not incorporated into these two graphs.

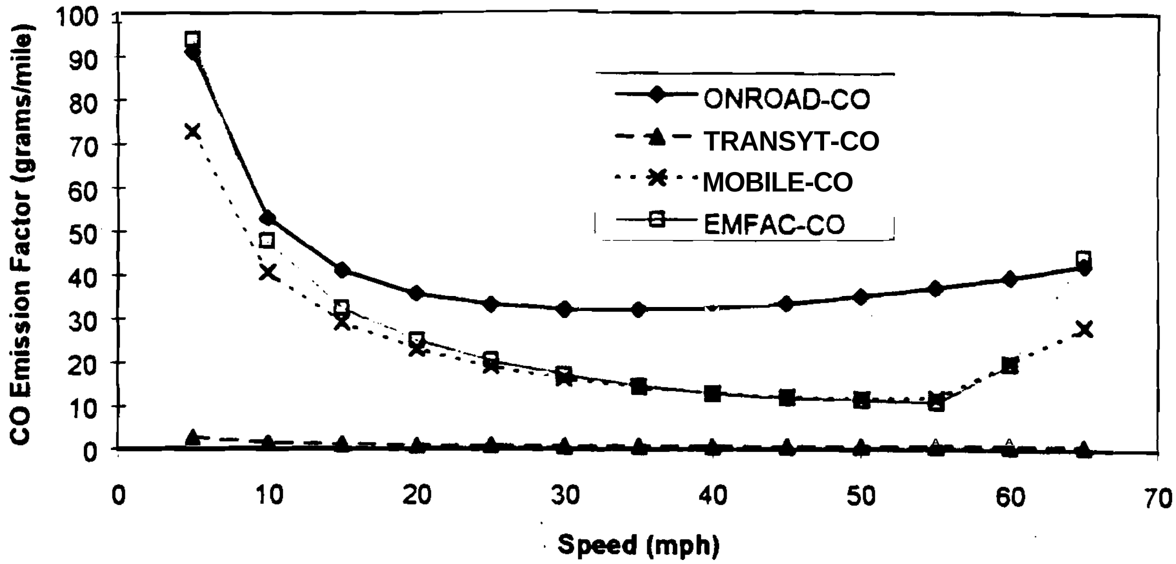


Figure 5-11: Emission factors at various instantaneous speeds for the aggregate CO emissions

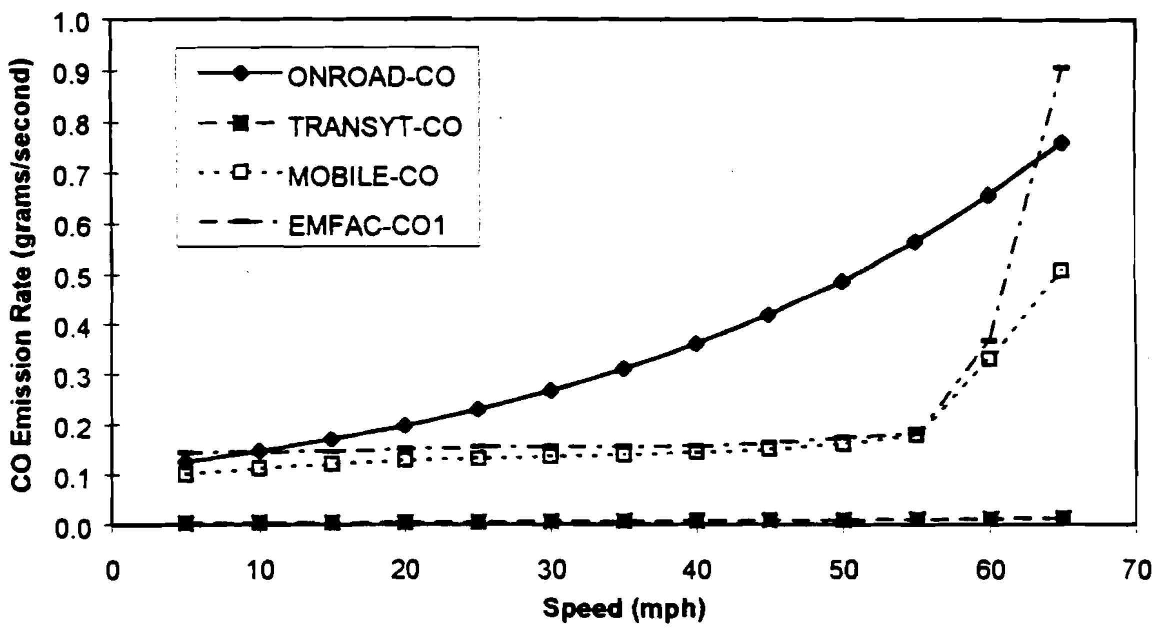


Figure 5-12: Emission rates at various instantaneous speeds for the aggregate CO emissions

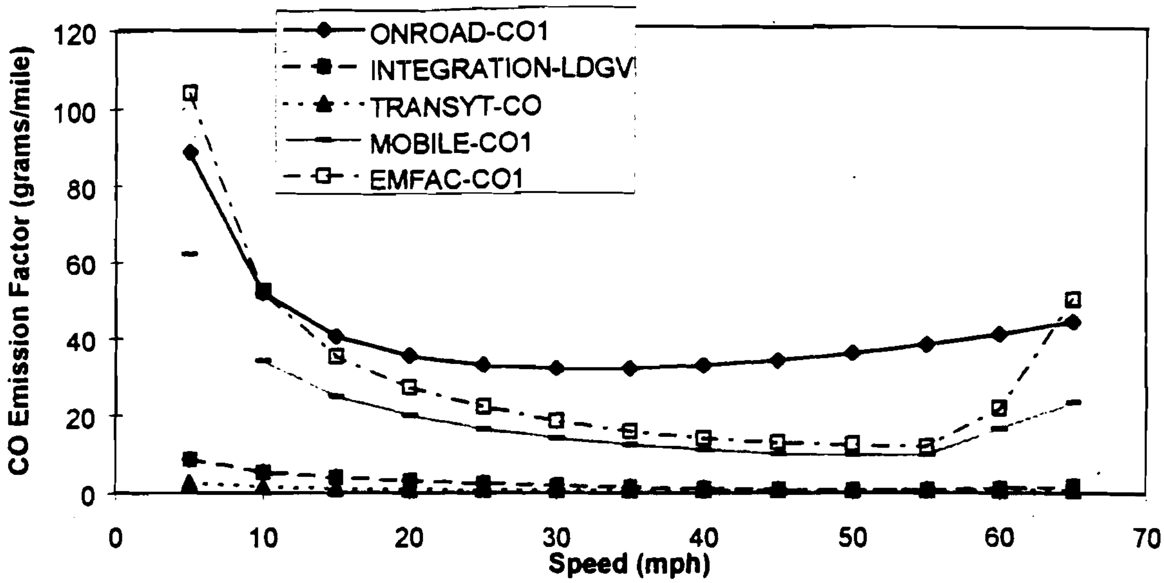


**Figure 5-13: Emission factors at various instantaneous speeds for the CO emissions for: vehicle type 1**

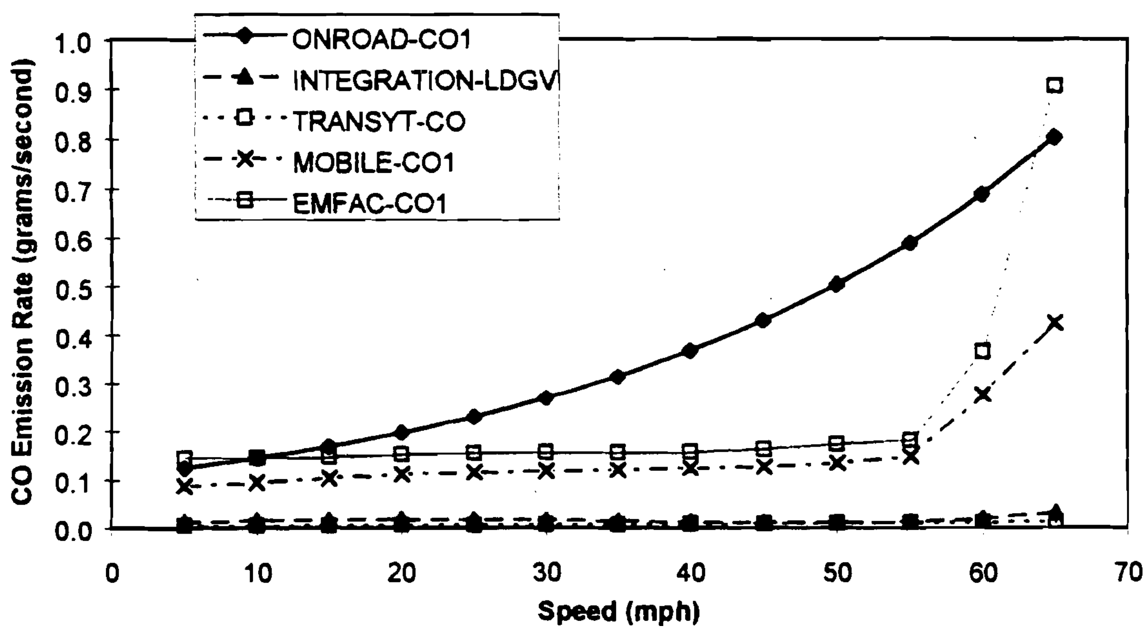


**Figure 5-14: Emission rates at various instantaneous speeds for the CO emissions for vehicle type 1**

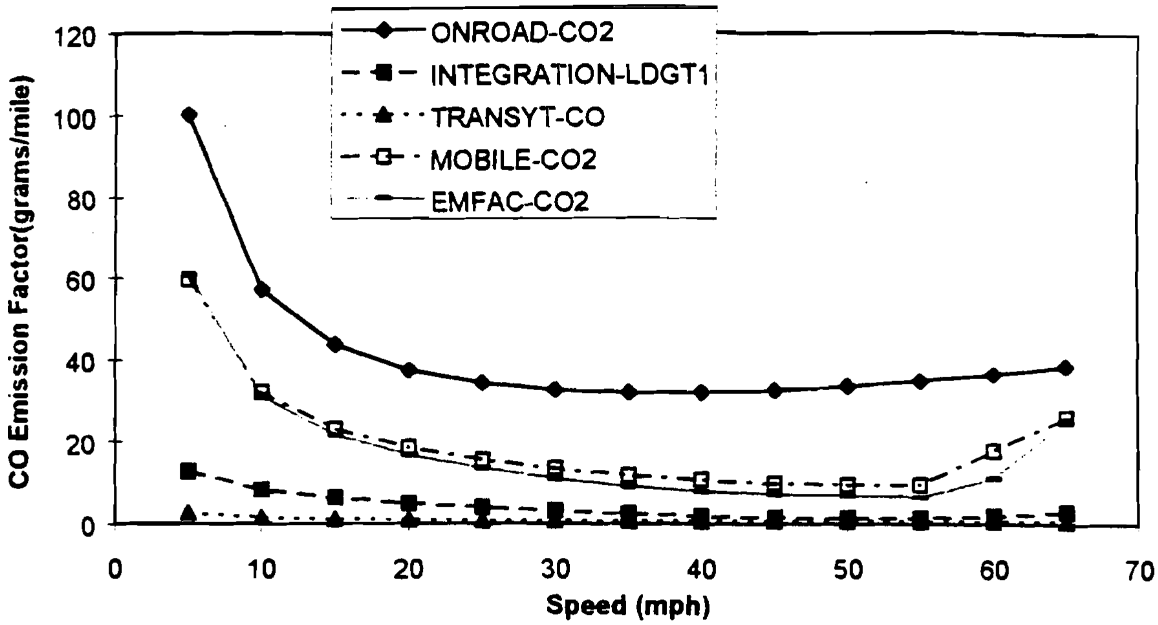


**Figure 5-15: Emission factors at various instantaneous speeds for the CO emissions for vehicle type 2**

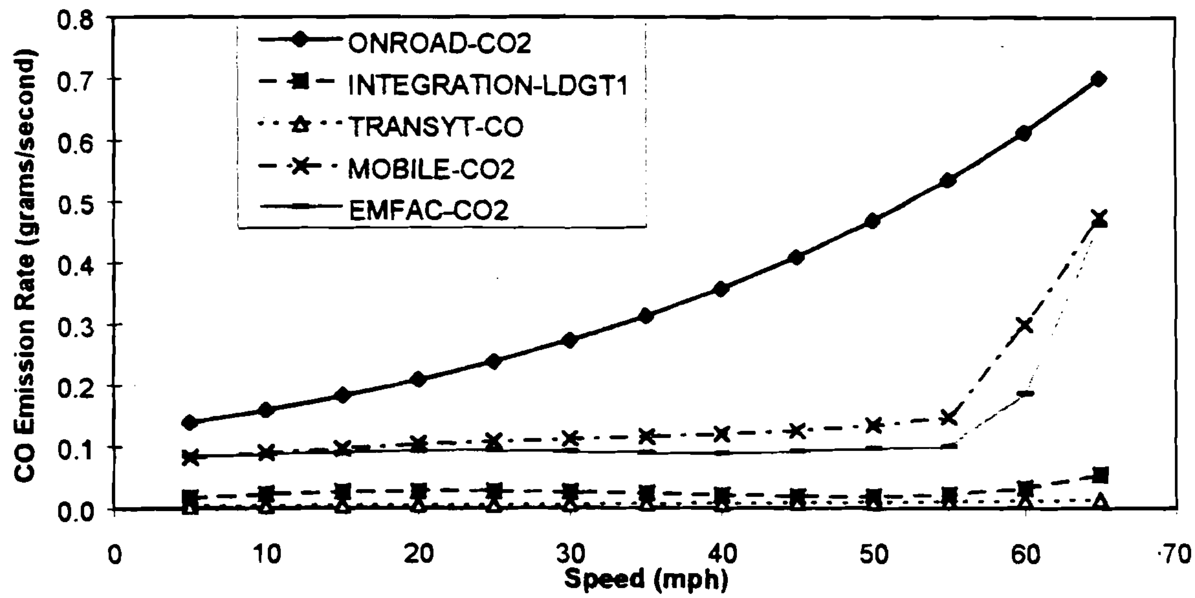


**Figure 5-16: Emission rates at various instantaneous speeds for the CO emissions for vehicle type 2**

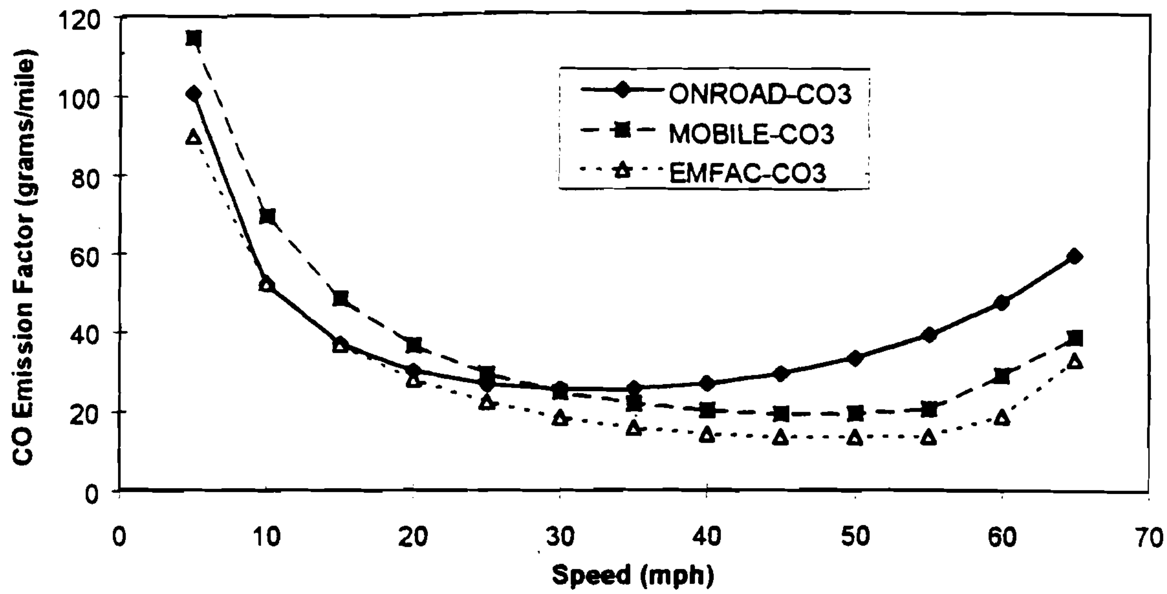


**Figure 5-17: Emission factors at various instantaneous speeds for the CO emissions for vehicle type 3**

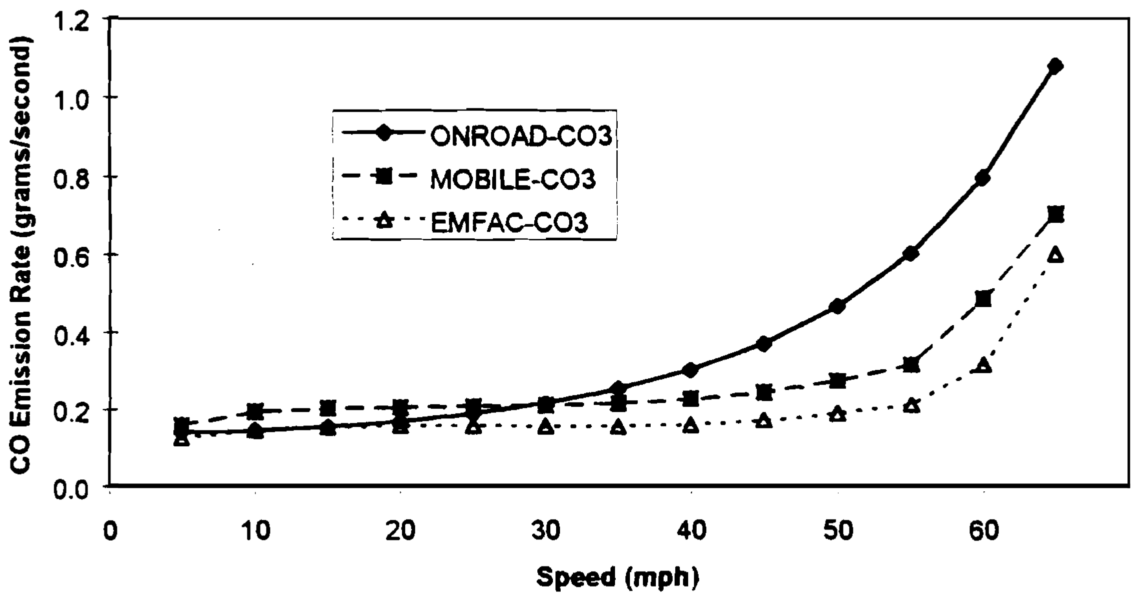


**Figure 5-18: Emission rates at various instantaneous speeds for the CO emissions for vehicle type 3**

The Figures 5-19 to 5-26 illustrate comparisons of emission factors and rates for hydrocarbon. It is first noted that at speeds lower than 20 mph, EMFAC and the ONROAD estimate almost identical HC emission factors. Similar to CO emissions, Figure 5-19 illustrates that both MOBILE and EMFAC assume that the emission factor reaches a minimum point at the speed of 55 mph. However, the HC emission factor curves for MOBILE deviates from the curve for EMFAC where EMFAC estimates higher emission factors. TRANSYT estimates much lower emission factors than other models due to its limited number of sample vehicles. Figure 5-20 illustrates the HC emission rates for the aggregate vehicle types. Again, MOBILE and EMFAC predict a sharp change of the slopes of curves at the speed of 55 mph.

The comparisons of HC emissions for vehicle type 1 include INTEGRATION emission estimation as shown in Figures 5-21 and 5-22. Different from the CO emissions, the curve for INTEGRATION almost' replicates the curve for MOBILE. At lower speeds, HC emission estimations by the ONROAD and MOBILE and EMFAC are more consistent. For other speeds (>20 mph), MOBILE and EMFACF estimate lower HC emission factors than the ONROAD, while estimation by EMFAC is higher than estimation by MOBILE. Figures 5-23 and 5-24 illustrate emission factors and emission rates for vehicle type 2. It is interesting to note that all the curves have similar trends but different values. All the emission models have ranked in terms of the magnitudes of emissions factors as ONROAD, EMFAC, MOBILE, INTEGRATION, and TRANSYT. Figures 5-25 and 5-26 illustrate HC emission factors and emission rates for the vehicle type 3. It is interesting to note from Figure 25 that MOBILE and EMFAC curves are almost identical, but are lower than the curve for the ONROAD. Figure 5-26 demonstrates that MOBILE and EMFAC estimate rather flat emission rates for speeds between 20 and 50 mph, while the ONROAD observes a smooth and parabolic increasing emission rates.

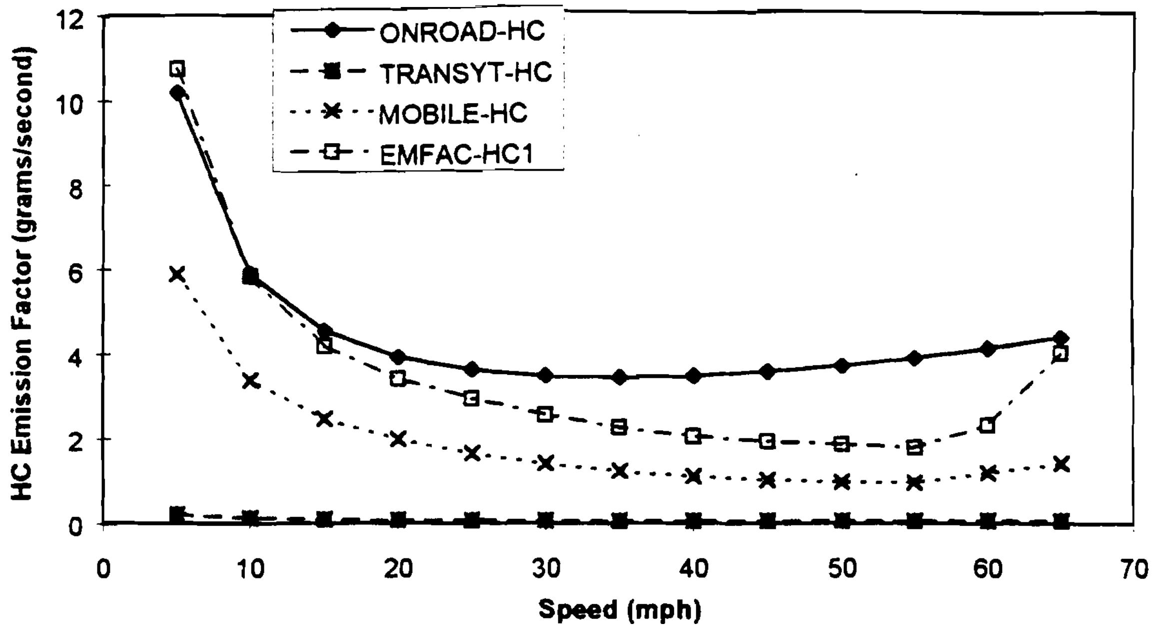


**Figure 5-19: Emission factors at various instantaneous speeds for the aggregate HC emissions**

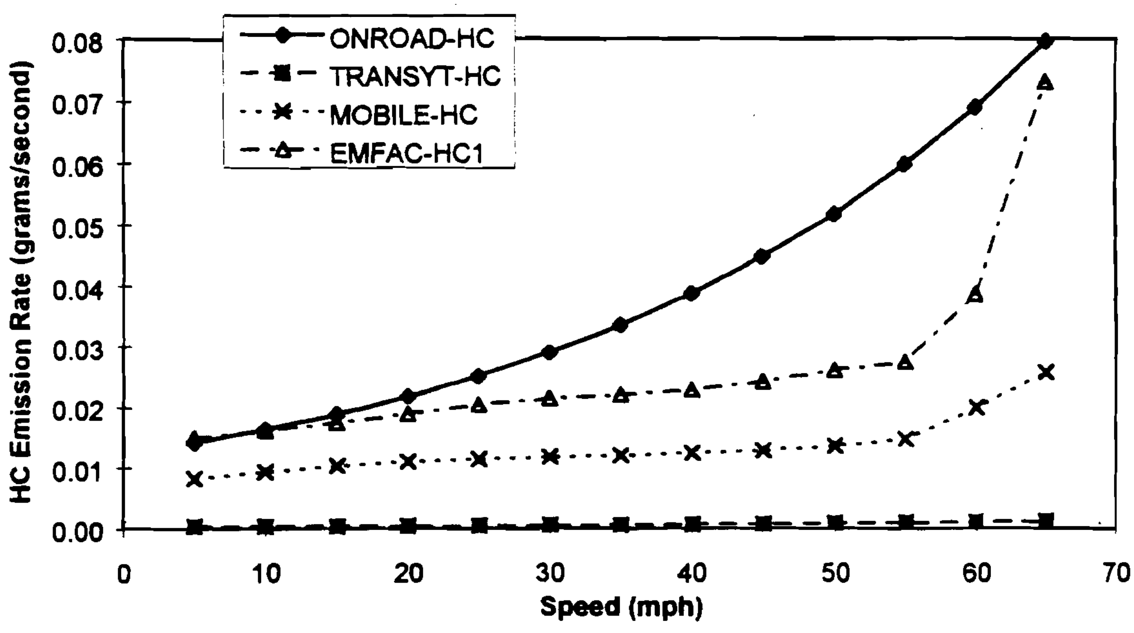


**Figure 5-20: Emission rates at various instantaneous speeds for the aggregate HC emissions**

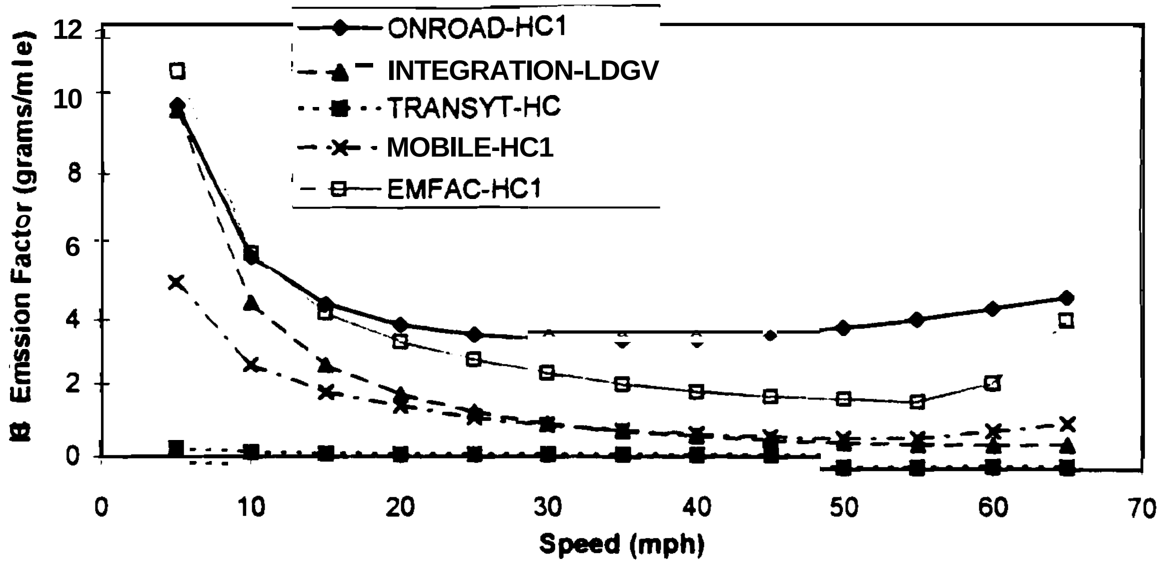


Figure 5-21: Emission factors at various instantaneous speeds for the HC emissions for vehicle type 1

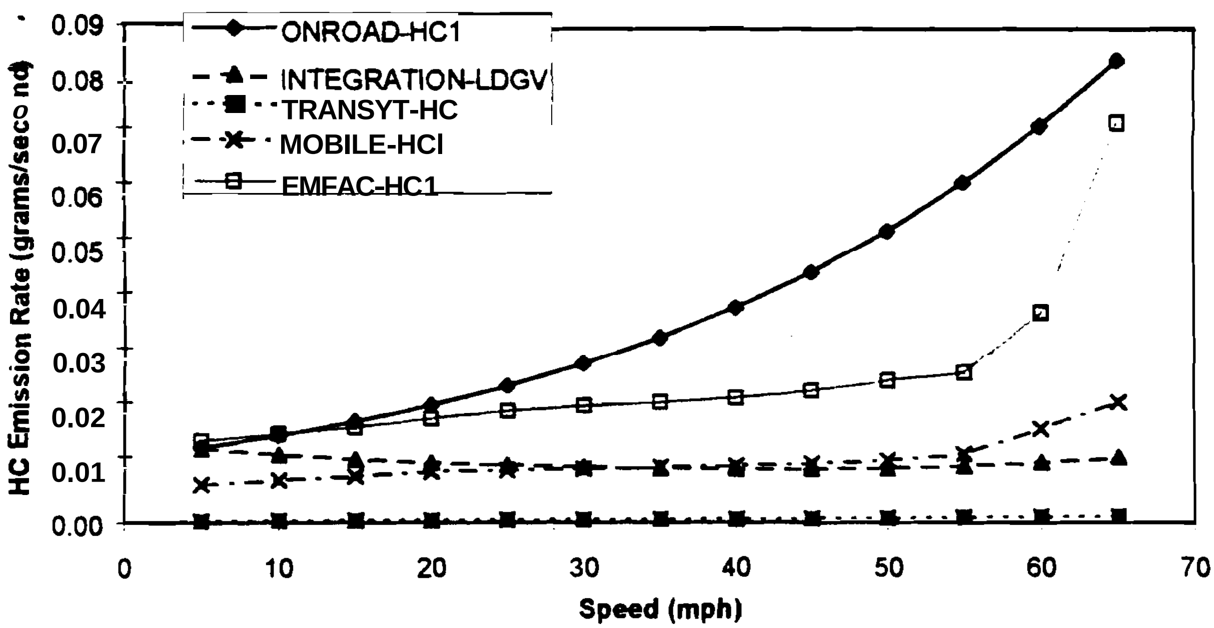


Figure 5-22: Emission rates at various instantaneous speeds for the HC emissions for vehicle type 1

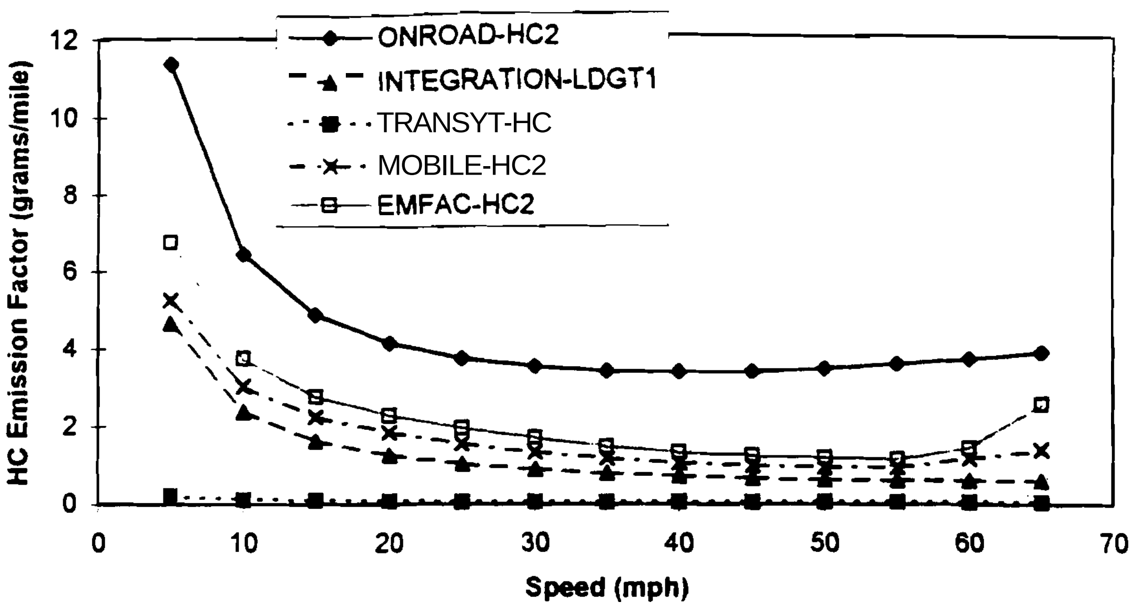


**Figure 5-23: Emission factors at various instantaneous speeds for the HC emissions for vehicle type 2**

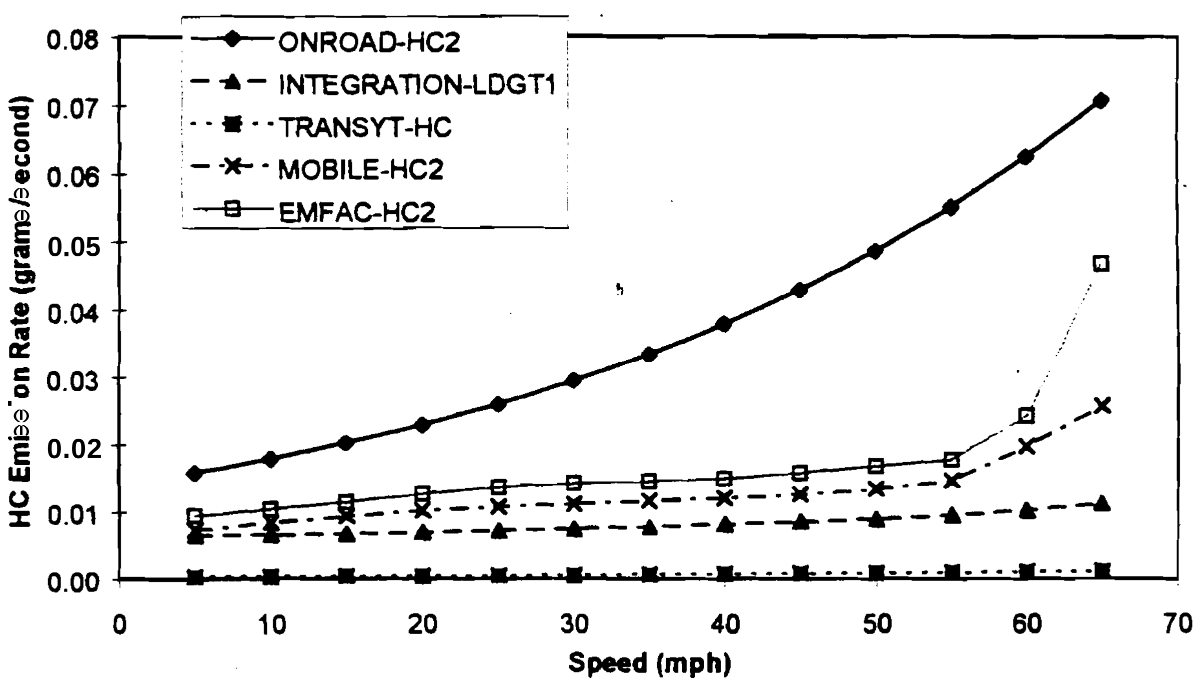


**Figure 5-24: Emission rates at various instantaneous speeds for the HC emissions for vehicle type 2**

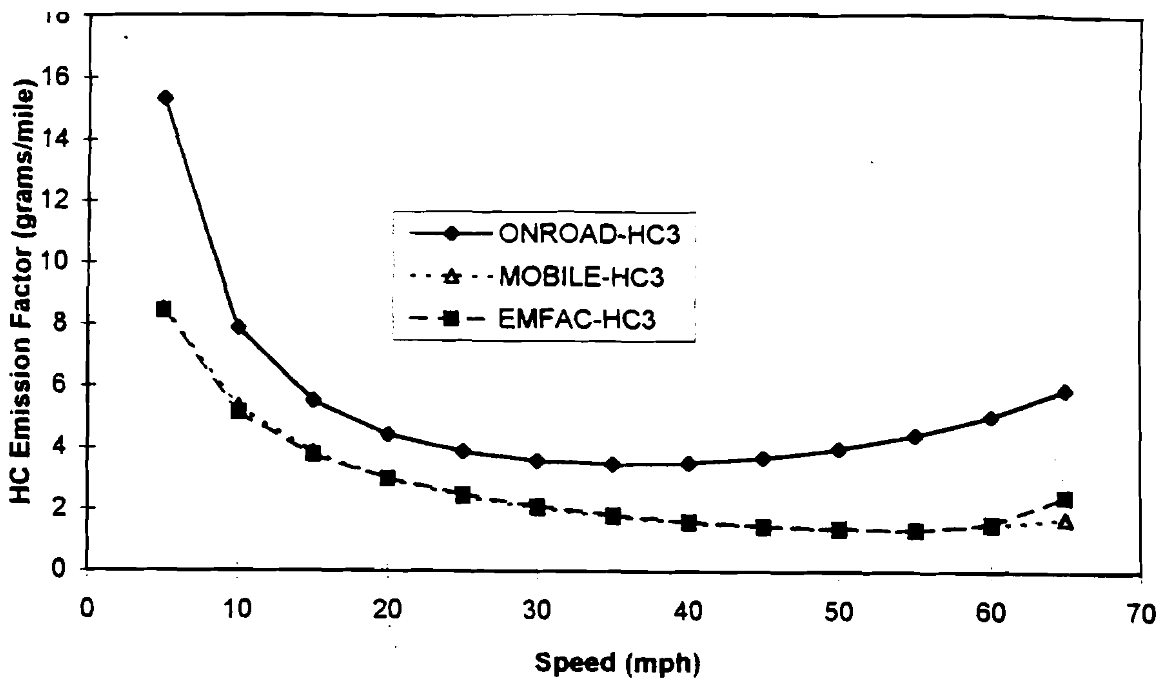


**Figure 5-25: Emission factors at various instantaneous speeds for the HC emissions for vehicle type 3**

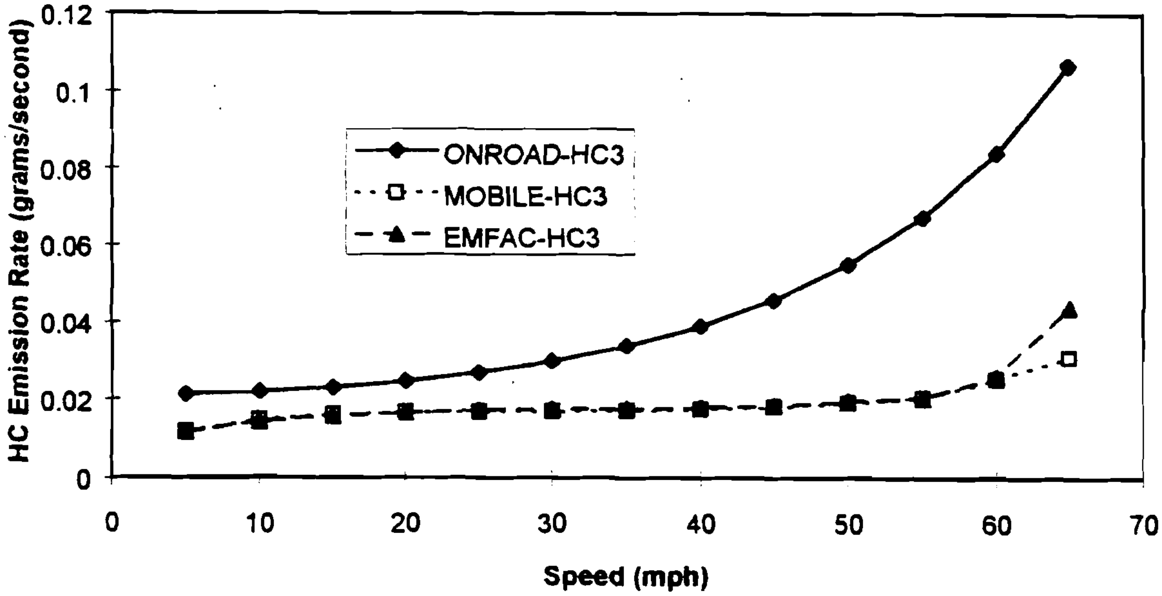


**Figure 5-26: Emission rates at various instantaneous speeds for the HC emissions for vehicle type 3**

# CHAPTER 6: FINDINGS AND RECOMMENDATIONS

Chapter 2 provided an overview of the existing emission estimation models and indicated the merits and shortcomings of each specific model. Chapter 3 presented an emission collection effort for the on-road vehicles at five selected .highway locations in Houston, while Chapter 4 described the development of the ONROAD emission model based on the collected emission data. Chapter 5 striven to compare the ONROAD emission factors and rates with various existing emission estimation models especially MOBILE and EMFAC. This chapter will summarize what has been found in the previous chapters and provide a recommendation on how the results from this research should be implemented and what further studies need to be conducted in the future.

## *Findings From This Research*

The research findings can be summarized into four parts: findings related to the capabilities of existing emission estimation models, findings related to the emission data collection and limitations of emission data, findings related to the ONROAD emission model, and findings in regard to the evaluation and comparisons of various emission models. These findings will be described respectively in the following.

### Capabilities of Existing Emission Models

There exists three types of emission models, emission factor models which include MOBILE and EMFAC, emission models for traffic simulation which include INTEGRATION, TRANSYT, NETSIM and so on, and new generation modal emission models which include the one developed by UC Riverside and the one developed by GIT. Emission factor models were developed based on the in-laboratory emission testing of FTP defined driving cycles and designed to perform various air quality planning functions. They use the average speed as the sole indicator of vehicles' modal activities and thus they are not responsive to a vehicle's instantaneous speed profile and cannot be used to evaluate the emission implications of various traffic control and management strategies.

Most of emission models in traffic simulation models are designed to be more sensitive to a vehicle's instantaneous speed and acceleration rate. Therefore, they can be used to evaluate emission implications of various traffic network control and demand scenarios. They are designed in appropriate formats that can be easily incorporated into traffic simulation or dynamic traffic assignment models and most suitable for performing various traffic engineering functions. However, the emission database for developing these models are very specific and limited and do not represent a wide range of vehicle types and on-road vehicle combinations.

The new generation 'emission models that are being developed at UC Riverside and Georgia Tech attempt to be modal .emission models which have a high level of flexibility for applications to both air quality planning functions and traffic engineering functions. However, these models are not workable yet and any further evaluation of these models will only be possible after they can be actually used for the field applications.

## Emission Data Collection

The traditional method in developing emission models is to conduct laboratory emission testing which is very costly and limited. The remote emission sensing technology was initially applied in transportation to screen for high emitter vehicles. It is very convenient and cost effective. With a minimum effort, a large amount of emission data can be collected. Usually a RES can detect the emission concentrations.

The SMOG DOG used in this research is an infrared RES equipment which can detect concentrations of HC, CO, and NOx, as well as a vehicle's instantaneous speed and acceleration rate. However, it cannot detect the vehicle emission rates directly, which presents an obstacle for us to develop any emission models or evaluate existing emission models based on these on-road emission data.

The SCAQMD regression equations are used to convert the emission concentrations to emission rates. Although these regression equations were developed based on limited emission test scenarios and do not perfectly reflect the relationships between emission concentrations and emission rates, they are the only ones available for the conversion purpose. It will be the best solution to this problem if the RES can detect the emission rates directly from the on-road vehicles.

## ONROAD Emission Model

The ONROAD emission model is developed using the collected emission data and the emission conversion equations of SCAQMD. Three vehicle types are used in ONROAD emission model, which include passehger cars, van and pick-up trucks, and other trucks. This classification of vehicle types is based on the videotapes that were recorded during the emission data collection. Although this classification is not as detailed as the one in MOBILE and EMFAC, it is sufficient for traffic engineering purposes. A traffic engineer is more concerned with the aggregate emission effect of any traffic control and management strategies as opposed to emission inventory of more detailed vehicle types.

The advantage of using on-road emission data for emission model development is that these data will naturally represent the combinations of various vehicle types, ages, and technologies. In other words, the on-road emission data reflect a realistic on-road vehicle population. The ONROAD emission model is designed as an exponential format and the emission rate is made a function of a vehicle's instantaneous speed, acceleration rate and/or ambient temperature.

Since the ONROAD emission model represents the on-road emissions, it can be used to evaluate the accuracy of existing emission models in representing on-road vehicle emissions. It is also in a format that can be easily incorporated into a traffic simulation or a dynamic traffic assignment model so that the emission implications of various traffic control and management strategies can be evaluated. It should be noted that the ONROAD emission model only estimates the vehicle tailpipe exhaust emissions and none of other emissions such as evaporative emissions, resting emissions, and running emissions are included.

While the ONROAD emission model initially intended to establish relationships between the emission rates and all of the available independent variables including speed, acceleration, temperature, and humidity, most of the finally resulting emission equations include only two of them. Specifically, humidity is not included in any of the final equations, temperature is included in only two equations, and acceleration is included in four equations. This result is due partly to the insufficient database or the bad quality of the collected data. However, the successful inclusion of the instantaneous speed into the emission estimation is the most importation part in the emission model development.

## Evaluation of Existing Models

The ONROAD emission model is used to emulate FTP defined driving cycles so that the emission factors can be derived which are comparable to the emission factors of MOBILE and EMFAC. The comparisons of emission factors indicate that both MOBILE and EMFAC underestimate the on-road vehicle emissions. For most of vehicle types, MOBILE estimates lower emissions than EMFAC.

In the comparisons of instantaneous emission factors and emission rates, TRANSYT estimates the lowest emissions for all vehicle types and emission species. This is because TRANSYT used only six sample vehicles in the development of its emission equations and thus the representativeness of these equations are very limited. Therefore, the emission estimation of TRANSYT is far lower than the realistic on-road emissions.

At speeds lower than 20 mph for passenger cars, the emission estimation by MOBILE and EMFAC are consistent with the ONROAD emissions. With the increase of speeds, the deviation between the MOBILE and EMAFC, and ONROAD increases and reaches the maximum at the speed 55 mph. Beyond the speed 55 mph, the deviation gets closer again. For van and pick-up trucks, the trends of curves are similar to those for passenger cars except for that there is no overlap of curves at low speeds.

While both MOBILE and EMFAC estimate lower CO emissions than the ONROAD, EMFAC's estimation is higher than MOBILE for passenger cars and MOBILE's estimation is higher than EMFAC for van and pick-up trucks and other trucks. MOBILE and EMFAC estimate that CO emission rates are flat for speeds lower than 55 mph and increase sharp thereafter, while the ONROAD emission rates demonstrate a more smooth increase with the increase of speeds. For the vehicle type 3, estimations of CO emissions from 'both MOBILE and EMFAC are very close to ONROAD emission rates especially at lower speeds.

For HC emissions, while the emission estimations from MOBILE and EMFAC show some degree of deviation from the ONROAD, the estimation from EMFAC is always higher than the estimation from MOBILE except for the vehicle type 3 where the estimations from two emission factor models are identical.

INTEGRATION estimates much lower emissions than ONROAD especially for CO emissions. For HC emissions, the estimation from INTEGRATION is much higher than TRANSYT but still lower than MOBILE, EMFAC, and ONROAD.

Therefore, all the existing emission estimation models underestimate on-road emissions. While the estimations from MOBILE and EMFAC are closer to ONROAD emissions in general, estimations from EMFAC is higher than the ones from MOBILE for most of vehicle types.

## *Recommendations*

Two types of recommendations are provided in the following: recommendations for implementation and recommendations for further work.

### Recommendation for Implementation

From all findings derived from this research, the following recommendations are provided for the purposes of implementation in TxDOT:

1. For the purpose of establishing the mobile source emission inventory, the emission factor model MOBILE should be continuously used. It is the only model that can generate emission factors for detailed vehicle types and other parameters. But it should be recognized that MOBILE underestimates on-road emissions.

2. For evaluating emission implications of traffic control and management strategies, the ONROAD emission equations can be used. The use of ONROAD should be in conjunction with a traffic simulation or a dynamic traffic assignment model.

3. SMOG DOG should be used routinely for collecting on-road emission data at various highway locations of Texas in order to establish more reliable source of on-road vehicle emission data.

### Recommendation for Further Work

The following work is recommended to further this research:

1. A Strategic plan should be established in regard to the collection of on-road emission data from various locations in Texas. The remote emission sensor is considered the most cost-effective equipment for performing this task.
2. A traffic simulation or a dynamic traffic assignment model should be selected that can be optimally used for TxDOT in conjunction with the ONROAD to evaluate the emission implications of traffic network control and demand scenarios.
3. Conversion equations from emission concentrations to emission rates should be improved in order to derive more accurate emission rates for on-road vehicles. Alternatively, this problem can also be solved if the remote emission sensing technology is further advanced such that the emission rate information can be directly recorded from the RES equipment.

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# APPENDIX A: A MOBILE INPUT FILE

*Italic: Control section*

Underline: One-time *Data* section

Normal: Scenario section

```
1            PROMPT
Demonstration of output format 4 (80-column descriptive).
1            TAMFLG
1            SPDFLG
1            VMFLAG
1            MYMRFG
1            NEWFLG
1            IMFLAG
1            ALHFLG
1            ATPFLG
1            RLFLAG
2            LOCFLG - LAP record will appear once, in one-time data section.
2            TEMFLG
4            OUTFMT - 80-column descriptive format.
4            PRTFLG - Print exhaust HC, CO and NOx results.
1            IDLFLG
1            NMHFLG - Calculate Total hydrocarbon emissions factors
2            HCFLAG - Print sum and components.
Scenario title.  C  72.  92. 11.5 08.7 92 1 1 1       Local Area Parameter record
1 96  2.5 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96  5.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 10.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 15.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 20.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 25.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 30.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 35.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 40.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 45.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 50.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 55.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 60.0 75.0 20.6 27.3 20.6 01                      Scenario description record
1 96 65.0 75.0 20.6 27.3 20.6 01                      Scenario description record
00000000000000000000000000000000000000000000000000000000000000000000000000000000
```

# APPENDIX B: A MOBILE OUTPUT FILE

```
1 Demonstration of output format 4 (80-column descriptive).
 MOBILE5a (26-Mar-93)
0
-M 52 Warning:
+             0.100     speed increased to 2.5 mph minimum
0Scenario title.
                    Minimum Temp: 72. (F)   Maximum Temp: 92. (F)
                    Period 1 RVP: 11.5      Period 2 RVP:  8.7 Period 2 Yr: 1992
0Total HC emission factors include evaporative HC emission factors.
0_______________________________________________________________________________
0Emission factors are as of Jan. 1st of the indicated calendar year.
0Cal. Year: 1996          Region: Low           Altitude:  500. Ft.
                      I/M Program: No        Ambient Temp:   75.0 / 75.0 / 75.0 F
                Anti-tam. Program: No      Operating Mode:   20.6 / 27.3 / 20.6
                 Reformulated Gas: No
0Veh. Type:  LDGV  LDGT1  LDGT2   LDGT    HDGV   LDDV    LDDT   HDDV    MC   All Veh
+           _____  _____  _____  ______  _____  _____  _____  _____  _____  ______
 Veh. Spd.:  2.5    2.5    2.5            2.5    2.5    2.5    2.5    2.5
  VMT Mix:  0.629  0.182  0.084          0.031  0.003  0.002  0.062  0.007
0Composite Emission Factors (Gm/Mile)
 Total  HC: 15.92  19.09  27.25  21.68  34.85   1.61   2.31   5.46  13.44  17.31
 Exhst  HC:  9.42  11.66  17.35  13.46  17.71   1.61   2.31   5.46  10.81  10.48
 Evap.  HC:  0.27   0.34   0.45   0.38   1.87                         2.29   0.35
 Refuel HC:  0.17   0.23   0.23   0.23   0.39                                0.18
 Runing HC:  5.99   6.80   9.16   7.55  14.78                                6.24
 Rsting HC:  0.07   0.06   0.06   0.06   0.10                         0.34   0.06
 Exhst  CO:117.19 147.20 225.05 171.83 286.44   5.57   6.40  38.84 149.39 131.88
 Exhst NOX:  2.37   2.64   3.25   2.83   4.64   2.81   3.27  23.59   0.95   3.88
 _______________________________________________________________________________
0Emission factors are as of Jan. 1st of the indicated calendar year.
0Cal. Year: 1996          Region: Low           Altitude:  500. Ft.
                      I/M Program: No        Ambient Temp:   75.0 / 75.0 / 75.0 F
                Anti-tam. Program: No      Operating Mode:   20.6 / 27.3 / 20.6
                 Reformulated Gas: No
0Veh. Type:  LDGV  LDGT1  LDGT2   LDGT    HDGV   LDDV    LDDT   HDDV    MC   All Veh
+           _____  _____  _____  ______  _____  _____  _____  _____  _____  ______
 Veh. Spd.:  5.0    5.0    5.0            5.0    5.0    5.0    5.0    5.0
  VMT Mix:  0.629  0.182  0.084          0.031  0.003  0.002  0.062  0.007
0Composite Emission Factors (Gm/Mile)
 Total  HC:  7.34   9.08  12.81  10.26  20.36   1.42   2.03   4.80   9.37   8.35
 Exhst  HC:  5.03   6.31   9.39   7.29  14.11   1.42   2.03   4.80   6.73   5.89
 Evap.  HC:  0.27   0.34   0.45   0.38   1.87                         2.29   0.35
 Refuel HC:  0.17   0.23   0.23   0.23   0.39                                0.18
 Runing HC:  1.80   2.13   2.67   2.30   3.89                                1.87
 Rsting HC:  0.07   0.06   0.06   0.06   0.10                         0.34   0.06
 Exhst  CO: 62.07  77.81 118.14  90.57 228.87   4.55   5.22  31.70  86.06  72.86
 Exhst NOX:  1.94   2.16   2.70   2.33   4.76   2.53   2.94  21.20   0.85   3.32
 _______________________________________________________________________________
```

# APPENDIX C: AN EMFAC INPUT FILE

```
PARAM     1996 1996 1
SPEED     2020  1  0  0  0  0  0  0
RUNTEMP   75 75  1 75 75  1 75 75  1
STRTTEMP  75 75  1 75 75  1 75 75  1
DEWPOINT  .... N/A .....
```

# APPENDIX D: AN EMFAC OUTPUT FILE

1 EMFAC7F EMISSION FACTORS RUN DATES: REPORT 12/13/93
YEAR: 1996 SUMMERTIME

TABLE 1: SUMMERTIME RUNNING I/M EXHAUST EMISSION FACTORS AT 75 DEG F

POLLUTANT NAME: TOTAL ORGANIC GASES UNITS: GRAMS PER MILE

| SPEED | LIGHT DUTY AUTOS | | | LIGHT DUTY TRUCKS | | | MD. DUTY TRUCKS | | HEAVY DUTY TRUCKS | | | URBAN BUS | MCY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MPH | NCAT | CAT | DIESEL | NCAT | CAT | DIESEL | NCAT | CAT | NCAT | CAT | DIESEL | DIESEL | ALL |
| 5 | 22.28 | 1.12 | 0.93 | 17.43 | 1.57 | 0.88 | 17.87 | 2.23 | 15.02 | 2.99 | 6.69 | 10.69 | 9.50 |
| 10 | 12.16 | 0.53 | 0.73 | 9.68 | 0.74 | 0.69 | 9.97 | 1.07 | 9.84 | 1.96 | 5.25 | 8.39 | 5.01 |
| 15 | 8.74 | 0.37 | 0.59 | 7.10 | 0.51 | 0.55 | 7.35 | 0.74 | 6.72 | 1.34 | 4.21 | 6.74 | 3.53 |
| 20 | 7.14 | 0.31 | 0.48 | 5.85 | 0.44 | 0.45 | 6.08 | 0.63 | 4.79 | 0.95 | 3.46 | 5.53 | 2.86 |
| 25 | 6.12 | 0.29 | 0.40 | 5.01 | 0.41 | 0.38 | 5.21 | 0.59 | 3.55 | 0.71 | 2.90 | 4.63 | 2.45 |
| 30 | 5.33 | 0.27 | 0.35 | 4.33 | 0.38 | 0.33 | 4.48 | 0.55 | 2.75 | 0.55 | 2.49 | 3.97 | 2.14 |
| 35 | 4.71 | 0.24 | 0.30 | 3.80 | 0.34 | 0.29 | 3.91 | 0.49 | 2.22 | 0.44 | 2.18 | 3.48 | 1.89 |
| 40 | 4.28 | 0.20 | 0.27 | 3.44 | 0.28 | 0.26 | 3.53 | 0.42 | 1.86 | 0.37 | 1.95 | 3.12 | 1.71 |
| 45 | 4.04 | 0.17 | 0.25 | 3.25 | 0.24 | 0.23 | 3.33 | 0.35 | 1.63 | 0.32 | 1.79 | 2.86 | 1.61 |
| 50 | 3.93 | 0.15 | 0.23 | 3.16 | 0.21 | 0.22 | 3.24 | 0.32 | 1.49 | 0.30 | 1.67 | 2.67 | 1.56 |
| 55 | 3.75 | 0.17 | 0.22 | 2.98 | 0.24 | 0.21 | 3.05 | 0.35 | 1.42 | 0.28 | 1.60 | 2.56 | 1.50 |
| 60 | 4.79 | 0.27 | 0.22 | 3.73 | 0.38 | 0.21 | 3.79 | 0.54 | 1.41 | 0.28 | 1.57 | 2.50 | 1.32 |
| 65 | 8.07 | 0.78 | 0.22 | 6.28 | 1.14 | 0.21 | 6.40 | 1.51 | 1.46 | 0.29 | 1.57 | 2.50 | 0.91 |

POLLUTANT NAME: CARBON MONOXIDE UNITS: GRAMS PER MILE

| SPEED | LIGHT DUTY AUTOS | | | LIGHT DUTY TRUCKS | | | MD. DUTY TRUCKS | | HEAVY DUTY TRUCKS | | | URBAN BUS | MCY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MPH | NCAT | CAT | DIESEL | NCAT | CAT | DIESEL | NCAT | CAT | NCAT | CAT | DIESEL | DIESEL | ALL |
| 5 | 195.82 | 12.01 | 4.66 | 143.88 | 15.08 | 4.56 | 165.09 | 13.36 | 224.35 | 27.68 | 37.15 | 66.36 | 52.45 |
| 10 | 97.81 | 6.70 | 3.21 | 73.20 | 8.25 | 3.15 | 84.07 | 7.27 | 149.26 | 18.41 | 25.61 | 45.75 | 25.22 |
| 15 | 65.80 | 4.60 | 2.32 | 50.44 | 5.68 | 2.27 | 58.73 | 5.01 | 104.92 | 12.94 | 18.48 | 33.02 | 16.56 |
| 20 | 50.92 | 3.59 | 1.75 | 39.10 | 4.48 | 1.71 | 46.25 | 3.97 | 77.92 | 9.61 | 13.96 | 24.94 | 12.70 |
| 25 | 41.63 | 3.01 | 1.38 | 31.31 | 3.80 | 1.36 | 37.46 | 3.39 | 61.14 | 7.54 | 11.03 | 19.71 | 10.40 |
| 30 | 34.78 | 2.62 | 1.14 | 25.31 | 3.32 | 1.12 | 30.48 | 2.97 | 50.69 | 6.25 | 9.13 | 16.30 | 8.73 |
| 35 | 29.68 | 2.31 | 0.99 | 20.91 | 2.93 | 0.97 | 25.31 | 2.62 | 44.40 | 5.48 | 7.90 | 14.11 | 7.47 |
| 40 | 26.20 | 2.09 | 0.90 | 18.07 | 2.62 | 0.88 | 22.06 | 2.34 | 41.09 | 5.07 | 7.16 | 12.79 | 6.60 |
| 45 | 24.11 | 1.98 | 0.85 | 16.49 | 2.46 | 0.83 | 20.44 | 2.18 | 40.17 | 4.96 | 6.79 | 12.12 | 6.08 |
| 50 | 22.88 | 2.06 | 0.84 | 15.52 | 2.54 | 0.83 | 19.55 | 2.25 | 41.50 | 5.12 | 6.73 | 12.03 | 5.85 |
| 55 | 21.30 | 2.50 | 0.88 | 13.82 | 3.11 | 0.86 | 17.49 | 2.76 | 45.30 | 5.59 | 6.99 | 12.49 | 5.66 |
| 60 | 40.13 | 3.87 | 0.95 | 24.29 | 5.00 | 0.93 | 30.38 | 4.50 | 52.23 | 6.44 | 7.60 | 13.58 | 5.08 |
| 65 | 91.74 | 8.71 | 1.08 | 55.54 | 12.20 | 1.06 | 69.46 | 11.21 | 63.64 | 7.85 | 8.64 | 15.44 | 3.65 |

# APPENDIX E: A SAMPLE OF COLLECTED EMISSION DATA

| Column | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 04-29-1996 | 11:19:32 | 10 | NOPLATE | 999.00 | 999.00 | 99999 | 0.9744 | 0.1323 | 7.4752 | 7.3174 | 0.9970 | 99.00 | 99.00 | 999.00 | 99999 | 0.0000 | 0.0000 |
| | 2 | 04-29-1996 | 11:20:37 | 10 | DUF4QP | 0.02 | 15.03 | 0 | 0.0014 | -0.0020 | 0.4797 | 0.0292 | 0.0037 | 50.04 | 50.10 | 0.53 | 99999 | 0.0050 | 0.0000 |
| | 3 | 04-29-1996 | 11:20:46 | 10 | 430YUV | 0.29 | 14.85 | 141 | 0.0196 | 0.0009 | 0.3679 | 0.0625 | 0.0158 | 44.13 | 44.27 | 1.05 | 99999 | -0.0200 | 0.0000 |
| | 4 | 04-29-1996 | 11:20:51 | 10 | GGX16F | 999.00 | 999.00 | 99999 | -0.0317 | -0.0055 | 0.1364 | 0.0418 | 0.0060 | 36.42 | 36.46 | 0.21 | 99999 | 0.0260 | 0.0000 |
| | 5 | 04-29-1996 | 11:21:29 | 10 | MLF01D | 1.97 | 13.64 | 78 | 0.1446 | 0.0006 | 0.2197 | 0.0447 | 0.0039 | 43.84 | 43.72 | -0.86 | 99999 | 0.0440 | 0.0000 |
| | 6 | 04-29-1996 | 11:21:37 | 10 | KA0991 | 999.00 | 999.00 | 99999 | -5.4591 | -0.0557 | 0.0189 | 0.1885 | 0.0042 | 30.67 | 30.50 | -0.74 | 99999 | 9.9900 | 0.0000 |
| | 7 | 04-29-1996 | 11:21:47 | 10 | 0334TD | 999.00 | 999.00 | 99999 | 0.0870 | 0.0020 | 0.1772 | 0.0967 | 0.0090 | 38.99 | 38.75 | -1.37 | 99999 | 0.0410 | 0.0000 |
| | 8 | 04-29-1996 | 11:22:17 | 10 | HLM97L | 4.74 | 11.65 | 0 | 0.4069 | -0.0010 | 0.3205 | 0.1521 | 0.0144 | 50.44 | 50.44 | 0.00 | 99999 | 0.0260 | 0.0000 |
| | 9 | 04-29-1996 | 11:22:24 | 10 | 5902YY | 999.00 | 999.00 | 99999 | 0.0350 | 0.0017 | 0.7677 | 0.0729 | 0.0152 | 46.59 | 46.61 | 0.21 | 99999 | 0.0050 | 0.0000 |
| | 10 | 04-29-1996 | 11:22:30 | 10 | HRV32X | 0.39 | 14.77 | 25 | 0.0264 | 0.0002 | 2.0840 | 0.0714 | 0.0080 | 36.25 | 36.52 | 1.70 | 300 | 0.0020 | 0.0000 |
| | 11 | 04-29-1996 | 11:22:37 | 10 | VJP73K | 0.07 | 15.00 | 25 | 0.0047 | 0.0002 | 1.4358 | 0.0469 | 0.0052 | 36.12 | 36.41 | 1.70 | 395 | 0.0020 | 0.0000 |
| | 12 | 04-29-1996 | 11:22:49 | 10 | U | 0.51 | 14.69 | 0 | 0.0345 | -0.0002 | 2.8852 | 0.1361 | 0.0152 | 53.33 | 53.30 | -0.29 | 92 | 0.0000 | 0.0000 |
| | 13 | 04-29-1996 | 11:22:53 | 10 | KVG58V | 999.00 | 999.00 | 99999 | -3.5648 | 0.0845 | 0.0070 | 0.0595 | 0.0120 | 55.96 | 56.03 | 0.79 | 99999 | -0.2990 | 0.0000 |
| | 14 | 04-29-1996 | 11:23:14 | 10 | HKT51D | 0.06 | 15.01 | 0 | 0.0039 | -0.0009 | 0.9551 | 0.0768 | 0.0207 | 33.46 | 33.80 | 2.06 | 99999 | 0.0060 | 0.0000 |
| | 15 | 04-29-1996 | 11:23:30 | 10 | UU2222 | 0.00 | 15.10 | 0 | -0.0041 | -0.0002 | 1.0740 | 0.0745 | 0.0128 | 57.69 | 57.90 | 1.73 | 0 | -0.0030 | 0.0000 |
| | 16 | 04-29-1996 | 11:23:38 | 10 | KFJ52Z | 0.01 | 15.05 | 195 | 0.0009 | 0.0013 | 1.2474 | 0.0714 | 0.0199 | 42.17 | 42.32 | 1.03 | 0 | -0.0110 | 0.0000 |
| | 17 | 04-29-1996 | 11:23:41 | 10 | 900XYU | 999.00 | 999.00 | 99999 | 0.0926 | -0.0022 | 0.2791 | 0.0423 | 0.0038 | 36.93 | 36.82 | -0.74 | 99999 | 0.0390 | 0.0000 |
| | 18 | 04-29-1996 | 11:23:44 | 10 | STZ33P | 0.00 | 15.12 | 8 | -0.0064 | 0.0001 | 3.2768 | 0.0743 | 0.0054 | 36.29 | 36.47 | 1.11 | 263 | 0.0010 | 0.0000 |
| | 19 | 04-29-1996 | 11:23:56 | 10 | NV9431 | 0.34 | 14.81 | 0 | 0.0230 | -0.0014 | 0.4427 | 0.1209 | 0.0180 | 50.41 | 50.56 | 1.37 | 99999 | -0.0170 | 0.0000 |
| | 20 | 04-29-1996 | 11:24:09 | 10 | GH2027 | 9.30 | 8.39 | 205 | 1.1084 | 0.0024 | 0.1788 | 0.1878 | 0.0125 | 42.76 | 42.94 | 1.28 | 99999 | 0.0000 | 0.0000 |
| | 21 | 04-29-1996 | 11:24:12 | 10 | DCM73U | 0.28 | 14.84 | 0 | 0.0187 | -0.0057 | 0.3666 | 0.0465 | 0.0076 | 42.32 | 42.34 | 0.16 | 99999 | 0.0190 | 0.0000 |
| | 22 | 04-29-1996 | 11:24:15 | 10 | WJB47Z | 999.00 | 999.00 | 99999 | 0.0848 | -0.0102 | 0.1694 | 0.0849 | 0.0176 | 43.61 | 43.47 | -0.95 | 99999 | 0.0920 | 0.0000 |
| | 23 | 04-29-1996 | 11:24:21 | 10 | NOPLATE | 999.00 | 999.00 | 99999 | -0.0681 | -0.0156 | 0.1491 | 0.0578 | 0.0145 | 43.03 | 42.99 | -0.34 | 99999 | 0.0320 | 0.0000 |
| | 24 | 04-29-1996 | 11:24:25 | 10 | P | 999.00 | 999.00 | 99999 | 0.3852 | 0.0037 | 0.0311 | 0.0765 | 0.0202 | 57.73 | 57.41 | -3.11 | 99999 | -0.2920 | 0.0000 |
| | 25 | 04-29-1996 | 11:24:38 | 10 | NOPLATE | 0.27 | 14.86 | 77 | 0.0182 | 0.0005 | 3.5995 | 0.0908 | 0.0062 | 38.84 | 39.18 | 0.98 | 1102 | 0.0070 | 0.0000 |
| | 26 | 04-29-1996 | 11:24:41 | 10 | CK7537 | 3.70 | 12.40 | 0 | 0.2982 | -0.0006 | 1.0100 | 0.3359 | 0.0121 | 34.60 | 34.63 | 0.16 | 1143 | 0.0090 | 0.0000 |
| | 27 | 04-29-1996 | 11:24:44 | 10 | CLX90L | 999.00 | 999.00 | 99999 | 0.3595 | -0.0059 | 0.1754 | 0.0914 | 0.0109 | 46.88 | 46.77 | -0.86 | 99999 | -0.0390 | 0.0000 |
| | 28 | 04-29-1996 | 11:24:50 | 10 | GHF20N | 1.04 | 14.31 | 460 | 0.0726 | 0.0032 | 0.5312 | 0.0463 | 0.0050 | 43.33 | 43.51 | 1.39 | 99999 | -0.0130 | 0.0000 |
| | 29 | 04-29-1996 | 11:24:54 | 10 | VZJ84K | 0.19 | 14.91 | 0 | 0.0126 | -0.0022 | 0.8177 | 0.0867 | 0.0107 | 39.75 | 39.85 | 0.63 | 99999 | -0.0060 | 0.0000 |
| | 30 | 04-29-1996 | 11:24:57 | 10 | MR2845 | 0.40 | 14.76 | 0 | 0.0270 | -0.0027 | 0.5879 | 0.0397 | 0.0083 | 42.17 | 42.13 | -0.25 | 99999 | 0.0070 | 0.0000 |
| | 31 | 04-29-1996 | 11:25:00 | 10 | DU3882 | 999.00 | 999.00 | 99999 | 0.0711 | 0.0055 | 0.4075 | 0.0474 | 0.0112 | 41.32 | 41.36 | 0.28 | 99999 | -0.0100 | 0.0000 |
| | 32 | 04-29-1996 | 11:25:04 | 10 | U | 999.00 | 999.00 | 99999 | 0.0738 | -0.0030 | 1.1528 | 0.0970 | 0.0134 | 42.85 | 43.08 | 1.39 | 99999 | 0.0000 | 0.0000 |
| | 33 | 04-29-1996 | 11:25:15 | 10 | 682OXC | 999.00 | 999.00 | 99999 | -0.0157 | 0.0138 | 0.2266 | 0.0772 | 0.0116 | 41.97 | 41.87 | -0.60 | 99999 | 0.0130 | 0.0000 |
| | 34 | 04-29-1996 | 11:25:25 | 10 | BYO585 | 5.19 | 11.34 | 348 | 0.4578 | 0.0031 | 0.2463 | 0.1179 | 0.0111 | 47.02 | 46.77 | -1.74 | 99999 | 0.0180 | 0.0000 |
| | 35 | 04-29-1996 | 11:25:29 | 10 | U | 0.31 | 14.84 | 4 | 0.0206 | 0.0000 | 0.7373 | 0.0677 | 0.0114 | 46.38 | 46.48 | 0.79 | 99999 | -0.0010 | 0.0000 |
| | 36 | 04-29-1996 | 11:25:34 | 10 | U | 0.00 | 15.10 | 0 | -0.0045 | -0.0010 | 1.0436 | 0.0837 | 0.0179 | 41.51 | 41.74 | 1.29 | 976 | 0.0060 | 0.0000 |
| | 37 | 04-29-1996 | 11:25:54 | 10 | 84512U | 0.92 | 14.39 | 0 | 0.0637 | -0.0015 | 1.0343 | 0.0867 | 0.0134 | 43.19 | 43.35 | 1.09 | 732 | 0.0050 | 0.0000 |
| | 38 | 04-29-1996 | 11:26:29 | 10 | BM2689 | 5.97 | 10.77 | 76 | 0.5546 | 0.0007 | 0.6970 | 0.3899 | 0.0160 | 47.43 | 47.73 | 1.99 | 99999 | -0.0070 | 0.0000 |
| | 39 | 04-29-1996 | 11:26:39 | 10 | KHC35B | 0.29 | 14.84 | 0 | 0.0196 | -0.0007 | 0.5516 | 0.0948 | 0.0131 | 45.60 | 46.12 | 3.93 | 99999 | 0.0230 | 0.0000 |
| | 40 | 04-29-1996 | 11:26:44 | 10 | DT9877 | 999.00 | 999.00 | 99999 | 0.4755 | -0.0026 | 0.2273 | 0.0973 | 0.0151 | 38.77 | 39.07 | 1.99 | 99999 | -0.0680 | 0.0000 |
| | 41 | 04-29-1996 | 11:26:48 | 10 | U | 999.00 | 999.00 | 99999 | -0.0490 | -0.0032 | 1.0800 | 0.1613 | 0.0183 | 45.50 | 45.73 | 1.41 | 99999 | 0.0070 | 0.0000 |
| | 42 | 04-29-1996 | 11:26:55 | 10 | MKG24R | 999.00 | 999.00 | 99999 | 0.2212 | -0.0018 | 0.1056 | 0.0786 | 0.0109 | 39.35 | 39.41 | 0.38 | 99999 | 0.0500 | 0.0000 |
| | 43 | 04-29-1996 | 11:27:00 | 10 | JXD24P | 999.00 | 999.00 | 99999 | 0.1667 | 0.0084 | 0.1526 | 0.0519 | 0.0088 | 41.44 | 41.30 | -1.07 | 99999 | 0.0200 | 0.0000 |
| | 44 | 04-29-1996 | 11:27:08 | 10 | MKH23T | 0.17 | 14.93 | 0 | 0.0112 | -0.0011 | 0.6605 | 0.0828 | 0.0144 | 43.28 | 43.65 | 2.77 | 99999 | 0.0010 | 0.0000 |
| | 45 | 04-29-1996 | 11:27:13 | 10 | 1465WD | 999.00 | 999.00 | 99999 | 0.0924 | 0.0006 | 0.7860 | 0.2283 | 0.0114 | 39.25 | 39.41 | 0.98 | 99999 | -0.0070 | 0.0000 |
| | 46 | 04-29-1996 | 11:27:26 | 10 | SB3337 | 999.00 | 999.00 | 99999 | 0.0120 | -0.0223 | 0.0360 | 0.0549 | 0.0146 | 44.83 | 44.73 | -0.68 | 99999 | -0.1590 | 0.0000 |
| | 47 | 04-29-1996 | 11:27:31 | 10 | U | 999.00 | 999.00 | 99999 | 1.0265 | 0.1384 | 6.2229 | 6.4354 | 0.8638 | 45.42 | 45.99 | 1.91 | 99999 | -0.0080 | 0.0000 |
| | 48 | 04-29-1996 | 11:27:34 | 10 | U | 0.79 | 14.51 | 99999 | 0.0545 | 0.0098 | 0.6107 | 0.1051 | 0.0163 | 42.59 | 42.48 | -0.68 | 99999 | 0.0170 | 0.0000 |
| | 49 | 04-29-1996 | 11:27:38 | 10 | PRY41M | 0.29 | 14.84 | 0 | 0.0194 | -0.0016 | 1.2714 | 0.0627 | 0.0078 | 39.09 | 39.33 | 1.66 | 1835 | 0.0120 | 0.0000 |
| | 50 | 04-29-1996 | 11:27:48 | 10 | U | 3.47 | 12.60 | 2850 | 0.2754 | 0.0226 | 1.1360 | 0.3367 | 0.0286 | 36.28 | 36.59 | 1.62 | 174 | 0.0010 | 0.0000 |

# APPENDIX F: A SUMMARY OF ONROAD EMISSION RATES

| Speed | CO | CO1 | C02 | C03 | HC | HC1 | HC2 | HC3 |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.1264 | 0.1233 | 0.1391 | 0.1398 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 10 | 0.1468 | 0.1441 | 0.1592 | 0.1450 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 15 | 0.1705 | 0.1685 | 0.1821 | 0.1541 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 20 | 0.1981 | 0.1970 | 0.2084 | 0.1678 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 25 | 0.2301 | 0.2303 | 0.2385 | 0.1872 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 30 | 0.2672 | 0.2692 | 0.2730 | 0.2139 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 35 | 0.3104 | 0.3147 | 0.3124 | 0.2506 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 40 | 0.3606 | 0.3679 | 0.3575 | 0.3007 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 45 | 0.4188 | 0.4301 | 0.4092 | 0.3697 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 50 | 0.4865 | 0.5028 | 0.4683 | 0.4658 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 55 | 0.5651 | 0.5878 | 0.5359 | 0.6013 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 60 | 0.6564 | 0.6872 | 0.6133 | 0.7952 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 65 | 0.7624 | 0.8034 | 0.7018 | 1.0777 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 70 | 0.8856 | 0.9392 | 0.8032 | 1.4964 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |
| 75 | 1.0287 | 1.0980 | 0.9192 | 2.1289 | 0.0123 | 0.0118 | 0.0139 | 0.0211 |

**Note 1:** Speed is in the unit of mph and emission rate is in the unit of grams per second

**Note 2:** CO and HC = Aggregate CO and HC emission rates
COI and HC1 = CO and HC emission rates for vehicle type 1, passenger cars
CO2 and HC2 = CO and HC emission rates for vehicle type 2, van and pick-up trucks
C03 and HC3 = CO and HC emission rates for vehicle type 3, other trucks

# APPENDIX G: A SUMMARY OF ONROAD EMISSION FACTORS

| Speed | CO | CO1 | C02 | C03 | HC | HC1 | HC2 | HC3 |
|---|---|---|---|---|---|---|---|---|
| 5 | 90.9952 | 88.7751 | 100.1334 | 100.6497 | 0.4383 | 0.4205 | 0.4974 | 37.0261 |
| 10 | 52.8484 | 51.8910 | 57.2969 | 52.1942 | 0.8452 | 0.8108 | 0.9592 | 4.1435 |
| 15 | 40.9245 | 40.4419 | 43.7141 | 36.9768 | 1.1930 | 1.1445 | 1.3539 | 3.4717 |
| 20 | 35.6523 | 35.4587 | 37.5202 | 30.1960 | 1.4610 | 1.4015 | 1.6580 | 3.5685 |
| 25 | 33.1300 | 33.1622 | 34.3508 | 26.9500 | 1.6369 | 1.5703 | 1.8577 | 3.7231 |
| 30 | 32.0688 | 32.3068 | 32.7596 | 25.6717 | 1.7184 | 1.6484 | 1.9502 | 3.8087 |
| 35 | 31.9286 | 32.3726 | 32.1346 | 25.7719 | 1.7117 | 1.6420 | 1.9426 | 3.8015 |
| 40 | 32.4512 | 33.1143 | 32.1783 | 27.0615 | 1.6302 | 1.5638 | 1.8500 | 3.7164 |
| 45 | 33.5059 | 34.4108 | 32.7335 | 29.5771 | 1.4915 | 1.4308 | 1.6927 | 3.5917 |
| 50 | 35.0273 | 36.2049 | 33.7146 | 33.5363 | 1.3154 | 1.2619 | 1.4928 | 3.4870 |
| 55 | 36.9877 | 38.4774 | 35.0757 | 39.3549 | 1.1210 | 1.0753 | 1.2721 | 3.4976 |
| 60 | 39.3833 | 41.2333 | 36.7960 | 47.7140 | 0.9246 | 0.8869 | 1.0493 | 3.8161 |
| 65 | 42.2273 | 44.4955 | 38.8705 | 59.6869 | 0.7391 | 0.7090 | 0.8388 | 5.0009 |
| 70 | 45.5462 | 48.3017 | 41.3064 | 76.9572 | 0.5732 | 0.5499 | 0.6505 | 9.6078 |
| 75 | 49.3778 | 52.7024 | 44.1201 | 102.1883 | 0.4317 | 0.4141 | 0.4899 | 41.1164 |

Note 1: The speed is in the unit of mph and the emission factor is in the unit of grams per mile

Note 2: CO and HC = Aggregate CO and HC emission factors
CO1 and HC1 = CO and HC emission factors for vehicle type 1, passenger cars
C02 and HC2 = CO and HC emission factors for vehicle type 2, van and pick-up trucks
C03 and HC3 = CO and HC emission factors for vehicle type 3, other trucks