VEHICULAR EMISSIONS MODELS USING MOBILE6.2 AND FIELD DATA

by

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ABSTRACT

VEHICULAR EMISSIONS MODELS USING MOBILE6.2 AND FIELD DATA

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Regression models to predict vehicular emissions for different categories of vehicles for different pollutants are presented in this thesis. Vehicular emissions are affected by numerous variables which, among others, include speed, temperature, acceleration, deceleration, driving behavior and meteorological data. Regression models are developed based on data obtained from Mobile 6.2 and on-board emissions measurements. The U.S. Department of Transportation (US DOT) conducted sensitivity analysis of Mobile6 where they evaluated different parameters used to find the emission factors, such as vehicle miles traveled, speed, humidity, etc. The sensitivity analysis investigated the overall Mobile6.2 model behavior for various conditions. In the analysis, speed was observed to be the most significant variable for all emission types. In this thesis, the regression model for estimating the emission factor for different classes of

vehicles for different pollutants considers speed as the predictor variable. CO_2 emission rate is estimated in Mobile 6.2 in a very simplistic way. The CO_2 calculations are based on the average fuel economy performance estimates built into the model or supplied by the user. For other pollutants, Mobile6.2 considers various factors, such as the ambient temperature, speeds, humidity, etc., but the CO_2 emission rates are not adjusted for the speed, temperature, fuel content, etc. Therefore, in this thesis, a model is proposed for estimating the CO_2 emission rate considering speed as the predictor variable based on the data obtained from on-board emission measurements. Finally, an analysis is performed to study the affect of acceleration and deceleration on the emission rates.

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CHAPTER 1

INTRODUCTION

Vehicular emission factors and fuel consumption are two major areas where a substantial amount of research is being conducted. Vehicular emissions and fuel consumption are two critical aspects that are considered in the transportation planning process. In the USA, on-road vehicles contribute a greater percentage of emissions than other sources like area, non-road, point, and biogenic. In the Dallas-Fort worth (DFW) region, nine counties are considered non-attainment for ozone. In DFW, 51% of nitrogen oxides (NO_x) emissions and 30% of hydrocarbons (HC) emissions are from the on-road sources (Figure 2.2). When the two pollutants NO_x and HC react in sunlight, ozone is formed. Two types of vehicle emissions are exhaust emissions and evaporative emissions. The three major pollutants (HC, NO_x, Carbon monoxide (CO)) and Carbon dioxide (CO_2) are exhaust pollutants. The three major pollutants have a direct impact on human health, but the CO_2 emissions do not directly impact human health. The impact of HC emissions on human health includes respiratory problems, eye irritation, and potential to cause cancer. CO emission reduces the flow of oxygen to blood (carboxyhemoglobin), which causes heart disease. NO_x is one of the pollutants in the formation of ozone and contributes to the formation of acid rain. CO_2 does not directly impact human health, but is a greenhouse gas, which traps heat on earth and causes global warming.

1.1 Objective of Thesis

The primary objective of this thesis is to develop mathematical models to predict vehicular emissions under different speeds. The model developed in this thesis will estimate only exhaust emissions, i.e., tailpipe emissions. A sensitivity analysis is performed using the U.S. Department of Transportation Mobile6 modeling software to evaluate different parameters, which are used to estimate the emission factors of different pollutants. In this sensitivity analysis, speed is the most significant parameter in estimating all emission factors for different pollutants. So, in this thesis, a model is developed by considering speed as the factor for vehicular emissions. A model is proposed to estimate the emission factor for CO_2 emissions, considering speed as the predictor variable using the on-board emission measurement data. Finally, an analysis is performed to study the effect of acceleration and deceleration on emission rate.

1.2 Thesis Structure

This thesis is organized into four chapters. The introduction chapter presents the objectives of the study.

The second chapter is the literature review. The literature review discusses the contribution of emissions from on-road sources and the factors that may affect the vehicular emission rates. Various other fuel consumption and vehicular emission software and methodologies to find the emission rates are discussed.

The third chapter discusses the data collection procedure, the methodology used and the resulting models for estimating emission rates for different pollutants and for different classes of vehicles in this thesis.

The final chapter presents a summary of the results, limitations of the models developed and further research for potential improvements in the proposed models.

CHAPTER 2

LITERATURE REVIEW

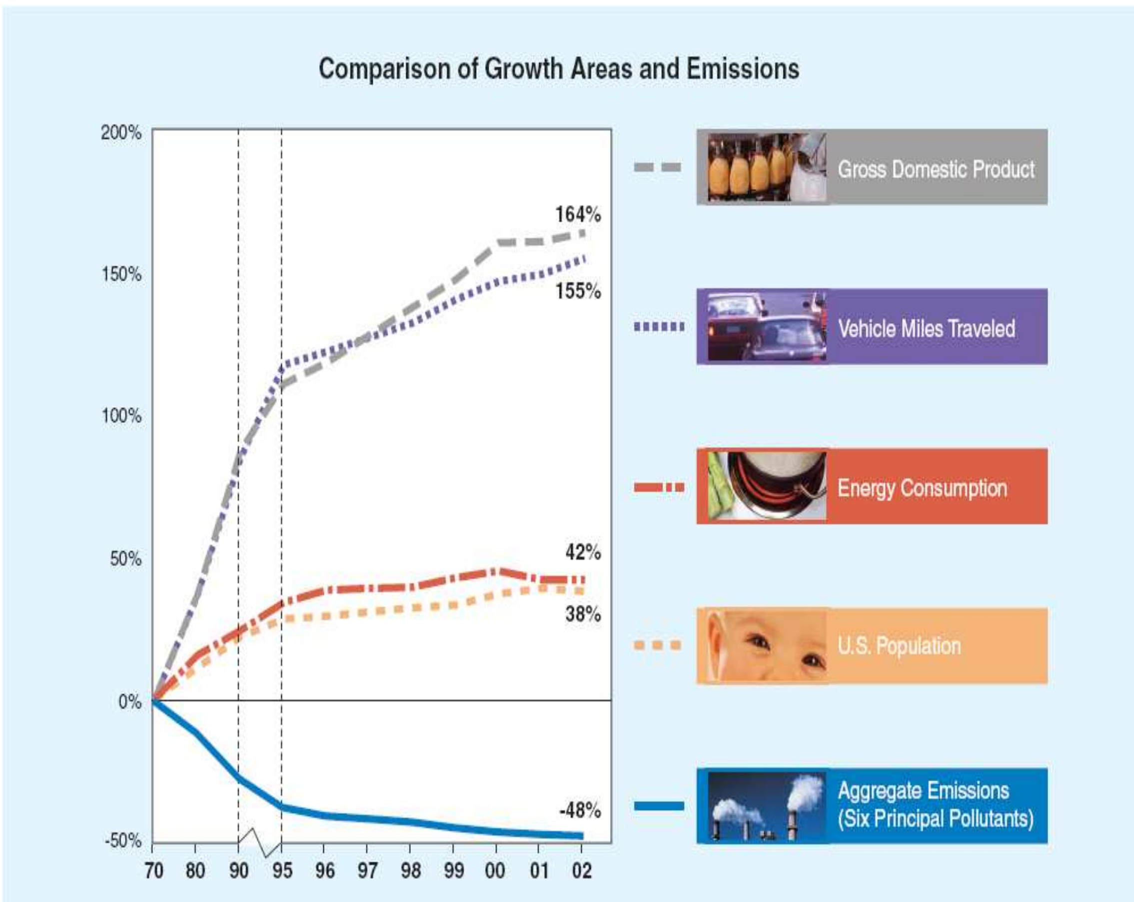
2.1 Introduction

This chapter has two sections related to the vehicular emission modeling. The first section discusses the contribution to emissions from on-road sources and air quality standards and requirements. The second section discusses the different models, which have been developed to estimate vehicular emissions, on-road emission measurement methods and software used to estimate vehicular emissions.

2.2 Contribution of Emissions from On-Road Sources

Emissions of different pollutants occur from different sources, like point and area, non-road engines, on-road vehicles, and miscellaneous other sources. In USA, on-road vehicles contribute a greater percentage of emissions compared to other sources. U.S. on-road transportation sources emit 36% of NOx, 63% of CO and 29% of HC (EPA Air Trends Report 2003). In 2003, 27% of total U.S. greenhouse gas (GHG) emissions were from the transportation sector [11].

Even though vehicle miles traveled, energy consumption, and population have increased dramatically over time, overall transportation-related emissions have fortunately decreased over the past 20 years (Figure 2.1). The reduction in emissions is due to the stringent tailpipe and evaporative emissions standards established by the Environmental Protection Agency (EPA), which includes improved catalytic converters, on-board diagnostic computers, and the ban of lead in motor vehicle fuel. In recent years, there has been a reduction of the three major pollutants from the transportation sector, but CO_2 emission rates from the transportation sector grew by 25.4 percent between 1990 and 2006 (1.4 % per year) [10]. In 2006, a slight decrease by 0.1 percent was observed [10]. The EPA has started to view the CO_2 emission rates as a pollution concern.



Between 1970 and 2002, gross domestic product increased 164 percent, vehicle miles traveled increased 155 percent, energy consumption increased 42 percent, and U.S. population increased 38 percent. At the same time, total emissions of the six principal air pollutants decreased 48 percent.

Figure 2.1 Comparison of Growth Areas and Emissions

(Source: http://www.epa.gov/airtrends/econ-emissions.html)

Vehicular emissions are a product of the combustion process in the engine. Vehicular emissions, like HC, CO and NO_x, include three major pollutants that are affecting the atmosphere and human health. In the combustion process under a fuel-rich condition, i.e. when the amount of oxygen is lower, an incomplete combustion takes place, due to which the pollutants CO and HC are emitted. The pollutant NO_x is emitted from the vehicles under stoichiometric conditions, i.e., when the temperature of combustion gases are maximized, which maximizes NO_x production. CO_2 emissions occur for both perfect combustion and typical engine combustion, as follows:

Perfect combustion [12]:

FUEL (HC) + AIR (Oxygen and Nitrogen) $\longrightarrow$ CO_2 + H_2O + Unaffected Nitrogen

Typical Engine Combustion [12]:

FUEL + AIR $\longrightarrow$ Unburned HC + NO_x + CO + CO_2 + H_2O

The pollutant CO has ill-effects on health, such as deterioration in visual perception, dizziness, headache, and carboxyhemoglobin poisoning. When HC and NOx react in sunlight, ozone is formed. Ozone has a major impact on human health, material, and plants and crops. CO_2 emissions do not affect human health directly. CO_2 is a GHG, which traps heat on earth, thereby contributing to the global warming.

In the DFW region, nine counties - Parker, Tarrant, Dallas, Denton, Collin, Rockwall, Kaufman, Johnson, and Ellis are considered non-attainment for ozone (Figure 2.3). In DFW, 51% of NO_x and 30% of HC emissions are from on-road sources (Figure 2.2).

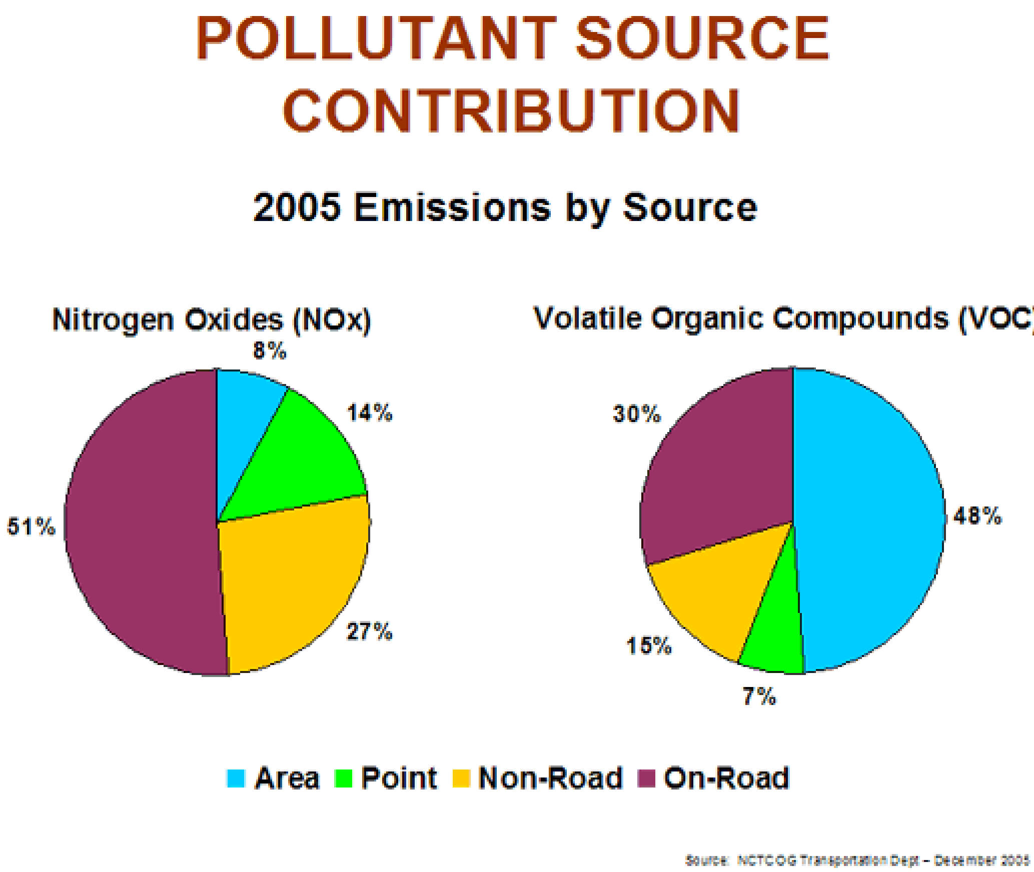


Figure 2.2 Pollutant Source Contribution

(Source: http://www.nctcog.org/trans/air/ozone/sources.asp)

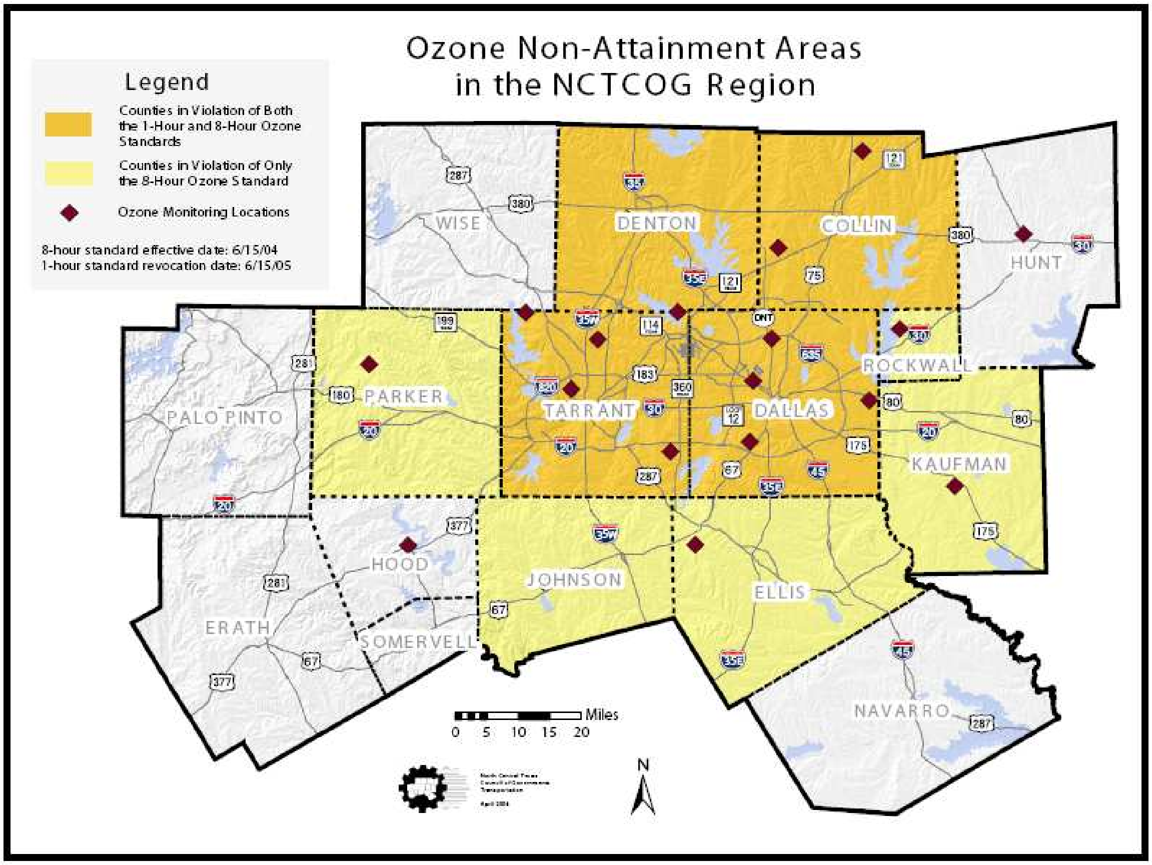


Figure 2.3 Ozone Non-Attainment Areas in the NCTCOG Region

(Source: http://www.nctcog.org/trans/images/other/07ozone.pdf)

In the U.S.A, CO_2 emissions are emitted from different sources, which include transportation, industrial, residential, and commercial sources. Among all sources, the transportation and industrial sectors contribute large quantities of CO_2 emissions (Figure 2.4). From the transportation sector the major contribution of CO_2 is from passenger cars, i.e., 35% (Figure 2.5). The total percentage increase of CO_2 emissions from the transportation sector was 25.4 percent between 1990 and 2006 [11]. In 2004-2005, there was an annual percentage growth of CO_2 emissions of 1.4% from the transportation sector. In 2005-2006, there was a decrease of 0.1%. [10]

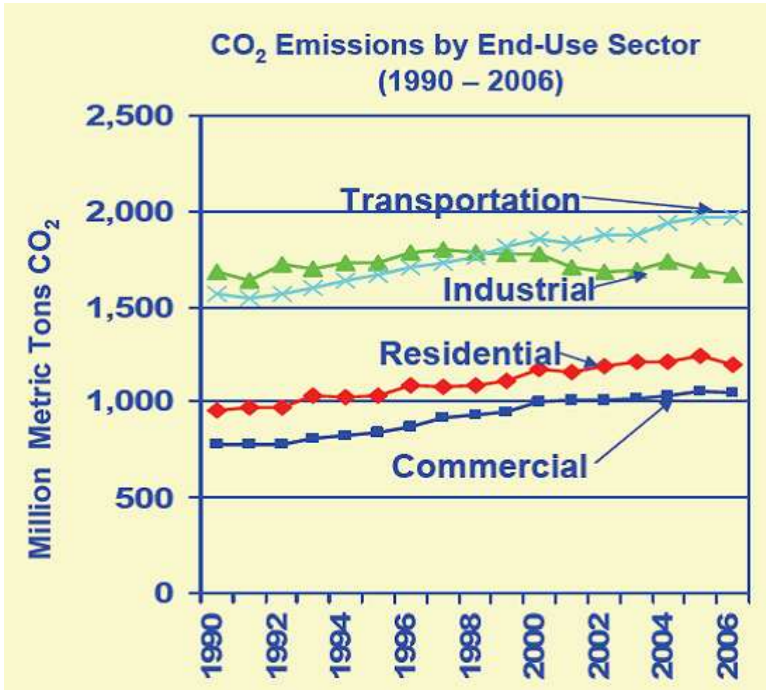


Figure 2.4 CO_2 Emissions for Different Sectors [10]

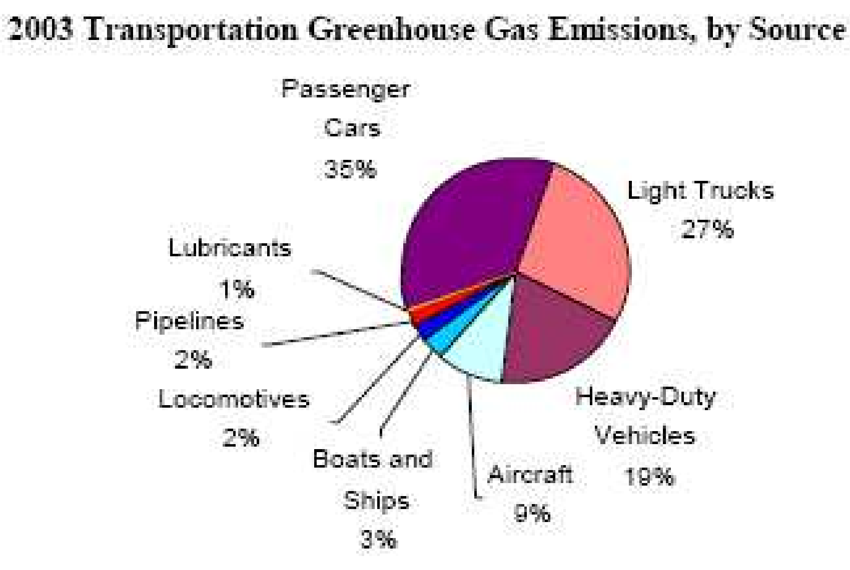


Figure 2.5 CO_2 Emissions from Different Sources [11]

2.3 Air Quality Standards and Requirements

In 1970, the Congress passed the Clean Air Act (CAA) to address air pollution problems from various sources which emit different pollutants. In the same year, the Congress created the EPA to implement and enforce the CAA. Since 1970, the EPA is responsible for different CAA programs to reduce air pollution. One of the major objectives of the CAA in 1970 was to attain clean air by 1975 [20].

The CAA required the EPA to set National Ambient Air Quality Standards (NAAQS). There are two standards for NAAQS. The primary standard is to protect human health and the secondary standard is to protect public welfare. The NAAQS sets standards for six criteria pollutants, which are ozone (O_3), lead (Pb), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and particulate matter (PM). Some of the standards set for reducing the automobile emissions are a 90% reduction of CO and HC from 1970 level and of NO_x from 1971 levels to be achieved by 1975. These standards proved to be unattainable and this part of the law has been amended several times.

In 1977, the CAA amendments were a major part of the legislation, which have incorporated many modifications and additions to the CAA. The 1977 standards areas are designated attainment or non-attainment based on whether or not they meet NAAQS.

By 1990, Congress noticed that, in spite of previous CAA amendments, there were still about 100 million Americans living in urban areas that did not meet the EPA standards for clean air. In the 1990 CAA amendments, they addressed several issues relating to criteria pollutants, mobile sources, air toxics, acid deposition, and stratospheric ozone protection.

The CAA requires transportation plans, programs, and projects in non-attainment regions that are funded by the FHWA or FTA, to conform to the State Implementation Plan (SIP). This ensures that transportation plans, programs, and projects do not produce new air quality violations, do not increase existing violations, and do not delay timely attainment of NAAQS.

The DFW region is non-attainment for Ozone but compliant for other pollutants CO, SO_2, PM, Pb, and NO_x. In 1991, four North Central Texas counties, Collin, Denton, Dallas, and Tarrant, were designated non-attainment for Ozone under the 1-hour NAAQS. The state's environmental agency, Texas Commission on Environmental Quality (TCEQ), is responsible to determine the best method to achieve the Clean Air Act's goal and develop a State Implementation Plan (SIP). In 1997, the EPA revised the NAAQS to establish an 8-hour NAAQS. The 8-hour standard became effective in the DFW region from June 15, 2004. After one year, the EPA stopped implementing the one-hour ozone standard. The North Central Council determined nine counties, Collin, Dallas, Denton, Ellis, Johnson, Kaufman, Parker, Rockwall, and Tarrant, were designated non-attainment for ozone. The region consisting of these nine counties was classified as a "Moderate" ozone non-attainment area. There are 19 monitors throughout the DFW region continuously monitoring the air quality. Some of the 8-hour ozone standards are: the averaging time is 8-hours; the threshold standard is less than 85 molecules of ozone per billion molecules of air. All the monitoring sites in the region must meet the standard. To determine the attainment or non-attainment status of a monitor, the annual 4th highest 8-hour ozone is averaged over a three-year period. A federal requirement called Transportation Conformity was due on June 15, 2005 because in the DFW region nine counties were in non-attainment for ozone under the 8-hour standard. The purpose of the Transportation Conformity is to demonstrate that projected vehicle emissions from regional projects and programs are within the emission budgets established in the applicable air quality plan and to document that transportation control measures are implemented in a timely manner. The EPA promotes strategies to reduce the GHG, emissions which include Clean Automotive Technology Research and a range of voluntary programs like shift from single occupancy travel to carpooling. (http://www.epa.gov/otaq/greenhousegases.htm).

2.4 Factors Affecting the Emission Rates

Emissions from the on-road sources depend on various variables. These variables are classified into different categories as follows:

- Traffic, travel and driver related factors
- Meteorological factors
- Vehicle characteristics
- Highway characteristics

The following sections describe these factors in detail

2.4.1 Traffic, Travel and Driver Related Factors

Emission rates of different pollutants depend on traffic, travel and driver related factors like the number of trips and distance traveled, i.e. vehicle miles traveled (VMT). The VMT depends on the roadway type (Freeway, Arterial/Collectors, Local, and Freeway ramps). The emissions will vary based on which roadway type the vehicle has been driven and the number of miles it has traveled. The emissions will vary according to accelerations and decelerations, but the most significant factor that affects the emission rates is speed. As speed increases, HC emissions decrease rapidly in a linear fashion to some extent and further decreases in a pseudo-linear trend. Both CO and NO_x emission rates illustrate a third order polynomial relationship with speed (Figure 2.6). Sensitivity analysis of Mobile6 software determined that vehicle speeds associated with all roadway facility types exert most significant and sensitive effects on all emission rates. There are other factors, like the number of stops, traffic conditions, vehicle mix, and drivers' behavior, which affect the emission rates. The emission rate models developed in this thesis for different categories of vehicles and for different types of pollutants consider speed as the predictor variable.

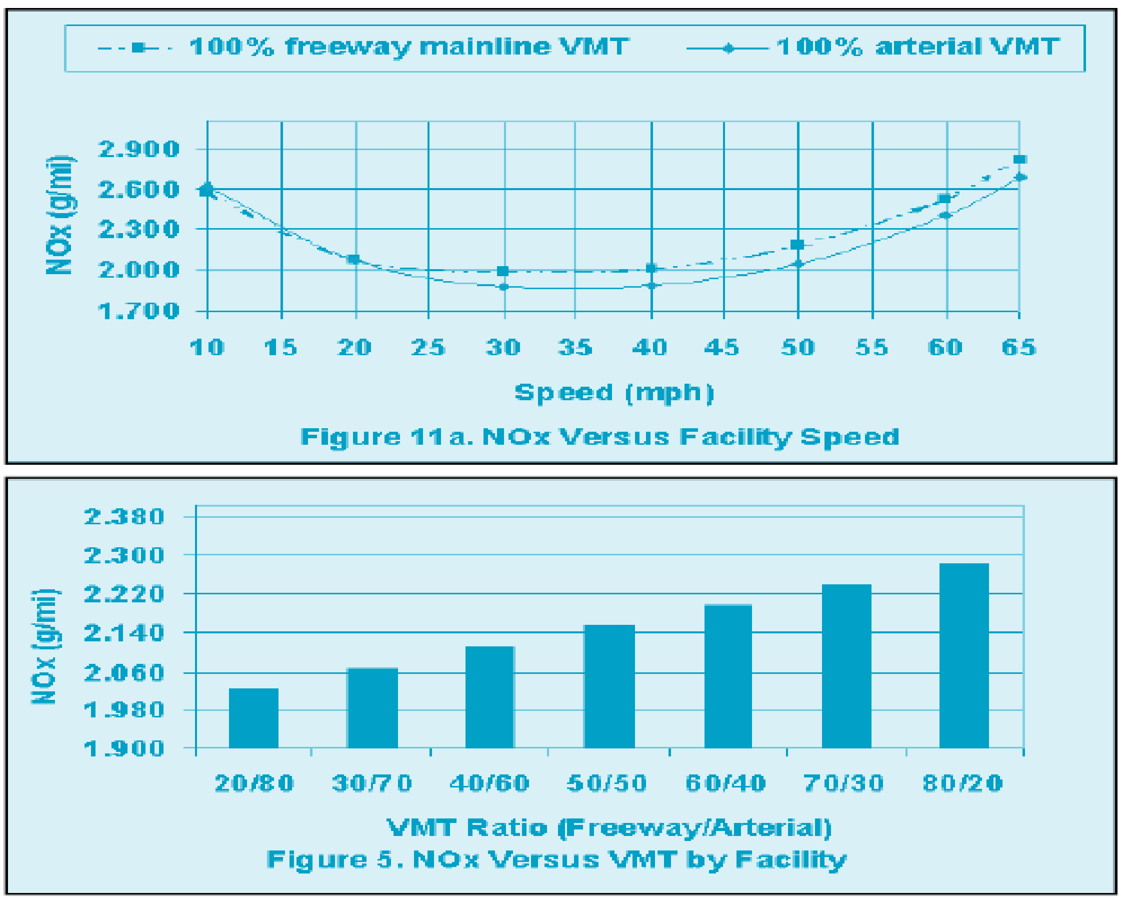


Figure 2.6 Emission Rates under Different Facility Speeds

(Source: Sensitivity Analysis of Mobile6, U.S. DOT)

2.4.2 Meteorological Factors

The emission rates of different pollutants are also dependent on meteorological factors like temperature, humidity, cloud cover, month of the year, sunrise and sunset.

NO_x emissions are more sensitive to humidity than HC and CO. As the humidity increases, the NO_x emissions decrease at a rate of 0.0030 g/mi. Humidity does not have any significant effect on the CO emission rate.

Temperature plays an important role in the emission rates. There is an increase in emission rates if the temperature falls below the standard temperature of 75 ^{o}F. This is due to the cold start problem. The emission control system (e.g., catalytic converter) takes a long time to warm up and additional fuel is required for smooth combustion. If the temperature increases above standard temperature of 75 ^{o}F, there is an increase in rates of HC due to an increase in evaporative emissions. The VOC emission rate decreases linearly from a range of 7.5^{o}F to 40^{o}F followed by a third order polynomial curve in the range of 42.5 ^{o}F to 100 ^{o}F (Figure 2.7). The emission rates of CO and NO_x follow the same pattern of decrease and increase in emission rates with respect to temperature (Figure 2.7).

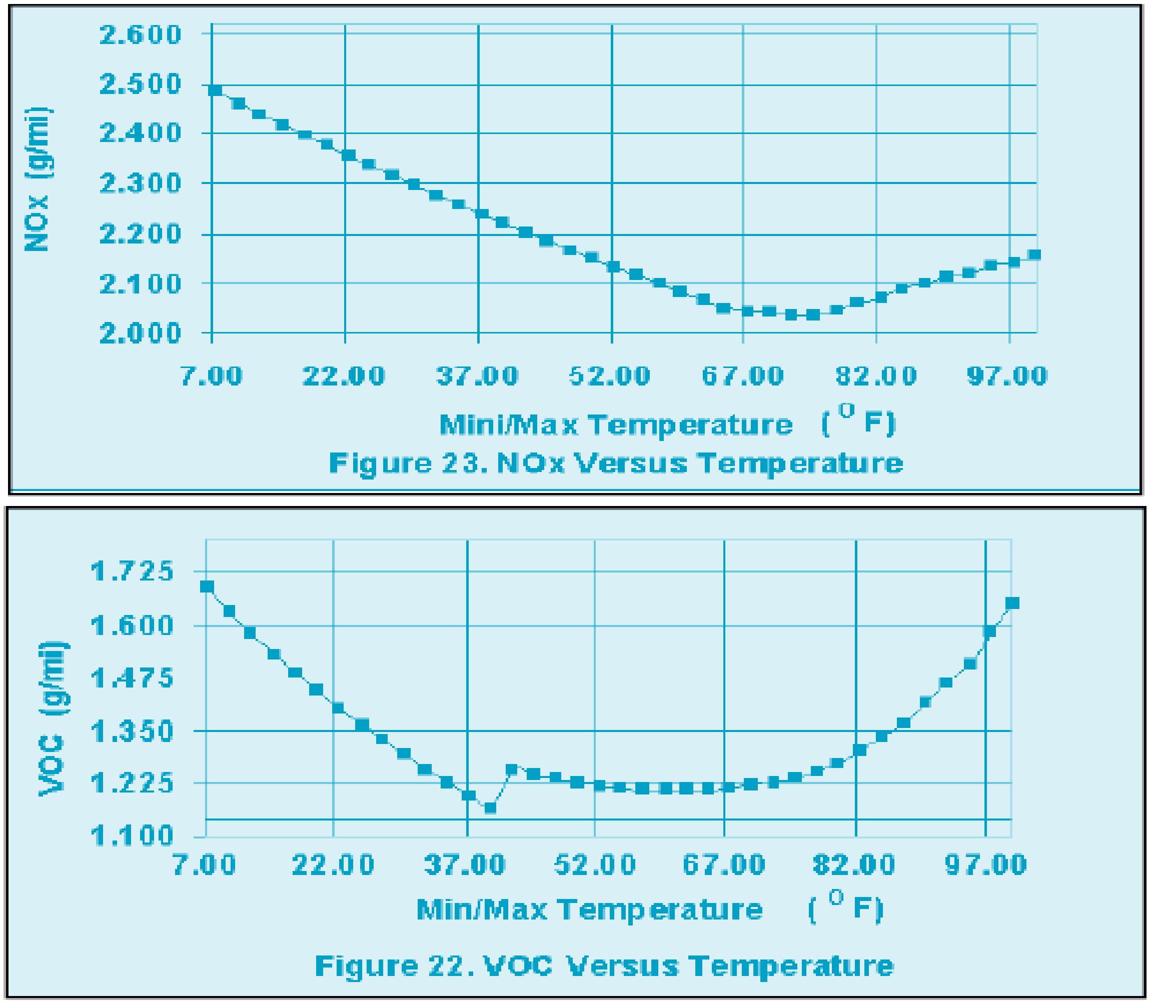


Figure 2.7 Emission Rates under Different Temperatures

(Source: Sensitivity Analysis of Mobile6, U.S. DOT)

The Reid vapor pressure (RVP) has a significant effect on evaporative emissions. VOC is more sensitive to RVP.

Other factors, like cloud cover, month of the year, sunrise, and sunset, do not have a significant effect on the emissions rates.

2.4.3 Vehicular Characteristics

Vehicle characteristics are also important factors that affect emission rates. There are different types of vehicle characteristics, like mass of the engine, engine size, engine type (gasoline, diesel, or electric), gasoline type (gasoline or diesel), auxiliary devices (air conditioning), vehicle age, and transmission type (manual or automatic) which affect the emission rate.

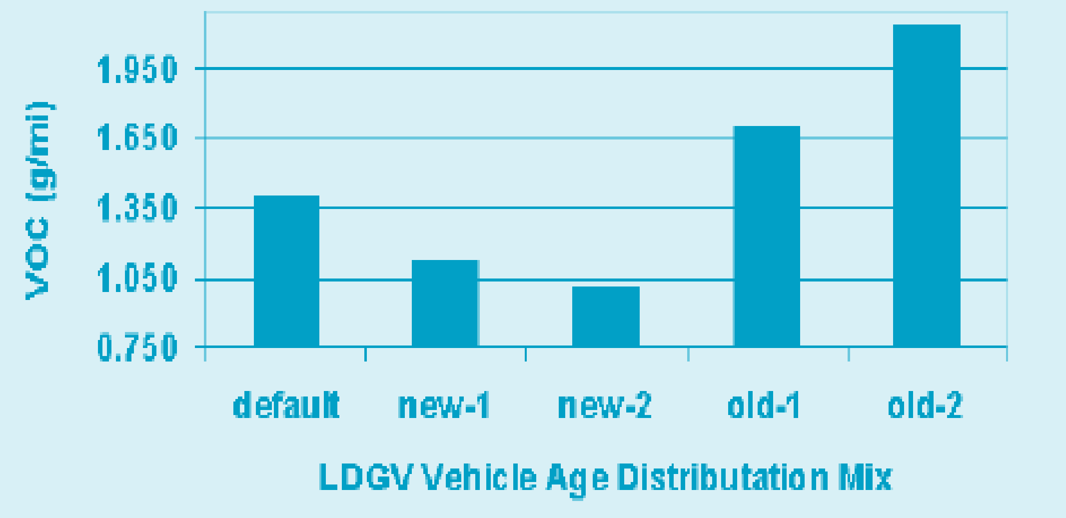


Figure 36. LDGV VOC Versus Vehicle Age Distributation

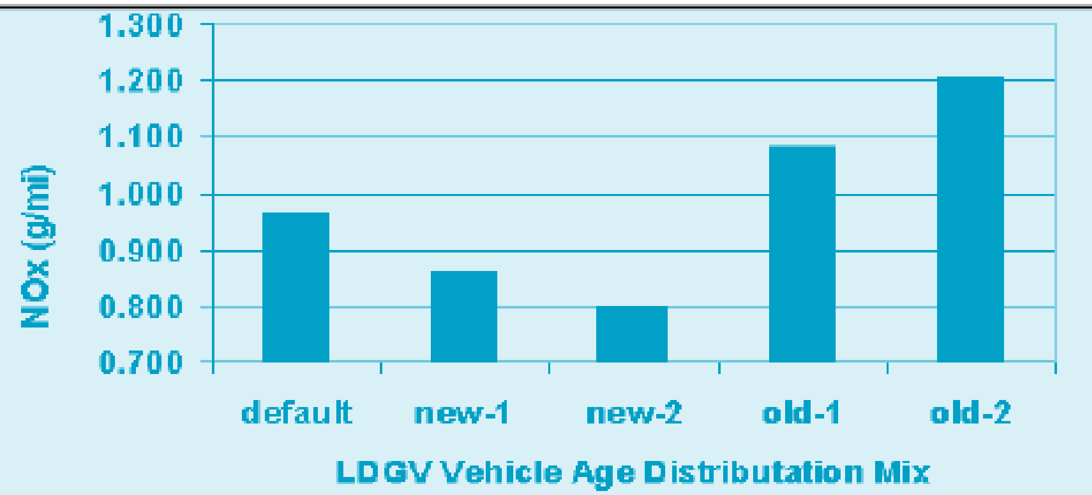


Figure 37. LDGV NOx Versus Vehicle Age Distributation

Figure 2.8 Emission Rates under Different Age Distribution

(Source: Sensitivity Analysis of Mobile6, U.S. DOT)

Vehicles with heavy weight emit more emissions than light weight vehicles. Vehicle age plays an important role in affecting the emission rates. Older vehicles emit higher emissions than newer vehicles (Figure 2.8). Newer vehicles emit 70% to 90% less pollution than older vehicles [16]. Some of the reasons that newer vehicles emit lower emissions are add-on controls like catalytic converter, on-board vapor recovery systems, and other fuel economy controls due to CAA amendments.

2.4.4 Highway Characteristics

Vehicular emission rates also vary due to highway geometric design features such as grade and curvature and highway facilities, like toll booths and interchange weaving sections. At toll booths and weaving sections, the emission rates increase due to accelerations and decelerations. Grades on highways play an important role in affecting the emission rates. The steeper the grade, the more emissions will be emitted. To maintain the same speeds on a steep grade, more engine power is required, causing a low air to fuel ratio (fuel-rich condition). Emission rates also depend on the traffic conditions, drivers' behavior, etc. on highway.

2.5 Emissions and Fuel Consumption Models

Various models are developed to estimate emissions and fuel consumption. These are the two areas where a substantial amount of research work is being conducted. Vehicular emission factors and fuel consumption are two critical aspects that are considered in the transportation planning process of freeway facilities.

2.5.1 Statistical Models

The following paragraphs describe some of the statistical models developed to estimate vehicular emissions.

2.5.1.1 Fuel Consumption and Emission Modeling Considering Power Demand as a Predictor Variable [3].

The emission model is based upon the instantaneous power demand experienced by the vehicle. The data is obtained from dynamometer testing. About 177 in-use Australian vehicles were used to collect the data. Motor vehicles are driven on dynamometer simulating on-road conditions covering a wide range of speeds and loads. On-road instantaneous power is derived from vehicle's mass, drag, velocity, acceleration and road-gradient. This model can be applied for any traffic situation if the on-road power demand is known. Validation of the model was carried out using an on-road power method i.e., by driving over 2281 links and 956 km recording the on-road velocity, acceleration, and gradient data. The models developed for estimating fuel consumption and emissions considering power demand as a predictor variable performed well for long trips.

$$HC\left(g/mile\right) = \alpha + \beta Z_{tot}\,; \quad Z_{tot} > 0$$

$$= \alpha \qquad ; \qquad \leq 0$$

Z_{tot} = overall instantaneous total power demand in kW

α *and* β = vehicle parameters. (Note: vehicle parameter can vary for each vehicle)

2.5.1.2 Microscopic Models Developed to Estimate the Fuel Consumption and Emission Rates [5].

The models developed in master's thesis by K. Ahn have two predictor variables, speed and acceleration. Eight light duty vehicles were used to collect the data. Data collected by the Oak Ridge National Laboratory was used to develop these models. The models were developed considering speed and accelerations as predictor variables on a second-by-second basis for individual vehicles. Two types of mathematical models, non-linear regression models and neural network models have been studied as part of this research. To validate the models developed for fuel consumption and emission rates three methods were adopted which are FTP cycle test, US06 cycle test, and Generalization test.

Non-linear regression model

$$\log\left(MOE_e\right) = \sum_{i=0}^{3}\sum_{j=0}^{3}\left(k_{i,j}^{e} \times s^{i} \times a^{j}\right)$$

Where MOE_e = Fuel consumption or emission rates (lt/hr or mg/s)

k = model regression coefficients

s = speed (m/s)

a = acceleration (m/s^2)

Neural network model

$$MOE_e = F^3\left(W^3 F^2 (W^2 F^1 (W^1 p + b^1) + b^2) + b^3\right)$$

Where MOE_e = fuel consumption or emission rates (lt/hr or mg/s)

W^1; W^2; and W^3 = model coefficients

b^1; b^2; and b^3 = bias matrices

p = an input vector containing pairs of (speed, acceleration) used as predictor variables

F^1 = nonlinear transfer function (hyperbolic tangent sigmoid, $F = \frac{1}{1+e^{-n}}$)

F^2 and F^3 = nonlinear transfer function (logarithmic sigmoid, $F = \frac{e^{n} - e^{-n}}{e^{n} + e^{-n}}$)

There are some limitations to these models. Start up emissions and ambient temperatures were not considered, which will affect the fuel consumption and emission rates significantly.

2.5.1.3 A Statistical Model Developed for Estimating Nitrogen Oxide Emissions from Light Duty Gasoline Vehicles [7].

This model considered engine load as the major factor, which affects the NO_x emission rates. The predictor variables are modal activity variables, which are used to estimate the emission rate. The in-use vehicle emission testing database compiled by United States Environmental Protection Agency (USEPA) was employed in developing the model, which contains 17,417 test results on hot stabilized testing cycles. Further, the data was constrained by limiting the types of vehicles to light duty vehicles (LDV). Therefore, a total of 13,012 vehicle test results representing 7,151 unique vehicles were tested. This data set contains 114 variables in which 50 variables were taken for analysis purposes. Two types of regression techniques, the Hierarchical tree based regression (HTBR) and the Ordinary least-squares (OLS) were used to develop the model:

$$E_p(g/s) = 0.0259 \times FTP\ Bag2 \times anti\log\left\{\begin{matrix} 0.0225(AVGSPD) + 0.3424(IPS.120) + \\ 0.6329(ACC.6) + 0.0247(DEC.2) + 0.0083(finj1) \\ + 0.0028(finj2) - 0.0021(cat1) + 0.0026(cat2) \\ + 0.0003(cat3) - 0.0085(flag1) - 0.0068(flag2) \end{matrix}\right\}$$

E_p = predicted emission rate (g/s) under tested driving conditions

AVGSPD = average speed of cycle in miles per hour

IPS.120 = percent of cycle time spent with inertial power surrogate greater than 120 mph^2/s

ACC.6 = percent of cycle time spent accelerating at rate greater than 6 mph/s

DEC.2 = percent of cycle time spent decelerating at rate greater than 6 mph/s

finj1 = an interaction variable between fuel injection type carburetor and odometer reading less than 25,000 miles

finj2 = variable representing vehicles that have carburetors with odometer reading between 25,000 and 50,000 miles

cat1 = variable for vehicle that have oxidation only type catalyst and odometer reading between 50,000 and 100,000miles

cat2 = variable for vehicle that have 3-way catalyst type converter and mileage between 25,000 and 50,000miles

cat3 = variable for vehicle that have 3-way catalyst type converter and mileage between 50,000 and 100,000miles

flag1 = variable with fuel injection type port with odometer reading between 50,000 and 100,000 miles, and is also a high emitter

flag2 = variable with throttle body fuel injector type and odometer reading between 50,000 and 100,000 miles, and is also a high emitter.

This model is a complicated one as the inputs are derived from the combustion mechanism and simulation of the fuel flow characteristics from the intake through the combustion chambers to the exhaust system.

2.5.1.4 Statistical Models were Developed for Estimating the Fuel Consumption

In this master's thesis one of the fuel consumption models was used to estimate the emission rates. Many factors that influence the fuel consumption also influence the emission rates. Some of the models which were developed to estimate the fuel consumption include:

The Vehicle Mix Model (by Lam et. al.) [18]

$F = K_1 + K_2 T$

F: Fuel Consumption (Lit / Km) K_1: a + b M

K_2: C.EC M: Engine Mass (Kg)

EC: Engine Capacity (Liters)

Transyt-7F Model (by Claffey and Akcelik) [18]

$F = K_1 TT + K_2 D + K_3 S$

F: Fuel Consumption TT: (veh-miles) of travel

D: (veh-hours) of delay S: Number of stops

Steady-Speed Models [18]

by Vincent et al.

$F = a + b V_c + c V^2_c$

F: Fuel Consumption (lit/km)

V_c: Cruise speed (km/hr)

b<0

by Post et al.

$$F = a + \frac{b}{V_c} + c V_c^2$$

F: Fuel Consumption (lit/km)

V_c: Cruise speed (km/hr)

In developing the vehicular emission rate models from the Mobile6.2 data, the Post et al. fuel consumption model was used because the model uses considers the cruise speed to estimate the fuel consumption. In this research the emissions data used to develop the models for the three major pollutants was collected under cruise speeds and the other reason to use the steady speed model is that the coefficient of correlation is above 0.99, as will be explained in chapter 3.

2.5.2 On-Road Emission Measurements

There are three different kinds of on-road emission measurements:

- Federal test procedure
- Remote sensing
- On-Board measurement

2.5.2.1 Federal Test Procedure (FTP): (FTP review project, EPA, May 1993)

The FTP is used to test vehicles for compliance with emission standards. The current test procedure used in the U.S. is referred to as FTP75. The FTP is conducted on a dynamometer for different driving cycles (Figure 2.9). The FTP is used to measure concentrations of different pollutants, like HC, CO, NO_x and CO_2. Both the evaporative and exhaust emissions are measured by dynamometer testing under several simulated situations. Evaporative emissions are measured after heating the fuel tank to simulate heating by the sun, i.e. diurnal test, and then the car is driven for some time and parked with the hot engine, i.e. hot soak test. Exhaust emissions are measured by driving the vehicles on a dynamometer for different simulated driving cycles. The vehicle is run on the dynamometer under two conditions. The first condition is cold start, i.e. after a period of non-use, and the second condition is hot start, i.e. while the engine is still hot. The FTP considers factors like ambient temperature, humidity, vehicle speed, fuel consumption, aerodynamic loss and vehicle inertia. Although the dynamometer is a reliable method for emission estimation, the drawback is that the dynamometer testing method may not simulate real world driving conditions and it may not consider short term events that will cause high emissions.

Figure 2.9 Federal Test Procedure

(Source:http://atofms.ucsd.edu/FieldStudy_files/Old%20Field%20Study%20Pics/Acuraa.gif)

2.5.2.2 Remote Sensing

The Remote Sensing Device (RSD) was developed in late 1980s at the University of Denver (US Remote Sensing Experience, Niranjan Vescio CITA conference, 2002). The RSD collects data, like speed and acceleration, captures license plate, and emission measurement of pollutants, like CO, NO_x, and HC. The RSD operates by continuously projecting two beams across the roadway (Figure 2.10). One is non-dispersive Infrared Spectroscopy, which is used to measure the concentrations of HC and CO and the other beam is Dispersive Ultraviolet Spectroscopy, which is used to measure the NOx emissions. As the vehicle passes through the beam, the emissions are calculated. The main advantage of a remote sensing device is that it identifies the high emitting vehicles and can measure a large number of on-road vehicles. The major disadvantage of using the remote sensing device is that it will not measure evaporative emissions. It gives the instantaneous estimate of emissions at a specific location, and it is not suitable for bad weather conditions.

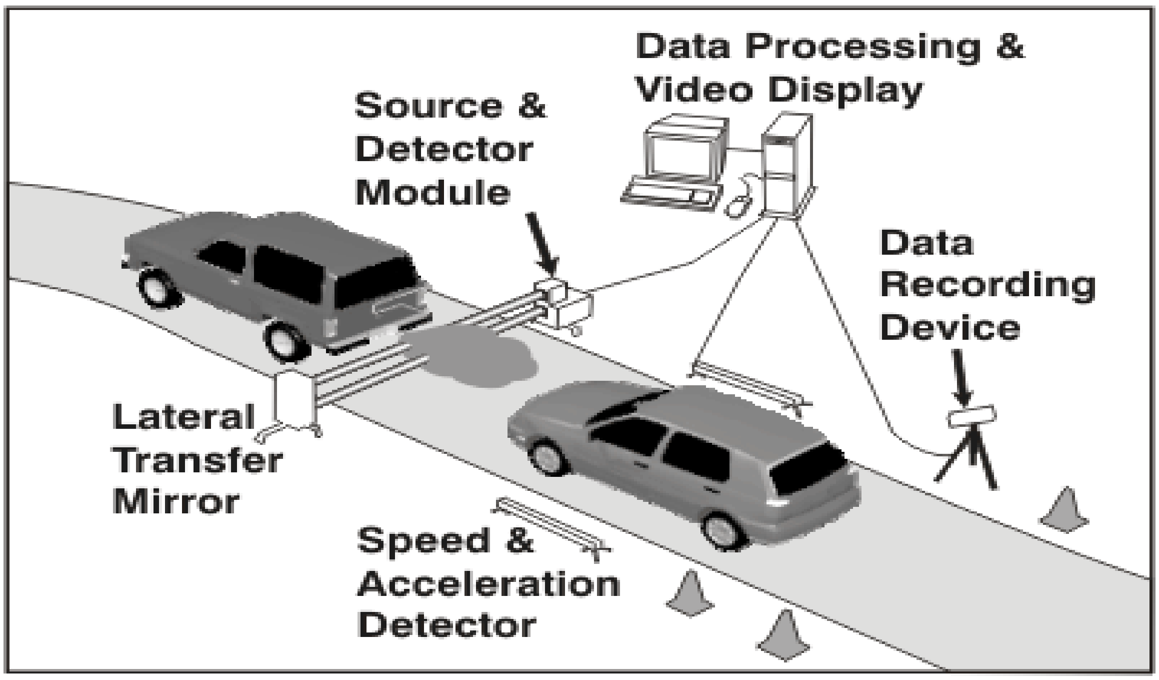


Figure 2.10 Remote Sensing

(Source: http://www.gatewaycleanair.com/images/rpdproc.gif)

2.5.2.3 On-Board Measurement [14]

The on-board measurement system is used to measure the exhaust emissions from vehicles under real-world travel conditions (Figure 2.11). This methodology has advantages over both dynamometer and remote sensing methods. The dynamometer testing method does not measure the emissions for real-world conditions and the remote sensing device method measures the emissions at a particular location, whereas the on-board measurement measures the emission rates under real world conditions and for all driving conditions. In on-board emission measurements, there are many factors considered while measuring the emissions, like speed, different driving modes (idle, acceleration, deceleration and cruising), ambient temperature, humidity, and different traffic conditions. In this master's thesis, on-board data is used in developing a model for carbon dioxide emission rate. An analysis to observe the difference in emission rates while considering the accelerations and decelerations versus constant speed was also performed. For this analysis, the data from on-board and Mobile6.2 were used. Mobile6.2 does not consider variable accelerations and decelerations while estimating the emission rates.

Figure 2.11 On-Board Emission Measurement

(Source: http://www.ats.horiba.com/on_board_systems.html)

2.5.3 Modeling Software

There are many software tools for estimating the vehicular emission rates of different pollutants. The most popular tools used in the U.S. to estimate emission rates are Mobile6.2 and Emission Factor Model (EMFAC).

2.5.3.1 EMFAC

EMFAC is the emission factor model used to calculate the emission inventories of on-road vehicles in California (Figure 2.12). EMFAC is a model in which the emission rate data and activity data are combined to calculate the emission inventory. The emissions for the following pollutants are calculated: CO, NO_x, HC, CO_2, lead, PM, and oxides of sulfur. Both exhaust and evaporative emissions are calculated for 13 different classes of vehicles. The model can estimate the emission rates for any calendar year between 1970 and 2040.

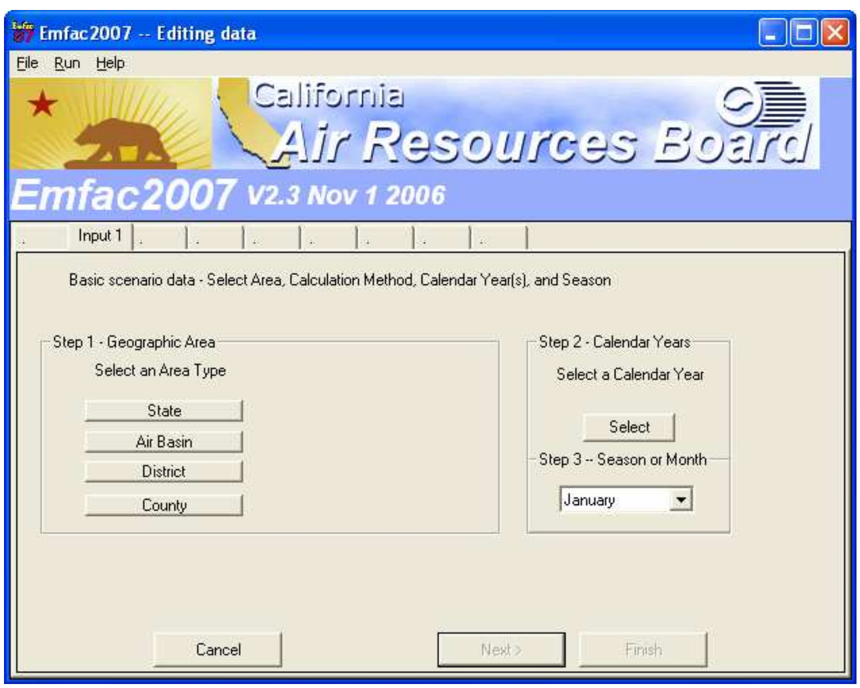


Figure 2.12 Windows Interface of EMFAC

(Source: User Guide)

2.5.3.2 Mobile

A brief history of the Mobile source emission factor model is as follows [22]:

Mobile1: The first Mobile model was developed in 1978 to estimate the highway vehicle emission factors.

Mobile2: In 1981, the model was updated with the new in-use data. The new data of emission controlled vehicles for higher ages and mileages was added to the model.

Mobile3: In 1984, the model was updated with the new in-use data. In this updated version of Mobile, anti-tampering program benefits were added to the model and eliminated the California vehicle emission rates.

Mobile4: In 1989, the model was updated with the new in-use data. In Mobile4 evaporative running losses were added for gasoline powered vehicles and modeled fuel volatility (RVP) effects on exhaust emission rates.

Mobile4.1: In 1991, the model was updated with the new in-use data. In this updated version of Mobile, the impact of oxygenated fuels on CO was included, added many features, which allow the user to control more parameters that affect the emission levels, and included more inspection and maintenance (I/M) program designs.

Mobile5 and Mobile5a: In 1993, the Mobile5 model was updated with the new in-use data. In this updated version, the effects of reformulated gasoline, the impact of oxygenated fuels on HC emissions were added. Later, after four months, Mobile5a was issued. Many errors, which were detected under specific conditions, were corrected in this updated version.

Mobile5b: In 1996, the model was updated by including the impacts of onboard refueling vapor recovery system, reformulated gasoline requirements, and expanded calendar year range from 2020 to 2050 for which the emission rates can be estimated.

Mobile6: In 2002, the model was updated by including the affects of air conditioning, high acceleration driving and expanded the classes of vehicles from eight to twenty eight.

Mobile6.2: In 2004, the model was updated by adding the ability to estimate the emission factors for particulate matter and six air toxins.

Each version of the Mobile model becomes more sophisticated in estimating the emission factor for different pollutants and different classes of vehicles. The new version of Mobile (Moblie6.2) provides users more advanced options to modify the emission factor estimates according to specific times and geographic locations.

Mobile estimates the emission factor for different pollutants, like HC, CO and NO_x for different classes of vehicles. The Mobile model was written in FORTRAN. FORTRAN is a computer programming language which is suitable for numeric computations and scientific computations. The Mobile model estimates emission factors for both exhaust emissions (tailpipe) and evaporative emissions. In estimating the emissions factors, the model considers various factors, including vehicle population, vehicle activity, and meteorological factors (temperature, humidity, and type of fuel). The interface of this modeling software is DOS (Figure 2.13). Mobile6.2 was used in this thesis to develop emission factor models for various pollutants for different classes of vehicles considering speed as the predictor variable.

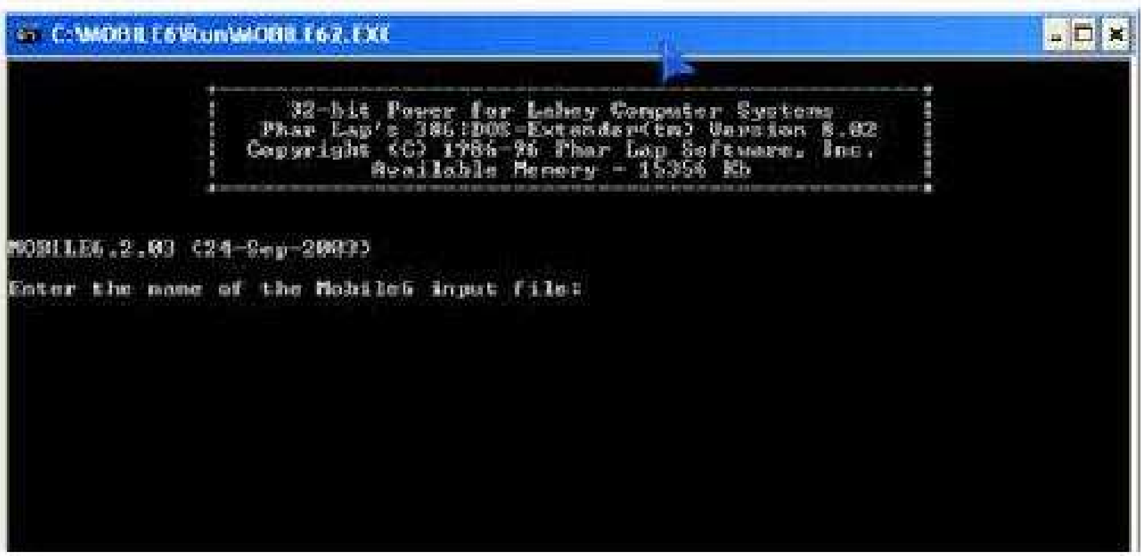


Figure 2.13 DOS Interface of Mobile6.2

(Source: Screen shot)

Mobile6.2 estimates the CO_2 emissions in a very simplistic way. The CO_2 calculations are based on the fuel economy performance estimates built into the model or supplied by the user. For other pollutants Mobile6.2 considers various factors like vehicle activity, speeds, and meteorological data to estimate emission rates. But for as the CO_2 pollutant Mobile6.2 do not adjust to the speed, temperature, and other factors. In this thesis, a model is being developed to estimate the CO_2 emission rate based on the speed. The data for developing the model for CO_2 is obtained from the on-board emission measurements.

Some of the other modeling software tools which calculate the emission inventories at micro level are MEASURE, FRESIM, and TRANSIMS etc. These software tools are discussed below:

MEASURE: MEASURE, is built in a Geographic Information System (GIS) framework and is able to estimate emissions for specific vehicle and engine operating modes (acceleration, deceleration and idling etc.). In developing and validating the MEASURE modeling software, the EPA used vehicle activity and emission data collected from different techniques which include remote sensing devices, automobiles and trucks equipped with on-board instrumentation. The MEASURE model estimates both spatially and temporally vehicle activities that result in emissions. [23]

FRESIM: FRESIM is a traffic simulation model used for freeway analysis. At the micro level of detail, traffic-simulation models can be combined with modal or instantaneous emissions models to predict emission inventories. Second by second vehicle trajectory data is generated and used as input to modal emission model. The resulting emissions data from all the vehicles are then integrated to provide a total emission inventory. [24]

The advantage of the micro level models is that they are best in estimating changes in emissions resulting from strategies that affect traffic flow and can account for the effects of the variance of driver behavior on emissions. The limitation of the microscale level models is: vehicle trajectory data which includes velocity-acceleration lookup tables may not be available, or may have old data, due to which emissions may not calculated accurately.

2.6 Summary of Chapter 2

The literature review has discussed various statistical models, measurement methods and modeling software used to estimate the emission rates. Many factors, like traffic or travel related factors, meteorological factors, vehicle characteristics, and highway characteristics, affect the emission rates. Especially, factors like speed, acceleration, ambient temperature, and humidity have a significant effect on emission rates. In the sensitivity analysis performed by the U.S. Department of Transportation, speed has a major impact on the emission rates.

The next chapter describes the data collection and methodology to develop regression models for various pollutants of different classes of vehicles considering speed as the predictor variable. These models can be used to estimate the emission rates at the macro level.

CHAPTER 3

DATA COLLECTION AND MODEL DEVELOPMENT

3.1 Introduction

This chapter discusses the data collection procedure from Mobile6.2 and on-board emission measurement, which is utilized in developing the vehicular emission models for various pollutants for different vehicle classes.

There are two sections related to vehicular emission modeling in this chapter. The first section describes the data collection procedure. The second section describes several mathematical approaches to estimate the vehicular emission rate for various pollutants for different vehicle classes. Finally, an analysis is performed to study the effect of acceleration and deceleration on the emission rate.

3.2 Data Collection Procedure

In developing the mathematical models, data was collected from Mobile6.2 modeling software and on-Board emission measurement method. For developing the models for the three major pollutants hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO_x), data from Mobile6.2 is used. Mobile6.2 estimates the CO_2 emissions in a very simplistic way. The CO_2 calculations are based on the fuel economy performance estimate built into the model or supplied by the user. The CO_2 pollutant is not adjusted to speed, temperature, and other factors. In this thesis, a model is developed to estimate the CO_2 emission rate considering speed as the predictor variable. The data for developing the model for CO_2 is obtained from the on-board emission measurements.

3.2.1 Mobile6.2 Data

Mobile6.2 estimates the emission rates of three major pollutants HC, CO, and NO_x. Mobile6.2 can estimate both exhaust and evaporative emissions for calendar years between 1952 and 2050. The input file (Figure 3.1) in Mobile6.2 is divided into three sections: header, run and scenario. The output file (Figure 3.2) can be obtained as text format or in a database format.

The overall structure of the input file is as follows:

```
MOBILE6 INPUT FILE :
POLLUTANTS          : HC CO NOx
REPORT FILE         : MOBILE6.txt
RUN DATA
MIN/MAX TEMP        : 64. 92.
FUEL RVP            : 7.0
STAGE II REFUELING :
89 4 80 60
ANTI-TAMP PROG      :
83 81 50 22222 11111111 1 11 100. 22222222
I/M DESC FILE       : Imtest.d
STARTS PER DAY      : Stperday.d
START DIST          : Sdist.d
WE DA TRI LEN DI    : Wedatrip.d
WE EN TRI LEN DI    : Weentrip.d
REG DIST            : Regdata.d
DIESEL FRACTIONS    :
0.0009 0.0006 0.0001 0.0003 0.0006 0.0013 0.0004 0.0004 0.0001 0.0027
```

0.0032 0.0097 0.0162 0.0241 0.0510 0.0706 0.0390 0.0269 0.0114 0.0093

0.0137 0.0155 0.0067 0.0067 0.0067

0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0007

0.0033 0.0048 0.0120 0.0223 0.0656 0.0616 0.0439 0.0316 0.0259 0.0000

0.0187 0.1038 0.1170 0.1170 0.1170

0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0007

0.0033 0.0048 0.0120 0.0223 0.0656 0.0616 0.0439 0.0316 0.0259 0.0000

0.0187 0.1038 0.1170 0.1170 0.1170

0.0126 0.0115 0.0111 0.0145 0.0115 0.0129 0.0096 0.0083 0.0072 0.0082

0.0124 0.0135 0.0169 0.0209 0.0256 0.0013 0.0006 0.0011 0.0001 0.0000

0.0000 0.0000 0.0001 0.0001 0.0001

0.0126 0.0115 0.0111 0.0145 0.0115 0.0129 0.0096 0.0083 0.0072 0.0082

0.0124 0.0135 0.0169 0.0209 0.0256 0.0013 0.0006 0.0011 0.0001 0.0000

0.0000 0.0000 0.0001 0.0001 0.0001

0.1998 0.2578 0.2515 0.3263 0.2784 0.2963 0.2384 0.2058 0.1756 0.1958

0.2726 0.2743 0.3004 0.2918 0.2859 0.0138 0.0000 0.0000 0.0000 0.0000

0.0000 0.0000 0.0000 0.0000 0.0000

0.6774 0.7715 0.7910 0.8105 0.8068 0.8280 0.8477 0.7940 0.7488 0.7789

0.7842 0.6145 0.5139 0.5032 0.4277 0.0079 0.0000 0.0000 0.0001 0.0003

0.0010 0.0028 0.0248 0.0000 0.0000

0.8606 0.8473 0.8048 0.8331 0.7901 0.7316 0.7275 0.7158 0.5647 0.3178

0.2207 0.1968 0.1570 0.0738 0.0341 0.0414 0.0003 0.0000 0.0000 0.0000

0.0259 0.0078 0.0004 0.0090 0.0112

0.4647 0.4384 0.3670 0.4125 0.3462 0.2771 0.2730 0.2616 0.1543 0.0615

0.0383 0.0333 0.0255 0.0111 0.0049 0.0060 0.0000 0.0000 0.0000 0.0000

0.0037 0.0011 0.0001 0.0013 0.0016

0.6300 0.6078 0.5246 0.5767 0.5289 0.5788 0.5617 0.4537 0.4216 0.4734

0.4705 0.4525 0.4310 0.3569 0.3690 0.4413 0.3094 0.1679 0.1390 0.0808

0.0476 0.0365 0.0288 0.0274 0.0297

```
0.8563 0.8443 0.7943 0.8266 0.7972 0.8279 0.8177 0.7440 0.7184 0.7588
0.7567 0.7431 0.7261 0.6602 0.6717 0.7344 0.6107 0.4140 0.3610 0.2353
0.1489 0.1170 0.0940 0.0897 0.0966
0.9992 0.9989 0.9987 0.9989 0.9977 0.9984 0.9982 0.9979 0.9969 0.9978
0.9980 0.9979 0.9976 0.9969 0.9978 0.9982 0.9974 0.9965 0.9964 0.9949
0.9920 0.9936 0.9819 0.9812 0.9720
1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
1.0000 1.0000 1.0000 1.0000 1.0000
0.9585 0.8857 0.8525 0.8795 0.9900 0.9105 0.8760 0.7710 0.7502 0.7345
0.6733 0.5155 0.3845 0.3238 0.3260 0.2639 0.0594 0.0460 0.0291 0.0240
0.0086 0.0087 0.0000 0.0000 0.0000
VMT FRACTIONS      :
0.354  0.089  0.297  0.092  0.041  0.040  0.004  0.00300
0.002  0.008  0.010  0.012  0.040  0.002  0.001  0.00500
```

SCENARIO RECORD   : Scenario Title : Example Input

```
CALENDAR YEAR      : 2012
EVALUATION MONTH   : 7
ABSOLUTE HUMIDITY  : 115.
CLOUD COVER        : 0.85
PEAK SUN           : 11 5
SUNRISE/SUNSET     : 7 9
WE VEH US          :
SULFUR CONTENT     : 250
FUEL PROGRAM       : 4
  300.0  299.0  279.0  259.0  121.0   92.0   33.0   33.0
   30.0   30.0   30.0   30.0   30.0   30.0   30.0   30.0
 1000.0 1000.0 1000.0 1000.0  303.0  303.0   87.0   87.0
   80.0   80.0   80.0   80.0   80.0   80.0   80.0   80.0
```

```
OXYGENATED FUELS   : 0.500 0.500 0.020 0.010 1

SEASON             : 1

END OF RUN
```

Figure 3.1 Mobile6.2 Sample Input File

Output File Example:

```
***************************************************************************
* MOBILE6  (28-Aug-2000)                                                 *
* Input file: TESTAIR4.IN (file 1, run 1).                                 *
***************************************************************************
  M603 Comment:
             User has disabled the calculation of REFUELING emissions.

* # # # # # # # # # # # # # # # # # # # # # # # # #
*
* File 1, Run 1, Scenario 1.
* # # # # # # # # # # # # # # # # # # # # # # # # #
  M 48 Warning:
            there are no sales for vehicle class HDGV8b

                  Calendar Year:  2000
                          Month:  Jan.
                       Altitude:  Low
            Minimum Temperature:   60. (F)
            Maximum Temperature:   84. (F)
               Nominal Fuel RVP:  11.5 psi
                  Weathered RVP:  11.2 psi
            Fuel Sulfur Content:  300. ppm

                    I/M Program:  No
                    ATP Program:  No
               Reformulated Gas:  No

            Following assumptions made for air conditioning adjustments:
                Absolute Humidity:   75. grains/lb
                Sun rise at  600; Sun set at 2100
                Peak sun occurring between 1000 and 1600.
                Fraction of cloud cover equal to  0.00

      Vehicle Type:      LDGV    LDGT12    LDGT34      LDGT      HDGV      LDDV      LDDT      HDDV        MC   All Veh
              GVWR:               <6000     >6000     (All)
                       ------    ------    ------    ------    ------    ------    ------    ------    ------    ------
  VMT Distribution:     0.494     0.283     0.097               0.036     0.001     0.002     0.081     0.006     1.000
 -----------------------------------------------------------------------------------------------------------------------
 Composite Emission Factors (g/mi):
    Composite THC :      2.45      2.57      3.92      2.92      3.30      0.76      0.92      0.82      2.93     2.524
    Composite CO  :     29.38     35.34     49.07     38.84     36.05      1.77      1.65      4.25     14.73    30.997
    Composite NOX :      1.33      1.46      1.85      1.56      5.10      1.81      1.81     18.47      1.25     2.948
 -----------------------------------------------------------------------------------------------------------------------
```

Figure 3.2 Mobile6.2 Sample Output File

The Mobile6.2 runs made for this study are specific to freeway facilities. The emissions estimated from the model are exhaust emissions. Many commands and default values of the input file are altered specific to the DFW region, which is non attainment for ozone.

The values of some of the commands were altered and this affected the tailpipe emissions. These commands are discussed below:

Registration distribution: This command allows user to supply vehicle registration by vehicle age. This data was supplied to the Mobile6.2 as an external file. [15]

Week Day Trip Length Distribution: This command allows user to specify the fraction of weekday vehicle miles traveled (VMT) that occurs during trips of various durations at each hour of the day. This data was supplied to the Mobile6.2 as an external file. [15]

VMT by facility: This command allows user to allocate VMT to various roadway or facility types by vehicle class. This data was supplied to the Mobile6.2 as an external file. [15]

VMT by hour: This command allows user to allocate the fraction of VMT that occur at each hour of the day. This data was supplied to the Mobile6.2 as an external file. [15]

Diesel Fractions: This command allows user to supply locality-specific diesel fractions by vehicle age. [15]

Inspection and Maintenance (I/M) programs: The I/M program is used to further reduce mobile source air pollution. Mobile6.2 allows user to model the impact of up to seven different exhaust and evaporative emission I/M programs on calculated emission factors. This data was supplied to the Mobile6.2 as an external file. [15]

Anti-Tampering Program: This command allows user to model the impact of the anit-tampering program and should be used only if the area being modeled has such program. [15]

Oxygenated Fuels: This command allows user to model the effects of oxygenated gasoline on exhaust emissions for all gasoline-fueled vehicle types. [15]

Fuel Reid Vapor Pressure (RVP): This command allows user to specify the fuel RVP for the area to be modeled. There is no default value for fuel RVP. User must enter a value for Fuel RVP. Exhaust and especially non-exhaust emissions vary with fuel volatility. [15]

Fuel Program: This command models the impact of reformulated gasoline program, or to specify sulfur content for gasoline after 1999. [15]

Average Speed: This command allows user to designate a single average speed to use for all freeways and/or arterials/collectors for the entire day. [15]

The default values of commands in Mobile6.2 input file which include Diesel Sulfur, Hourly temperatures, Relative humidity, Barometric pressure, and sunrise/sunset were also altered, but they mainly affect the evaporative emissions.

The data required for altering the input file was obtained from the North Central Texas Council of Governments (NCTCOG). The input files required to estimate the emissions rates in DFW region are included in Appendix A.

The Mobile6.2 was run at different speeds to estimate the emission rates on the freeway facility and develop a model for emission rates of the different pollutants on the freeway considering speed as the predictor variable.

3.2.2 On-Board Emission Measurements

The on-board emission measurements are collected under real-world conditions. On-road emissions are measured second by second from the tailpipe using a portable instrument. In this thesis, the instrument used for the on-board data collection is the OBS-1300, manufactured by Horiba Instrument, Inc. This system measures HC, CO, NO_x and CO_2 emissions.

3.2.2.1 Study Vehicle

The study vehicle used in collecting the on-road emissions data is a light duty gasoline vehicle (passenger car). The overall specifications of the study vehicle are listed below (Table3.1).

Table 3.1 Specifications of Study Vehicle

Type of Vehicle	Dodge Charger (Passenger Car)
Model	2007
Empty Weight	3800 pounds

3.2.2.2 Components of OBS-1300 [6]

The various components of the on-board emission system (OBS-1300) include:

1. MEXA-1170 HNDIR Unit: This unit uses heated non-dispersive infrared (HNDIR) detection technique to measure HC, CO, and CO_2 emissions (Figure 3.3).
2. Data integration Unit (DIU): This unit houses MEXA-720 and NO_x analyzer which measures the NO_x concentrations and Air to Fuel Ratio (AFR) (Figure 3.4).

Figure 3.3 MEXA-1170 Unit and DIU

Figure 3.4 MEXA-720 Unit and NO_x sensor

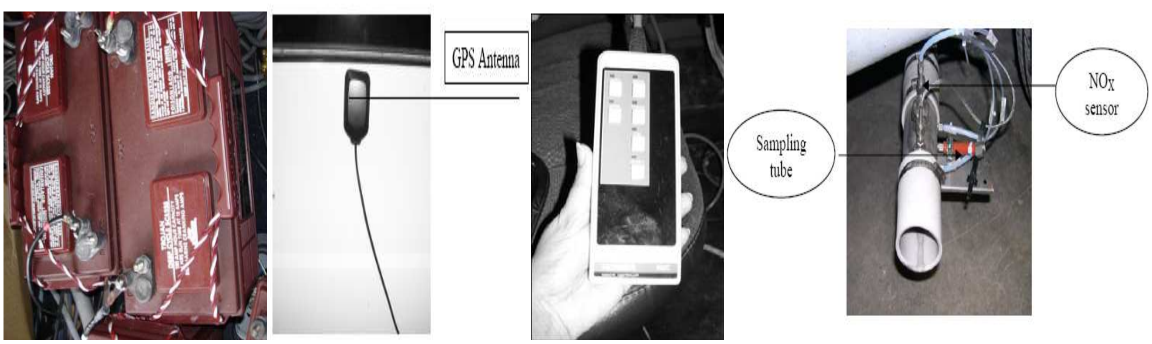
3. Data logger PC: The data logger PC is a laptop connected to OBS-1300 and has suitable software for data collection (Figure 3.5).

Figure 3.5 Data Logger PC

4. Power Supply Unit (PSU): This unit converts 24 V DC to AC current supplied to the OBS setup (Figure 3.6).

Figure 3.6 Power Supply Unit

5. Other Accessories: There are many other accessories which include batteries, Geographic Positioning System (GPS), humidity sensor, and tailpipe attachment (Figure 3.7).



(a) (b) (c) (d)

Figure 3.7 Other Accessories: (a) Volt deep cycle batteries, (b) GPS antenna, (c) Remote Controller, (d) Tailpipe attachment

3.2.2.3 Location of the Study

The test vehicle runs in a roadway loop (I-30 – I-820 – I-20 – SH-408 – I-30) shown in Figure 3.8. The data was collected during peak and off peak traffic conditions.

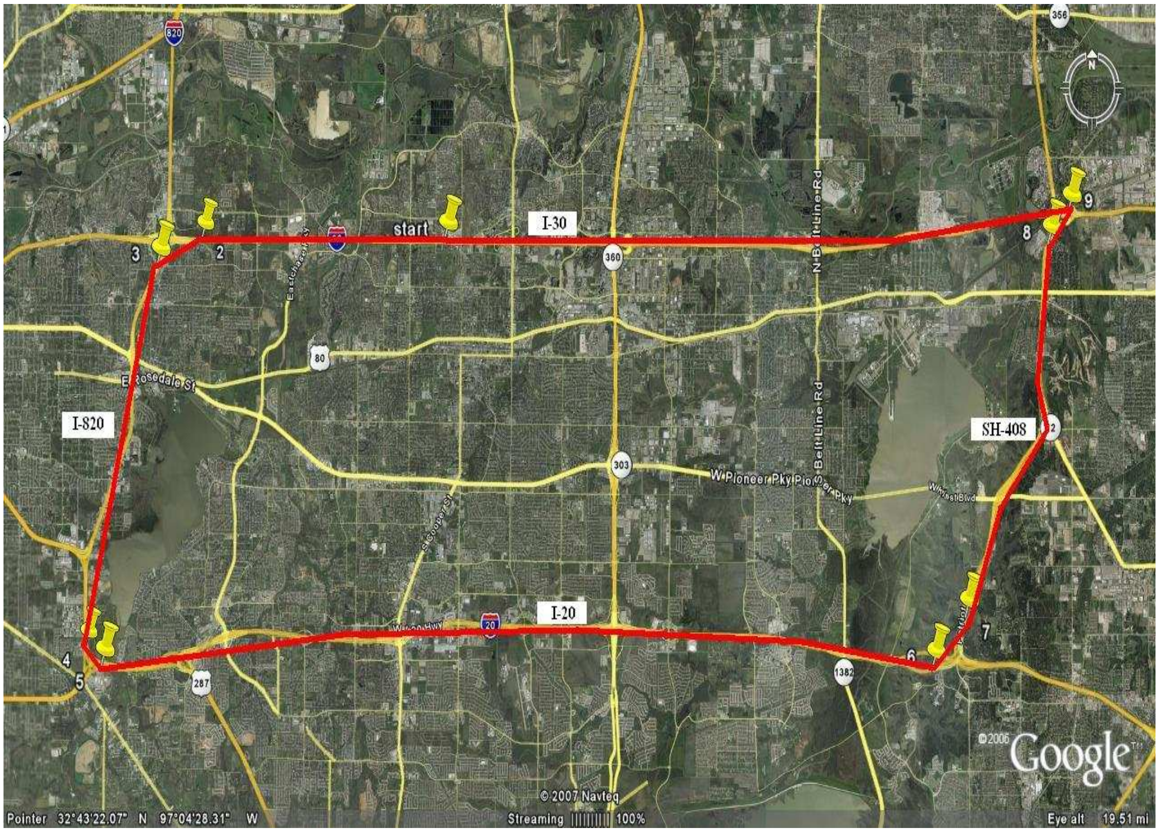


Figure 3.8 Study Location

(Source: Google Earth)

The on-board emission measurements by OBS-1300 are affected by many factors which include calibration of the analyzer and sensor, time of the day, drivers' behavior, data logging software, weather, and battery power. Calibration of the on-board emission measurement system (OBS-1300) is also essential for collecting accurate data. There are different calibrations required before and during the runs.

3.3 Model Description

This section describes models, which were developed to estimate the vehicular emission rates for various pollutants for different vehicle classes. In this research, models were developed from Mobile6.2 modeling software data and on-board emission measurement method data. This section discusses the research work in two parts:

- Vehicular emissions regression models from Mobile6.2 data
- Vehicular emission regression model for CO_2 emission rate from on-board emission measurement data

3.3.1 Vehicular Emissions Regression Models from Mobile6.2 Data

Mobile6.2 data was used to develop the statistical models for three major pollutants and 28 classes of vehicles considering speed as the predictor variable. These models have some limitations. The models estimate freeway vehicles' tailpipe emissions. In the input file of Mobile6.2, many commands and default values have been changed to suit the study region (DFW). The values for the input file were obtained from NCTCOG. The regression models developed to estimate the vehicular emission rates are based on the steady speed models, which estimate the fuel consumption considering speed as a predictor variable. The steady speed model was used for this research because the emissions rates obtained from Mobile6.2 are based on cruise mode and the models were developed based on speeds for cruise mode. Two regression models were tested for each pollutant: a second degree polynomial equation and the Post et al. steady speed model. There are 28 categories of vehicles for which the regression models were developed. For each category of vehicle, three regression models were developed corresponding to the pollutants HC, CO and NO_x.

Vehicle type: Light-Duty Gasoline Vehicles (Passenger Car) - LDGV

Table 3.2 shows the emission rates at different freeway speeds for different pollutants estimated from the Mobile6.2 modeling software for DFW region. The emission rates were estimated for three major pollutants HC, CO, and CO_2 for 28 different vehicle classes under cruise driving mode on a freeway facility.

Table 3.2 Emission Rates from Passenger Car for Three Major Pollutants

Ave. Speed (mph)	**HC (g/mile)**	**CO (g/mile)**	**NO_x (g/mile)**
5	0.267	7.80	0.608
10	0.145	4.64	0.391
15	0.097	3.77	0.284
20	0.087	3.56	0.274
25	0.083	3.50	0.273
30	0.081	3.48	0.270
35	0.078	3.56	0.266
40	0.079	3.86	0.269
45	0.079	4.16	0.275
50	0.080	4.48	0.282
55	0.081	4.80	0.289
60	0.081	5.13	0.296
65	0.081	5.18	0.296

Regression Model I: (Second Order Polynomial Model)

The first regression model is a second order polynomial model. The data to develop these models was obtained from Mobile6.2.

Regression Model I for HC

$EF = 0.2567 - 0.0097V + 0.0001V^2$; $R^2 = 0.77$

EF: Emission rate of HC (g/mile)   V: Cruise speed (mph)

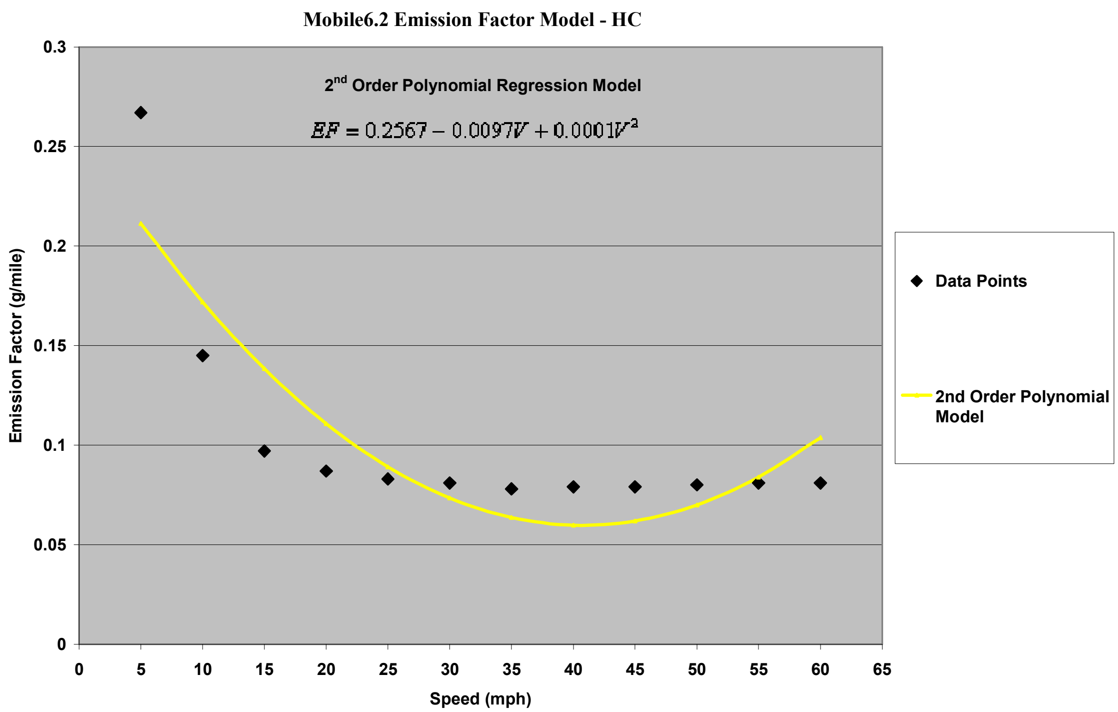


Figure 3.9 Predicted Emission Rates of HC for Second Order Polynomial Model

From Figure 3.9, at lower speeds from below 25 mph, the HC emission rate is high and decreases rapidly. The HC emission rate is constant at speeds between 30 mph to 45 mph. There is a slight decrease in the emission rates after 45 mph. The model used to fit the data points is a second order polynomial model, with a coefficient of correlation of 0.77.

Regression Model I for CO

$$EF = 7.5823 - 0.2497V + 0.0036V^2 \;; \qquad R^2 = 0.72$$

EF: Emission rate of CO (g/mile) V: Cruise speed (mph)

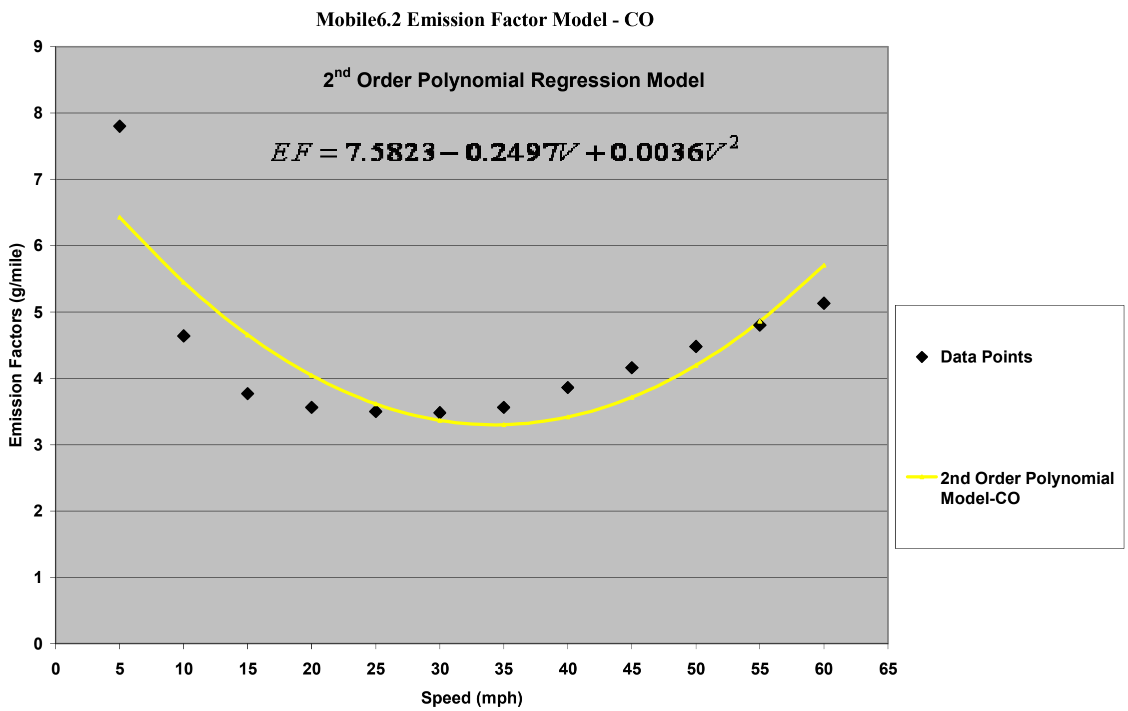


Figure 3.10 Predicted Emission Rates of CO for Second Order Polynomial Model

Usually CO emission rates are higher than HC and NO_x rates. From Figure 3.10, for lower speeds below 25 mph, the CO emission rate is high and decreases rapidly. The CO emission rate is relatively constant at speeds between 25 mph to 35 mph, then the emission rate starts increasing gradually as the speed increases. The model used to fit the data points is a second order polynomial model, with a coefficient of correlation of 0.72.

Regression Model I for NO_x

$$EF = 0.592 - 0.0183V + 0.0002V^2 \; ; \qquad R^2 = 0.75$$

EF: Emission rate of NO_x (g/mile)   V: Cruise speed (mph)

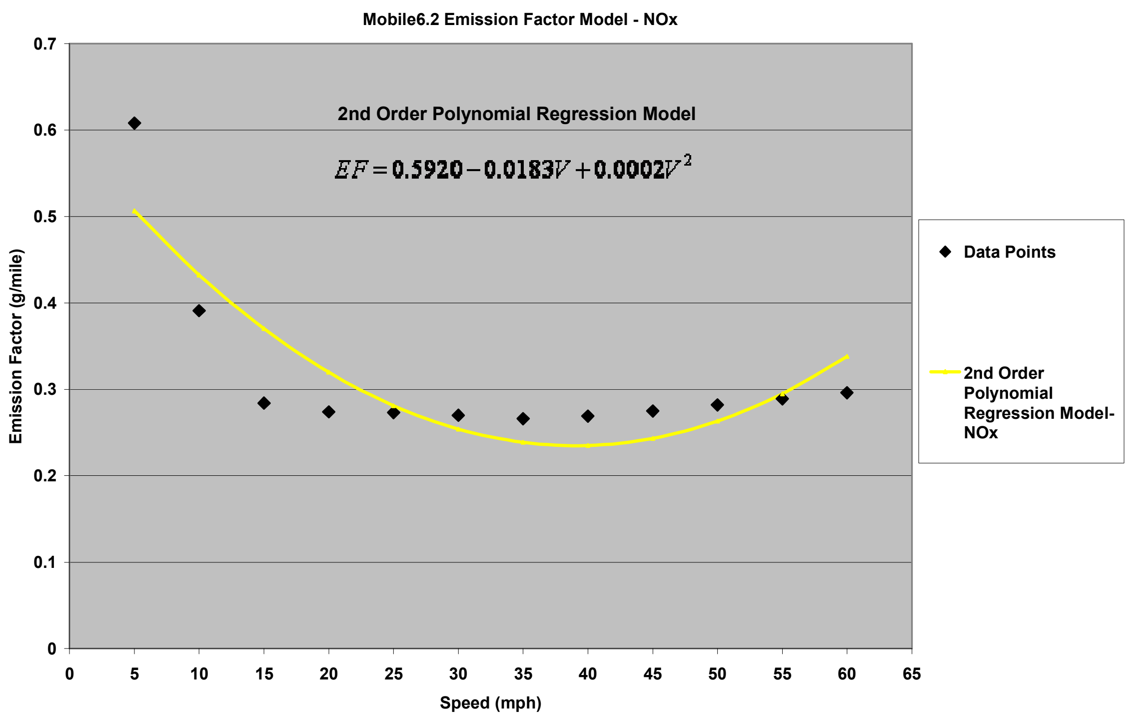


Figure 3.11 Predicted Emission Rates of NO_x for Second Order Polynomial Model

From Figure 3.11, at lower speeds, below 25 mph, the NO_x emission rate is high but decreases rapidly. The NO_x emission rate is fairly constant at speeds between 30 mph to 40 mph. There is a gradual increase in the rate after 45 mph. The model used to fit the data points is a second order polynomial model, with a coefficient of correlation of 0.75.

Regression Model II: (Steady Speed Model, Post et al.)

The second regression model is a steady speed model (Post et al. Model). The data to calibrate these models was obtained from Mobile6.2.

Regression Model II for HC

$$EF = 0.026 + \frac{1.18}{V} + 1.12 * 10^{-5} V^2 \; ; \qquad R^2 = 0.99$$

EF: Emission rate of HC (g/mile) V: Cruise speed (mph)

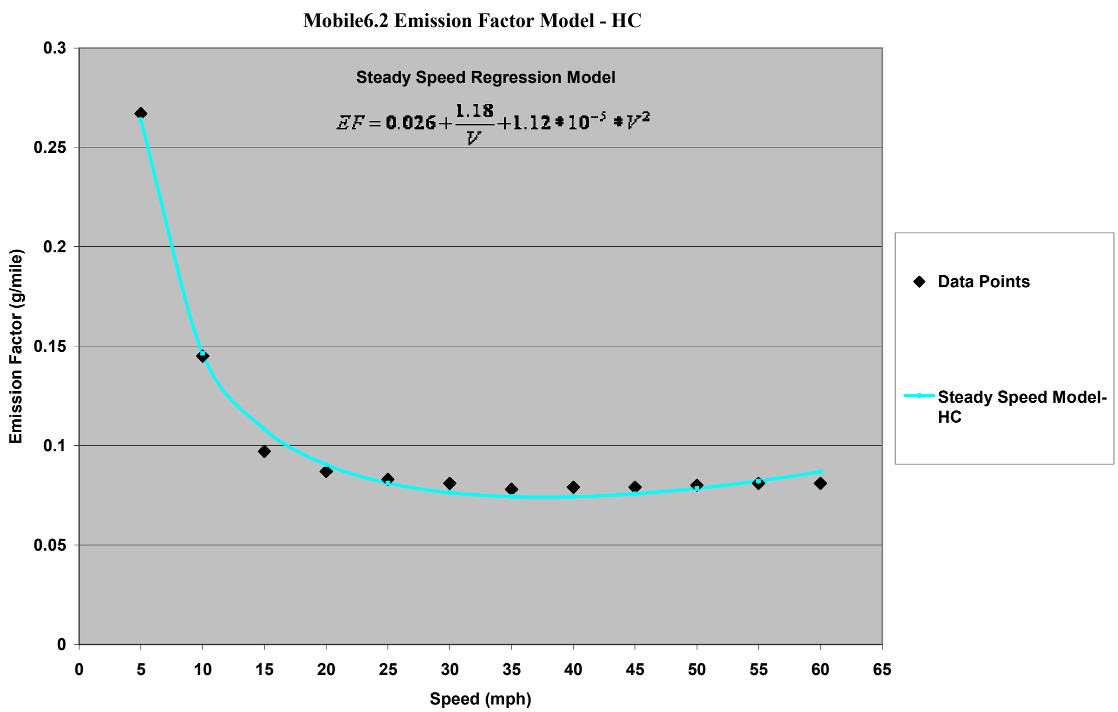


Figure 3.12 Predicted Emission Rates of HC for Steady Speed Model

From Figure 3.12, at lower speeds, below 25 mph, the HC emission rate is high but decreases rapidly. The HC emission rate is constant at speeds between 30 mph to 45 mph. There is a slight decrease in emission rates after 45 mph. The model used to fit the data points is a steady speed model. The model fits accurately to the data points. The coefficient of correlation R^2 is 0.99.

Regression Model II for CO

$$EF = 1.691 + \frac{30.058}{V} + 0.0008V^2 \; ; \qquad R^2 = 0.99$$

EF: Emission rate of CO (g/mile) V: Cruise speed (mph)

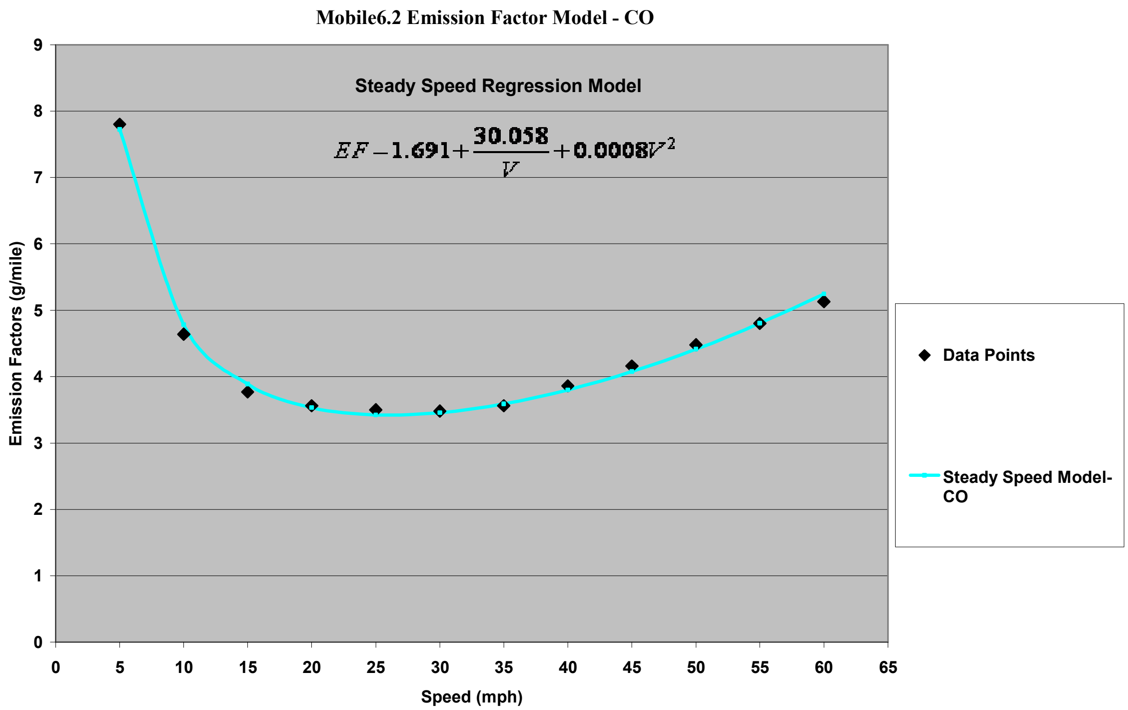


Figure 3.13 Predicted Emission Rates of CO for Steady Speed Model

Usually, CO emission rates are higher than HC and NO_x emission rates. From Figure 3.13, at lower speeds, below 25 mph, the CO emission rate is high and decreases rapidly. The CO rate is constant at speeds between 25 mph to 35 mph, then the emission rate start increasing rapidly as the speed increases. The model used to fit the data points is a steady speed model. The model fits accurately to the data points, with a coefficient of correlation R^2 of 0.99.

Regression Model II for NO_x

$$EF = 0.1579 + \frac{2.229}{V} + 3.066 * 10^{-5} V^2 \; ; \qquad R^2 = 0.99$$

EF: Emission rate of NO_x (g/mile) V: Cruise speed (mph)

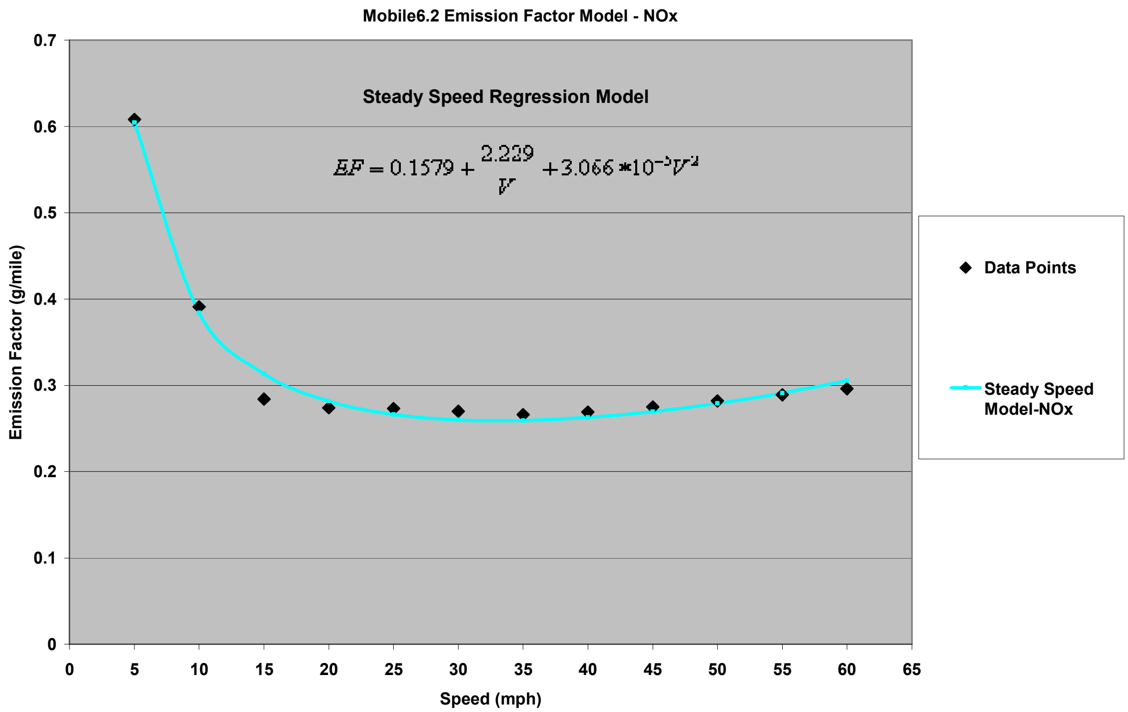


Figure 3.14 Predicted Emission Rates of NO_x for Steady Speed Model

From Figure 3.14, at lower speeds below 25 mph the NO_x emission rate is high and decreases rapidly. The NO_x emission rates are constant at speeds between 30 mph to 40 mph. There is a gradual increase in emission observed after 45 mph. The model used to fit the data points is a steady speed model. The model fits accurately to the data points, with a coefficient of correlation R^2 of 0.99.

Table 3.3 Summary of Regression Models for Major Pollutant's from Passenger Car

Type of Pollutant	Type of Regression Model	Regression Model	R^2
HC	2^{nd} Order Poly. Model	$EF = 0.2567 - 0.0097V + 0.0001V^2$	0.77
	Steady Speed Model (Post et al.)	$EF = 0.026 + \frac{1.18}{V} + 1.12*10^{-5}V^2$	0.99
CO	2^{nd} Order Poly. Model	$EF = 7.5823 - 0.2497V + 0.0036V^2$	0.72
	Steady Speed Model (Post et al.)	$EF = 1.691 + \frac{30.058}{V} + 0.0008V^2$	0.99
NO_x	2^{nd} Order Poly. Model	$EF = 0.592 - 0.0183V + 0.0002V^2$	0.75
	Steady Speed Model (Post et al.)	$EF = 0.1579 + \frac{2.229}{V} + 3.066*10^{-5}V^2$	0.99

The models developed in Table 3.3 estimate emission rates at constant speed. To estimate emissions, the steady speed model is selected as it offers higher coefficients of correlation than the second order polynomial model. So, steady speed models will be applicable for passenger car vehicles to estimate the emission rates for different freeway speeds. Similarly, for the other 27 classes of vehicles, the regression models developed in this research for three pollutants HC, CO and NO_x, the models with better coefficient of correlation for these different vehicle classes and three major pollutants are shown in Table 3.4, 3.5, and 3.6.

Table 3.4 Regression Models for HC Pollutant for Different Vehicle Classes

VEHICLE TYPE	REGRESSION MODEL	R^2
LDGV	EF = 0.0267 + 1.184 V^2 + 1.11815E-05(1/V)	0.99
LDGT 1	EF = 0.0326 + 1.6 V^2 + 1.3754E-05(1/V)	0.99
LDGT 2	EF = 0.0364 + 1.862 V^2 + 1.5996E-05(1/V)	0.99
LDGT 3	EF = 0.0251 + 1.574 V^2 + 1.1203E-05(1/V)	0.97
LDGT 4	EF = 0.0274 + 1.880 V^2 + 1.7849E-05(1/V)	0.99
HDGV 2B	EF = 0.0573 + 2.652 V^2 – 1.8528E-05(1/V)	0.97
HDGV 3	EF = 0.1117 + 5.173 V^2 – 3.602E-05(1/V)	0.97
HDGV 4	EF = 0.1406 + 6.54 V^2 – 4.5492E-05(1/V)	0.97
HDGV 5	EF = 0.303 + 14.064 V^2 – 9.775E-05(1/V)	0.97
HDGV 6	EF = 0.1027 + 5.482 V^2 – 3.453E-05(1/V)	0.97
HDGV 7	EF = 0.1575 + 7.225 V^2 – 5.0762E-05(1/V)	0.97
HDGV 8A	EF = 0.2258 + 10.451 V^2 – 7.2833E-05(1/V)	0.97
HDGV 8B	EF = 0.2167 + 10.045 V^2 – 6.9948E-05(1/V)	0.97

Table 3.4 - continued

HDGV 8B	$EF = 0.2167 + 10.045\ V^2 - 6.9948E\text{-}05(1/V)$	0.97
LDDV	$EF = 0.3061 - 0.009489V + 9.44855V^2$	0.99
LDDT 12	$EF = 2.5122 - 0.0779V + 0.000775V^2$	0.99
HDDV 2B	$EF = 0.3762 - 0.011677V + 0.0001163V^2$	0.99
HDDV 3	$EF = 0.4621 - 0.01429V + 0.000142V^2$	0.99
HDDV 4	$EF = 0.6158 - 0.0191V + 0.0001902V^2$	0.99
HDDV 5	$EF = 0.6954 - 0.02158V + 0.0002151V^2$	0.99
HDDV 6	$EF = 0.87144 - 0.02703V + 0.0002693V^2$	0.99
HDDV 7	$EF = 1.1241 - 0.03486V + 0.0003472V^2$	0.99
HDDV 8A	$EF = 1.2578 - 0.03903V + 0.000388V^2$	0.99
HDDV 8B	$EF = 1.2479 - 0.0387V + 0.0003854V^2$	0.99
MC	$EF = 0.2572 + 25.029\ V^2 - 0.00015E\text{-}05(1/V)$	0.99
HDGB	$EF = 0.4632 + 21.510\ V^2 - 0.00014E\text{-}05(1/V)$	0.97
HDDBT	$EF = 0.8393 - 0.0260V + 0.000258V^2$	0.99
HDDBS	$EF = 1.7154 - 0.05322V + 0.00053V^2$	0.99
LDDT 34	$EF = 0.5049 - 0.01567V + 0.0001561V^2$	0.99

Table 3.5 Regression Models for CO pollutant for Different Vehicle Classes

VEHICLE TYPE	REGRESSION MODEL	R^2
LDGV	$EF = 1.6915 + 30.0587\ V^2 + 0.0008483(1/V)$	0.99
LDGT 1	$EF = 1.9579 + 29.850\ V^2 + 0.000942(1/V)$	0.99
LDGT 2	$EF = 2.0254 + 31.417\ V^2 + 0.0009984(1/V)$	0.99
LDGT 3	$EF = 1.5768 + 23.7166\ V^2 + 0.000677(1/V)$	0.98
LDGT 4	$EF = 1.5321 + 24.5034\ V^2 + 0.0007499(1/V)$	0.99
LDDT 12	$EF = 4.5859 – 0.1792V + 0.00203V^2$	0.97
HDGV 2B	$EF = 21.9057 – 0.90247V + 0.010716V^2$	0.96
HDGV 3	$EF = 28.5502 – 1.1759V + 0.01396V^2$	0.96
HDGV 4	$EF = 28.7406 – 1.183V + 0.01405V^2$	0.96
HDGV 5	$EF = 52.1645 – 2.1485V + 0.0255V^2$	0.96
HDGV 6	$EF = 32.050 – 1.3199V + 0.01567V^2$	0.96
HDGV 7	$EF = 36.3809 – 1.4985V + 0.01779V^2$	0.96
HDGV 8A	$EF = 40.570 – 1.671V + 0.01983V^2$	0.96
HDGV 8B	$EF = 50.313 – 2.0725V + 0.024609V^2$	0.96
LDDV	$EF = 1.9950 – 0.07797V + 0.000885V^2$	0.97

Table 3.5 - continued

HDDV 2B	$EF = 1.6343 – 0.06389V + 0.000725V^2$	0.97
HDDV 3	$EF = 2.245 – 0.08776V + 0.00099V^2$	0.97
HDDV 4	$EF = 3.357 – 0.1312V + 0.00149V^2$	0.97
HDDV 5	$EF = 3.3507 – 0.1309V + 0.00148V^2$	0.97
HDDV 6	$EF = 3.7704 – 0.1473V + 0.00167V^2$	0.97
HDDV 7	$EF = 4.9749 – 0.1944V + 0.0022V^2$	0.97
HDDV 8A	$EF = 7.7059 – 0.30121V + 0.00342V^2$	0.97
HDDV 8B	$EF = 7.0599 – 0.2759V + 0.0031336V^2$	0.97
MC	$EF = 0.2572 + 25.029 V^2 – 0.00015E\text{-}05(1/V)$	0.98
HDGB	$EF = 70.8397 – 2.80546V + 0.033V^2$	0.99
HDDBT	$EF = 10.2842 – 0.40203V + 0.00456V^2$	0.97
HDDBS	$EF = 7.9726 – 0.3116V + 0.00353V^2$	0.97
LDDT 34	$EF = 1.1928 – 0.0466V + 0.000529V^2$	0.97

Table 3.6 Regression Models for NO_x pollutant for Different Vehicle Classes

VEHICLE TYPE	REGRESSION MODEL	R^2
LDGV	$EF = 0.1579 + 2.229V^2 + 3.0664E\text{-}05(1/V)$	0.99
LDGT 1	$EF = 0.1827 + 1.9855V^2 + 3.747E\text{-}05(1/V)$	0.98
LDGT 2	$EF = 0.29083 + 2.7069V^2 + 4.904E\text{-}05(1/V)$	0.98
LDGT 3	$EF = 0.2132 + 2.1353V^2 + 4.554E\text{-}05(1/V)$	0.95
LDGT 4	$EF = 0.3422 + 2.878V^2 + 4.9308E\text{-}05(1/V)$	0.98
HDGV 2B	$EF = 0.8548 – 0.00724V + 2.3146E\text{-}05V^2$	0.99
HDGV 3	$EF = 1.8823 – 0.1591V + 5.1308E\text{-}05V^2$	0.99
HDGV 4	$EF = 2.4321 – 0.02062V + 6.5334E\text{-}05V^2$	0.99
HDGV 5	$EF = 3.8222 – 0.3247V + 0.000102228V^2$	0.99
HDGV 6	$EF = 1.8958 – 0.01606V + 5.1098E\text{-}05V^2$	0.99
HDGV 7	$EF = 2.6868 – 0.0228V + 7.19081E\text{-}05V^2$	0.99
HDGV 8A	$EF = 4.0646 – 0.0344V + 0.000109V^2$	0.99
HDGV 8B	$EF = 3.9078 – 0.03320V + 0.0001045V^2$	0.99
LDDV	$EF = 0.5718 – 0.0187V + 0.000291V^2$	0.99
LDDT 12	$EF = 4.012 – 0.1317V + 0.00204V^2$	0.99
HDDV 2B	$EF = 2.8849 – 0.09477V + 0.001471V^2$	0.99

Table 3.6 - continued

HDDV 3	$EF = 3.8905 – 0.1295V + 0.00199V^2$	0.99
HDDV 4	$EF = 5.4554 – 0.1792V + 0.002782V^2$	0.99
HDDV 5	$EF = 5.8422 – 0.1918V + 0.0029V^2$	0.99
HDDV 6	$EF = 7.6281 – 0.2494V + 0.00387V^2$	0.99
HDDV 7	$EF = 10.2137 – 0.3318V + 0.00515V^2$	0.99
HDDV 8A	$EF = 14.6292 – 0.4268V + 0.006628V^2$	0.99
HDDV 8B	$EF = 11.5719 – 0.37173V + 0.00577V^2$	0.99
MC	$EF = 0.5123 – 0.00454V + 0.0002082V^2$	0.98
HDGB	$EF = 5.4089 – 0.04593V + 0.000144V^2$	0.99
HDDBT	$EF = 21.5820 – 0.7171V + 0.01113V^2$	0.99
HDDBS	$EF = 16.0137 – 0.5308V + 0.00824V^2$	0.99
LDDT 34	$EF = 0.6927 – 0.02275V + 0.0003533V^2$	0.99

3.3.2 Vehicular Emission Regression Model for CO_2 Emissions from On-Board Emission Measurement Data

In Mobile6.2 the emission rates for CO_2 are calculated in a very simplistic way. The CO_2 calculations are based on the fuel economy performance estimates built into the model or supplied by the user. For other pollutants, Mobile6.2 considers various factors, such as the ambient temperature, speeds, humidity, etc., to estimate the emission factors, but the CO_2 emission rates will not adjust to these factors, which include speed, temperature, fuel content, etc. So, in this research, a model is proposed to estimate the CO_2 emission rate for passenger cars considering speed as the predictor variable. The data is obtained from on-board emission measurements. For other vehicle classes the models are developed based on the multiplying factors used in Mobile6.2. The models have some limitations such as: they are applicable only to freeway traffic conditions, and they only estimate tailpipe emissions. The data was collected in the DFW region, which is non attainment for ozone. Two regression models: second order polynomial model and steady speed model were tested in estimating the emission rates of CO_2.

The data from the on-board emission measurement method was measured second by second. In this research, the data was aggregated to 30 seconds as there was a delay in measuring the GPS velocity.

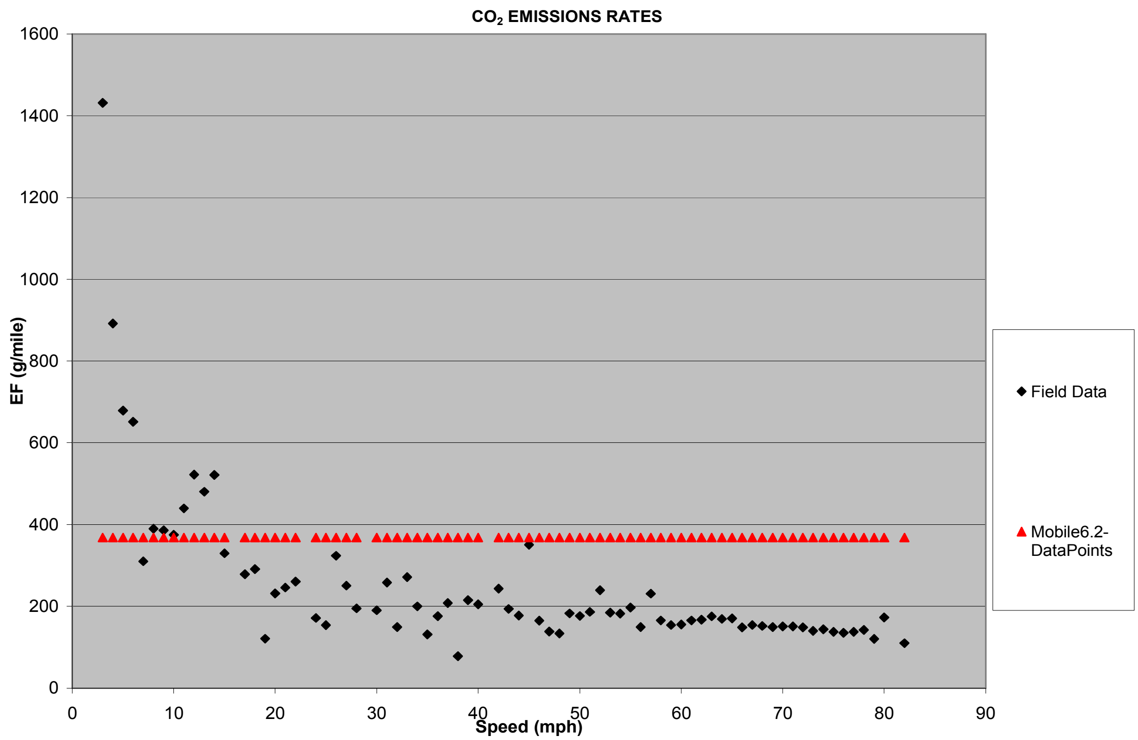


Figure 3.15 CO_2 Emission Rates vs. Speeds

Figure 3.15 compares the data points between the Mobile6.2 and field data. Mobile6.2 does not consider the speed, vehicular activity, and other meteorological data in estimating the CO_2 emission rates and only considers the average fuel economy performance estimates built into the model or supplied by the user. The data points are constant for all speeds. From the data points obtained from on-board emission measurements, the CO_2 emission rates are higher at lower speeds. There is a rapid decrease in emissions from 5 mph to 25 mph and a relatively constant emission rate is observed from 30 mph to 45 mph. From 45 mph, there is a gradual decrease in emissions. So, in mobile6.2 the emission rates for CO_2 are over-estimated for most ranges of speed when compared to the field data.

Regression Model I: (Second Order Polynomial Model)

The first regression model is a second order polynomial model. The data to develop these models was obtained from on-board emission measurements.

Regression Model I for CO_2

$$EF = 699.2 - 20.4V + 0.1795V^2 \; ; \qquad R^2 = 0.57$$

EF: Emission rate of CO_2 (g/mile) V: Cruise speed (mph)

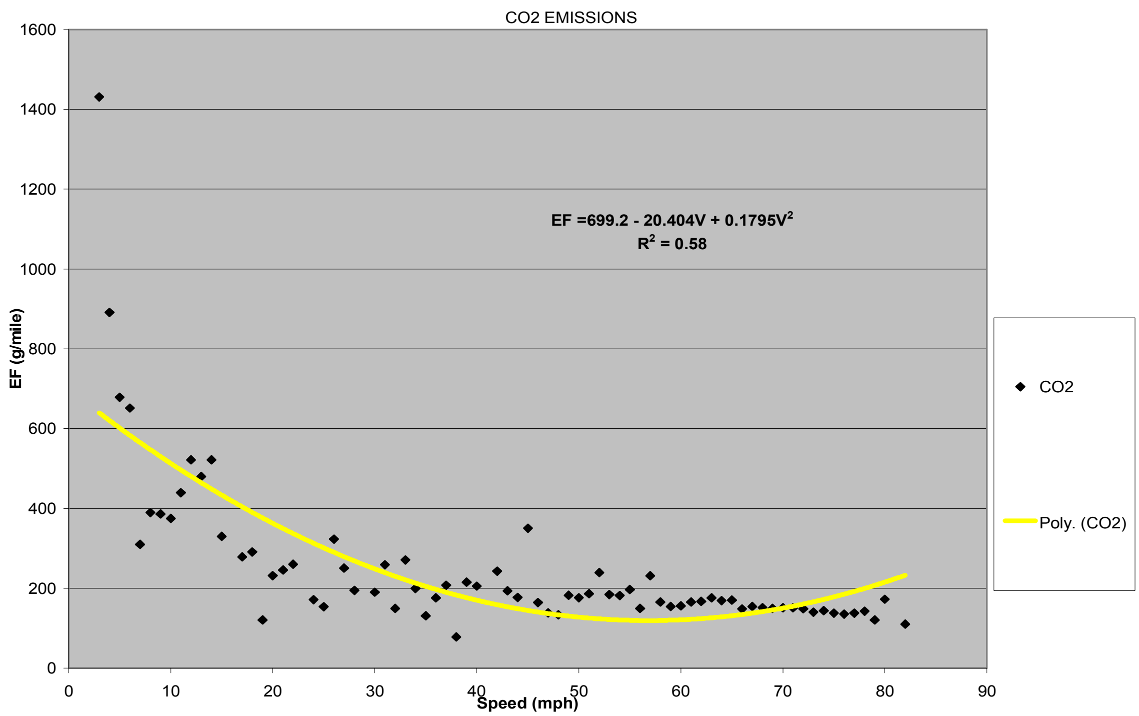


Figure 3.16 Predicted Emission Rates of CO_2 for Second Order Polynomial Model

From Figure 3.16, at speeds below 25 mph, the CO_2 emission rate is high but decreases rapidly. The CO_2 emission rate is constant at speeds between 30 mph to 50 mph. There is a gradual decrease in emission rate after 55 mph. The model used to fit the data points is a second order polynomial equation, and its coefficient of correlation R^2 is 0.58.

Regression Model II: (Steady Speed Model, Post et al.)

The second regression model is a steady speed model (Post et al. Model). The data to calibrate this model was obtained from on-board emission measurements.

Regression Model II for CO_2

$$EF = 94.416 + \frac{3384.6}{V} + 0.0026V^2 \; ; \qquad R^2 = 0.88$$

EF: Emission rate of CO_2 (g/mile) V: Cruise speed (mph)

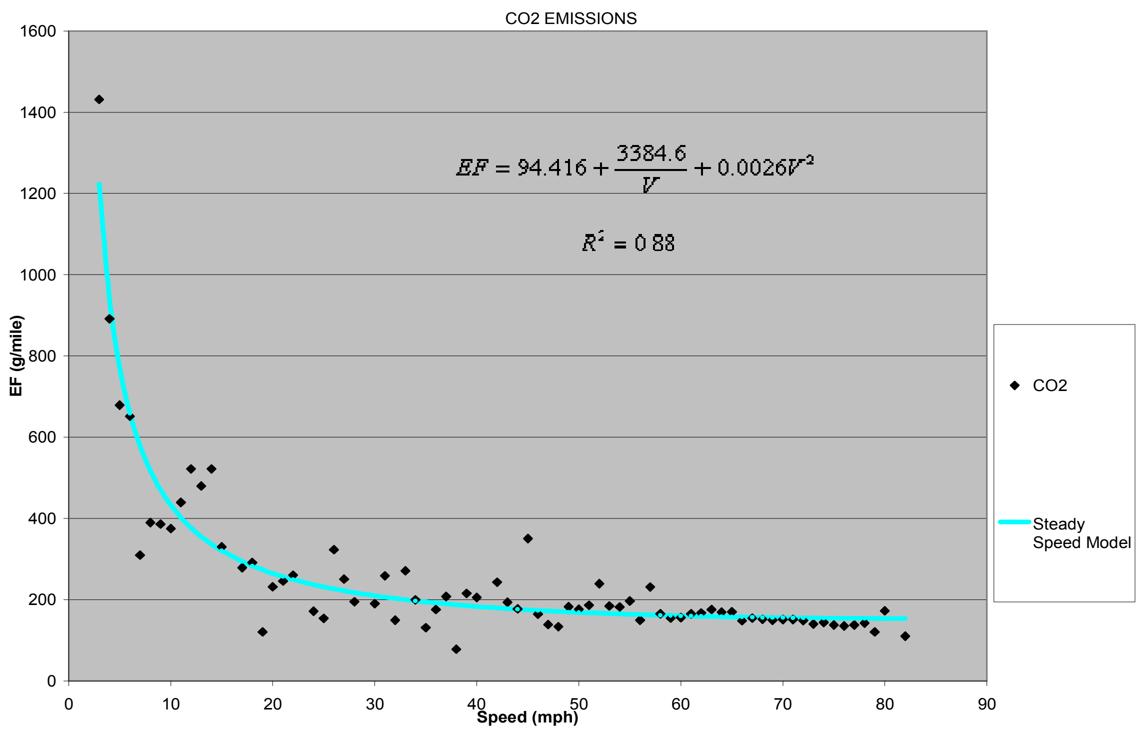


Figure 3.17 Predicted Emission Rates of CO_2 for Steady Speed Model

From Figure 3.17, at speeds below 25 mph the CO_2 emission rate is high and decreasing rapidly. The CO_2 emission rate is fairly constant at speeds between 30 mph to 50 mph. There is a gradual decrease in emission rate after 55 mph. The model used to fit the data points was steady speed model. The model fits accurately to the data points. The coefficient of correlation is 0.88.

Table 3.7 Summary of Regression Models for CO_2 from Passenger Cars

Type of Pollutant	**Type of Regression Model**	**Regression Model**	**R^2**
CO_2	2^{nd} Order Poly. Model	$EF = 699.2 - 20.4V + 0.1795V^2$	0.58
	Steady Speed Model (Post et al.)	$EF = 94.416 + \frac{3384.6}{V} + 0.0026V^2$	0.88

As can be observed from Table 3.7, the steady speed model has a considerably higher coefficient of correlation than the second order polynomial model. So, the steady speed model is recommended to estimate the CO_2 emission rates for passenger car vehicles for different freeway speeds. For other vehicle classes the models are calibrated based on the multiplying factors (Table 3.8) calculated based on the mobile6.2 value for the passenger car versus other vehicle classes. The models for 28 categories of vehicles are shown in appendix A.

Table 3.8 Multiplying Factors

Type of Vehicle	**Ratio**
1	1.0000
2	1.2972
3	1.2972
4	1.6938
5	1.6938
6	2.3820

Table 3.8 - continued

7	2.5773
8	2.5939
9	3.0630
10	2.9788
11	3.2510
12	3.4358
13	3.5759
14	0.8525
15	1.1342
16	2.1337
17	2.3730
18	2.7142
19	2.8060
20	3.1771
21	3.6724
22	4.2111
23	4.3898
24	0.4819
25	3.8169
26	6.3632
27	4.4616
28	1.6259

3.4 Analysis of Emission Rates for Different Driving Modes

This section discusses the effect of acceleration and deceleration, and cruise modes on the emission rates at various speeds on the freeway. The Mobile6.2 modeling software estimates the emission rates for the cruise mode. So, the emission rates estimated in Mobile6.2 do not consider the effect of acceleration and deceleration modes. For this analysis, the data was obtained from Mobile6.2 and on-board emission measurements. Mobile6.2 does not consider the acceleration and deceleration effect but the on-board emission measurement includes the effect of the acceleration and deceleration in estimating the emission rates for various speeds. The analysis was performed for the three major pollutants for passenger cars. The data from on-board emission measurement was collected in the peak hour on freeway, and from Mobile6.2, the input file was modified to estimate the data according to the field data conditions.

Hydrocarbons (HC):

From Figure 3.18, the HC emission rates are higher from on-board emission measurement than from Mobile6.2.

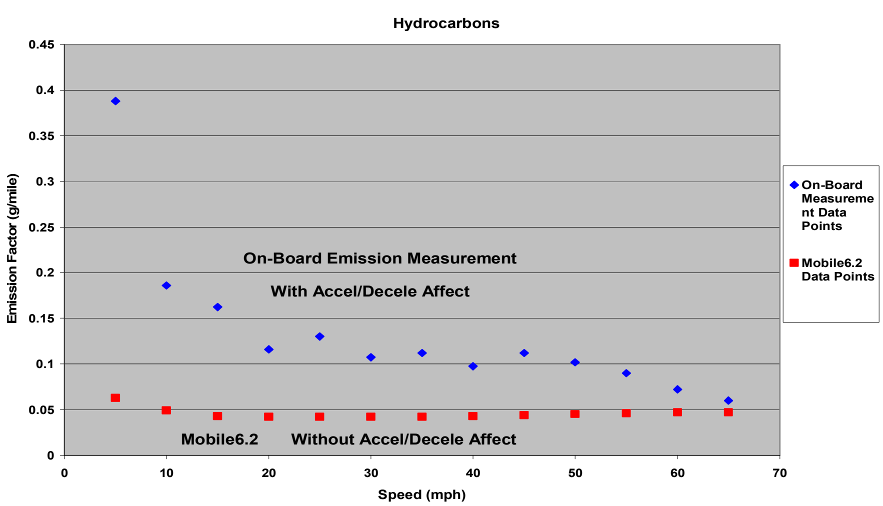


Figure 3.18 Comparison of HC Data Points from Mobile6.2 and Field Data

Carbon monoxide (CO):

From Figure 3.19, for speeds higher than 30mph, the CO emission rates from on-board emission measurement are about the same as the emission rates from Mobile6.2.

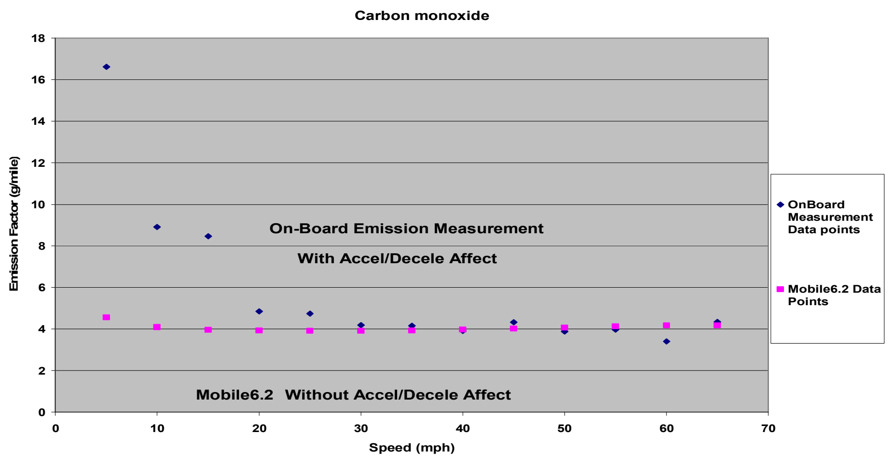


Figure 3.19 Comparison of CO Data Points from Mobile6.2 and Field data

Nitrogen oxides (NO_x):

From Figure 3.20, the NO_x emission rates are higher from Mobile6.2 than from on-board emission measurement for speeds over 15mph.

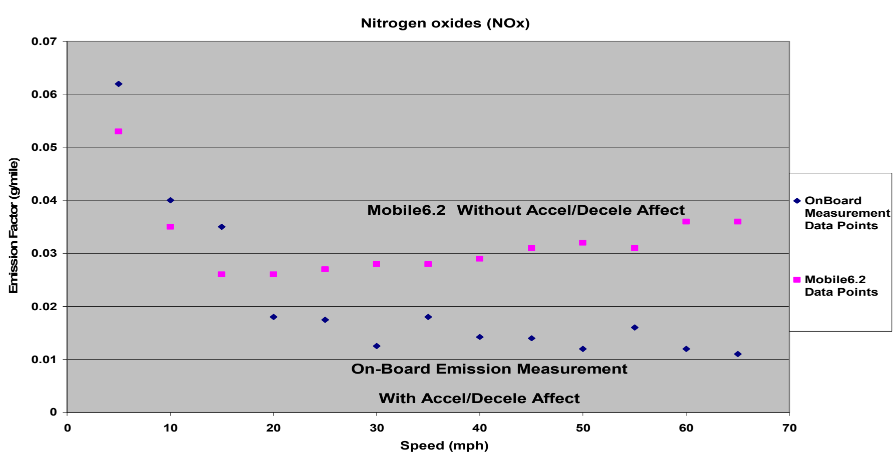


Figure 3.20 Comparison of NO_x Data Points from Mobile6.2 and Field Data

A statistical analysis (paired t-test) is performed from Mobile6.2 and on-board emission measurement data, to check whether the data from Mobile6.2 is statistically different from the on-board emission measurement data.

Table 3.9 Results of Paired t-test

$H_0: \mu_1 = \mu_2$; $H_1: \mu_1 \neq \mu_2$						
Reject H_0 if $t_0 > t_{\alpha/2, n1+n2-2}$ or $t_0 < -t_{\alpha/2, n1+n2-2}$						
Type of pollutant	t_0	$t_{\alpha/2, n1+n2-2}$	$T_0 > t_{\alpha/2, n1+n2-2}$	$t_0 < -t_{\alpha/2, n1+n2-2}$	H_0	**Conclusion**
HC	-4.08592	1.78228	FALSE	TRUE	REJECT	$\mu_1 \neq \mu_2$
CO	-1.8126	1.78228	FALSE	TRUE	REJECT	$\mu_1 \neq \mu_2$
NOx	-4.08592	1.78228	TRUE	FALSE	REJECT	$\mu_1 \neq \mu_2$

It was concluded from the paired t-test in Table 3.9, that there is a significant difference between Mobile6.2 and on-board emission measurement data in all three pollutant cases. There are many potential reasons for the significant differences in the data between Mobile6.2 and the on-board emission measurements. The most important factor is the driving mode. The Mobile6.2 emission rates are estimated in cruise (constant speed) mode driving and on-board emission measurement emission rates are collected in cruise, acceleration and deceleration driving modes. The traffic conditions also play an important role. Due to the traffic conditions in the on-board emission measurement method, there are lots of fluctuations in driving modes (i.e., if there is a congested traffic condition, more accelerations and decelerations take place which eventually increase the fuel consumption and emission rates). Mobile6.2 does not consider the acceleration and deceleration effects in estimating the emission rates for different pollutants. So, the emission measurements estimated in the Mobile6.2 underestimate the effect of other driving modes i.e., accelerations and decelerations. To demonstrate the effect of the acceleration and deceleration on the emission rates, first a discussion on how the fuel consumption is affected by acceleration and deceleration is presented below.

A similar pattern is typically observed between the fuel consumption and emission rates due to common factors which affect both. Research was conducted to analyze the fuel consumption for urban traffic management (ARRB Internal Report by D.P.Bowyer, R.Akcelik, and D.C.Biggs- September 1984). This research is a guide to use various existing techniques for estimating the fuel consumption in urban traffic systems.

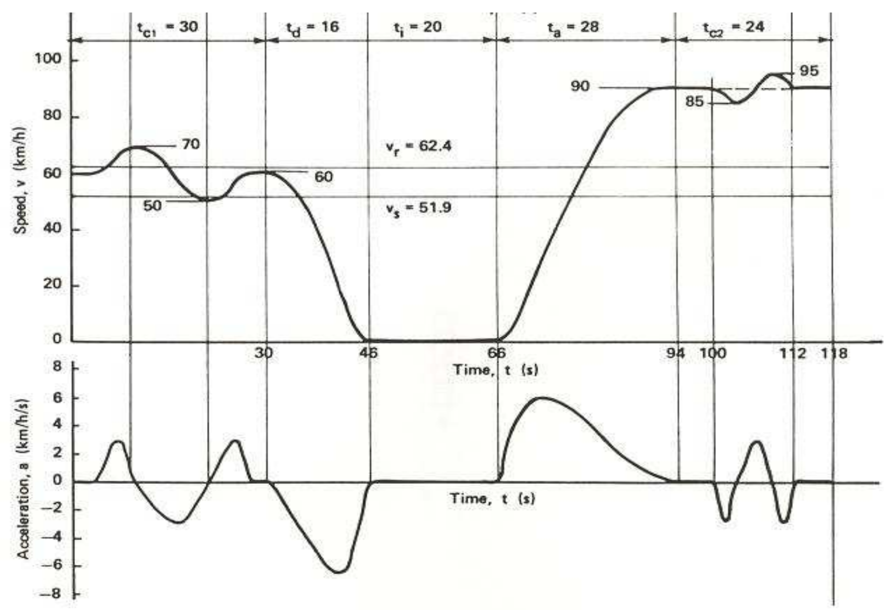


Fig 15 Distance, speed and acceleration-time traces over cruise-deceleration-idle-acceleration-cruise (CDIAC) cycle

Figure 3.21 Speed and Acceleration-Time Traces over Different Driving Modes

(Source: ARRB Internal Report by D.P.Bowyer et. al. - September 1984)

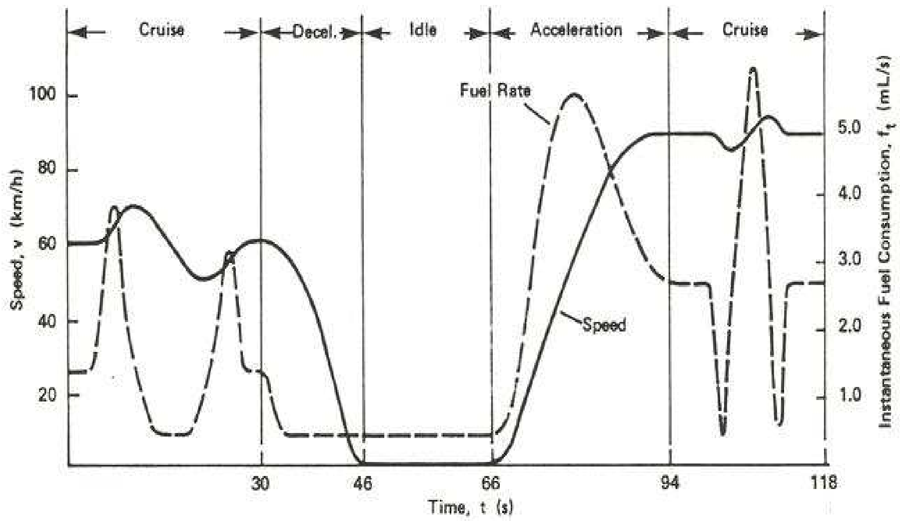


Fig 16 Distance, cumulative fuel consumption, speed and instantaneous fuel consumption over a cruise-deceleration-idle-acceleration-cruise (CDIAC) cycle

Figure 3.22 Fuel Consumption and Speed-Time Traces over Different Driving Modes

(Source: ARRB Internal Report by D.P.Bowyer et. al. - September 1984)

Figures 3.21 and 3.22 show the effect of acceleration and deceleration on speeds with respect to time and the resulting fuel consumption for different driving modes. At higher speeds, 60 km/h and above, even a small change in speed can vary the fuel consumption rate to a large extent. For the analysis of emission rates with accelerations and decelerations, the on-board emission measurement data was used. The analysis was conducted on the three major pollutants and carbon dioxide.

Hydrocarbons (HC):

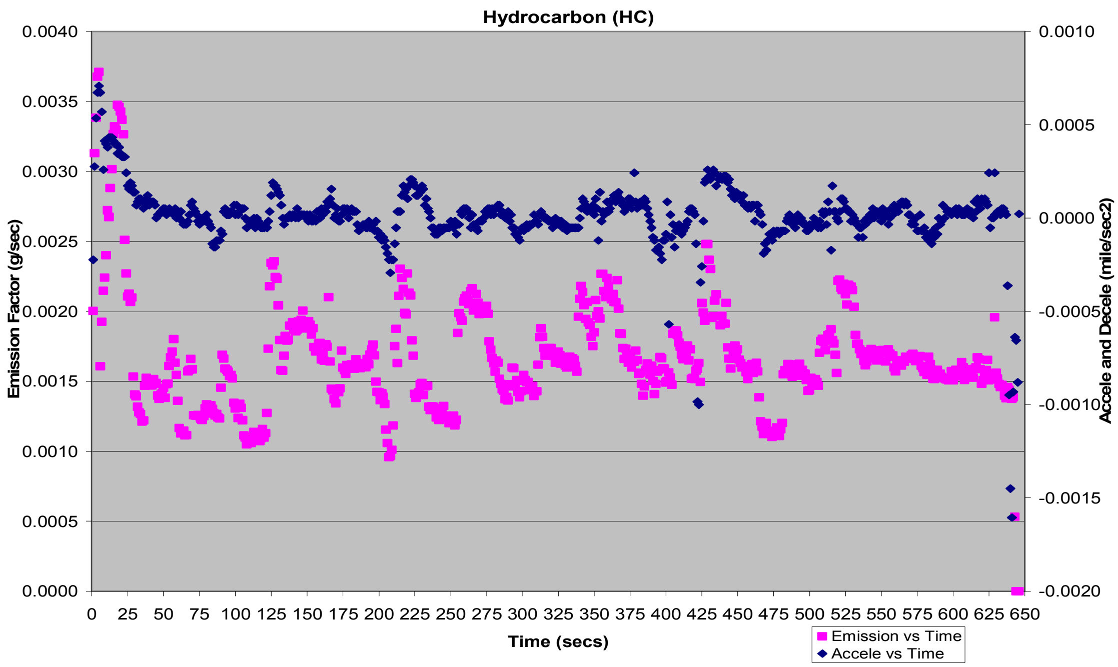


Figure 3.23 Affect of Acceleration and Deceleration on HC Emission Rate

Carbon monoxide (CO):

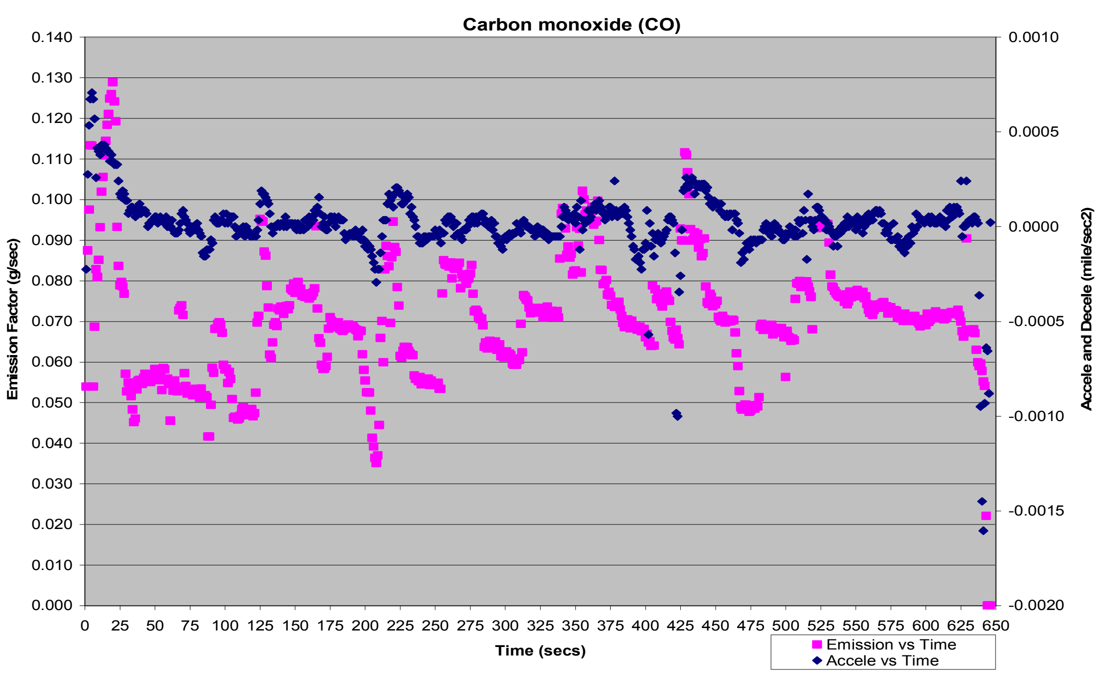


Figure 3.24 Affect of Acceleration and Deceleration on CO Emission Rate

Nitrogen oxides (NO_x):

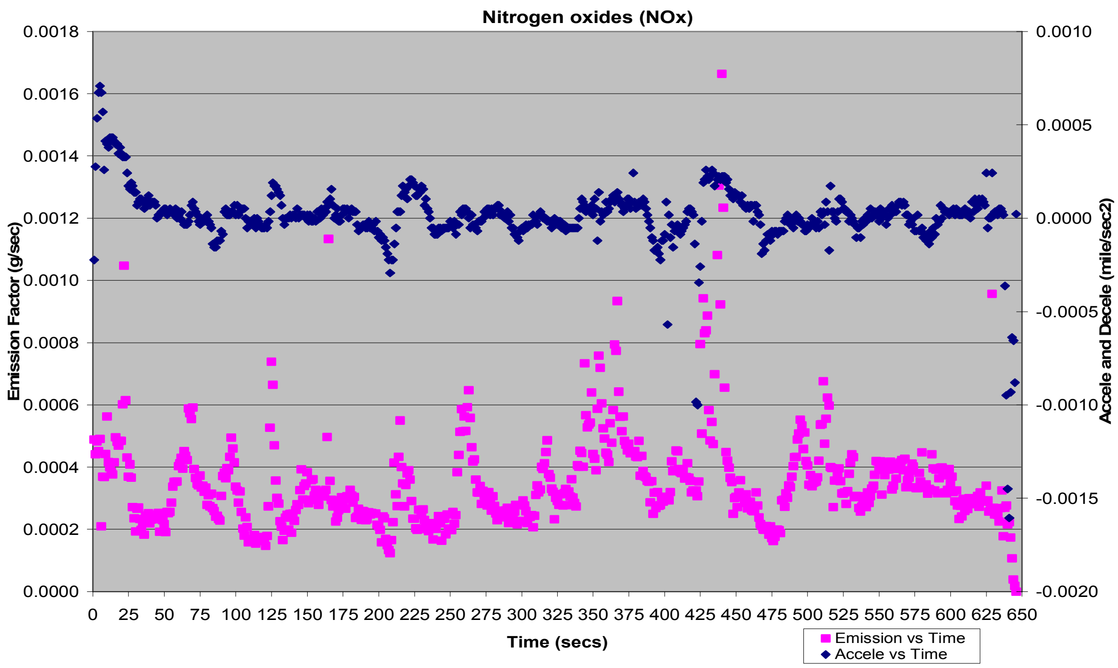


Figure 3.25 Affect of Acceleration and Deceleration on NO_x Emission Rate

Carbon dioxide (CO_2):

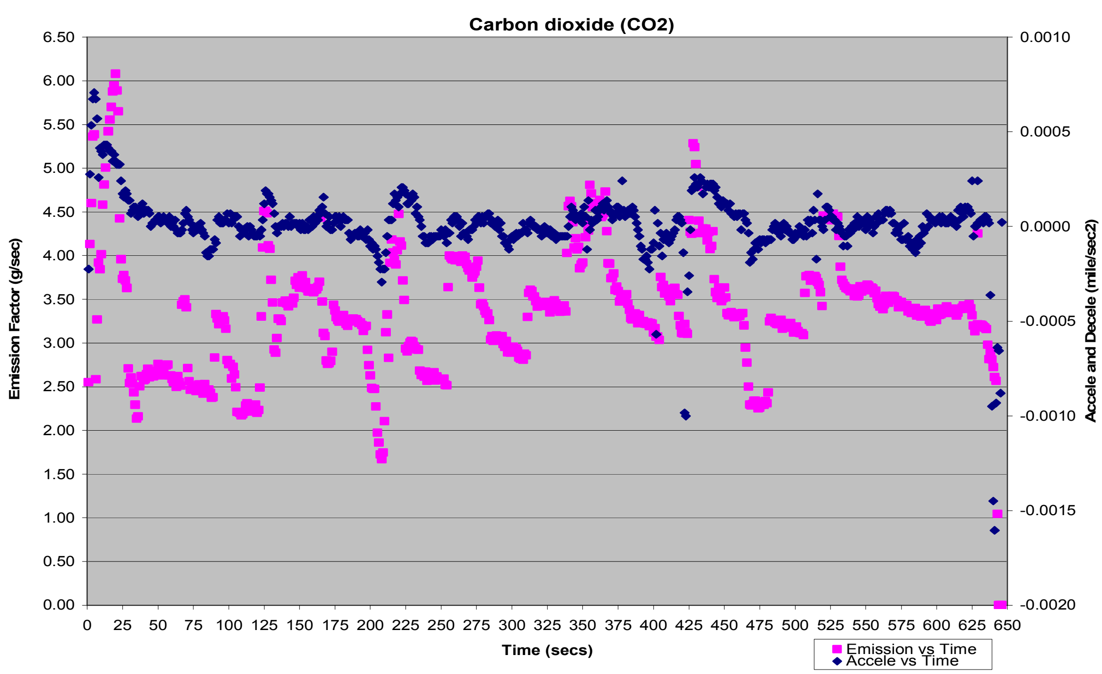


Figure 3.26 Affect of Acceleration and Deceleration on CO_2 Emission Rate

A statistical analysis (Paired t-test) was conducted to check whether the coefficient of variation of acceleration and deceleration and coefficient of variation of emission rates in Figures 3.23-3.26 are equal. In performing this statistical analysis a class width of 65 was considered based on the sturges rule for both acceleration and deceleration, and emission rates data. The paired t-test shown in Table 3.10 indicates that the two coefficients are not statistically different. The number of accelerations and decelerations will be more in urban traffic conditions, due to low speed limits and signalized and un-signalized intersections. But on freeways there are fewer acceleration and decelerations cycles due to high speeds, and absence of at-grade intersections. Based on the data obtained from the on-board emission measurement it was observed that the range of accelerations and decelerations was very low (i.e., -0.0002 m/sec^2 to 0.0002 m/sec^2 from Figures 3.27 to 3.30). Usually for urban traffic conditions the range will be higher (i.e., -0.001 m/sec^2 to 0.001 m/sec^2 in Figure 3.21). At higher speeds, even a small difference in speeds will affect the fuel consumption rate. Similarly, at higher speeds, a small difference in speeds will have an impact on emission rates. So, the ideal driving mode on a freeway is cruise mode (relatively constant speed), which can reduce the emission rates to a great extent.

Table 3.10 Results of Paired t-test

$H_0: \mu_1 = \mu_2$; $H_1: \mu_1 \neq \mu_2$						
Reject H_0 if $t_0 > t_{\alpha/2,\ n1+n2-2}$ or $t_0 < -t_{\alpha/2,\ n1+n2-2}$						
Type of pollutant	**t_0**	**$t_{\alpha/2,\ n1+n2-2}$**	**$t_0 > t_{\alpha/2,\ n1+n2-2}$**	**$t_0 < -t_{\alpha/2,\ n1+n2-2}$**	**H_0**	**Conclusion**
HC	-0.8485	1.8595	FALSE	FALSE	Can't Reject	$\mu_1 = \mu_2$
CO	-0.8482	1.8595	FALSE	FALSE	Can't Reject	$\mu_1 = \mu_2$
NO_x	-0.8514	1.8595	FALSE	FALSE	Can't Reject	$\mu_1 = \mu_2$
CO_2	-0.8482	1.8595	FALSE	FALSE	Can't Reject	$\mu_1 = \mu_2$

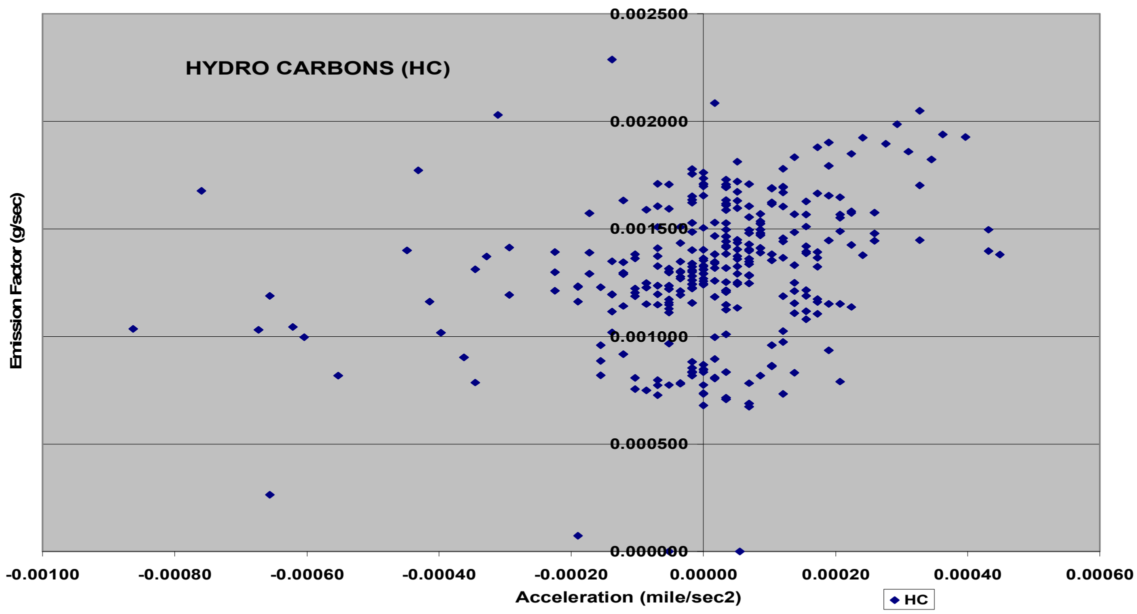


Figure 3.27 HC Emission Trend for Acceleration and Deceleration

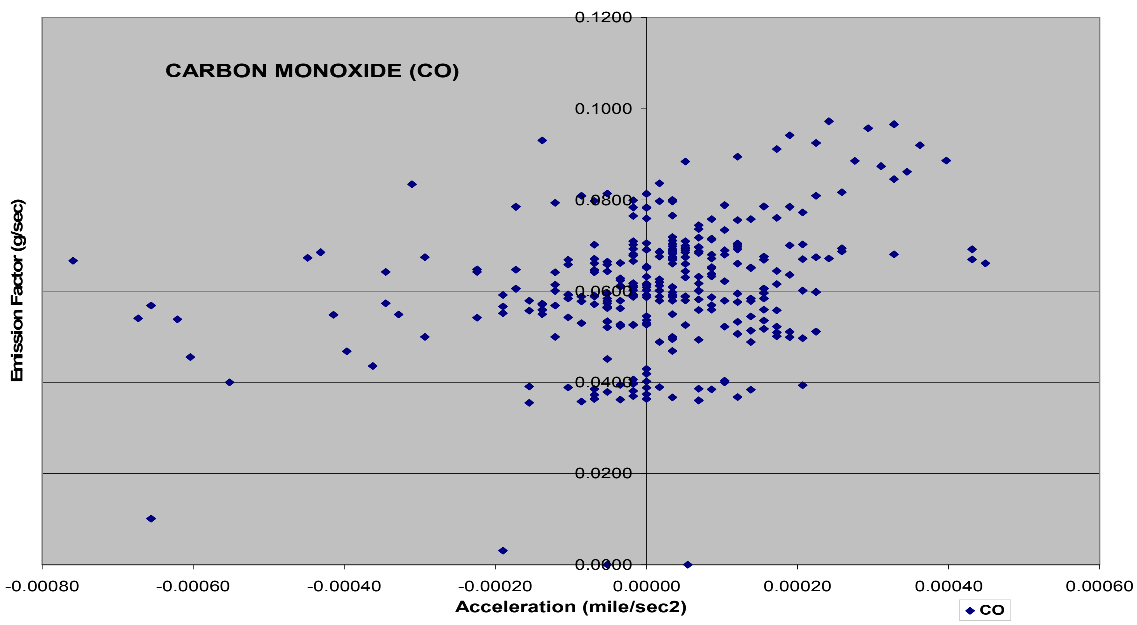


Figure 3.28 CO Emission Trend for Acceleration and Deceleration

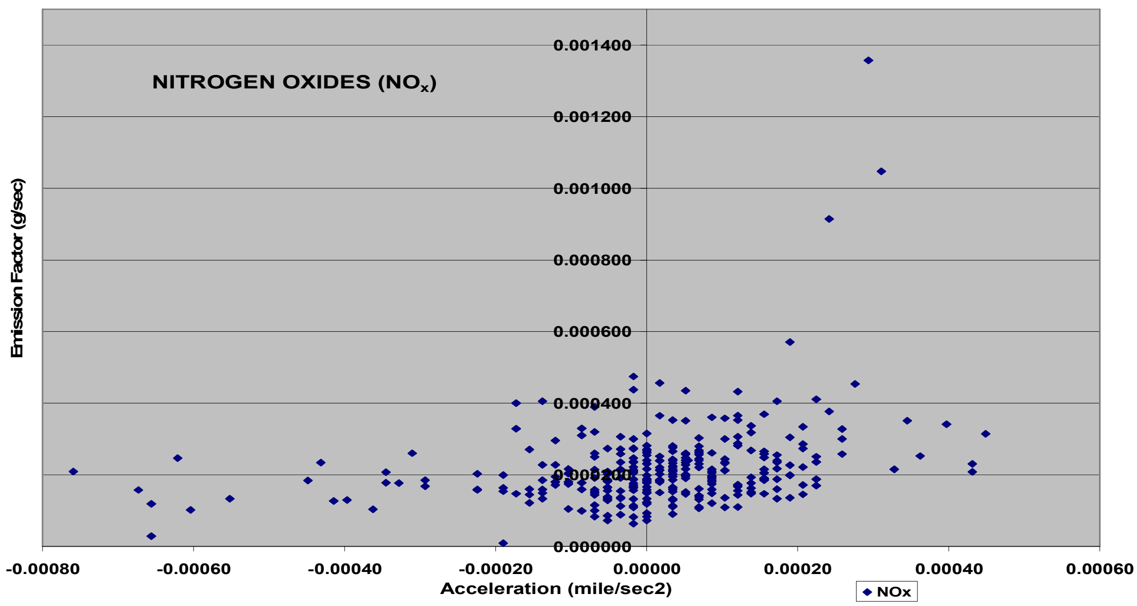


Figure 3.29 NO_x Emission Trend for Acceleration and Deceleration

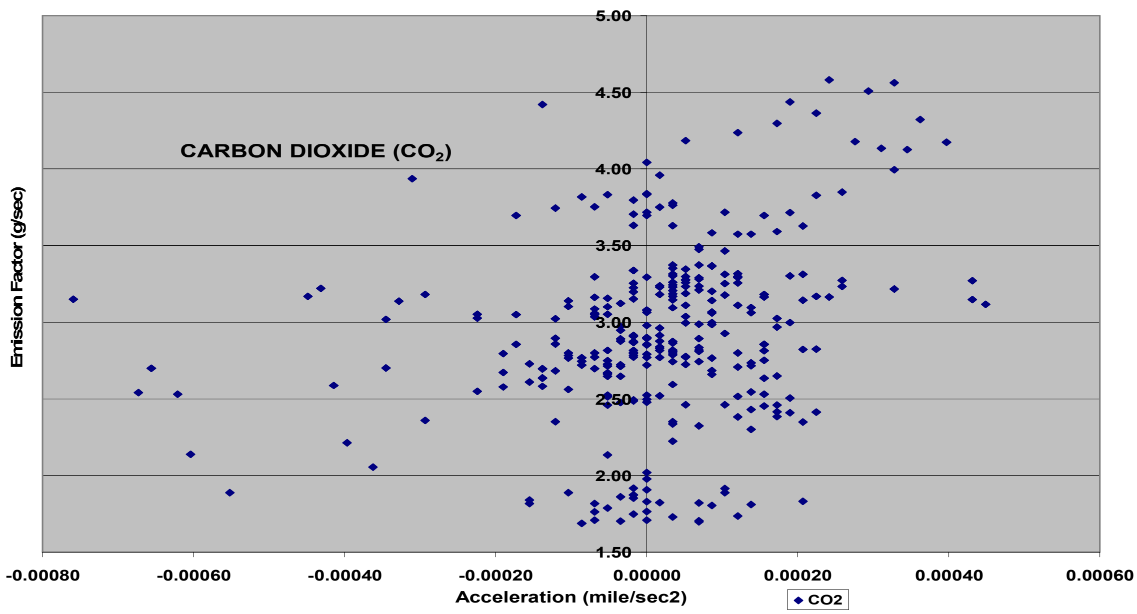


Figure 3.30 CO_2 Emission Trend for Acceleration and Deceleration

3.5 Summary of Chapter 3

This chapter discussed the data collection procedure and methodology for developing the emission rate models for different pollutants from 28 classes of vehicles.

The emission rate models for three major pollutants for 28 classes of vehicles were developed from the data obtained from the Mobile6.2. The model for the carbon dioxide was developed with the data obtained from the on-board emission measurement. For other vehicle classes the CO_2 emission rate models were developed based on the multiplying factors. In developing the models for each pollutant, two mathematical models were tested for the best fit. The first was a second order polynomial equation and the second was a steady speed model (by Post et. al. developed to estimate fuel consumption). Finally, an analysis was performed to study the effect of different driving modes on emission rates for different pollutants.

CHAPTER 4

CONCLUSIONS

4.1 Summary of the Thesis

In this thesis, models for emission rates for different pollutants for 28 classes of vehicles were developed. These models estimate only the exhaust emission rates (tail pipe emission rates). Speed was considered as the predictor variable for estimating the emission rates. There are many factors which affect the emission rates of different pollutants for different vehicles. From the sensitivity analysis conducted by the US DOT, speed was considered the most sensitive factor affecting the emission rates. Totally, 28 models for 28 categories of vehicles for each major pollutant (HC, CO and NO_x) were developed from the Mobile6.2 data. Also, a model for Carbon dioxide was developed from the on-board emission measurement data. The purpose of developing a model for CO_2 was that Mobile6.2 estimates the emission rate for CO_2 based on the fuel economy performance estimates built into the software and CO_2 emission rates are not adjusted to the other factors like speed, meteorological data, etc. So, a model was proposed for CO_2 to estimate the emission rates considering speed as the predictor variable. In developing the models, two mathematical models were tested for each pollutant for each class of vehicle. The two models are a second-order polynomial equation and a steady speed model. Finally, an analysis was performed to test the effect of different driving modes on emission rates. At higher speeds, small differences in speed will affect the emission rates to a greater extent.

The emission inventories from the models developed in this research were used in the Managed Lane Toll Pricing Model (TPM-2.1) developed for TX DOT [17]. The TPM-2.1 is the revised model of an existing Toll Pricing Model. In the older version, the model allowed toll calculations only for Single Occupant Vehicles (SOVs), and did not include the air quality as a measure. But in the new version, TPM-2.1, it allows toll charging for non-SOV vehicle classes and estimates emissions under various vehicle mixes and operating conditions. Finally, an attempt was being made to develop web-based software with all the revisions made to the Toll Pricing Model and to develop a user guide for the software.

The results of this modeling study support the following conclusions:

- Speed is the major factor affecting the emission rates.
- The accuracy of models developed in estimating the emission rates for different pollutants for different classes of vehicles are reasonable, with the coefficient of correlation of 0.99.
- The Mobile6.2 does not consider the speed in estimating the emission rates for carbon dioxide. A model was developed for CO_2 considering the speed as the predictor variable. Finally, it was observed that the emission rates from the Mobile6.2 were over-estimated when compared with field data.
- In an analysis that was performed to study the effect of the accelerations and decelerations on the emission rates, it was determined that at higher speeds, small fluctuations in speed would significantly affect the emission rates.

- Cruise mode was found to be the ideal driving mode in minimizing vehicular emissions rates.
- It was observed that the emission rates on freeways are the lowest at speeds between 30 mph and 40mph.

4.2 Limitations of the Models

There are some limitations in the use of the models developed. These limitations include the following:

- The developed models estimate only the exhaust emission rates for freeway traffic conditions.
- The CO_2 model is not validated. More data is required to validate the model.
- The models developed to estimate the three major pollutants (HC, CO, and NO_x) from Mobile6.2 are based on the cruise driving mode.

4.3 Further Research

Further research is needed to estimate the vehicular emissions models based on Mobile6.2 and Field Data. The areas where further research can be conducted include the following:

- Consider the evaporative emissions in the models,
- Validate the CO_2 emission rate model by collecting more data points from the on-board emission measurement,
- Consider all driving modes (acceleration, deceleration and idle) to estimate the emission rates for the three major pollutants,
- As the on-board emission measurement data was collected for both peak and offpeak traffic conditions, two regime models for estimating the emissions of different

pollutants for different vehicle classes can be developed considering the congested traffic conditions (LOS E and above) and uncongested traffic conditions (LOS below E).

APPENDIX A

MOBILE6.2 TABLES AND INPUT FILES

Mobile6.2 Reference Tables

Table A.1 Mobile6.2 vehicle classifications

Number	Abbreviation	Description
1	LDGV	Light-Duty Gasoline Vehicles (Passenger Cars)
2	LDGT1	Light-Duty Gasoline Trucks 1 (0-6,000 lbs. GVWR, 0-3750 lbs. LVW)
3	LDGT2	Light-Duty Gasoline Trucks 2 (0-6,000 lbs. GVWR, 3751-5750 lbs. LVW)
4	LDGT3	Light-Duty Gasoline Trucks 3 (6,001-8,500 lbs. GVWR, 0-5750 lbs. ALVW)
5	LDGT4	Light-Duty Gasoline Trucks 4 (6,001-8,500 lbs. GVWR, 5751 lbs. and greater ALVW)
6	HDGV2B	Class 2b Heavy-Duty Gasoline Vehicles (8501-10,000 lbs. GVWR)
7	HDGV3	Class 3 Heavy-Duty Gasoline Vehicles (10,001-14,000 lbs. GVWR)
8	HDGV4	Class 4 Heavy-Duty Gasoline Vehicles (14,001-16,000 lbs. GVWR)
9	HDGV5	Class 5 Heavy-Duty Gasoline Vehicles (16,001-19,500 lbs. GVWR)
10	HDGV6	Class 6 Heavy-Duty Gasoline Vehicles (19,501-26,000 lbs. GVWR)
11	HDGV7	Class 7 Heavy-Duty Gasoline Vehicles (26,001-33,000 lbs. GVWR)
12	HDGV8A	Class 8a Heavy-Duty Gasoline Vehicles (33,001-60,000 lbs. GVWR)
13	HDGV8B	Class 8b Heavy-Duty Gasoline Vehicles (>60,000 lbs. GVWR)
14	LDDV	Light-Duty Diesel Vehicles (Passenger Cars)
15	LDDT12	Light-Duty Diesel Trucks 1 and 2 (0-6,000 lbs. GVWR)
16	HDDV2B	Class 2b Heavy-Duty Diesel Vehicles (8501-10,000 lbs. GVWR)
17	HDDV3	Class 3 Heavy-Duty Diesel Vehicles (10,001-14,000 lbs. GVWR)
18	HDDV4	Class 4 Heavy-Duty Diesel Vehicles (14,001-16,000 lbs. GVWR)
19	HDDV5	Class 5 Heavy-Duty Diesel Vehicles (16,001-19,500 lbs. GVWR)
20	HDDV6	Class 6 Heavy-Duty Diesel Vehicles (19,501-26,000 lbs. GVWR)
21	HDDV7	Class 7 Heavy-Duty Diesel Vehicles (26,001-33,000 lbs. GVWR)
22	HDDV8A	Class 8a Heavy-Duty Diesel Vehicles (33,001-60,000 lbs. GVWR)
23	HDDV8B	Class 8b Heavy-Duty Diesel Vehicles (>60,000 lbs. GVWR)
24	MC	Motorcycles (Gasoline)
25	HDGB	Gasoline Buses (School, Transit and Urban)
26	HDDBT	Diesel Transit and Urban Buses
27	HDDBS	Diesel School Buses
28	LDDT34	Light-Duty Diesel Trucks 3 and 4 (6,001-8,500 lbs. GVWR)

Table A.2 Mobile6.2 Average Speed Ranges for Speed Bins

Number	Abbreviation	Description
1	2.5 mph	Miles with average speed 0-2.5 mph
2	5 mph	Miles with average speed 2.5-7.5 mph
3	10 mph	Miles with average speed 7.5-12.5 mph
4	15 mph	Miles with average speed 12.5-17.5 mph
5	20 mph	Miles with average speed 17.5-22.5 mph
6	25 mph	Miles with average speed 22.5-27.5 mph
7	30 mph	Miles with average speed 27.5-32.5 mph
8	35 mph	Miles with average speed 32.5-37.5 mph
9	40 mph	Miles with average speed 37.5-42.5 mph
10	45 mph	Miles with average speed 42.5-47.5 mph
11	50 mph	Miles with average speed 47.5-52.5 mph
12	55 mph	Miles with average speed 52.5-57.5 mph
13	60 mph	Miles with average speed 57.5-62.5 mph
14	65 mph	Miles with average speed >62.5 mph

Table A.3.3 CO_2 Emission Models for 28 categories vehicle classes based on the multiplying factors

Number	Type of Vehicle	Multiplying Factor	EF MODEL FOR CARBON DIOXIDE (CO2)
1	LDGV	1	$EF = 94.416 + 3384.6 (1/V) + 0.0026 V^2$
2	LDGT1	1.297202	$EF = 122.476 + 4309.5 (1/V) + 0.0034 V^2$
3	LDGT2	1.297202	$EF = 122.476 + 4309.5 (1/V) + 0.0034 V^2$
4	LDGT3	1.693833	$EF = 159.924 + 5732.9 (1/V) + 0.0044 V^2$
5	LDGT4	1.693833	$EF = 159.924 + 5732.9 (1/V) + 0.0044 V^2$
6	HDGV2B	2.381961	$EF = 224.894 + 8062.0 (1/V) + 0.0062 V^2$
7	HDGV3	2.577289	$EF = 243.336 + 8723.1 (1/V) + 0.0067 V^2$
8	HDGV4	2.59386	$EF = 244.901 + 8779.2 (1/V) + 0.0067 V^2$
9	HDGV5	3.063026	$EF = 289.197 + 10367.1 (1/V) + 0.0080 V^2$
10	HDGV6	2.97881	$EF = 281.246 + 10082.1 (1/V) + 0.0077 V^2$
11	HDGV7	3.251019	$EF = 306.947 + 11003.4 (1/V) + 0.0085 V^2$
12	HDGV8A	3.435751	$EF = 324.389 + 11628.6 (1/V) + 0.0089 V^2$
13	HDGV8B	3.57593	$EF = 337.624 + 12103.1 (1/V) + 0.0093 V^2$
14	LDDV	0.852486	$EF = 80.488 + 2885.3 (1/V) + 0.0022 V^2$
15	LDDT12	1.134203	$EF = 107.086 + 3838.8 (1/V) + 0.0029 V^2$
16	HDDV2B	2.133659	$EF = 210.451 + 7221.6 (1/V) + 0.0055 V^2$
17	HDDV3	2.372996	$EF = 224.048 + 8031.6 (1/V) + 0.0062 V^2$
18	HDDV4	2.714208	$EF = 256.264 + 9186.5 (1/V) + 0.0071 V^2$
19	HDDV5	2.806031	$EF = 264.933 + 9497.3 (1/V) + 0.0073 V^2$
20	HDDV6	3.177126	$EF = 299.970 + 10753.3 (1/V) + 0.0083 V^2$
21	HDDV7	3.672372	$EF = 346.729 + 12429.5 (1/V) + 0.0095 V^2$
22	HDDV8A	4.211084	$EF = 397.592 + 14252.8 (1/V) + 0.0109 V^2$
23	HDDV8B	4.38984	$EF = 414.469 + 14857.9 (1/V) + 0.0114 V^2$
24	MC	0.481934	$EF = 45.502 + 1631.2 (1/V) + 0.0013 V^2$
25	HDGB	3.816898	$EF = 360.375 + 12918.7 (1/V) + 0.0099 V^2$
26	HDDBT	6.363217	$EF = 600.787 + 21536.9 (1/V) + 0.0165 V^2$
27	HDDBS	4.461559	$EF = 421.241 + 15100.6 (1/V) + 0.0116 V^2$
28	LDDT34	1.625917	$EF = 153.512 + 5503.1 (1/V) + 0.0042 V^2$

Input Files used in Mobile6.2 for estimating the emission rates for different pollutants from different classes of vehicles.

1. MOBILE6 INPUT FILE used to develop the models for three major pollutants.

```
******************  Header Section  ************************
POLLUTANTS         : HC CO NOx CO2
PARTICULATES       : SO2 NH3 SO4 OCARBON ECARBON GASPM LEAD BRAKE TIRE
DATABASE OUTPUT    :
WITH FIELDNAMES    :
AGGREGATED OUTPUT  :
*DAILY OUTPUT       :
******************  Run Section  ***************************
RUN DATA           :
EXPRESS HC AS VOC  :
EXPAND EXHAUST     :
EXPAND EVAPORATIVE :
EXPAND LDT EFS     :
EXPAND HDGV EFS    :
EXPAND HDDV EFS    :
EXPAND BUS EFS     :
NO REFUELING       :
REG DIST           : reg06_w.dfw
WE DA TRI LEN DI   : 10wdtrip.ubn
VMT BY FACILITY    : fvmt.wkd
VMT BY HOUR        : hvmt.wkd
*SPEED VMT         : svmt.wkd
DIESEL FRACTIONS   :
```

0.00090 0.00090 0.00090 0.00090 0.00090 0.00090
0.00090 0.00090 0.00090 0.00090 0.00090
0.00090 0.00090 0.00090 0.00090 0.00060
0.00010 0.00030 0.00060 0.00130 0.00040
0.00040 0.00010 0.00270 0.00320
0.00000 0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.00070 0.00330
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0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.00070 0.00330
0.01260 0.01260 0.01260 0.01260 0.01260 0.01260
0.01260 0.01260 0.01260 0.01260 0.01260
0.01260 0.01260 0.01260 0.01260 0.01150
0.01110 0.01450 0.01150 0.01290 0.00960
0.00830 0.00720 0.00820 0.01240
0.01260 0.01260 0.01260 0.01260 0.01260 0.01260
0.01260 0.01260 0.01260 0.01260 0.01260
0.01260 0.01260 0.01260 0.01260 0.01150
0.01110 0.01450 0.01150 0.01290 0.00960
0.00830 0.00720 0.00820 0.01240
0.52959 0.52959 0.52959 0.52959 0.52959 0.77336
0.79707 0.68191 0.63458 0.62026 0.40911
0.49719 0.27384 0.19922 0.31537 0.13368

    0.32604   0.33803   0.35556   0.31500   0.27027
    0.30128   0.14103   0.09091   0.16760
0.67727   0.67727   0.67727   0.67727   0.67727   0.66286
    0.72727   0.59271   0.61168   0.56316   0.63387
    0.60348   0.39936   0.47619   0.37801   0.33488
    0.55481   0.59649   0.68205   0.49242   0.63636
    0.42742   0.30000   0.11351   0.21053
0.90598   0.90598   0.90598   0.90598   0.90598   0.73942
    0.79333   0.69231   0.65000   0.68798   0.67422
    0.55927   0.72086   0.74952   0.64365   0.37952
    0.81176   0.59783   0.55714   0.84071   0.54464
    0.81132   0.12500   0.11842   0.03145
0.94426   0.94426   0.94426   0.94426   0.94426   0.91126
    0.90984   0.90833   0.84066   0.82520   0.92027
    0.90545   0.63291   0.76250   0.86413   0.49213
    0.56923   0.58108   0.75000   0.88608   0.63359
    0.60630   0.26761   0.18367   0.03676
0.84944   0.84944   0.84944   0.84944   0.84944   0.86853
    0.90909   0.89507   0.94527   0.89269   0.84012
    0.81828   0.80458   0.86931   0.82704   0.62500
    0.84838   0.78545   0.62617   0.66383   0.79902
    0.79769   0.64912   0.76119   0.62037
0.91111   0.91111   0.91111   0.91111   0.91111   0.96457
    0.96648   0.98246   0.92486   0.86134   0.91857
    0.93631   0.86400   0.78531   0.83410   0.49519
    0.89333   0.82308   0.89691   0.85047   0.77778
    0.93056   0.86792   0.82143   0.78571
0.97992   0.97992   0.97992   0.97992   0.97992   0.97328
    0.94472   0.89252   0.96629   0.94333   0.93506

```
      0.95297     0.96563     0.90514     0.94688     0.71493
      0.95860     0.94545     0.96682     0.91509     0.93778
      0.93909     0.93373     0.95313     0.93684
0.99140     0.99140     0.99140     0.99140     0.99140     0.99123
      0.98058     0.99346     0.97436     0.98897     0.99819
      0.98370     1.00000     0.96341     0.99248     0.83562
      1.00000     0.92593     1.00000     1.00000     0.92857
      1.00000     1.00000     1.00000     0.84615
0.95850     0.95850     0.95850     0.95850     0.95850     0.95850
      0.95850     0.95850     0.95850     0.95850     0.95850
      0.95850     0.95850     0.95850     0.95850     0.88570
      0.85250     0.87950     0.99000     0.91050     0.87600
      0.77100     0.75020     0.73450     0.67330
REBUILD EFFECTS    : 0.90
FUEL RVP           : 6.8
FUEL PROGRAM       : 4
                     150.0  149.0  129.0  120.0  120.0   90.0   30.0
30.0
                      30.0   30.0   30.0   30.0   30.0   30.0   30.0
30.0
                    1000.0 1000.0 1000.0 1000.0  303.0  303.0   87.0
87.0
                      80.0   80.0   80.0   80.0   80.0   80.0   80.0
80.0
OXYGENATED FUELS   : 1.000 0.000 0.021 0.000 1
I/M DESCRIPT FILE  : im10.ubn
ANTI-TAMP PROGRAM  : 86 86 08 22222 22222222 2 11 096. 22112222
*******************  Scenario Section 1 **********************
SCENARIO RECORD    : SCENARIO TITLE : SPEED 5mph
```

CALENDAR YEAR   : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED   : 5 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1 90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0 75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8 51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5 84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 8

******************* Scenario Section 2 *********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 10mph

CALENDAR YEAR   : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED   : 10 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1 90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0

75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 8

******************* Scenario Section 3 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 15mph

CALENDAR YEAR   : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED   : 15 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1

90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0

75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 8

******************* Scenario Section 4 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 20mph

CALENDAR YEAR   : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED   : 20 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1 90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0 75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8 51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5 84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 8

******************* Scenario Section 5 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 25mph

CALENDAR YEAR   : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED   : 25 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1 90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0

75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES : 29.4

SUNRISE/SUNSET : 7 8

******************* Scenario Section 6 **********************

SCENARIO RECORD : SCENARIO TITLE : SPEED 30mph

CALENDAR YEAR : 2010

EVALUATION MONTH : 7

AVERAGE SPEED : 30 Freeway

DIESEL SULFUR : 15.0

PARTICLE SIZE : 2.5

PARTICULATE EF : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1

90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0

75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES : 29.4

SUNRISE/SUNSET : 7 8

******************* Scenario Section 7 **********************

SCENARIO RECORD : SCENARIO TITLE : SPEED 35mph

```
CALENDAR YEAR      : 2010
EVALUATION MONTH   : 7
AVERAGE SPEED      : 35 Freeway
DIESEL SULFUR      : 15.0
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
HOURLY TEMPERATURES: 78.9  81.5  83.9  85.9  87.8  89.3  89.8  90.1
90.0  89.5  88.0  85.9
                     83.3  81.8  80.7  79.7  78.6  77.6  76.8  76.0
75.4  74.7  74.4  76.2
RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8
51.3  51.8  54.1  57.7
                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5
84.7  86.6  88.0  85.0
BAROMETRIC PRES    : 29.4
SUNRISE/SUNSET     : 7 8
*******************  Scenario Section 8 **********************
SCENARIO RECORD    : SCENARIO TITLE : SPEED 40mph
CALENDAR YEAR      : 2010
EVALUATION MONTH   : 7
AVERAGE SPEED      : 40 Freeway
DIESEL SULFUR      : 15.0
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
HOURLY TEMPERATURES: 78.9  81.5  83.9  85.9  87.8  89.3  89.8  90.1
90.0  89.5  88.0  85.9
```

```
                     83.3  81.8  80.7  79.7  78.6  77.6  76.8  76.0
75.4  74.7  74.4  76.2
RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8
51.3  51.8  54.1  57.7
                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5
84.7  86.6  88.0  85.0
BAROMETRIC PRES    : 29.4
SUNRISE/SUNSET     : 7 8
*******************  Scenario Section 9 **********************
SCENARIO RECORD    : SCENARIO TITLE : SPEED 45mph
CALENDAR YEAR      : 2010
EVALUATION MONTH   : 7
AVERAGE SPEED      : 45 Freeway
DIESEL SULFUR      : 15.0
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
HOURLY TEMPERATURES: 78.9  81.5  83.9  85.9  87.8  89.3  89.8  90.1
90.0  89.5  88.0  85.9
                     83.3  81.8  80.7  79.7  78.6  77.6  76.8  76.0
75.4  74.7  74.4  76.2
RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8
51.3  51.8  54.1  57.7
                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5
84.7  86.6  88.0  85.0
BAROMETRIC PRES    : 29.4
SUNRISE/SUNSET     : 7 8
*******************  Scenario Section 10 **********************
SCENARIO RECORD    : SCENARIO TITLE : SPEED 50mph
```

CALENDAR YEAR   : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED   : 50 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1

90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0

75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 8

******************* Scenario Section 11 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 55mph

CALENDAR YEAR   : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED   : 55 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1

90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0

75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 8

******************* Scenario Section 12 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 60mph

CALENDAR YEAR   : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED   : 60 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9 81.5 83.9 85.9 87.8 89.3 89.8 90.1

90.0 89.5 88.0 85.9

83.3 81.8 80.7 79.7 78.6 77.6 76.8 76.0

75.4 74.7 74.4 76.2

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 8

******************* Scenario Section 13 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 65mph

```
CALENDAR YEAR      : 2010

EVALUATION MONTH   : 7

AVERAGE SPEED      : 65 Freeway

DIESEL SULFUR      : 15.0

PARTICLE SIZE      : 2.5

PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 78.9  81.5  83.9  85.9  87.8  89.3  89.8  90.1

90.0  89.5  88.0  85.9

                     83.3  81.8  80.7  79.7  78.6  77.6  76.8  76.0

75.4  74.7  74.4  76.2

RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8

51.3  51.8  54.1  57.7

                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5

84.7  86.6  88.0  85.0

BAROMETRIC PRES    : 29.4

SUNRISE/SUNSET     : 7 8

*******************  End of Run  ****************************

END OF RUN
```

2.   MOBILE6 INPUT FILE used to study the affect of different driving modes on emission rates.

```
*******************  Header Section  ************************

POLLUTANTS         : HC CO NOx CO2

PARTICULATES       : SO2 NH3 SO4 OCARBON ECARBON GASPM LEAD BRAKE TIRE

DATABASE OUTPUT    :

DATABASE OPTIONS   : Dbase.d

*******************  Run Section  ***************************
```

```
RUN DATA           :
EXPRESS HC AS VOC  :
EXPAND EXHAUST     :
NO REFUELING       :
REG DIST           : reg06_w.dfw
WE DA TRI LEN DI   : 07wdtrip.ubn
VMT BY FACILITY    : 07fvmt.wkd
VMT BY HOUR        : 07hvmt_wkd
*SPEED VMT         : 07svmt.wkd
DIESEL FRACTIONS   :
0.00000     0.00000     0.00000     0.00000     0.00000     0.00000
      0.00000     0.00000     0.00000     0.00000     0.00000
      0.00000     0.00000     0.00000     0.00000     0.00000
      0.00000     0.00000     0.00000     0.00000     0.00000
      0.00000     0.00000     0.00000     0.00000
0.00000     0.00000     0.00000     0.00000     0.00000     0.00000
      0.00000     0.00000     0.00000     0.00000 0.00000   0.00000
      0.00000     0.00000     0.00000     0.00000     0.00000
      0.00000     0.00000     0.00000 0.00070   0.00330     0.00480
      0.01200     0.02230
0.00000     0.00000     0.00000     0.00000     0.00000     0.00000
      0.00000     0.00000     0.00000     0.00000 0.00000   0.00000
      0.00000     0.00000     0.00000     0.00000     0.00000
      0.00000     0.00000     0.00000 0.00070   0.00330     0.00480
      0.01200     0.02230
0.01260     0.01260     0.01260     0.01260     0.01260     0.01260
      0.01260     0.01260     0.01260     0.01260 0.01260   0.01260
      0.01150     0.01110     0.01450     0.01150     0.01290
```

0.00960 0.00830 0.00720 0.00820 0.01240 0.01350
0.01690 0.02090

0.01260 0.01260 0.01260 0.01260 0.01260 0.01260
0.01260 0.01260 0.01260 0.01260 0.01260 0.01260
0.01150 0.01110 0.01450 0.01150 0.01290
0.00960 0.00830 0.00720 0.00820 0.01240 0.01350
0.01690 0.02090

0.52959 0.52959 0.77336 0.79707 0.68191 0.63458
0.62026 0.40911 0.49719 0.27384 0.19922 0.31537
0.13368 0.32604 0.33803 0.35556 0.31500
0.27027 0.30128 0.14103 0.09091 0.16760 0.10656
0.19549 0.18750

0.67727 0.67727 0.66286 0.72727 0.59271 0.61168
0.56316 0.63387 0.60348 0.39936 0.47619 0.37801
0.33488 0.55481 0.59649 0.68205 0.49242
0.63636 0.42742 0.30000 0.11351 0.21053 0.03521
0.09302 0.21429

0.90598 0.90598 0.73942 0.79333 0.69231 0.65000
0.68798 0.67422 0.55927 0.72086 0.74952 0.64365
0.37952 0.81176 0.59783 0.55714 0.84071
0.54464 0.81132 0.12500 0.11842 0.03145 0.02857
0.25000 0.00000

0.94426 0.94426 0.91126 0.90984 0.90833 0.84066
0.82520 0.92027 0.90545 0.63291 0.76250 0.86413
0.49213 0.56923 0.58108 0.75000 0.88608
0.63359 0.60630 0.26761 0.18367 0.03676 0.13084
0.08989 0.50000

0.84944 0.84944 0.86853 0.90909 0.89507 0.94527
0.89269 0.84012 0.81828 0.80458 0.86931 0.82704

```
      0.62500     0.84838     0.78545     0.62617     0.66383
      0.79902     0.79769     0.64912 0.76119   0.62037     0.46923
      0.49485     0.45902
0.91111     0.91111     0.96457     0.96648     0.98246     0.92486
      0.86134     0.91857     0.93631     0.86400 0.78531   0.83410
      0.49519     0.89333     0.82308     0.89691     0.85047
      0.77778     0.93056     0.86792 0.82143   0.78571     0.75510
      0.65625     0.77778
0.97992     0.97992     0.97328     0.94472     0.89252     0.96629
      0.94333     0.93506     0.95297     0.96563 0.90514   0.94688
      0.71493     0.95860     0.94545     0.96682     0.91509
      0.93778     0.93909     0.93373 0.95313   0.93684     0.92958
      0.94545     0.87805
0.99140     0.99140     0.99123     0.98058     0.99346     0.97436
      0.98897     0.99819     0.98370     1.00000 0.96341   0.99248
      0.83562     1.00000     0.92593     1.00000     1.00000
      0.92857     1.00000     1.00000 1.00000   0.84615     0.88889
      0.83333     0.00000
0.95850     0.95850     0.95850     0.95850     0.95850     0.95850
      0.95850     0.95850     0.95850     0.95850 0.95850   0.95850
      0.88570     0.85250     0.87950     0.99000     0.91050
      0.87600     0.77100     0.75020 0.73450   0.67330     0.51550
      0.38450     0.32380
REBUILD EFFECTS    : 0.90
FUEL RVP           : 12.13
FUEL PROGRAM       : 4
                     300.0 299.0 279.0 259.0 121.0 30.0 33.0 33.0 30.0
30.0 30.0 30.0 30.0 30.0 30.0 30.0
```

1000.0 1000.0 1000.0 1000.0 303.0 303.0 87.0 87.0 80.0 80.0 80.0 80.0

80.0 80.0 80.0 80.0

OXYGENATED FUELS : 1.000 0.000 0.017 0.000 1

I/M DESCRIPT FILE : im10.ubn

ANTI-TAMP PROG :

86 84 05 22222 22222222 2 11 096. 22112222

******************* Scenario Section 1 *********************

SCENARIO RECORD : SCENARIO TITLE : SPEED 5mph

CALENDAR YEAR : 2007

EVALUATION MONTH : 1

AVERAGE SPEED : 5 Freeway

DIESEL SULFUR : 15.0

PARTICLE SIZE : 2.5

PARTICULATE EF : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

HOURLY TEMPERATURES: 45.6 46.5 48.9 51.3 53.5 55.6 57.5 59.0

59.8 60.0 59.4 57.5

55.5 54.0 53.2 52.3 51.2 50.5 49.1 48.7

47.9 47.6 47.0 46.1

RELATIVE HUMIDITY : 81.2 79.7 73.9 66.1 61.5 57.8 54.5 52.1

50.5 50.5 52.3 55.4

60.5 64.9 66.4 68.1 70.2 72.0 75.3 76.5

77.8 77.4 78.4 80.4

BAROMETRIC PRES : 29.5

SUNRISE/SUNSET : 7 8

******************* Scenario Section 2 *********************

SCENARIO RECORD : SCENARIO TITLE : SPEED 10mph

CALENDAR YEAR : 2007

EVALUATION MONTH : 1

```
AVERAGE SPEED      : 10 Freeway

DIESEL SULFUR      : 15.0

PARTICLE SIZE      : 2.5

PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8

51.3  51.8  54.1  57.7

                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5

84.7  86.6  88.0  85.0

BAROMETRIC PRES    : 29.4

SUNRISE/SUNSET     : 7 6

*******************  Scenario Section 3 *********************

SCENARIO RECORD    : SCENARIO TITLE : SPEED 15mph

CALENDAR YEAR      : 2007

EVALUATION MONTH   : 1

AVERAGE SPEED      : 15 Freeway

DIESEL SULFUR      : 15.0

PARTICLE SIZE      : 2.5

PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8

51.3  51.8  54.1  57.7

                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5

84.7  86.6  88.0  85.0

BAROMETRIC PRES    : 29.4

SUNRISE/SUNSET     : 7 6

*******************  Scenario Section 4 *********************
```

```
SCENARIO RECORD    : SCENARIO TITLE : SPEED 20mph
CALENDAR YEAR      : 2007
EVALUATION MONTH   : 1
AVERAGE SPEED      : 20 Freeway
DIESEL SULFUR      : 15.0
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
MIN/MAX TEMPERATURE: 75. 89.
RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8
51.3  51.8  54.1  57.7
                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5
84.7  86.6  88.0  85.0
BAROMETRIC PRES    : 29.4
SUNRISE/SUNSET     : 7 6
*******************  Scenario Section 5 **********************
SCENARIO RECORD    : SCENARIO TITLE : SPEED 25mph
CALENDAR YEAR      : 2007
EVALUATION MONTH   : 1
AVERAGE SPEED      : 25 Freeway
DIESEL SULFUR      : 15.0
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
MIN/MAX TEMPERATURE: 75. 89.
RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8
51.3  51.8  54.1  57.7
                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5
84.7  86.6  88.0  85.0
```

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 6

******************* Scenario Section 6 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 30mph

CALENDAR YEAR   : 2007

EVALUATION MONTH   : 1

AVERAGE SPEED   : 30 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 6

******************* Scenario Section 7 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 35mph

CALENDAR YEAR   : 2007

EVALUATION MONTH   : 1

AVERAGE SPEED   : 35 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 6

******************* Scenario Section 8 *********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 40mph

CALENDAR YEAR   : 2007

EVALUATION MONTH   : 1

AVERAGE SPEED   : 40 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 6

******************* Scenario Section 9 *********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 45mph

CALENDAR YEAR   : 2007

EVALUATION MONTH   : 1

AVERAGE SPEED   : 45 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 6

******************* Scenario Section 10 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 50mph

CALENDAR YEAR   : 2007

EVALUATION MONTH   : 1

AVERAGE SPEED   : 50 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 6

******************* Scenario Section 11 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 55mph

CALENDAR YEAR   : 2007

EVALUATION MONTH   : 1

AVERAGE SPEED   : 55 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 6

******************* Scenario Section 12 **********************

SCENARIO RECORD   : SCENARIO TITLE : SPEED 60mph

CALENDAR YEAR   : 2007

EVALUATION MONTH   : 1

AVERAGE SPEED   : 60 Freeway

DIESEL SULFUR   : 15.0

PARTICLE SIZE   : 2.5

PARTICULATE EF   : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY : 79.3 72.5 66.5 61.9 57.5 54.4 52.6 51.8

51.3 51.8 54.1 57.7

63.5 67.7 70.1 71.7 74.8 78.0 80.1 82.5

84.7 86.6 88.0 85.0

BAROMETRIC PRES   : 29.4

SUNRISE/SUNSET   : 7 6

******************* Scenario Section 13 **********************

```
SCENARIO RECORD     : SCENARIO TITLE : SPEED 65mph

CALENDAR YEAR       : 2007

EVALUATION MONTH    : 1

AVERAGE SPEED       : 65 Freeway

DIESEL SULFUR       : 15.0

PARTICLE SIZE       : 2.5

PARTICULATE EF      : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV

PMDDR1.CSV PMDDR2.CSV

MIN/MAX TEMPERATURE: 75. 89.

RELATIVE HUMIDITY  : 79.3  72.5  66.5  61.9  57.5  54.4  52.6  51.8

51.3  51.8  54.1  57.7

                     63.5  67.7  70.1  71.7  74.8  78.0  80.1  82.5

84.7  86.6  88.0  85.0

BAROMETRIC PRES     : 29.4

SUNRISE/SUNSET      : 7 6

*******************  End of Run  ****************************

END OF RUN
```

APPENDIX B

GRAPHICAL ANALYSIS OF DIFFERENT VEHICLE CLASSES FOR DIFFERENT POLLUTANTS

Emission Trends: Graphical presentation of emission rates with respect to speed for different pollutants for different classes of vehicles.

1. Light-Duty Gasoline Vehicles (LDGV)

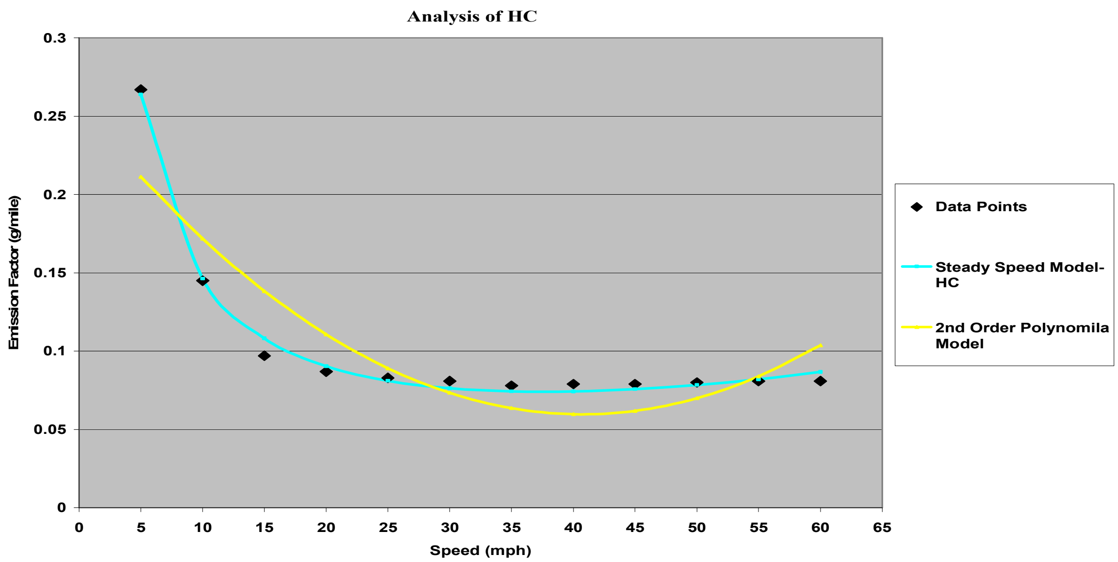

Figure B.1 Emission Trend of HC for Different Freeway Speeds

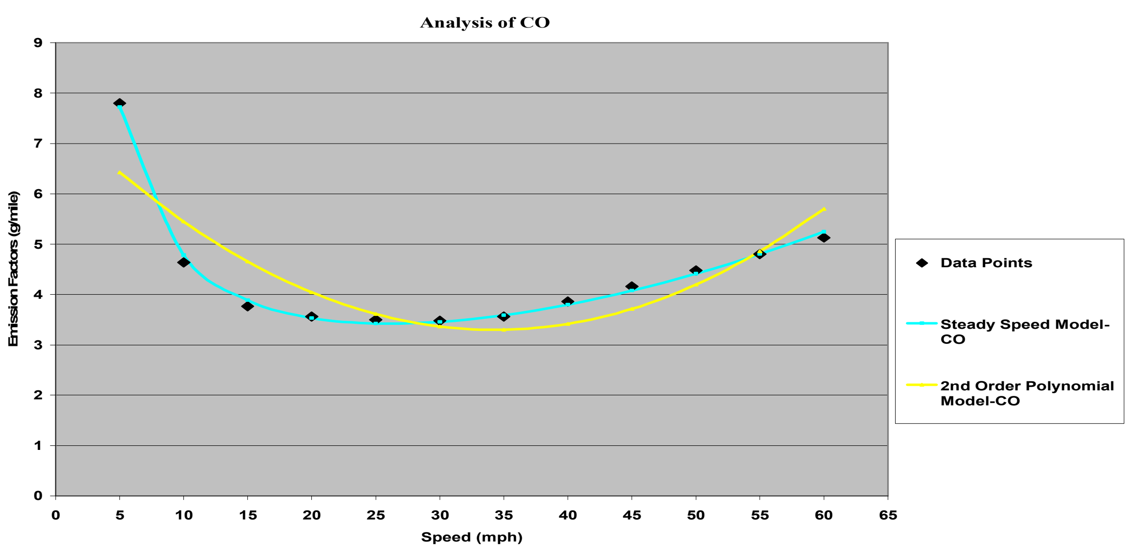

Figure B.2 Emission Trend of CO for Different Freeway Speeds

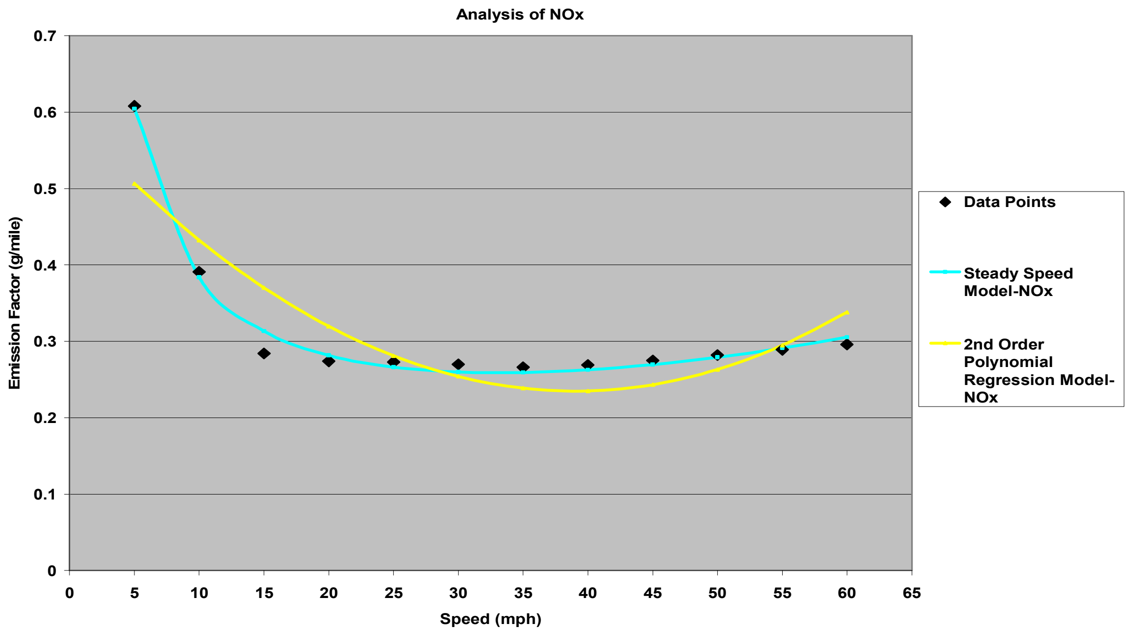

Figure B.3 Emission Trend of NO_x for Different Freeway Speeds

2. Light-Duty Gasoline Trucks 1 (LDGT1)

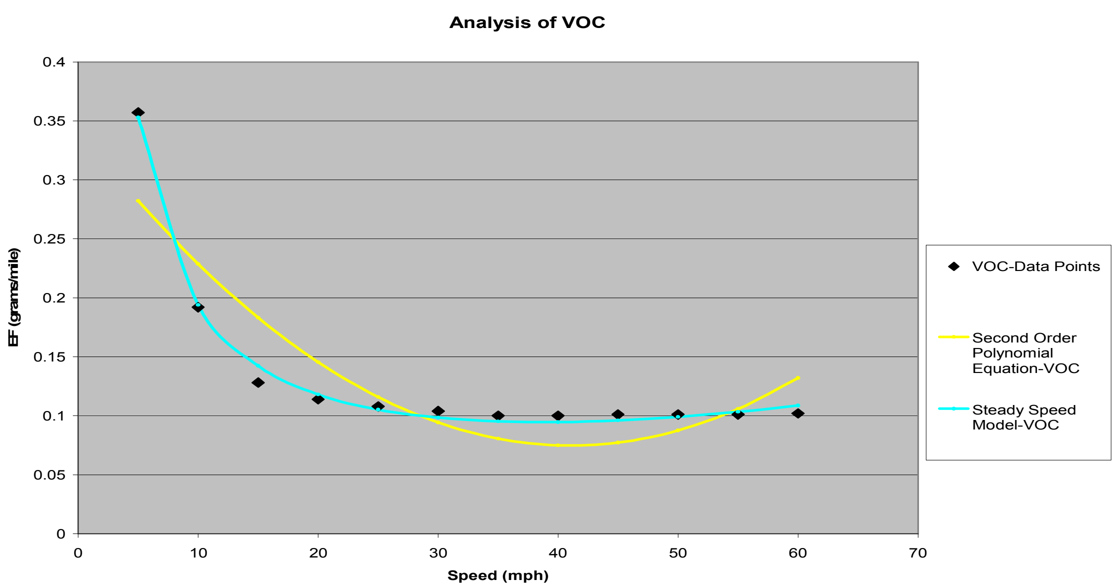

Figure B.4 Emission Trend of HC for Different Freeway Speeds

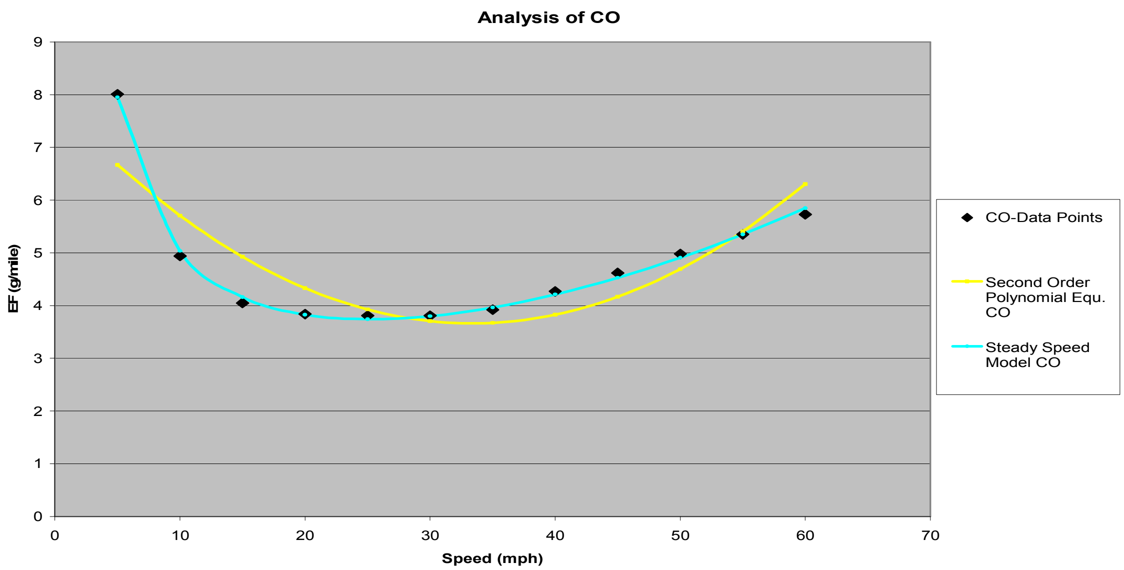

Figure B.5 Emission Trend of CO for Different Freeway Speeds

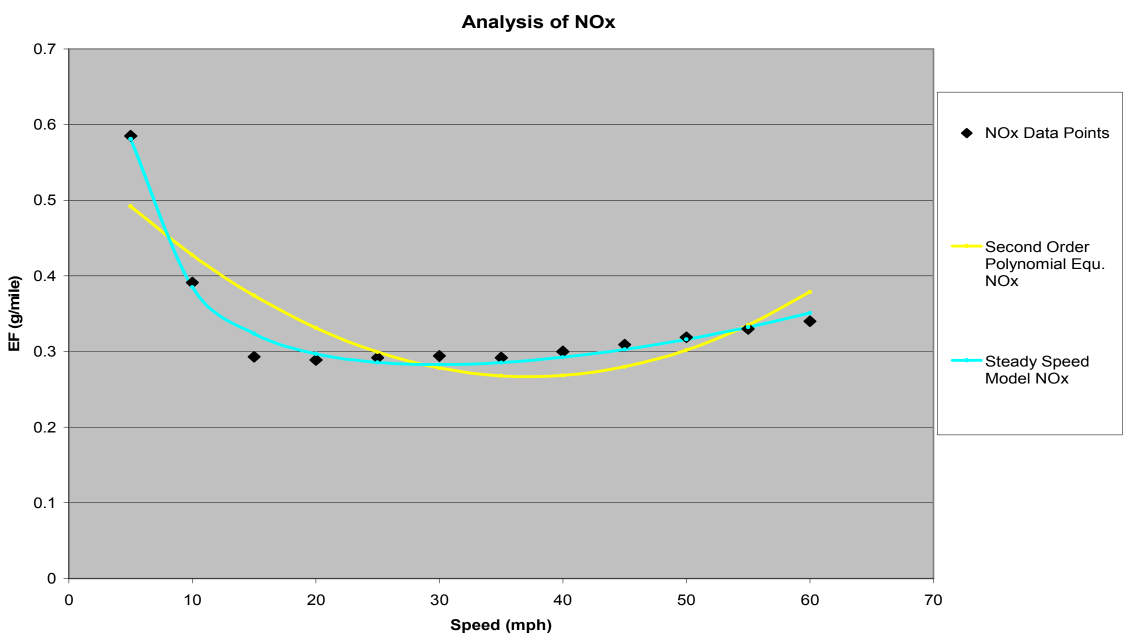

Figure B.6 Emission Trend of NO_x for Different Freeway Speeds

3. Light Duty Gasoline Trucks 2 (LDGT 2)

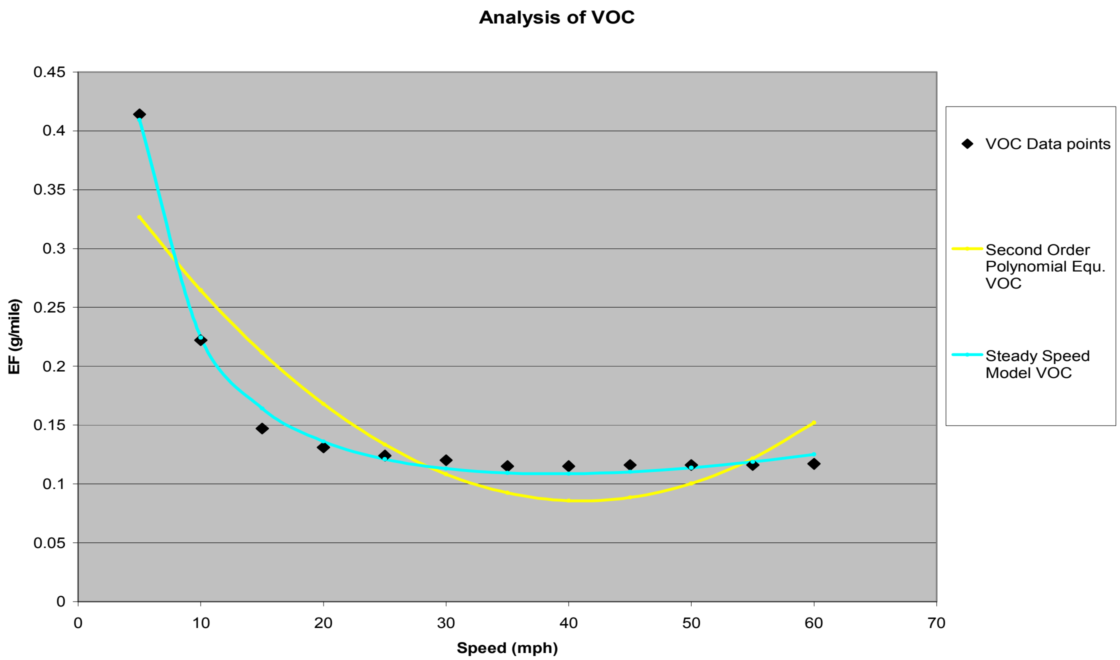

Figure B.7 Emission Trend of HC for Different Freeway Speeds

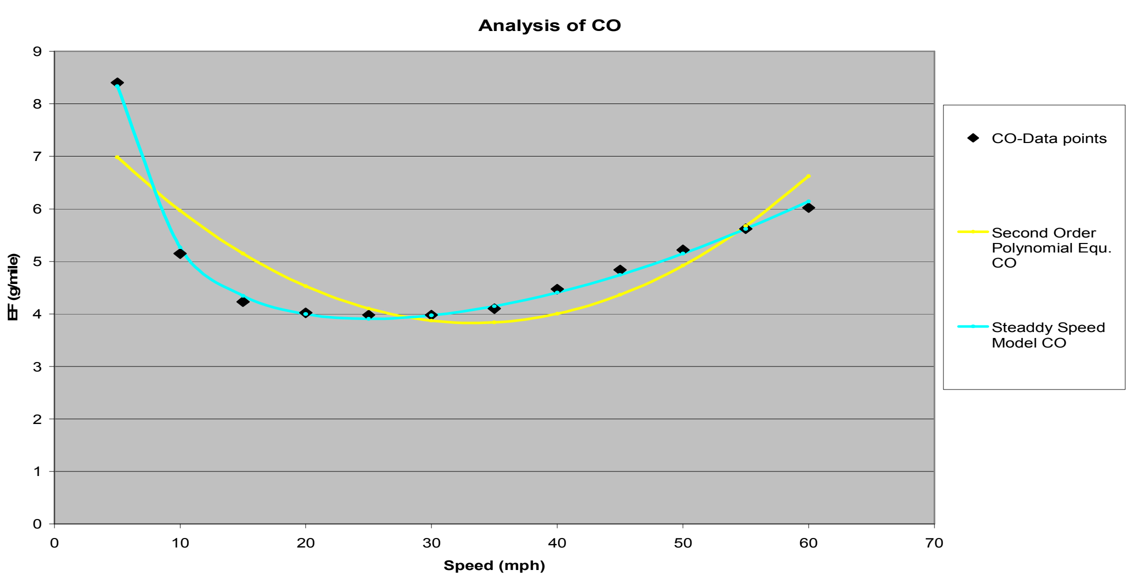

Figure B.8 Emission Trend of CO for Different Freeway Speeds

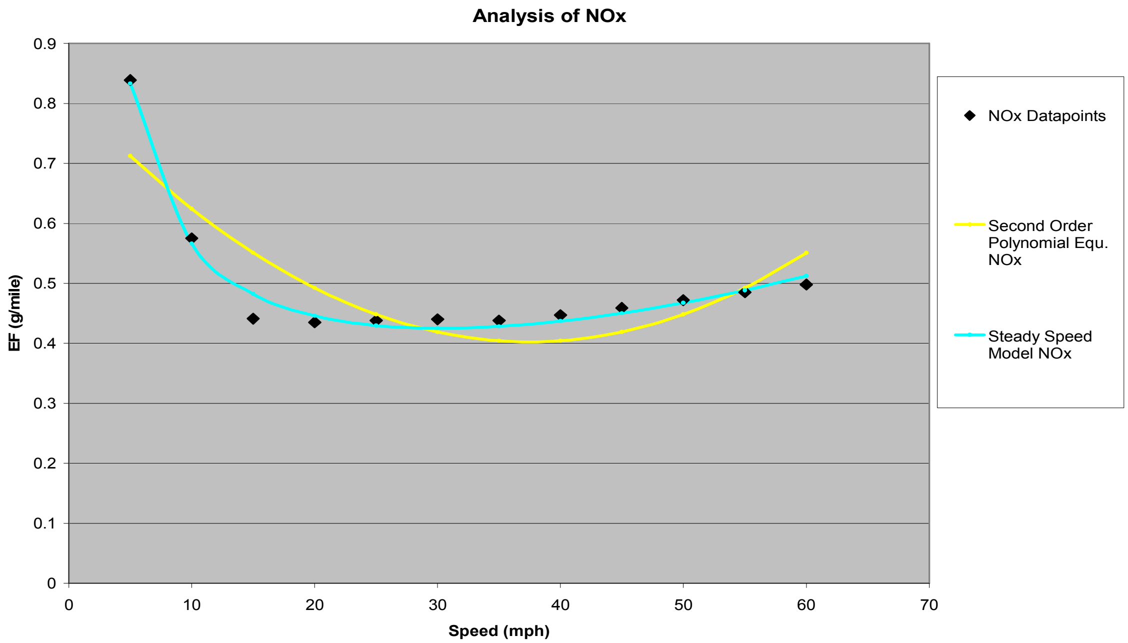

Figure B.9 Emission Trend of NO_x for Different Freeway Speeds

4. Light Duty Gasoline Trucks 3 (LDGT 3)

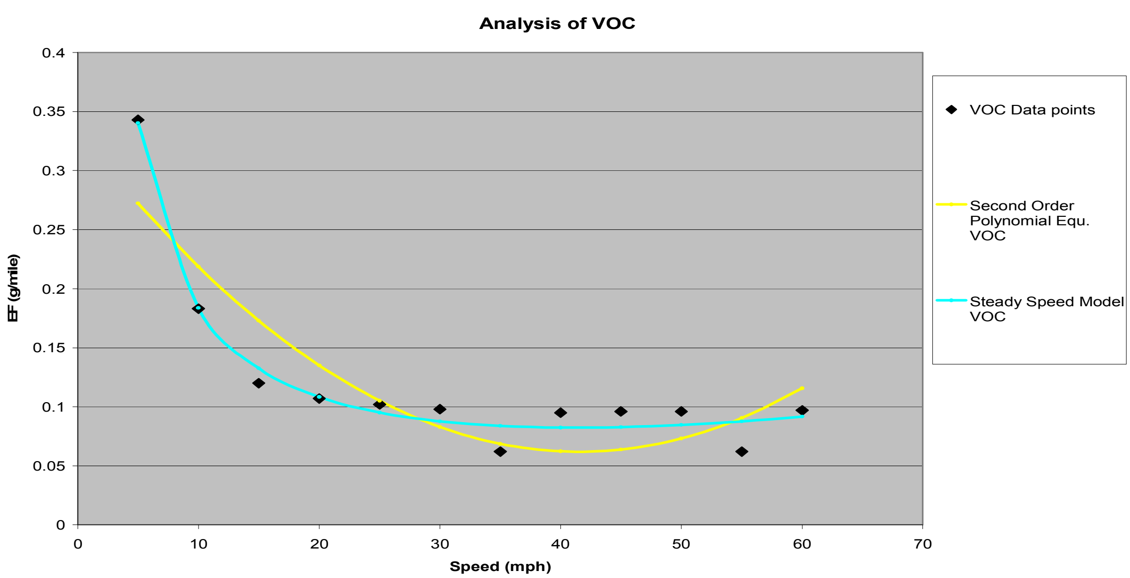

Figure B.10 Emission Trend of HC for Different Freeway Speeds

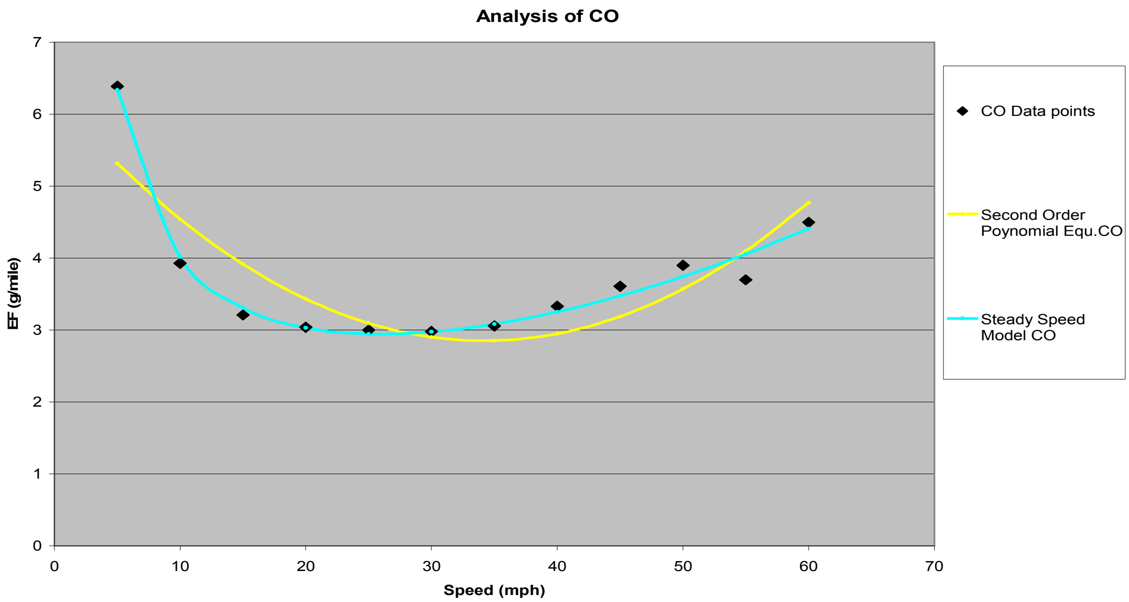

Figure B.11Emission Trend of CO for Different Freeway Speeds

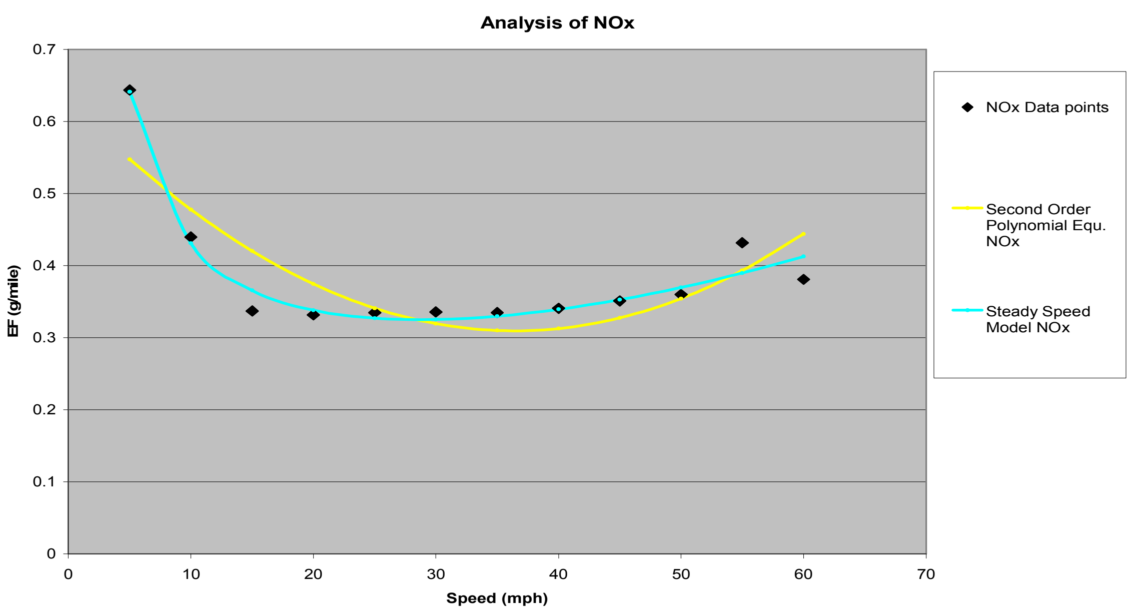

Figure B.12 Emission Trend of NO_x for Different Freeway Speeds

5. Light Duty Gasoline Trucks 4 (LDGT 4)

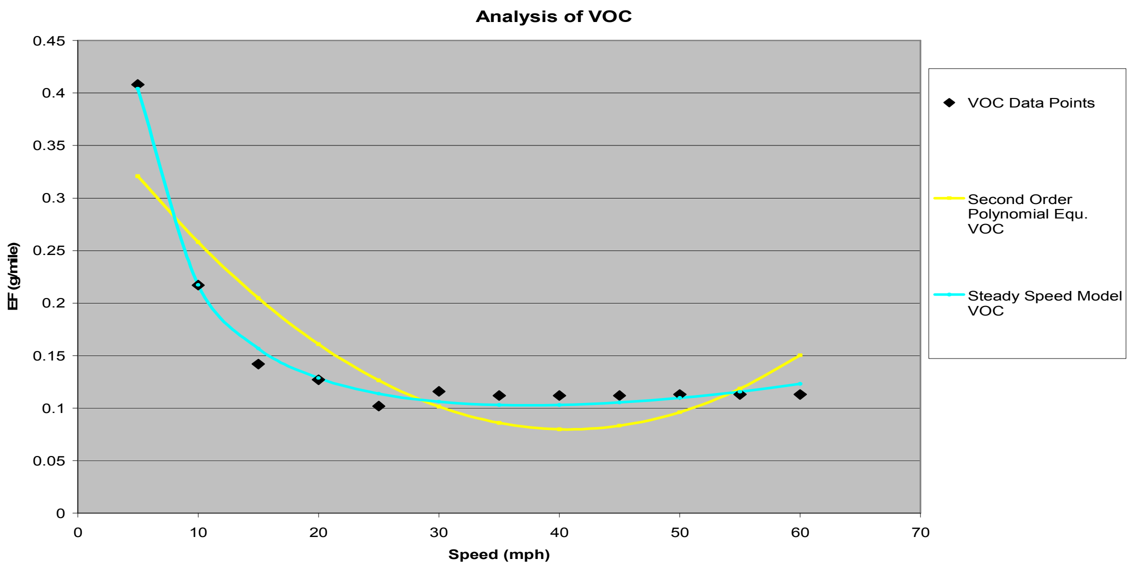

Figure B.13 Emission Trend of HC for Different Freeway Speeds

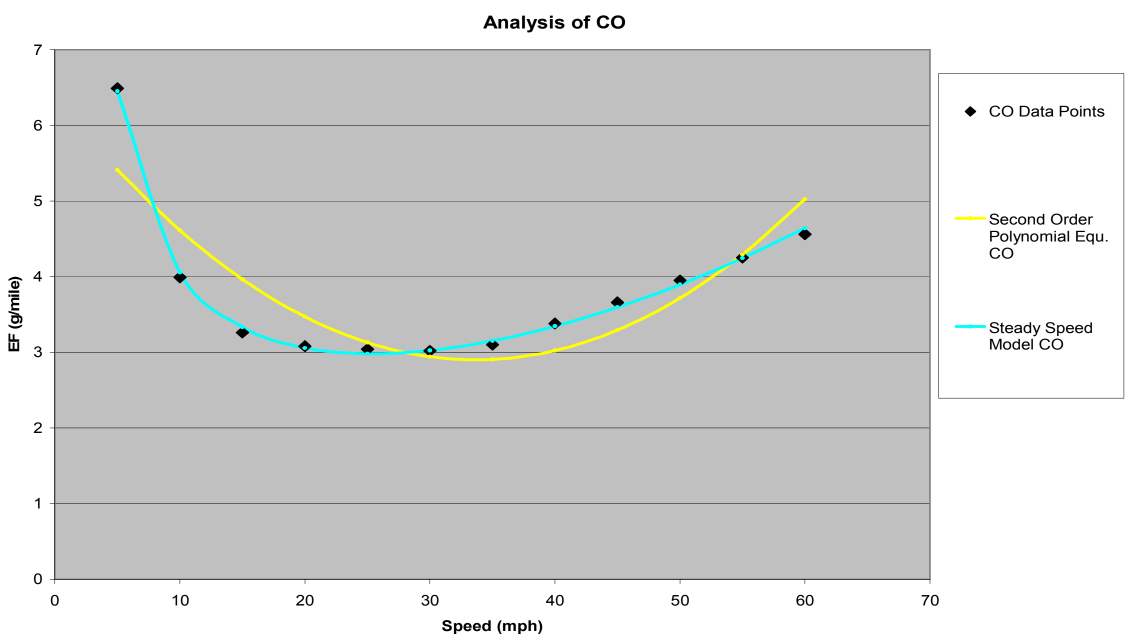

Figure B.14 Emission Trend of CO for Different Freeway Speeds

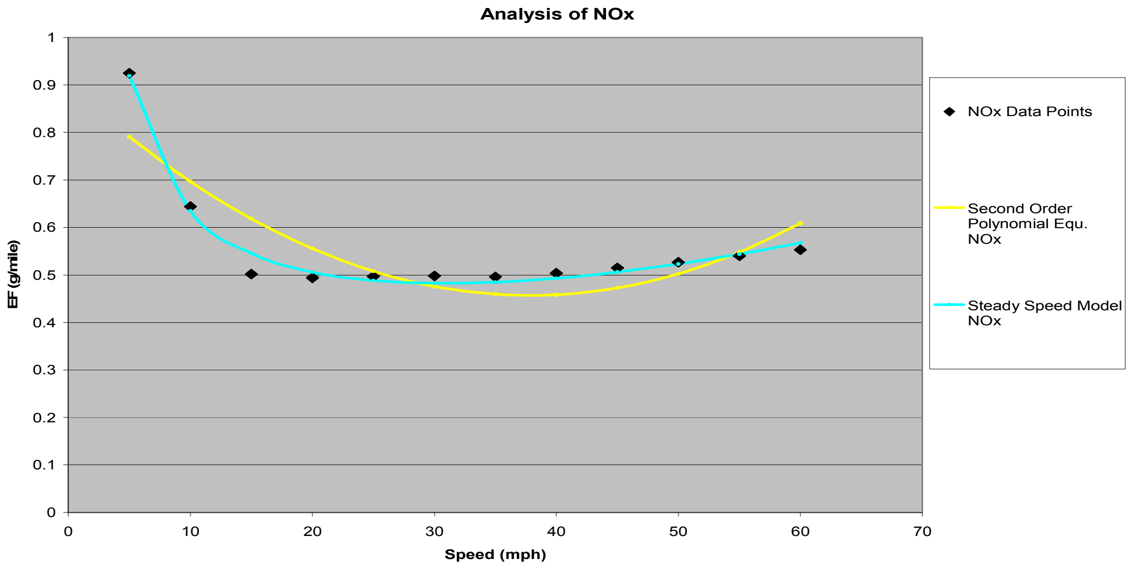

Figure B.15 Emission Trend of NO_x for Different Freeway Speeds

6. Class 2b Heavy Duty Gasoline Vehicles (HDGV2B)

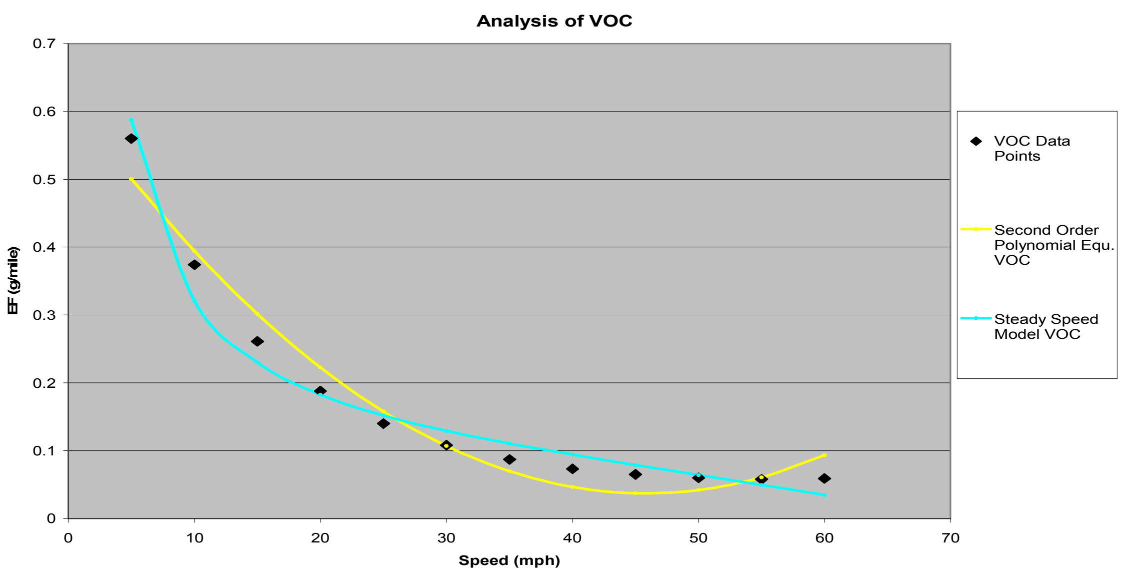

Figure B.16 Emission Trend of HC for Different Freeway Speeds

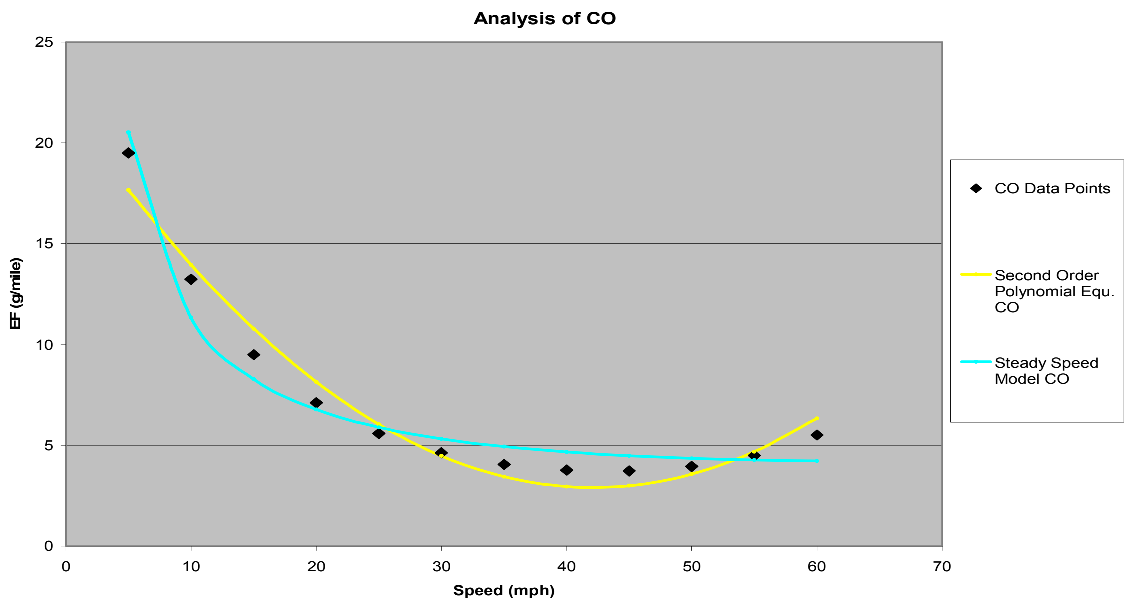

Figure B.17 Emission Trend of CO for Different Freeway Speeds

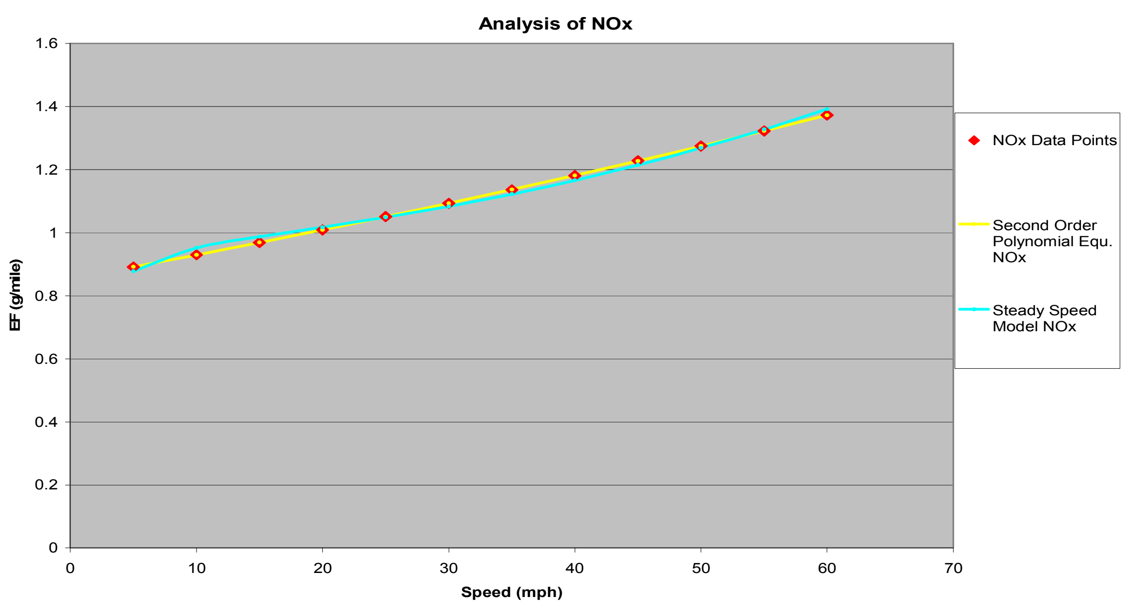

Figure B.18 Emission Trend of NO_x for Different Freeway Speeds

7. Class 3 Heavy Duty Gasoline Vehicles (HDGV 3)

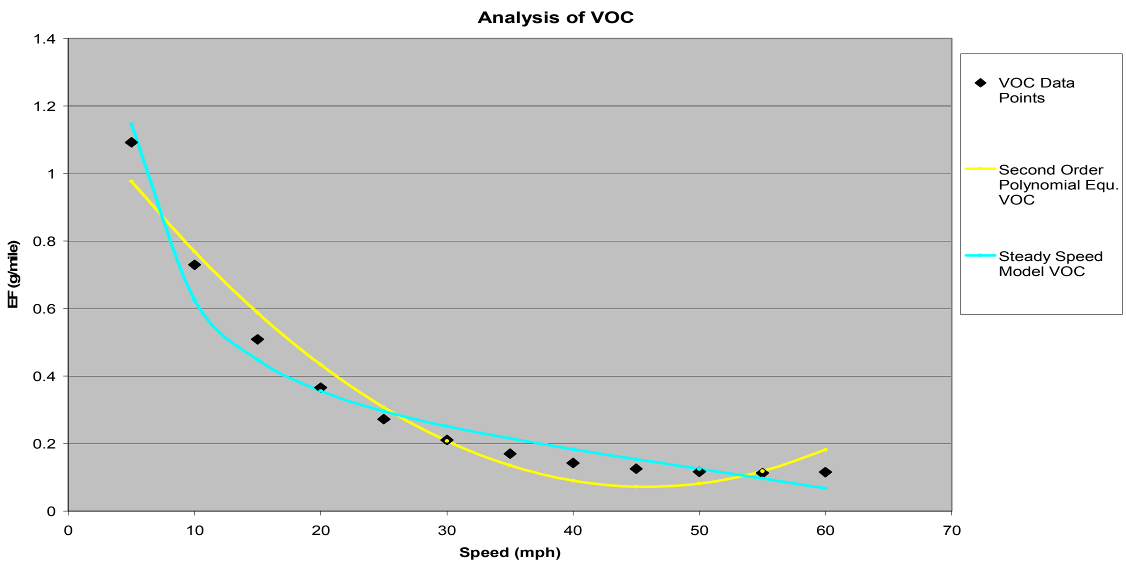

Figure B.19 Emission Trend of HC for Different Freeway Speeds

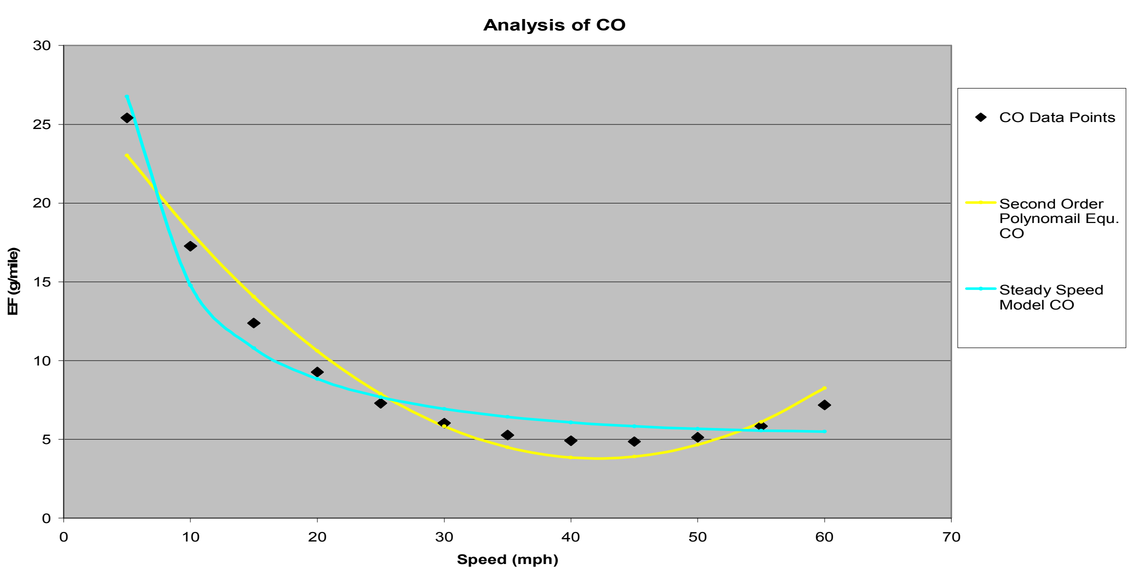

Figure B.20 Emission Trend of CO for Different Freeway Speeds

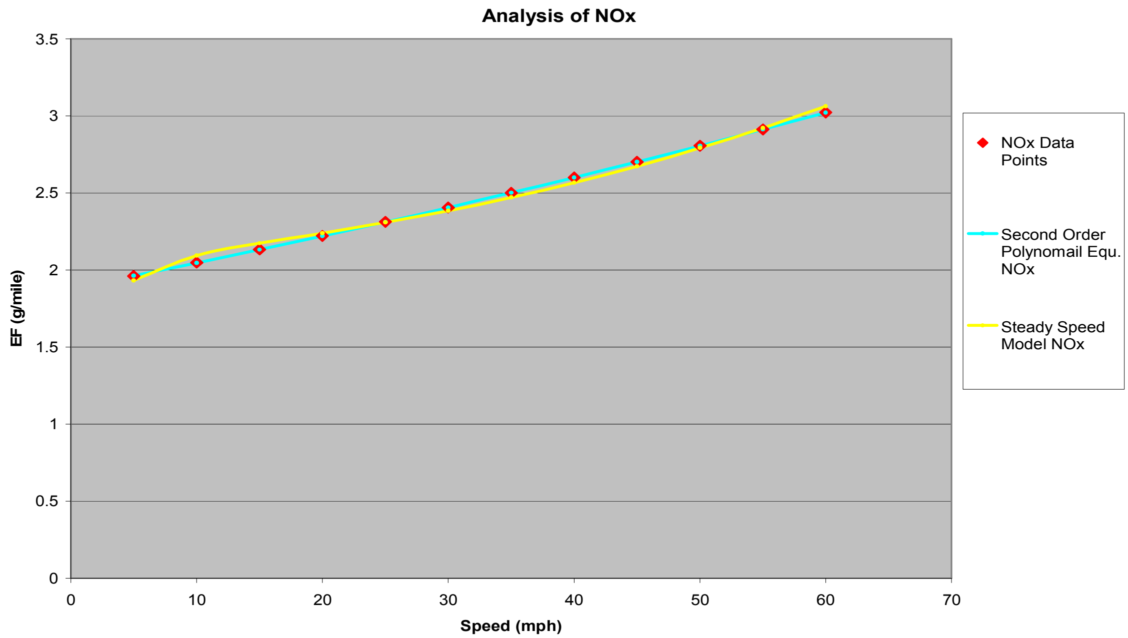

Figure B.21 Emission Trend of NO_x for Different Freeway Speeds

8. Class 4 Heavy Duty Gasoline Vehicles (HDGV 4)

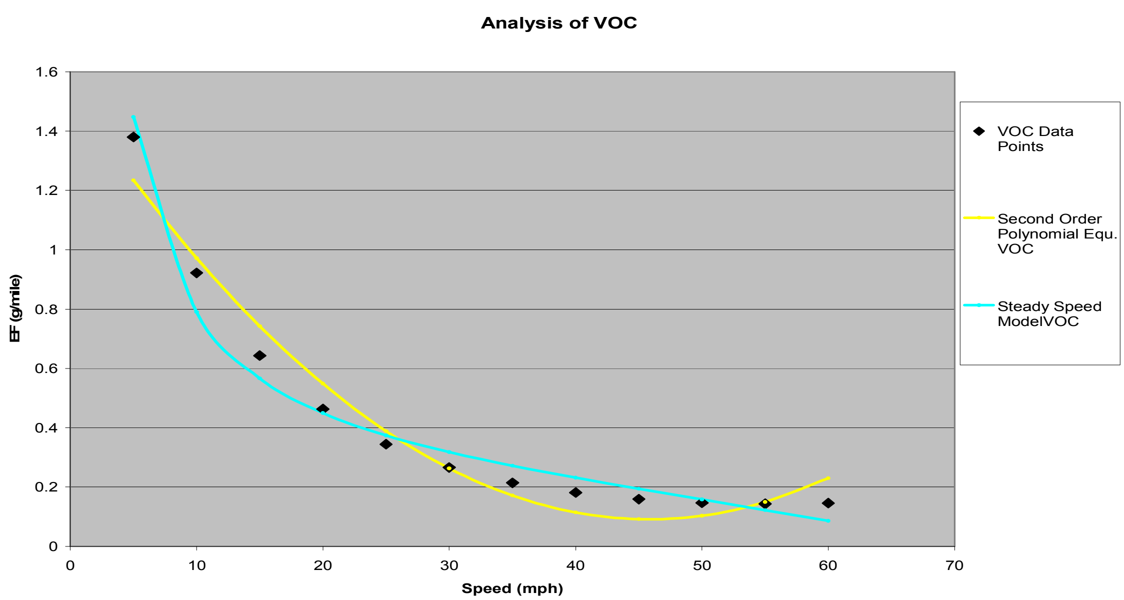

Figure B.22 Emission Trend of HC for Different Freeway Speeds

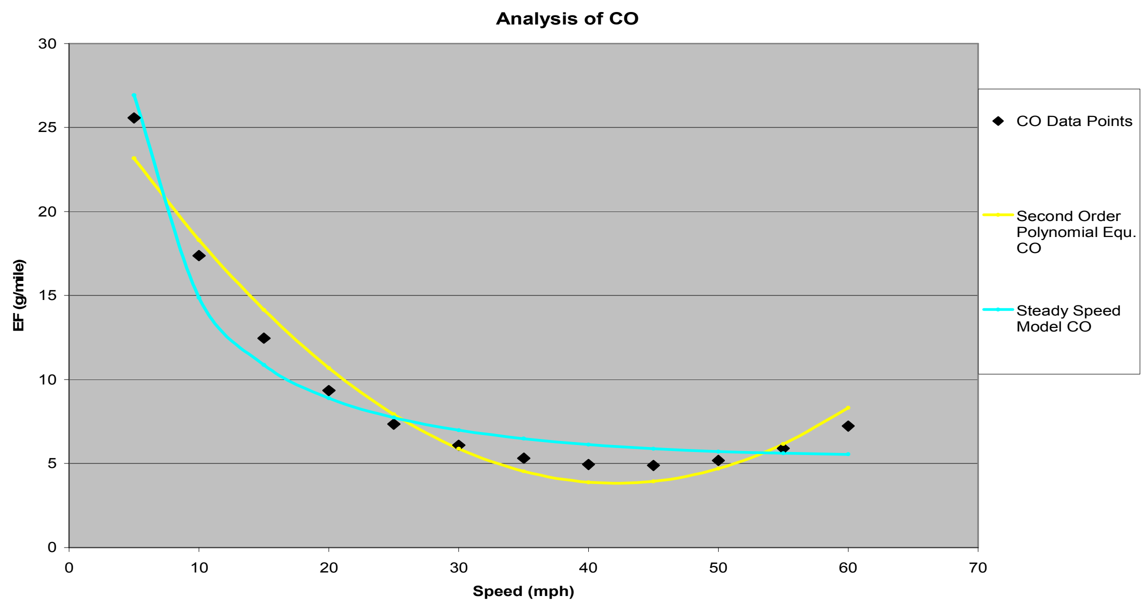

Figure B.23 Emission Trend of CO for Different Freeway Speeds

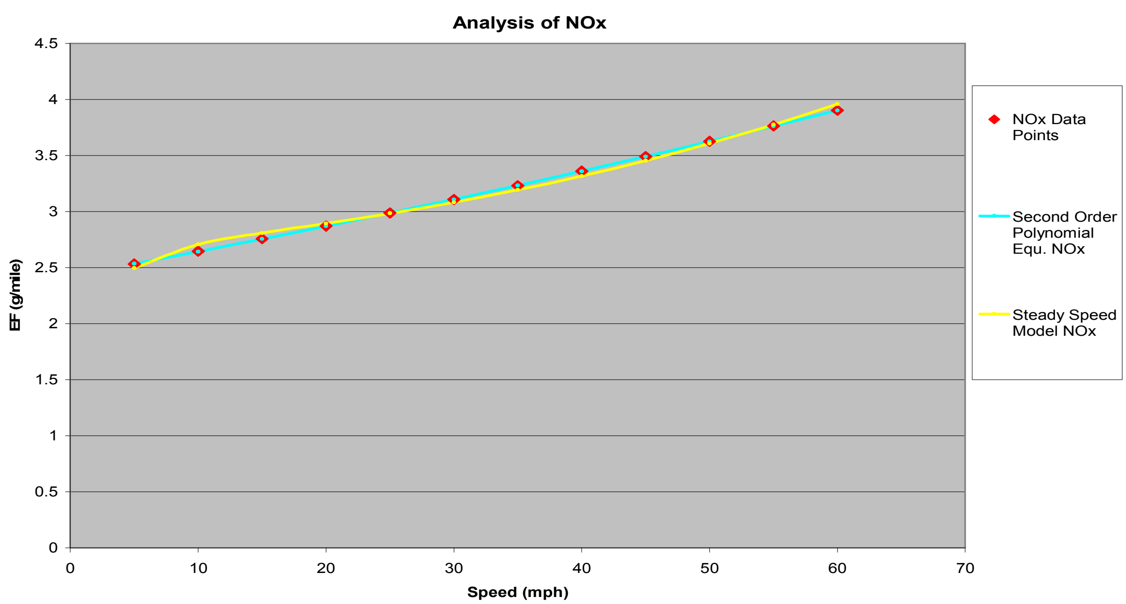

Figure B.24 Emission Trend of NO_x for Different Freeway Speeds

9. Class 5 Heavy Duty Gasoline Vehicles (HDGV 5)

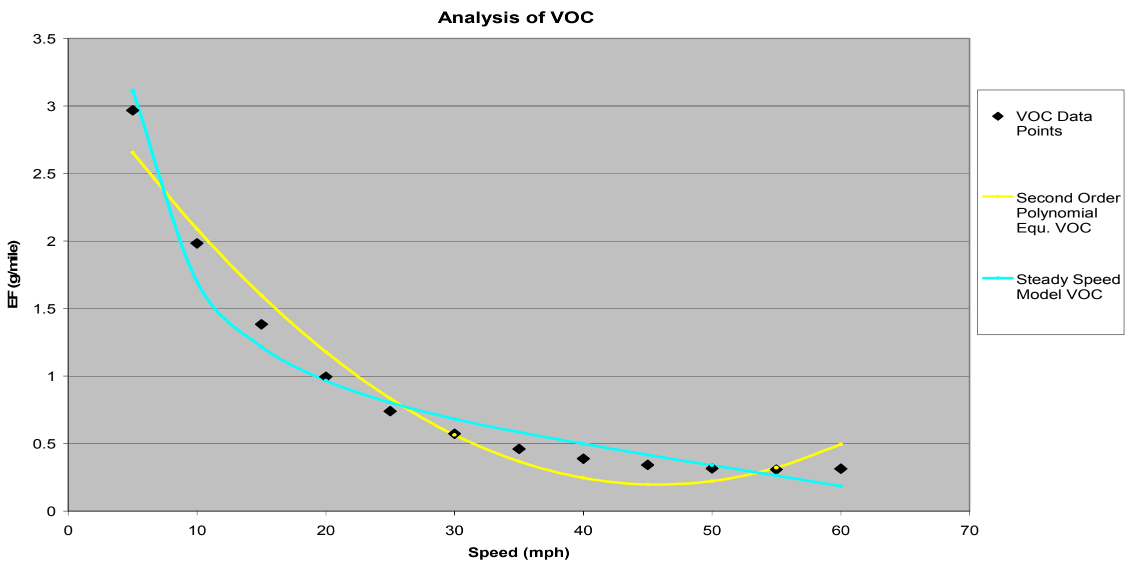

Figure B.25 Emission Trend of HC for Different Freeway Speeds

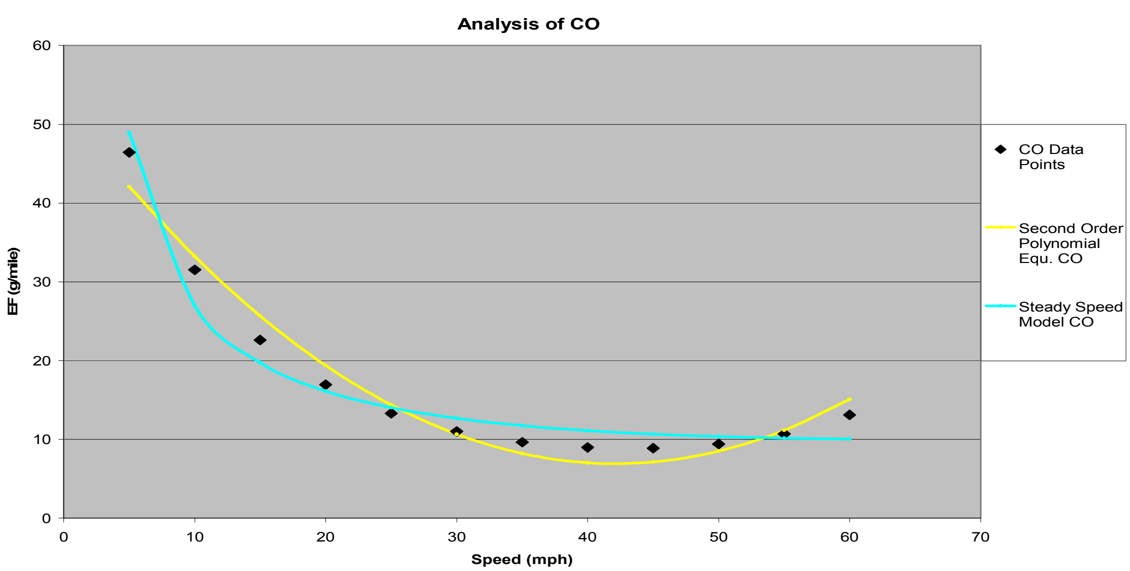

Figure B.26 Emission Trend of CO for Different Freeway Speeds

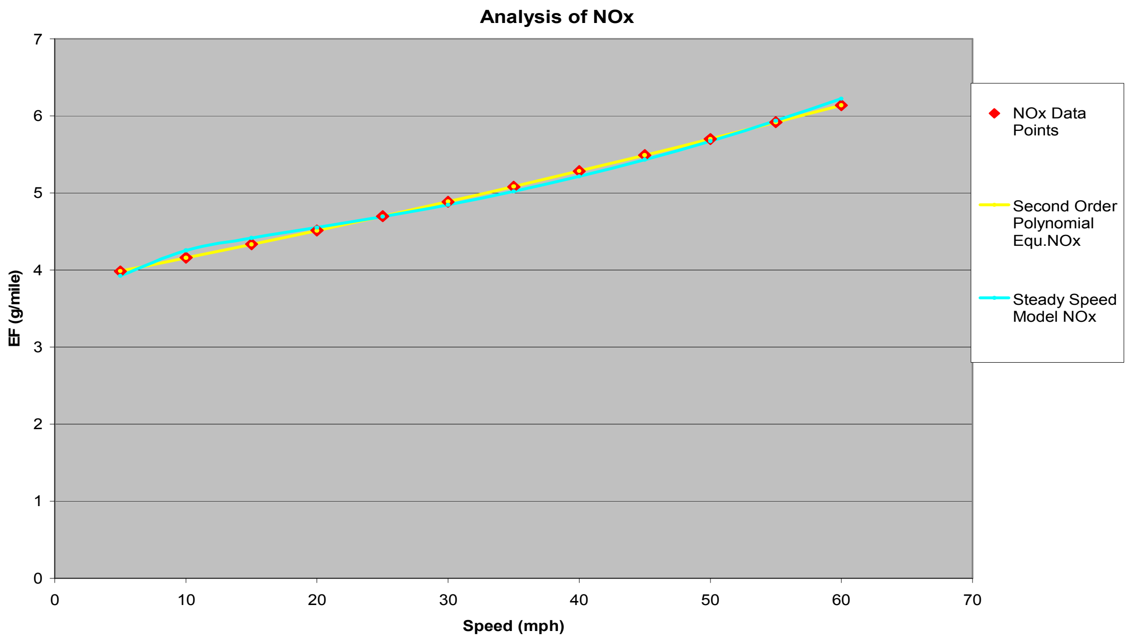

Figure B.27 Emission Trend of NO_x for Different Freeway Speeds

10. Class 6 Heavy Duty Gasoline Vehicles (HDGV 6)

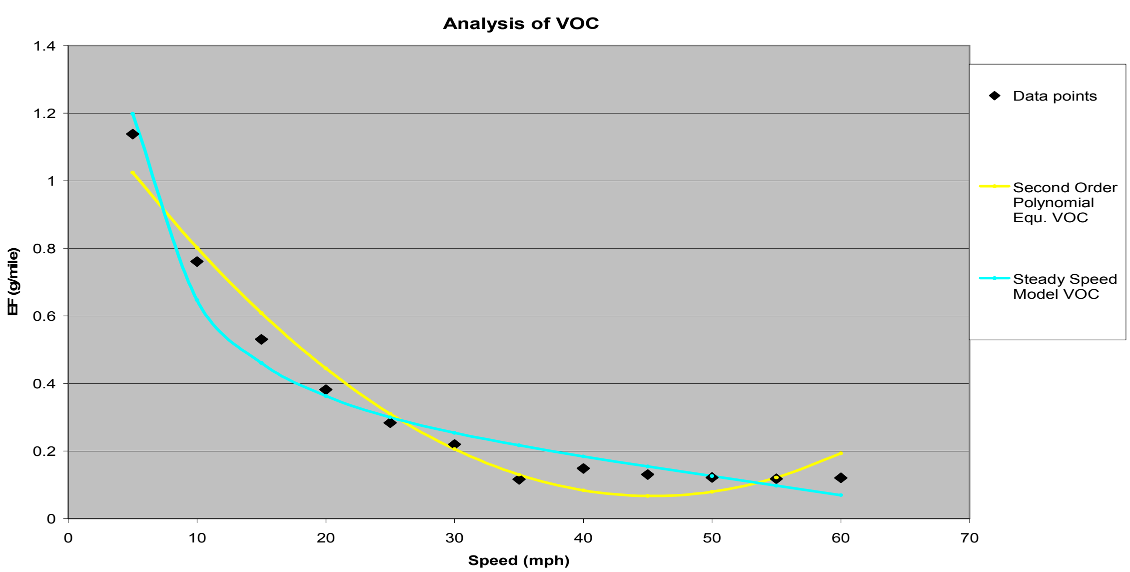

Figure B.28 Emission Trend of HC for Different Freeway Speeds

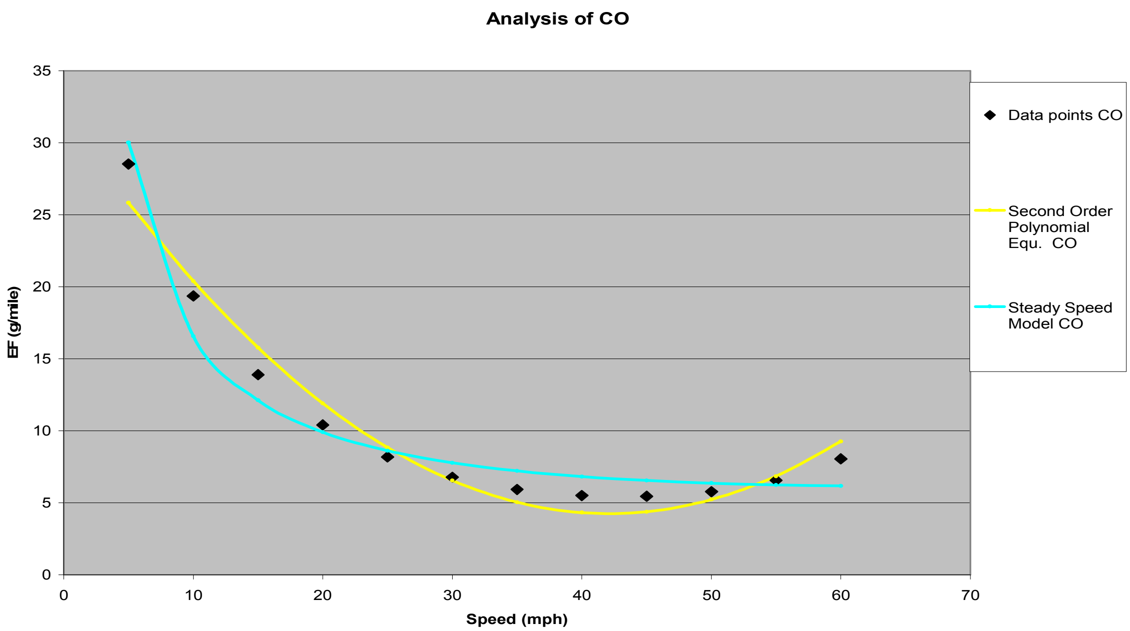

Figure B.29 Emission Trend of CO for Different Freeway Speeds

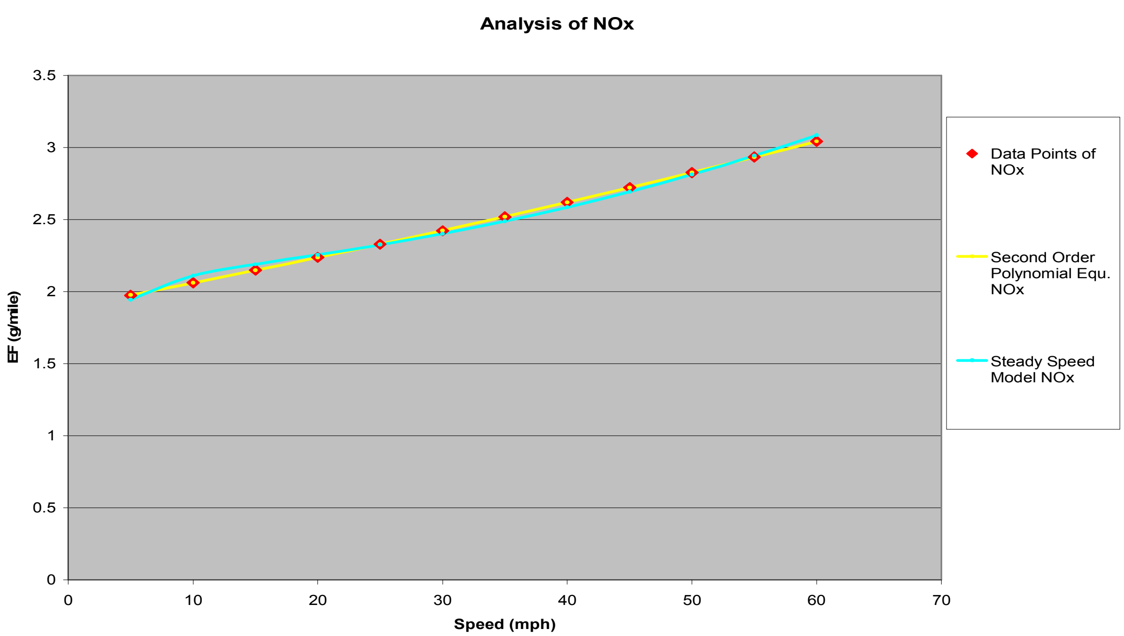

Figure B.30 Emission Trend of NO_x for Different Freeway Speeds

11. Class 7 Heavy Duty Gasoline Vehicles (HDGV 7)

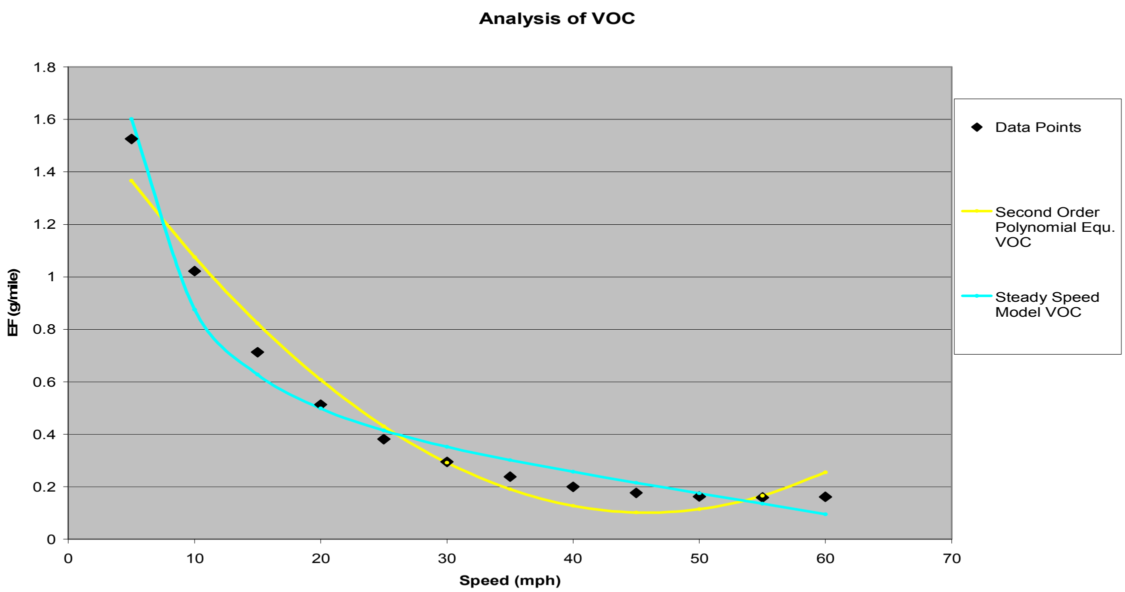

Figure B.31 Emission Trend of HC for Different Freeway Speeds

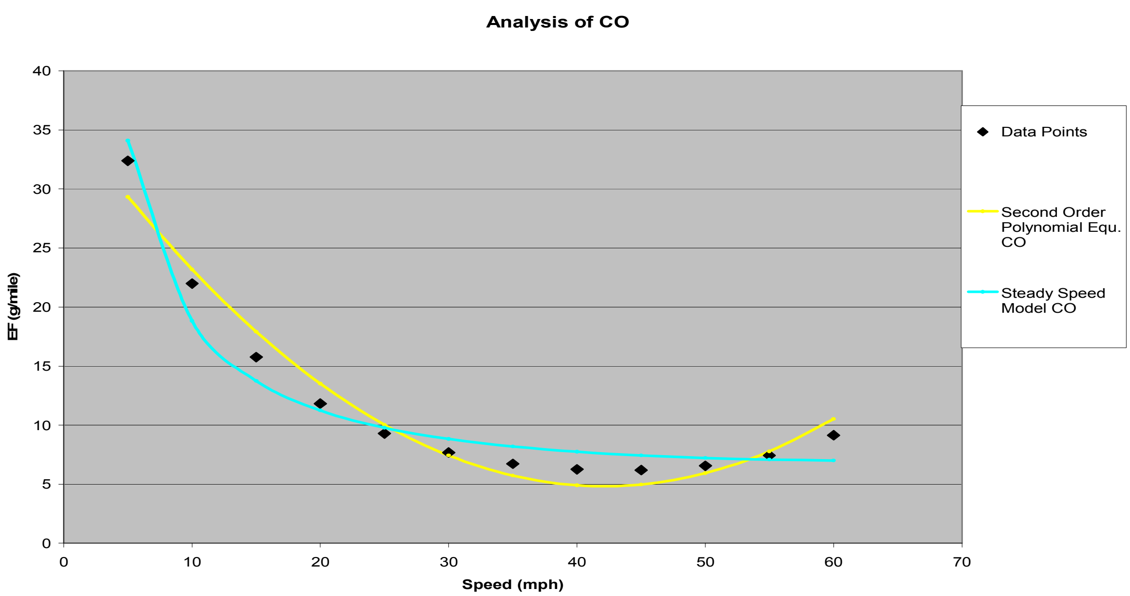

Figure B.32 Emission Trend of CO for Different Freeway Speeds

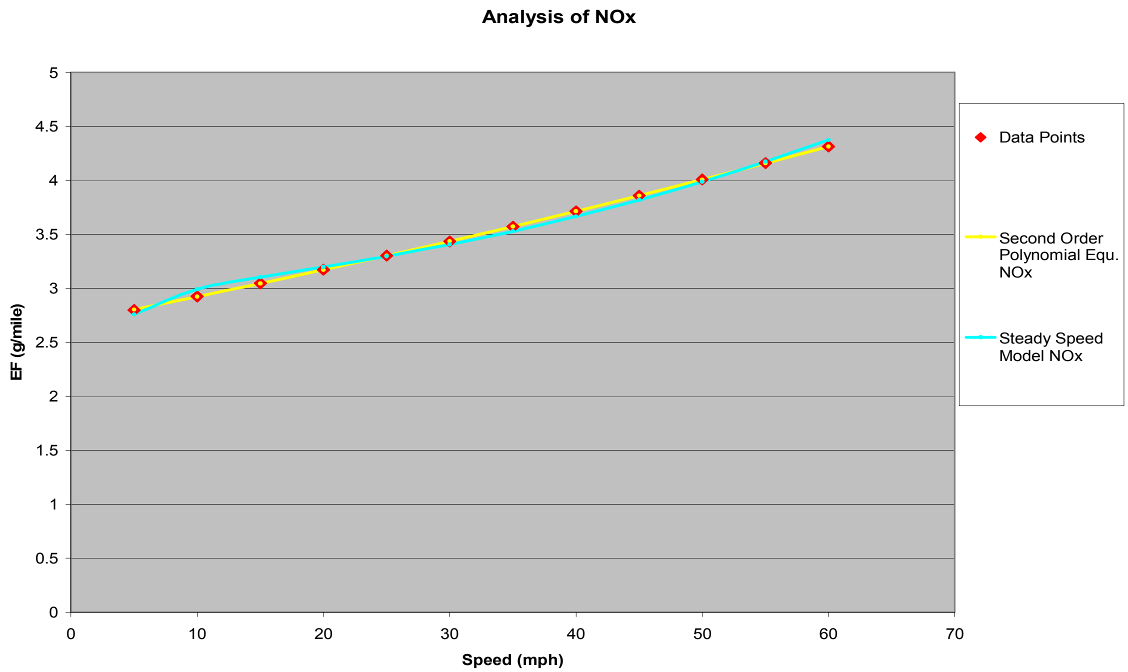

Figure B.33 Emission Trend of NO_x for Different Freeway Speeds

12. Class 8a Heavy Duty Gasoline Vehicles (HDGV 8A)

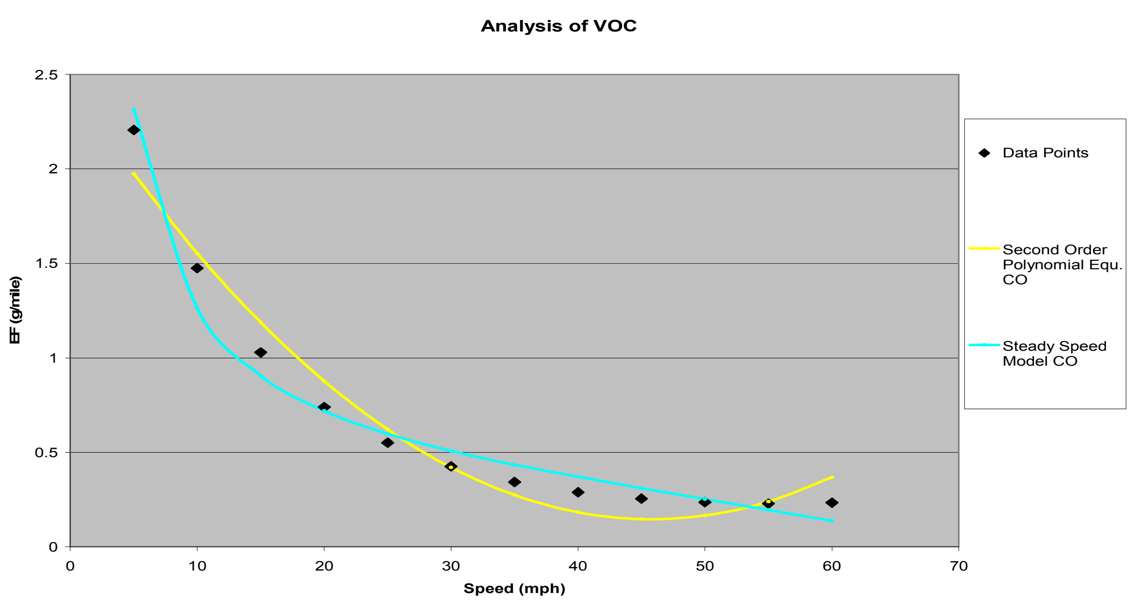

Figure B.34 Emission Trend of HC for Different Freeway Speeds

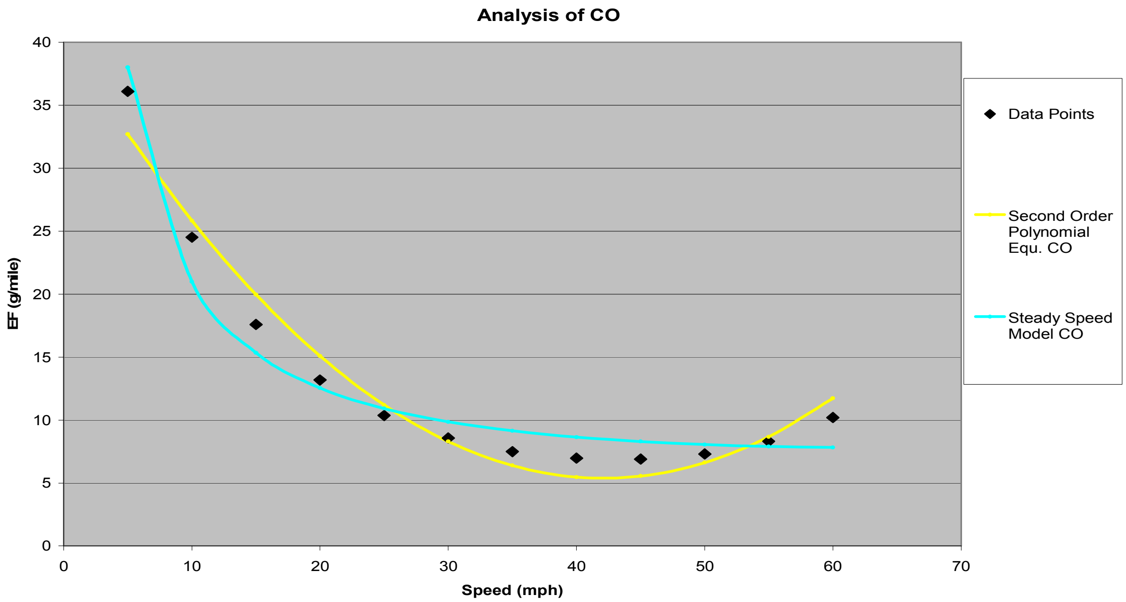

Figure B.35 Emission Trend of CO for Different Freeway Speeds

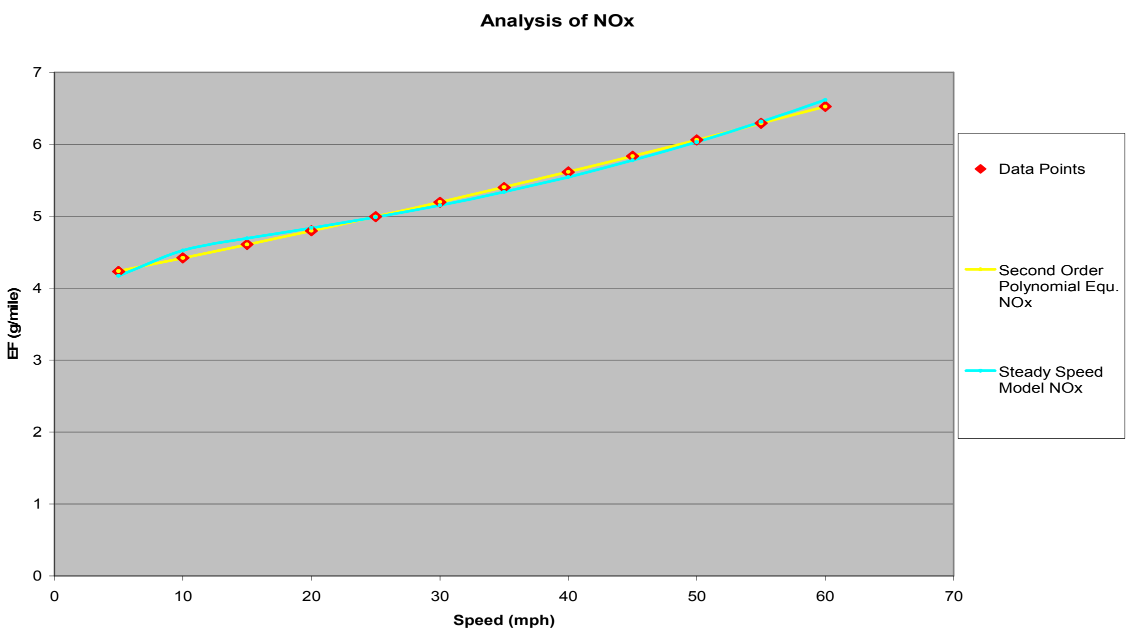

Figure B.36 Emission Trend of NO_x for Different Freeway Speeds

13. Class 8B Heavy Duty Gasoline Vehicles (HDGV 8B)

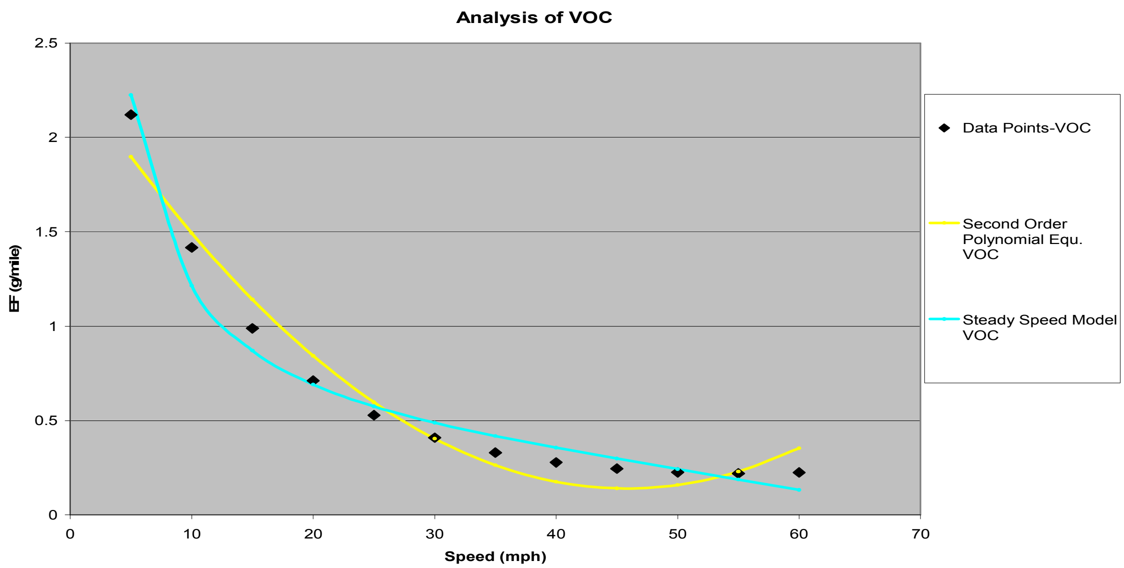

Figure B.37 Emission Trend of HC for Different Freeway Speeds

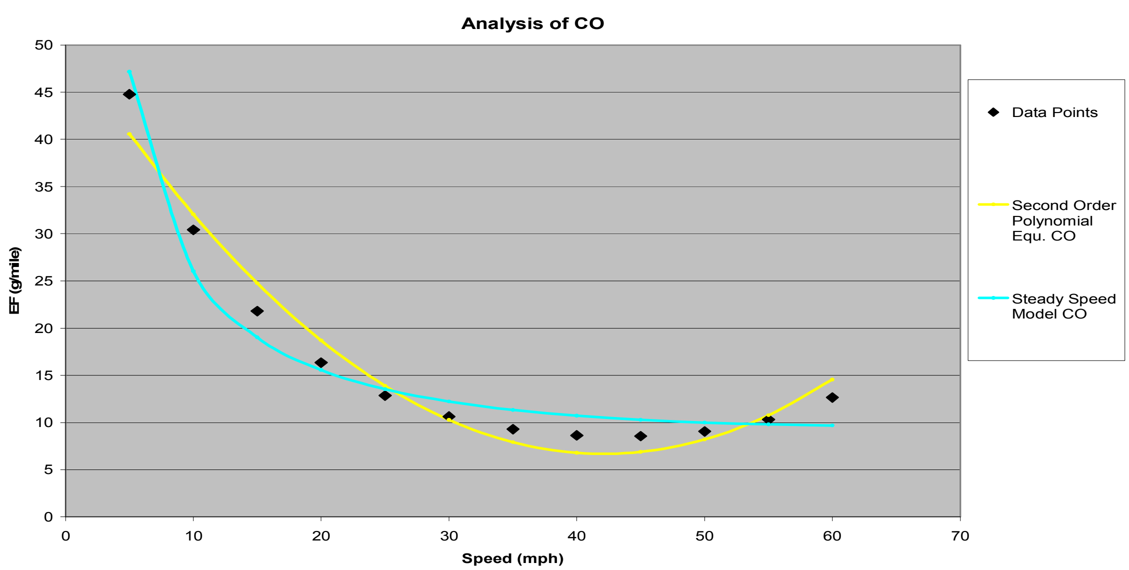

Figure B.38 Emission Trend of CO for Different Freeway Speeds

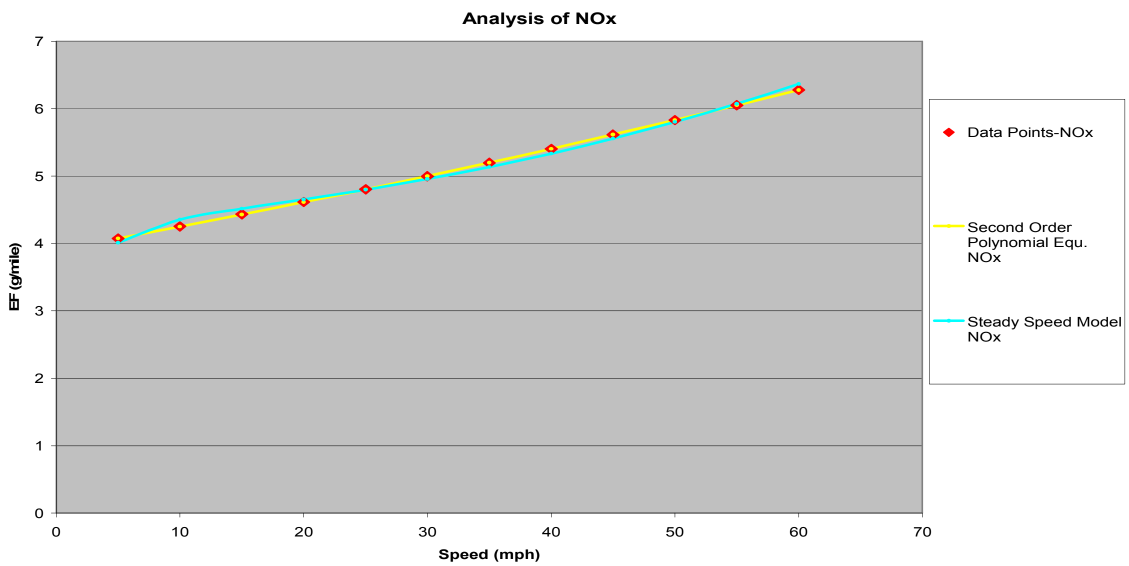

Figure B.39 Emission Trend of NO_x for Different Freeway Speeds

14. Light Duty Diesel Vehicles (LDDV)

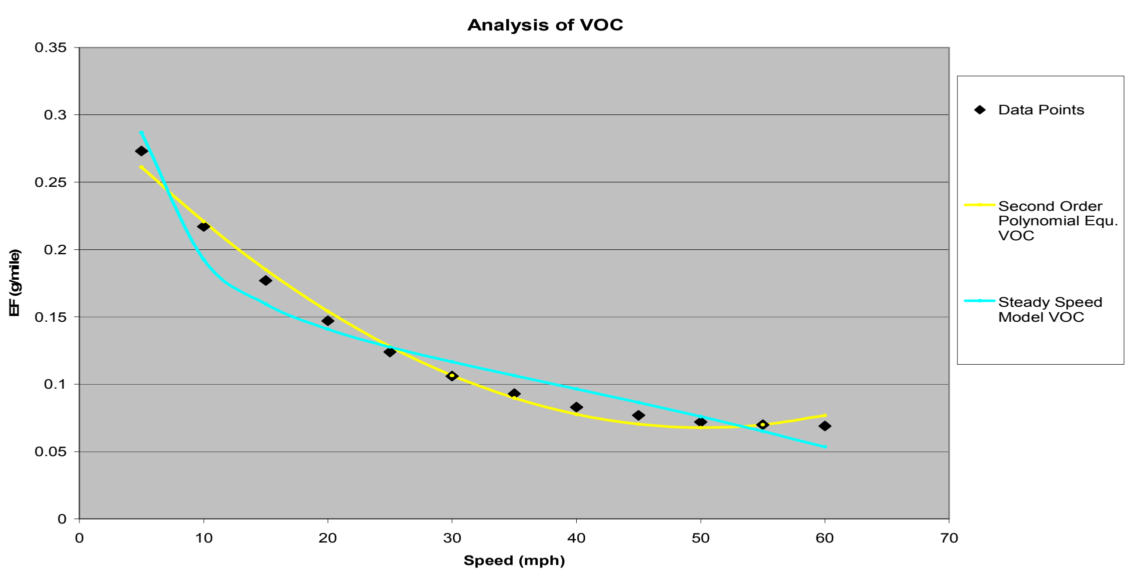

Figure B.40 Emission Trend of HC for Different Freeway Speeds

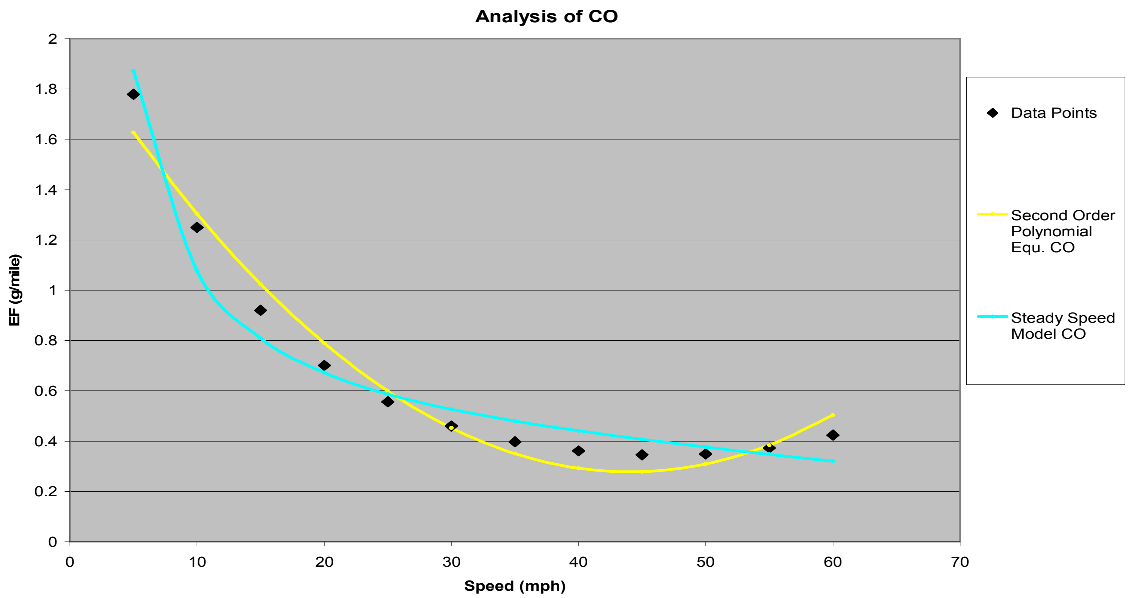

Figure B.41 Emission Trend of CO for Different Freeway Speeds

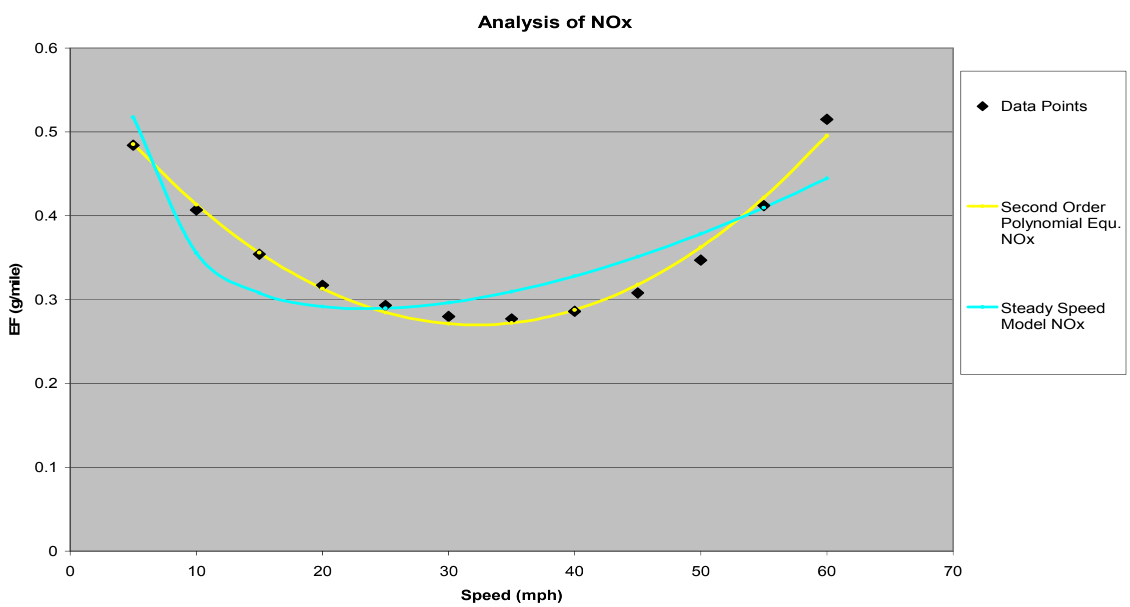

Figure B.42 Emission Trend of NO_x for Different Freeway Speeds

15. Light Duty Diesel Trucks 1 and 2 (LDDT 12)

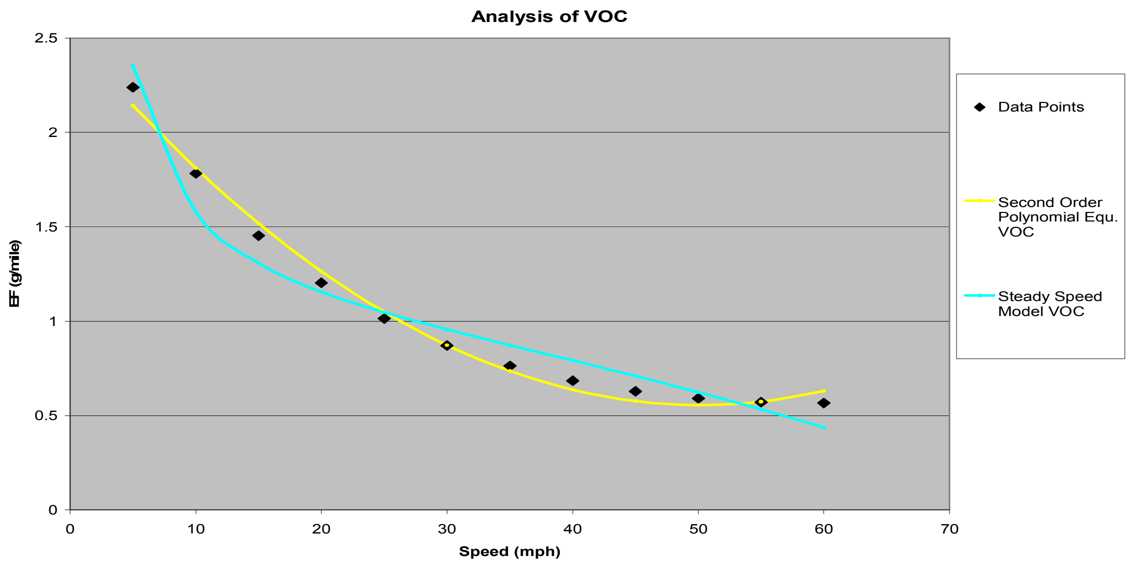

Figure B.43 Emission Trend of HC for Different Freeway Speeds

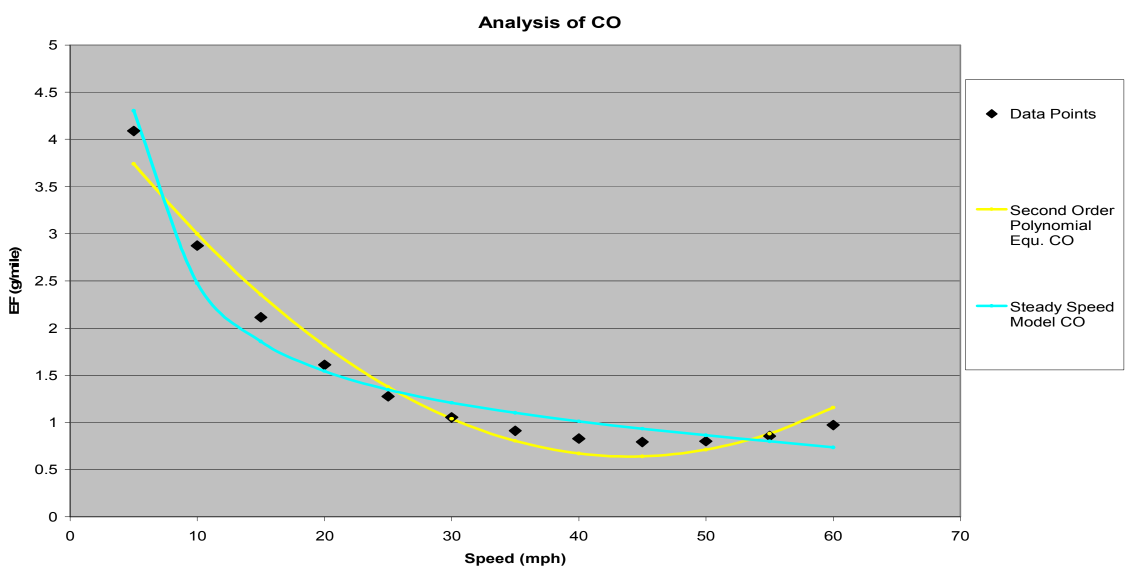

Figure B.44 Emission Trend of CO for Different Freeway Speeds

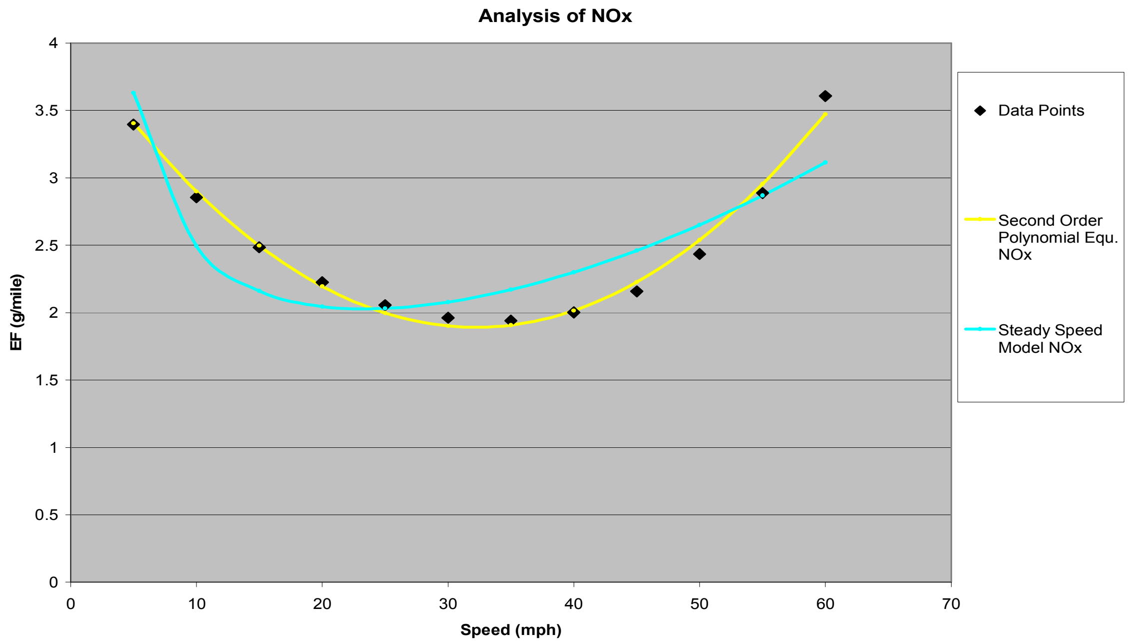

Figure B.45 Emission Trend of NO_x for Different Freeway Speeds

16. Class 2b Heavy Duty Diesel Vehicles (HDDV 2B)

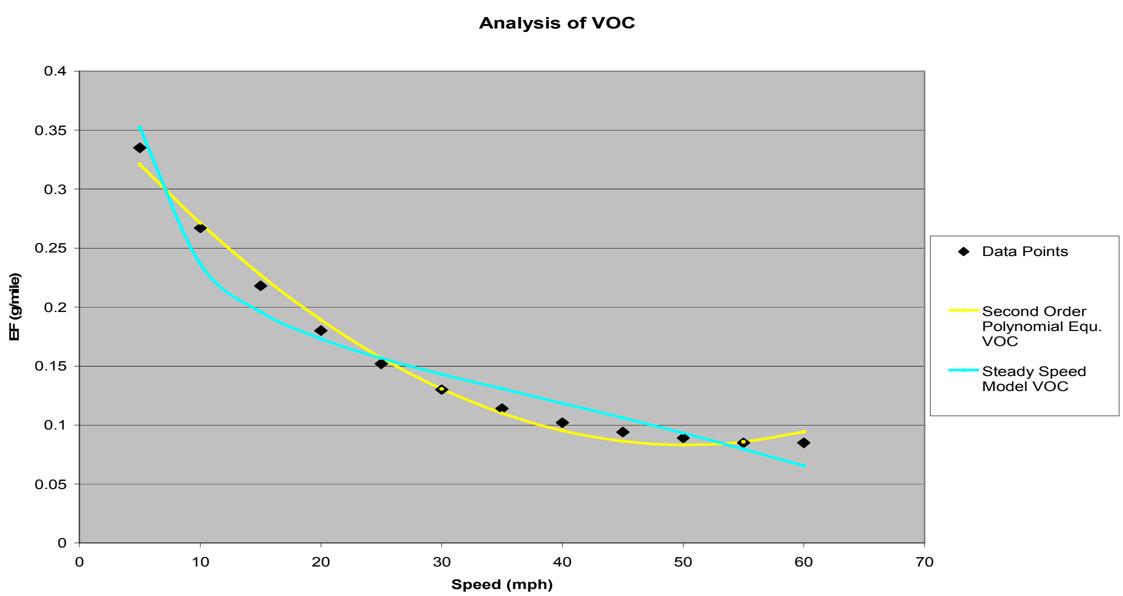

Figure B.46 Emission Trend of HC for Different Freeway Speeds

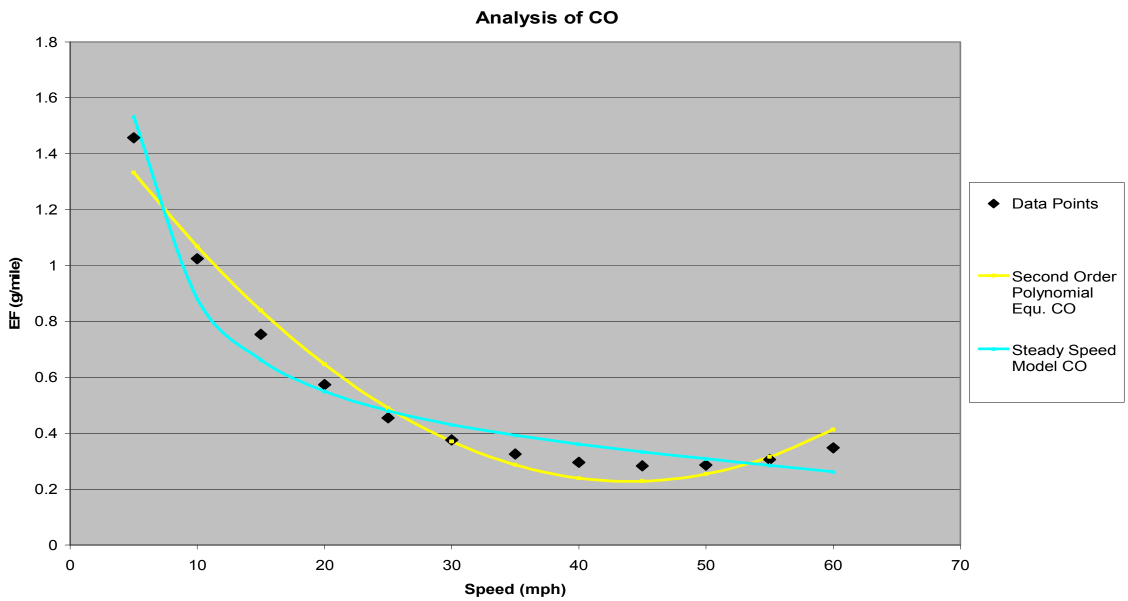

Figure B.47 Emission Trend of CO for Different Freeway Speeds

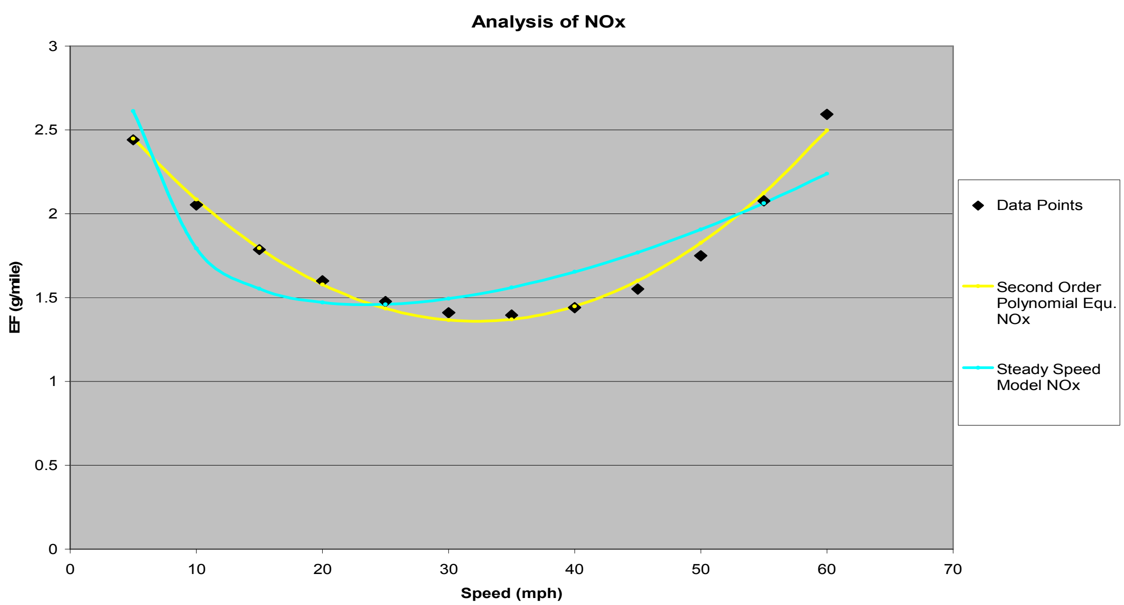

Figure B.48 Emission Trend of NO_x for Different Freeway Speeds

17. Class 3 Heavy Duty Diesel Vehicles (HDDV 3)

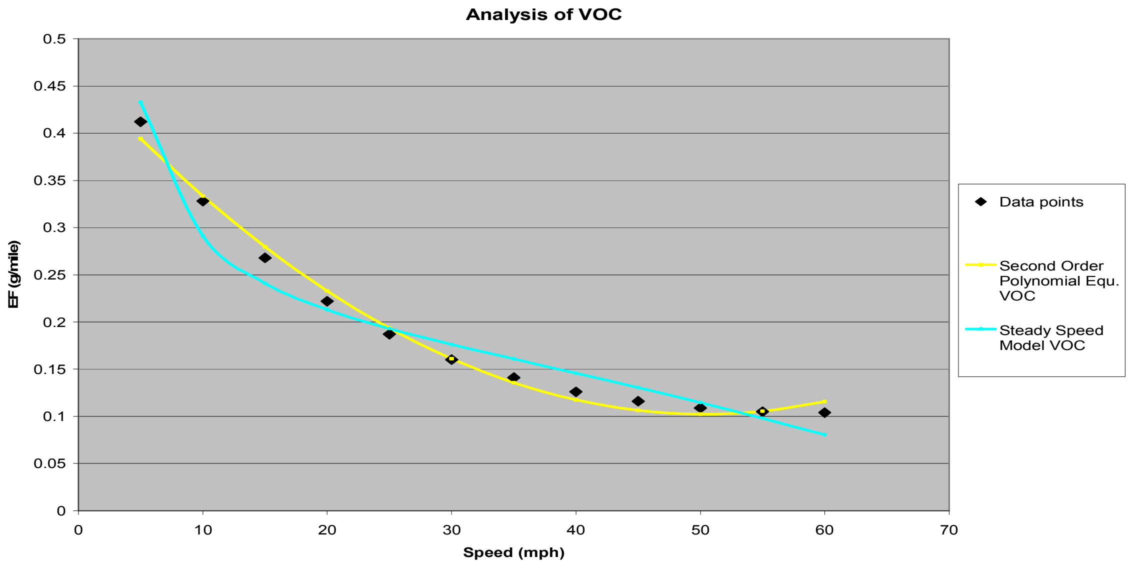

Figure B.49 Emission Trend of HC for Different Freeway Speeds

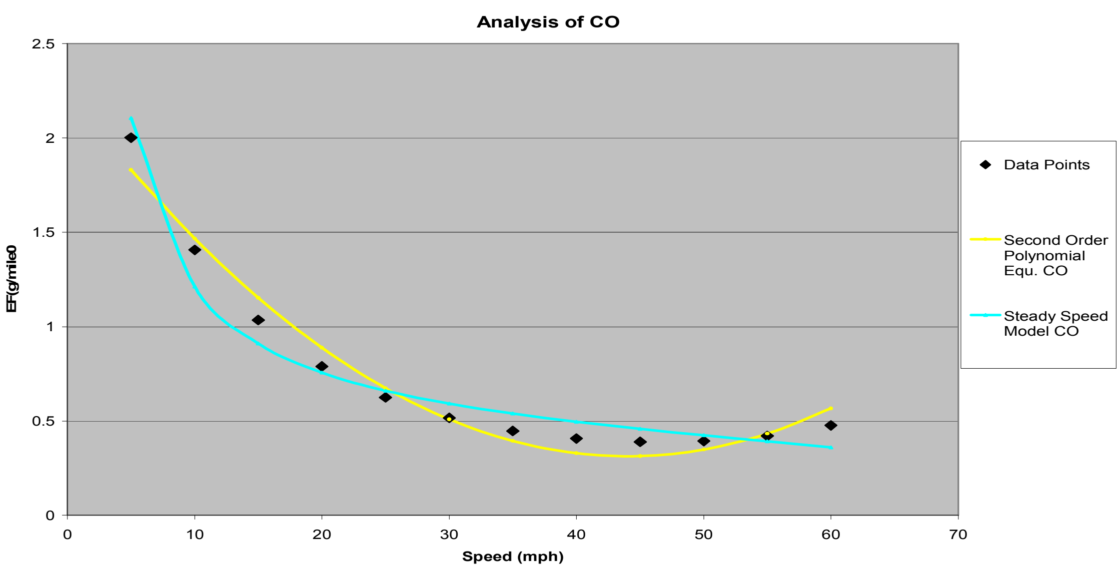

Figure B.50 Emission Trend of CO for Different Freeway Speeds

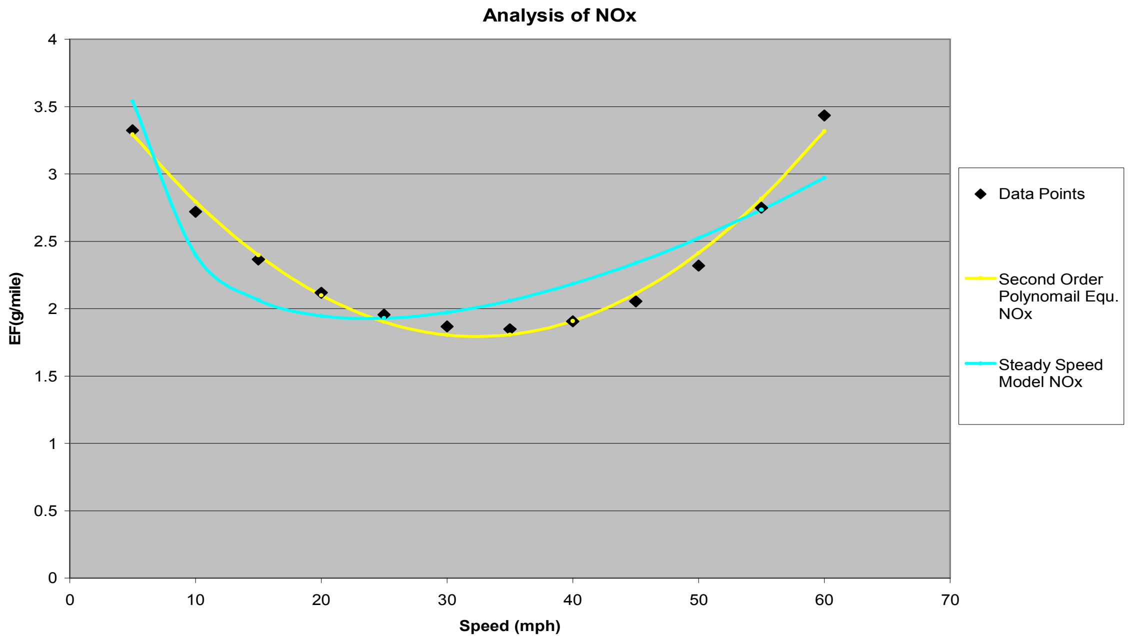

Figure B.51 Emission Trend of NO_x for Different Freeway Speeds

18. Class 4 Heavy Duty Diesel Vehicles (HDDV4)

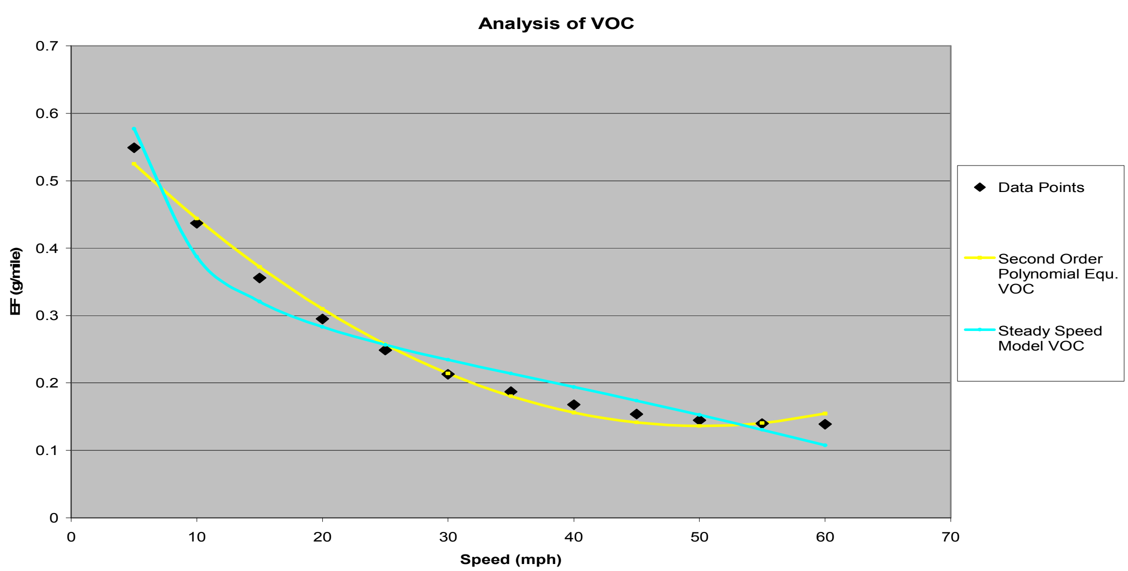

Figure B.52 Emission Trend of HC for Different Freeway Speeds

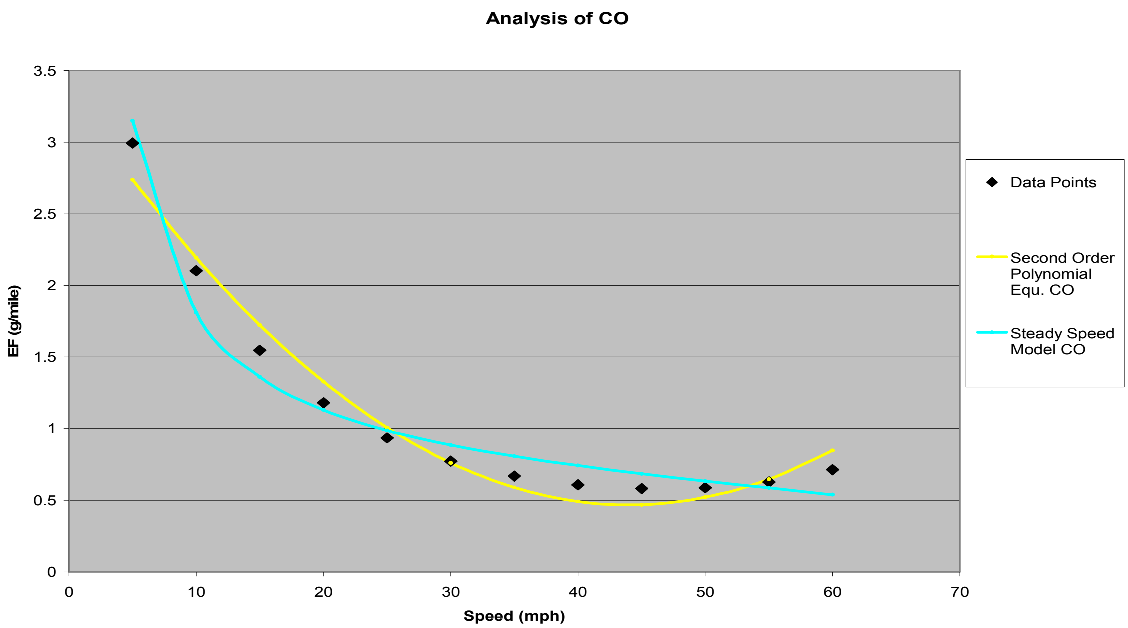

Figure B.53 Emission Trend of CO for Different Freeway Speeds

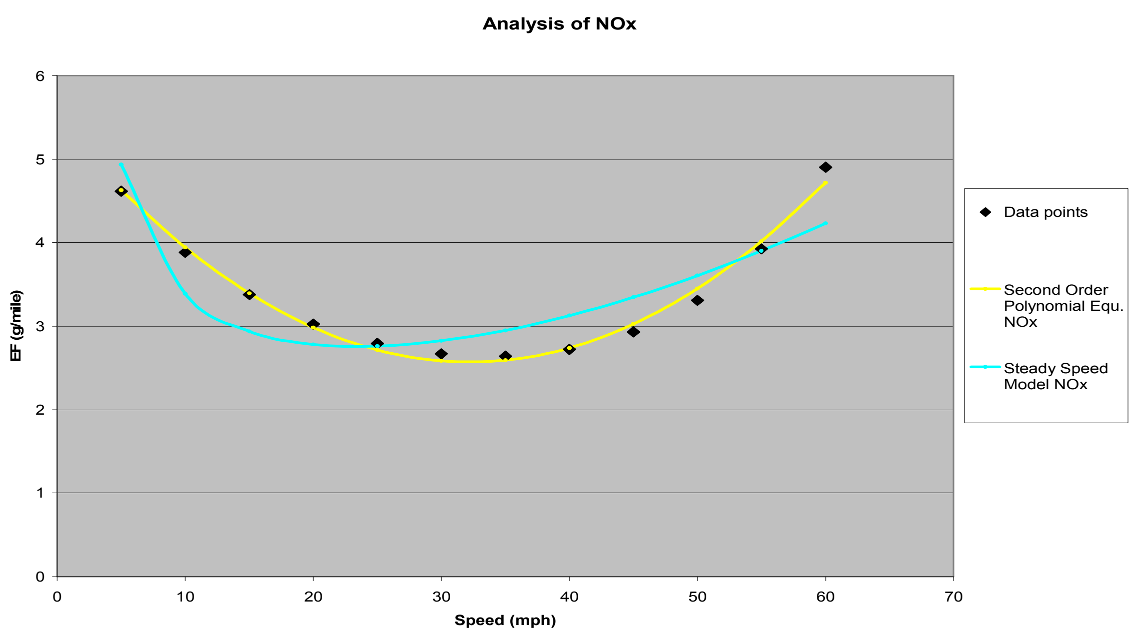

Figure B.54 Emission Trend of NO_x for Different Freeway Speeds

19. Class 5 Heavy Duty Diesel Vehicles (HDDV 5)

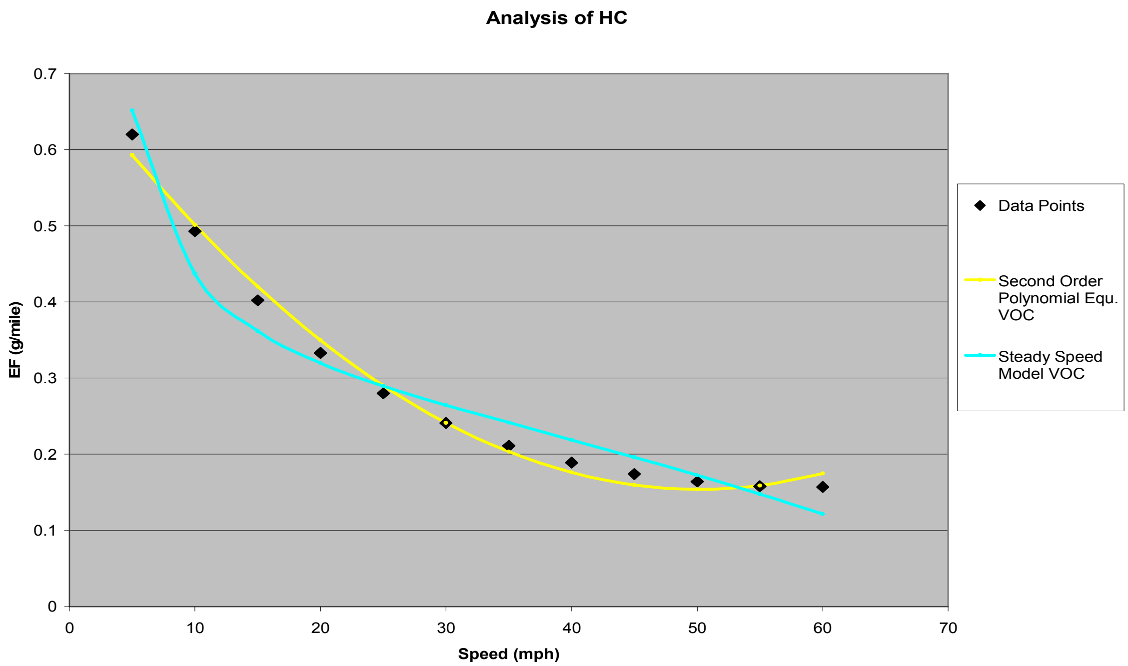

Figure B.55 Emission Trend of HC for Different Freeway Speeds

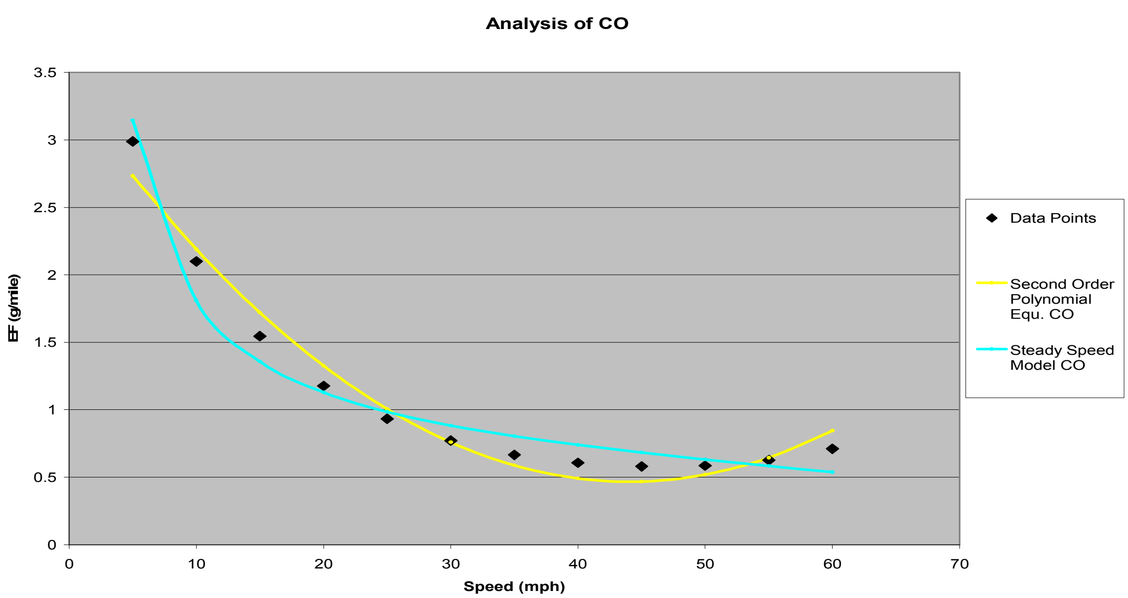

Figure B.56 Emission Trend of CO for Different Freeway Speeds

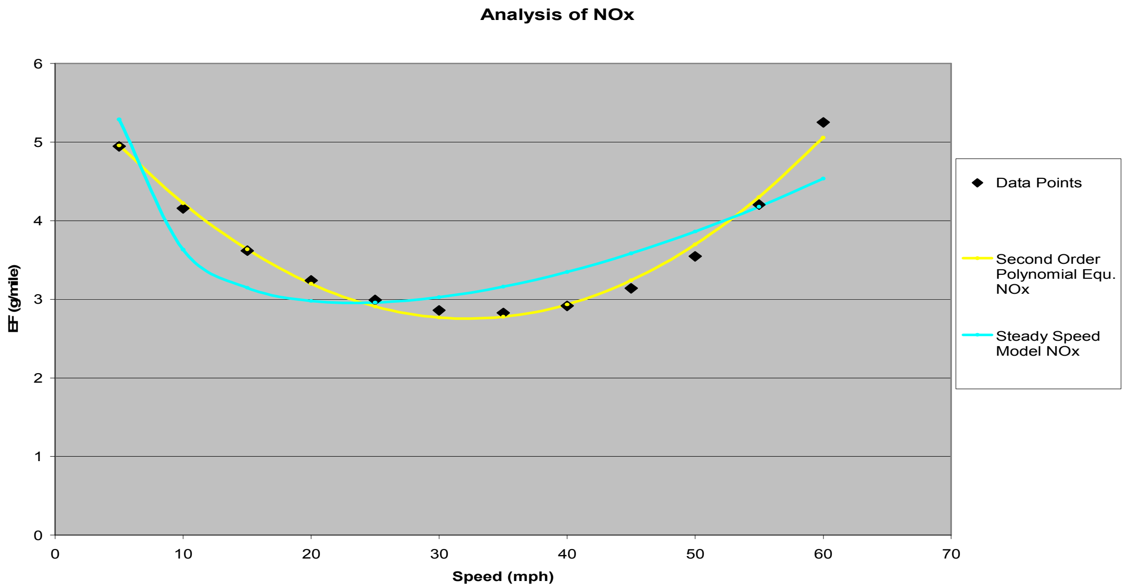

Figure B.57 Emission Trend of NO_x for Different Freeway Speeds

20. Class 6 Heavy Duty Diesel Vehicles (HDDV 6)

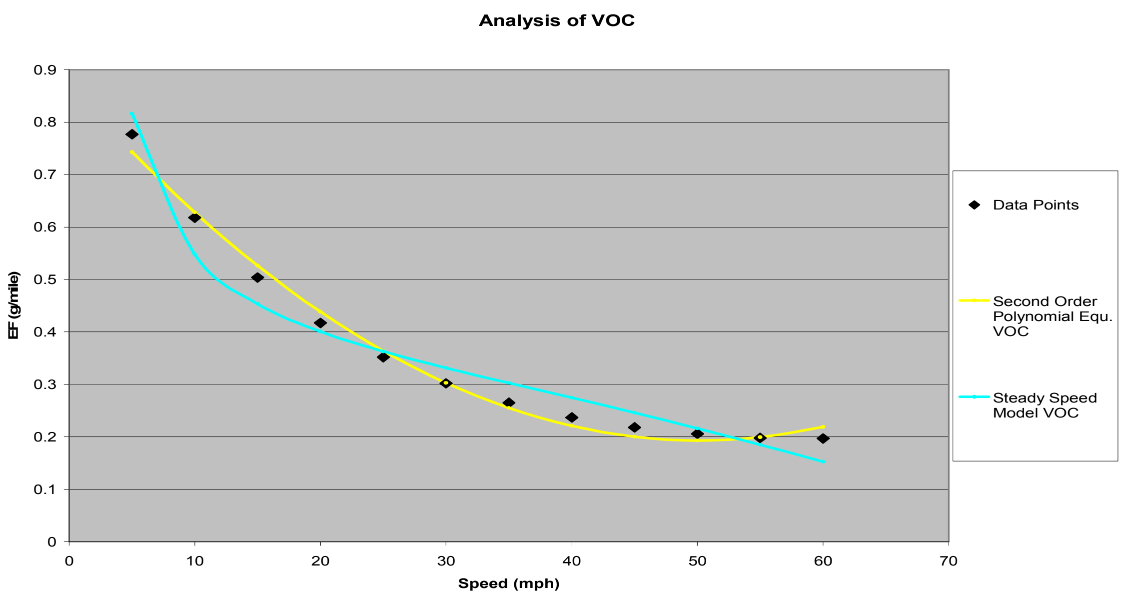

Figure B.58 Emission Trend of HC for Different Freeway Speeds

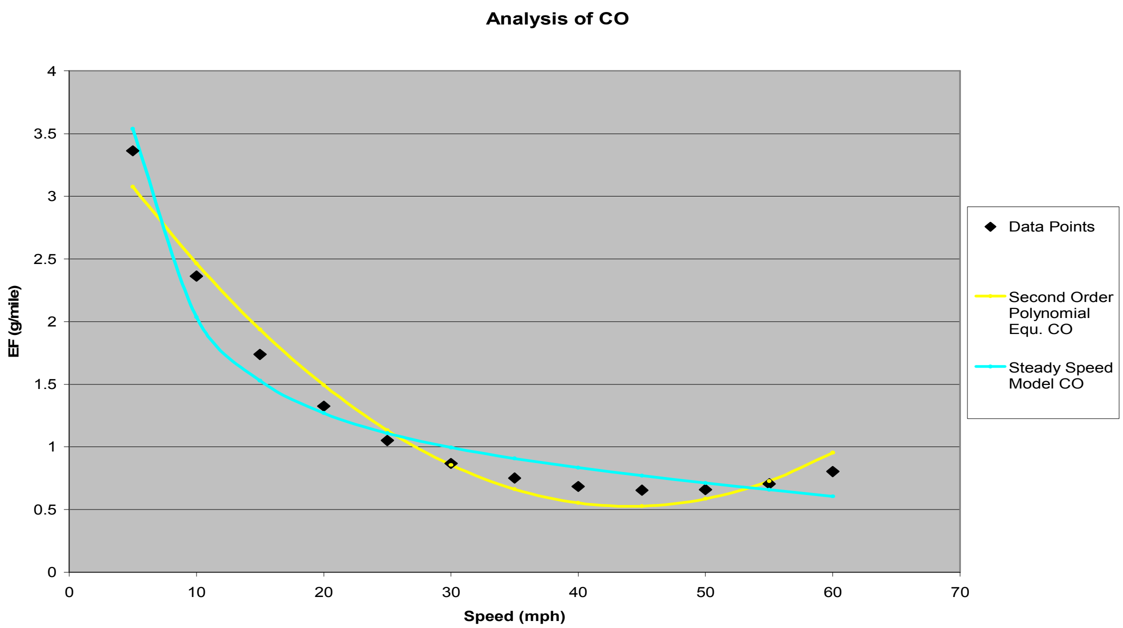

Figure B.59 Emission Trend of CO for Different Freeway Speeds

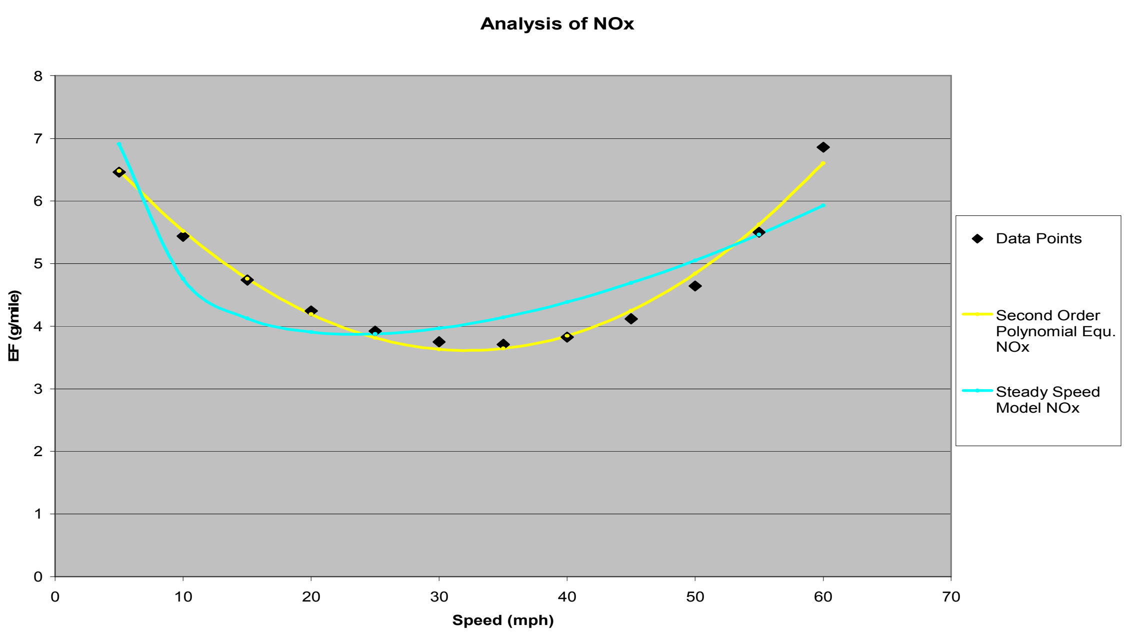

Figure B.60 Emission Trend of NO_x for Different Freeway Speeds

21. Class 7 Heavy Duty Diesel Vehicles (HDDV 7)

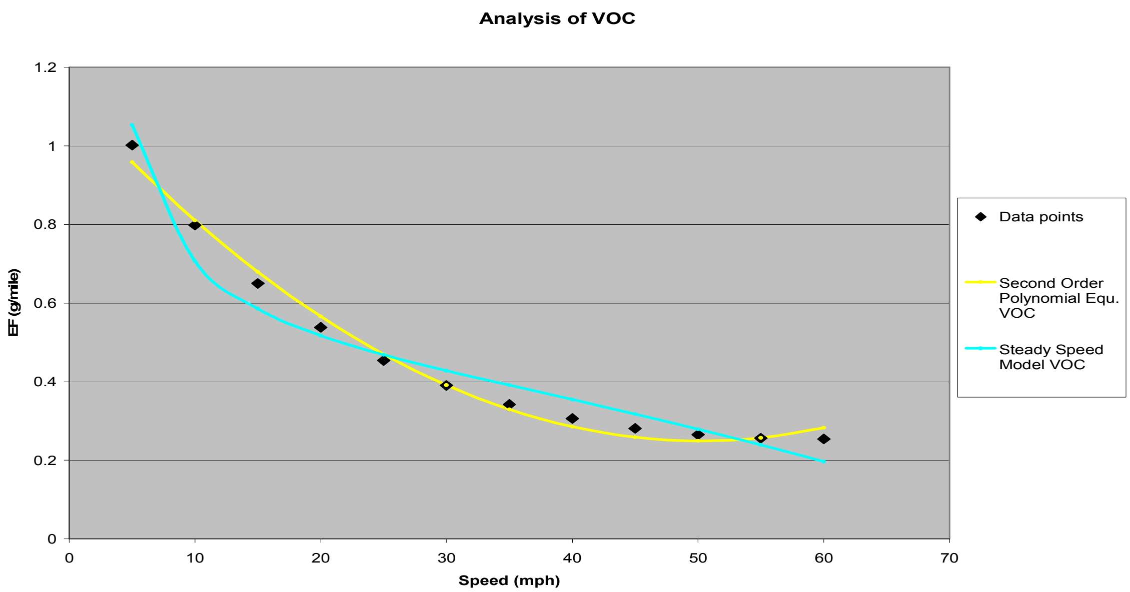

Figure B.61 Emission Trend of HC for Different Freeway Speeds

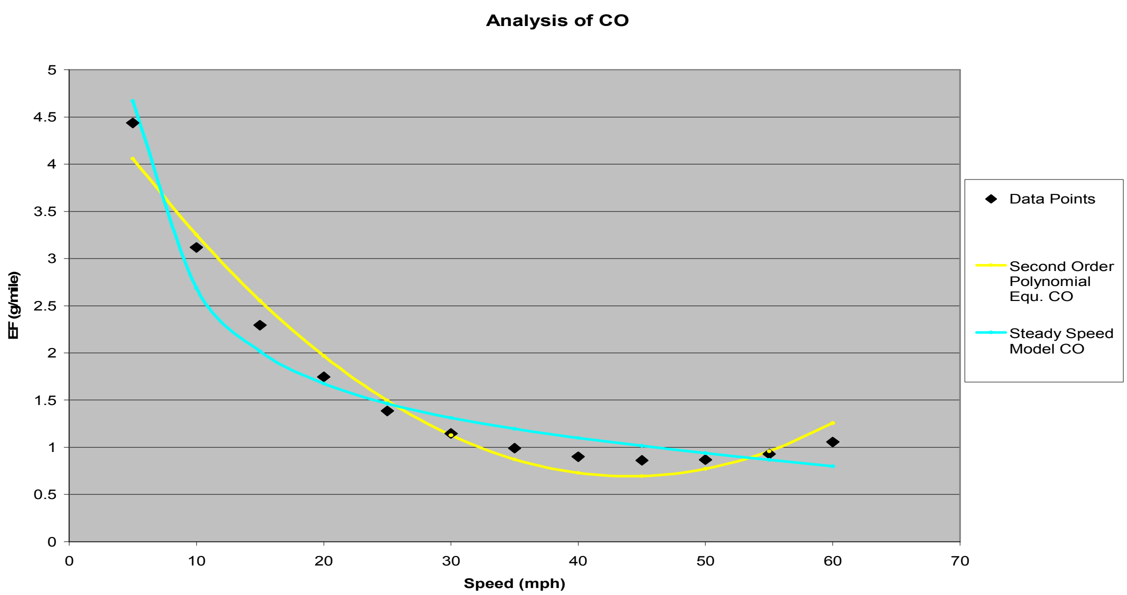

Figure B.62 Emission Trend of CO for Different Freeway Speeds

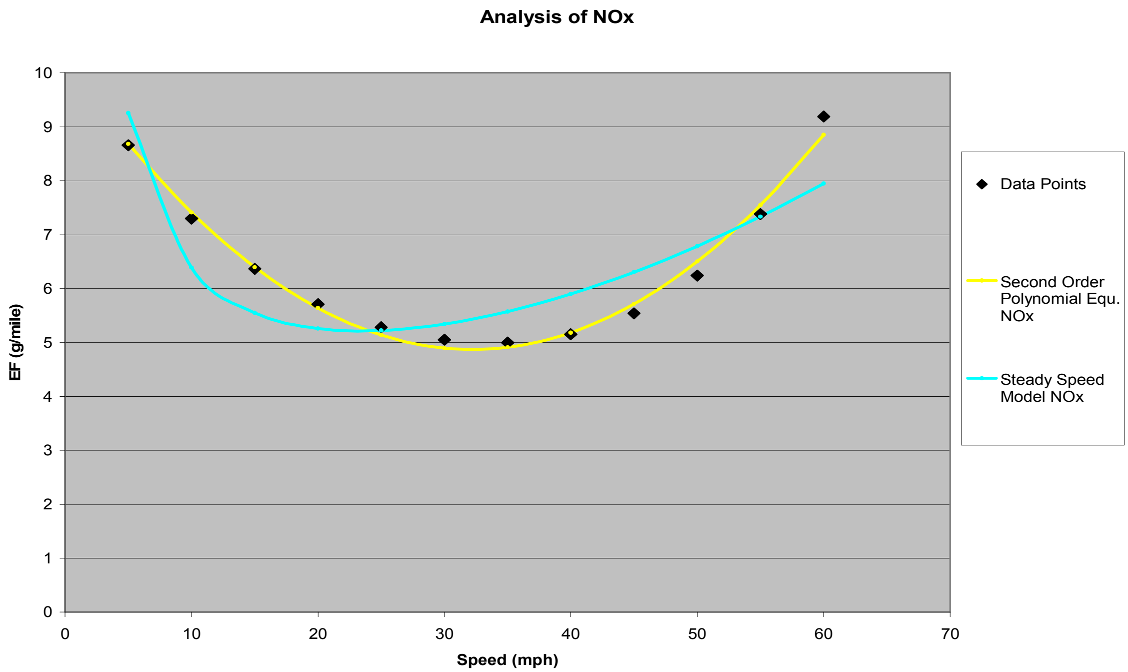

Figure B.63 Emission Trend of NO_x for Different Freeway Speeds

22. Class 8a Heavy Duty Diesel Vehicles (HDDV 8B)

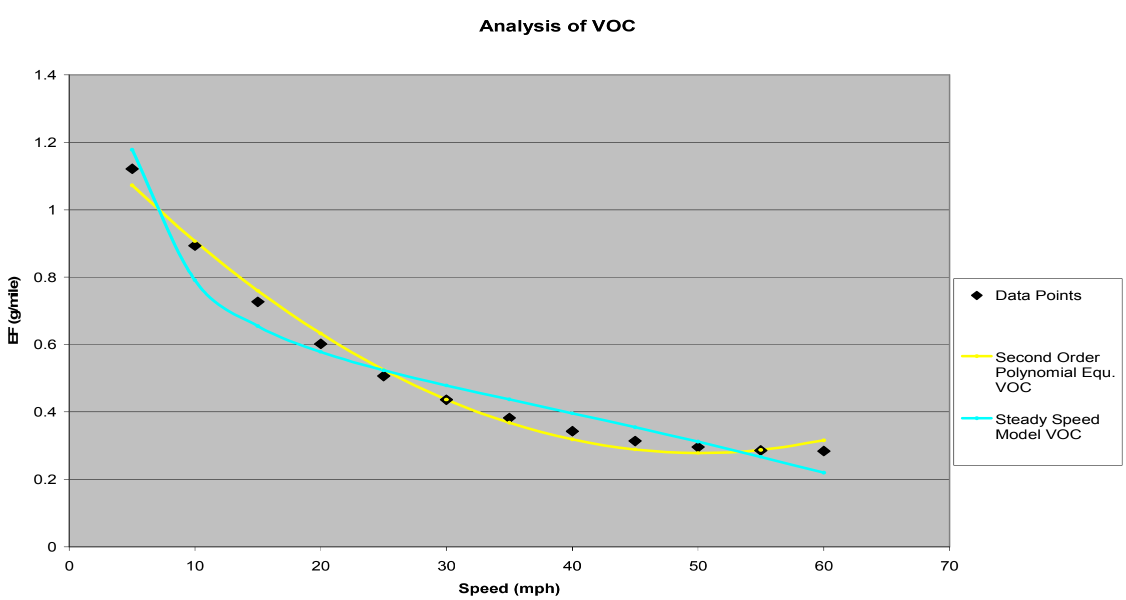

Figure B.64 Emission Trend of HC for Different Freeway Speeds

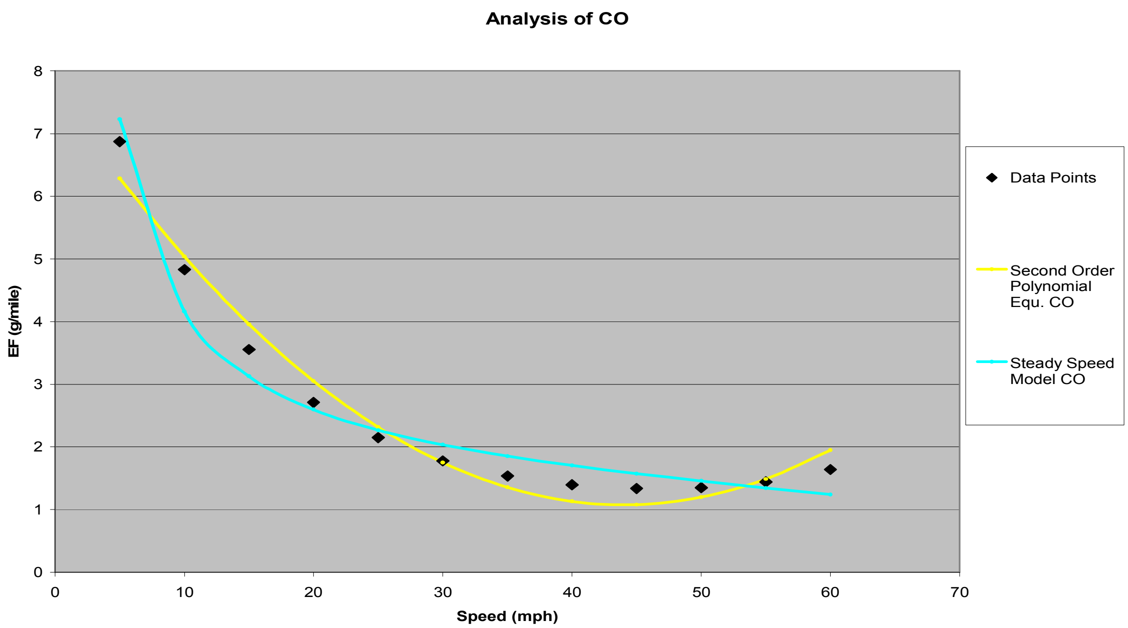

Figure B.65 Emission Trend of CO for Different Freeway Speeds

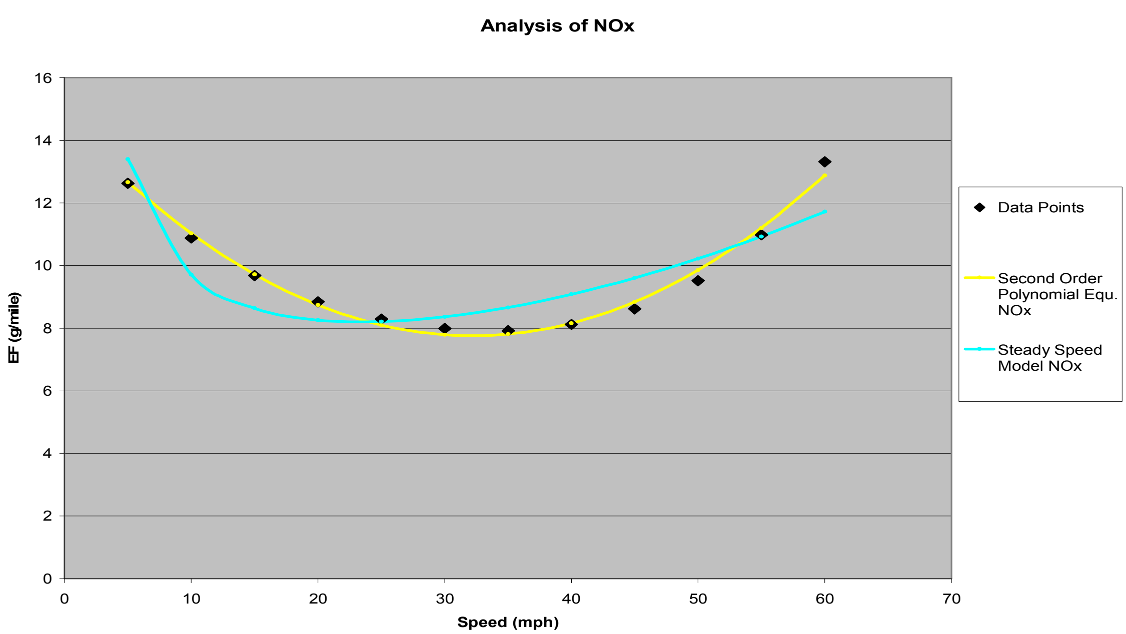

Figure B.66 Emission Trend of NO_x for Different Freeway Speeds

23. Class 8b Heavy Duty Diesel Vehicles (HDDV 8B)

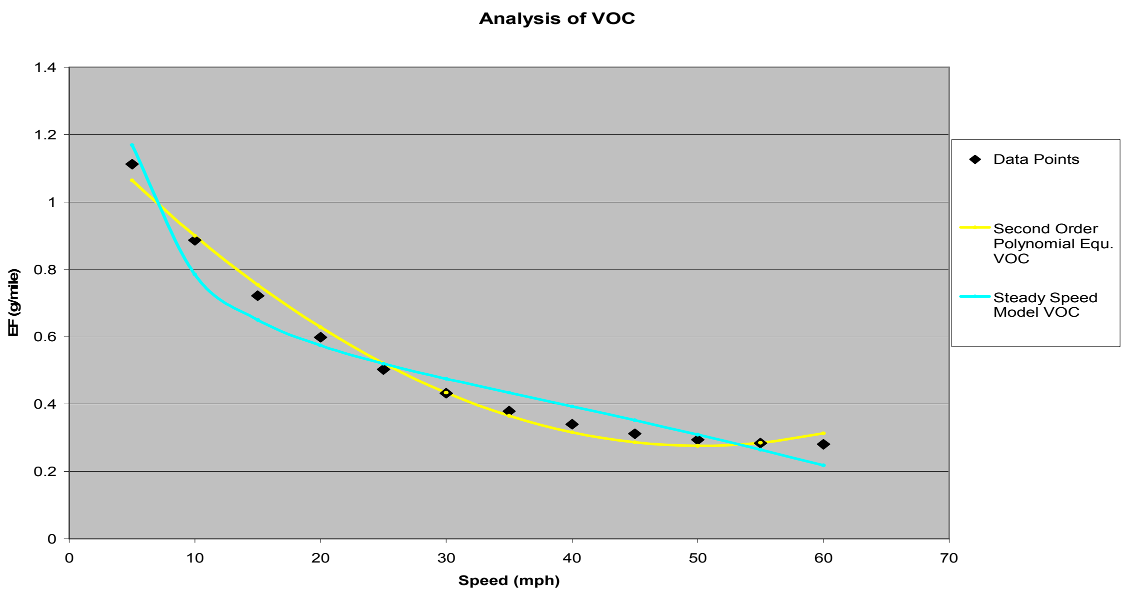

Figure B.67 Emission Trend of HC for Different Freeway Speeds

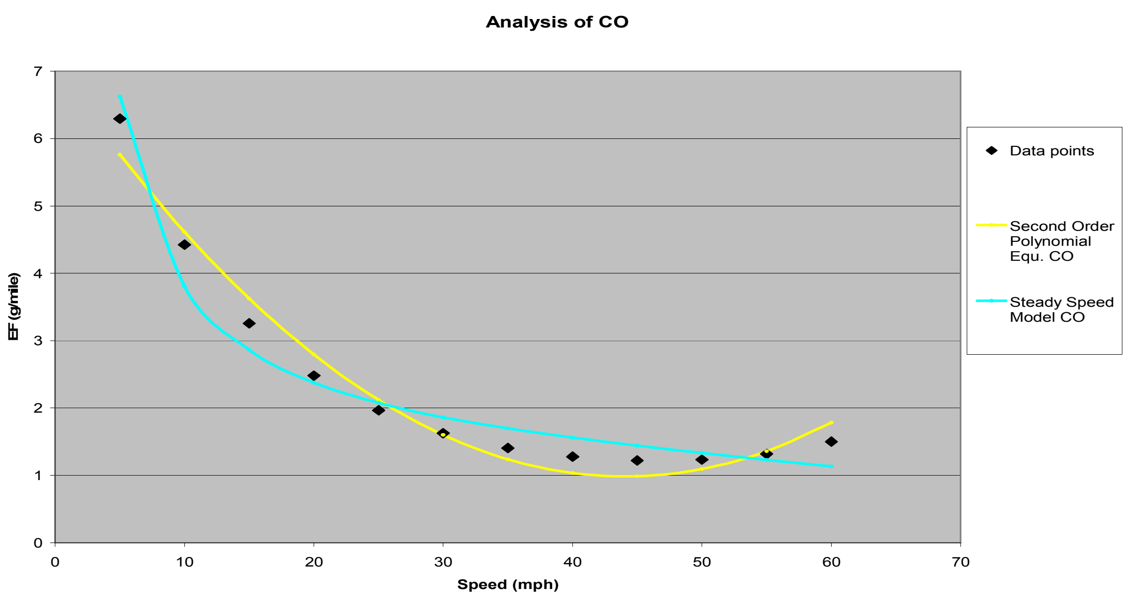

Figure B.68 Emission Trend of CO for Different Freeway Speeds

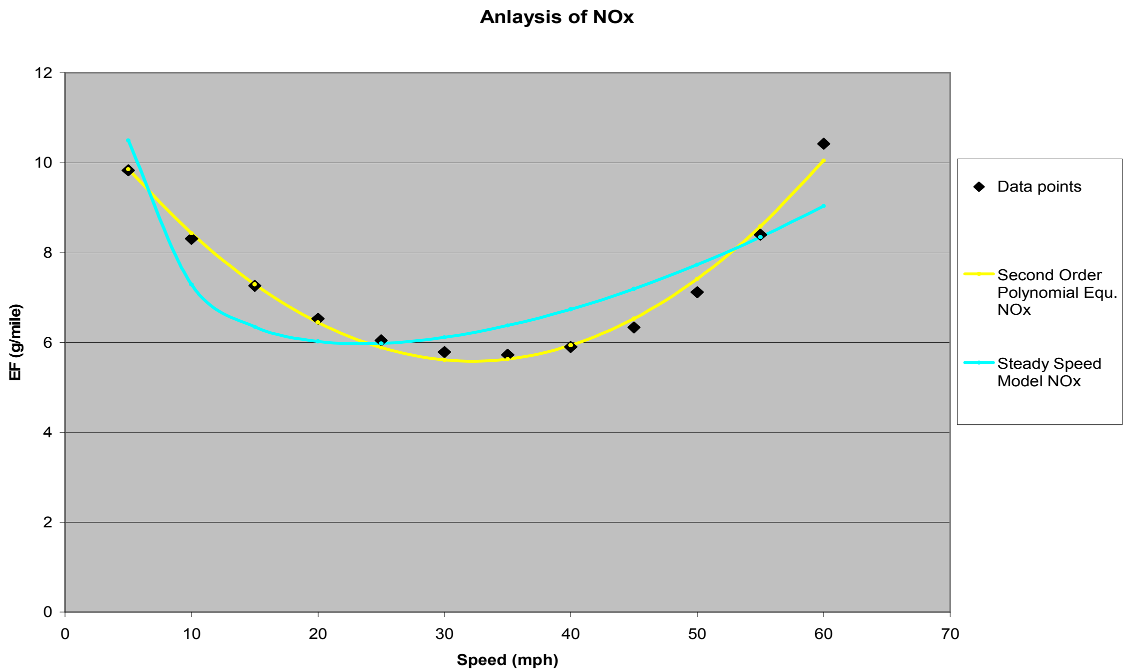

Figure B.69 Emission Trend of NO_x for Different Freeway Speeds

24. Motor Cycles (Gasoline-MC)

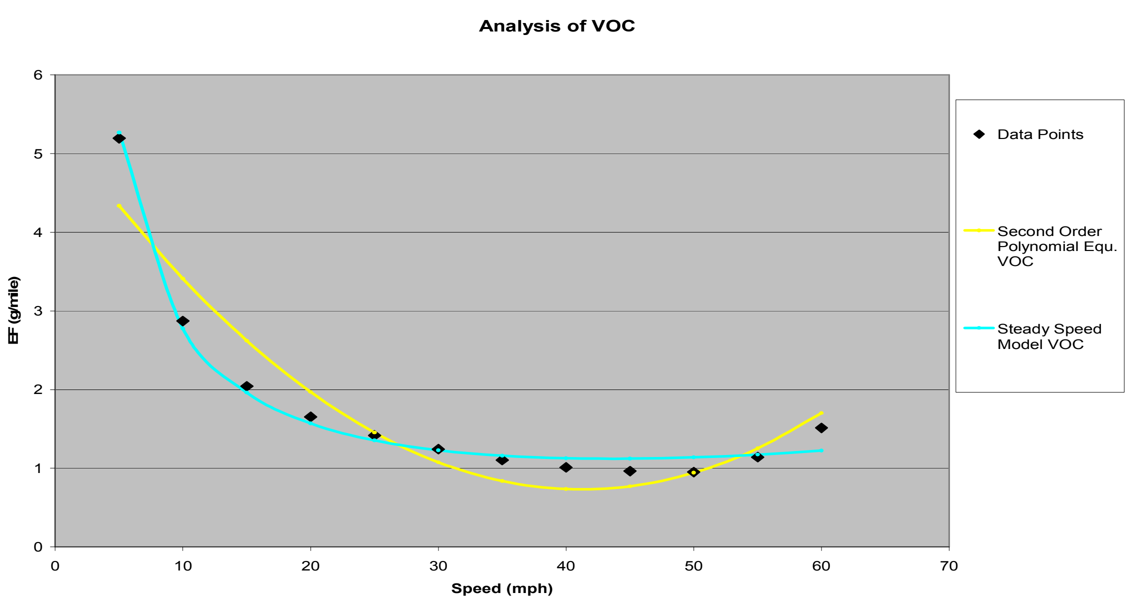

Figure B.70 Emission Trend of HC for Different Freeway Speeds

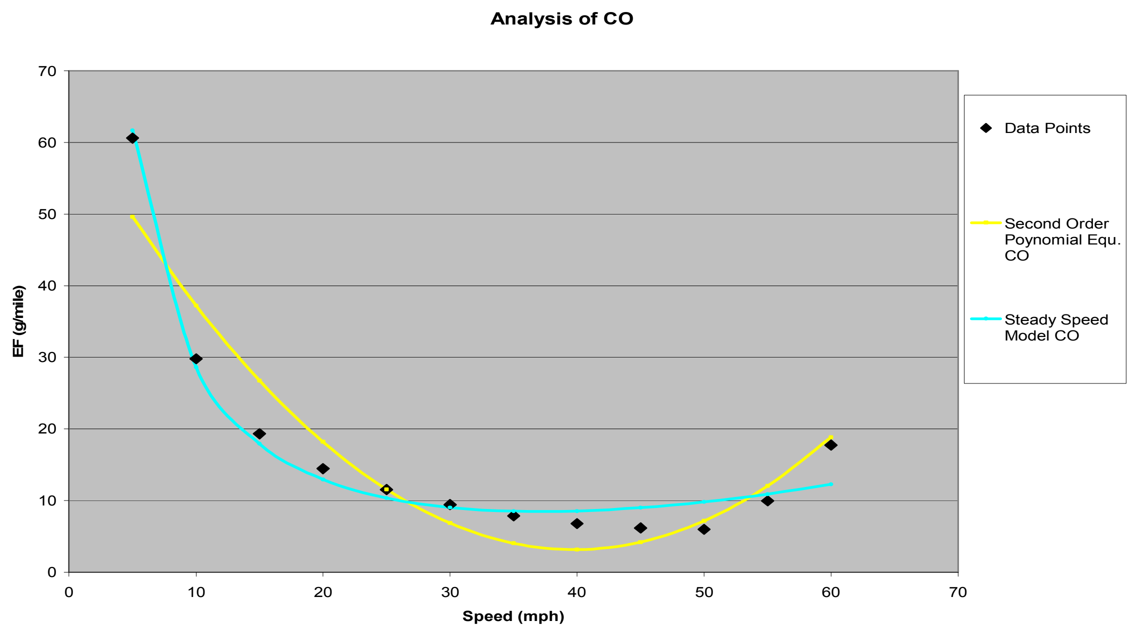

Figure B.71 Emission Trend of CO for Different Freeway Speeds

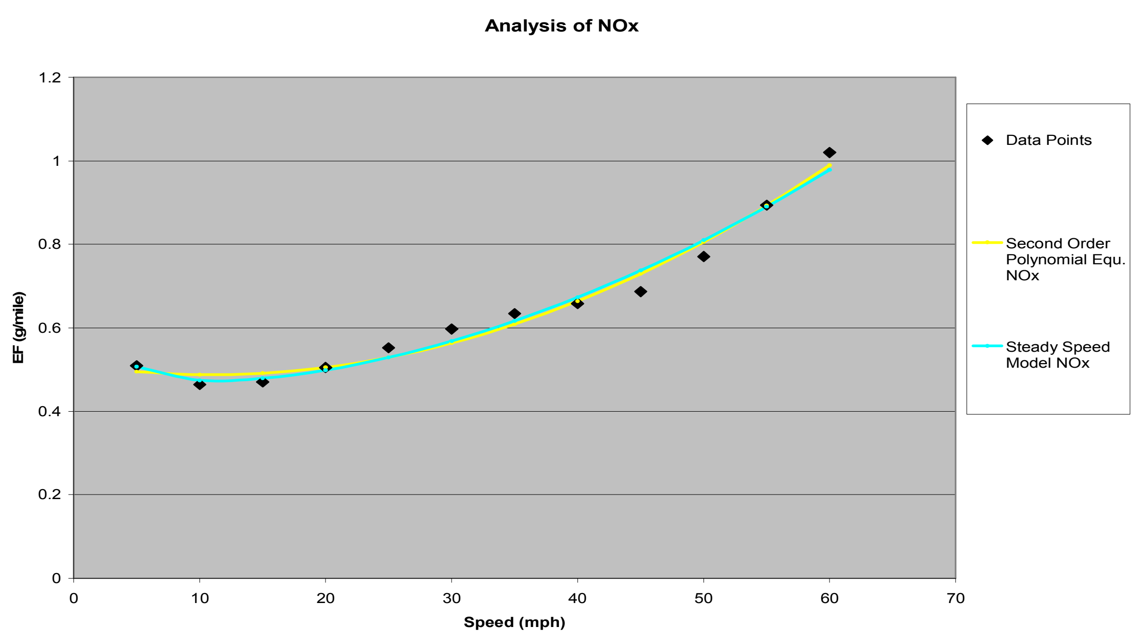

Figure B.72 Emission Trend of NO_x for Different Freeway Speeds

25. Gasoline Buses (School, Transit, and Urban-HDGB)

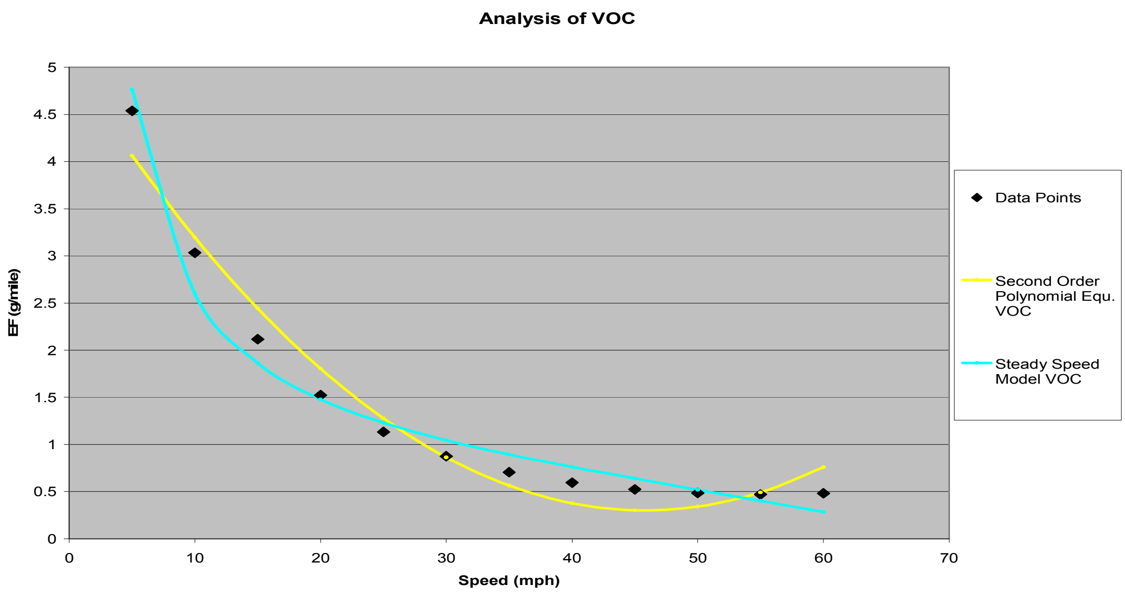

Figure B.73 Emission Trend of HC for Different Freeway Speeds

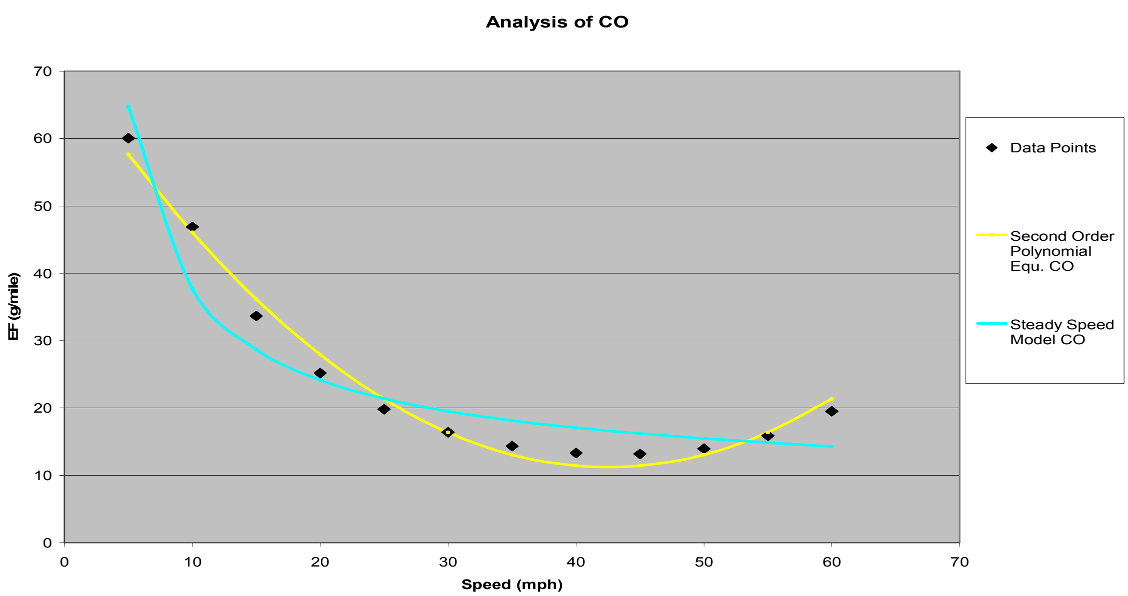

Figure B.74 Emission Trend of CO for Different Freeway Speeds

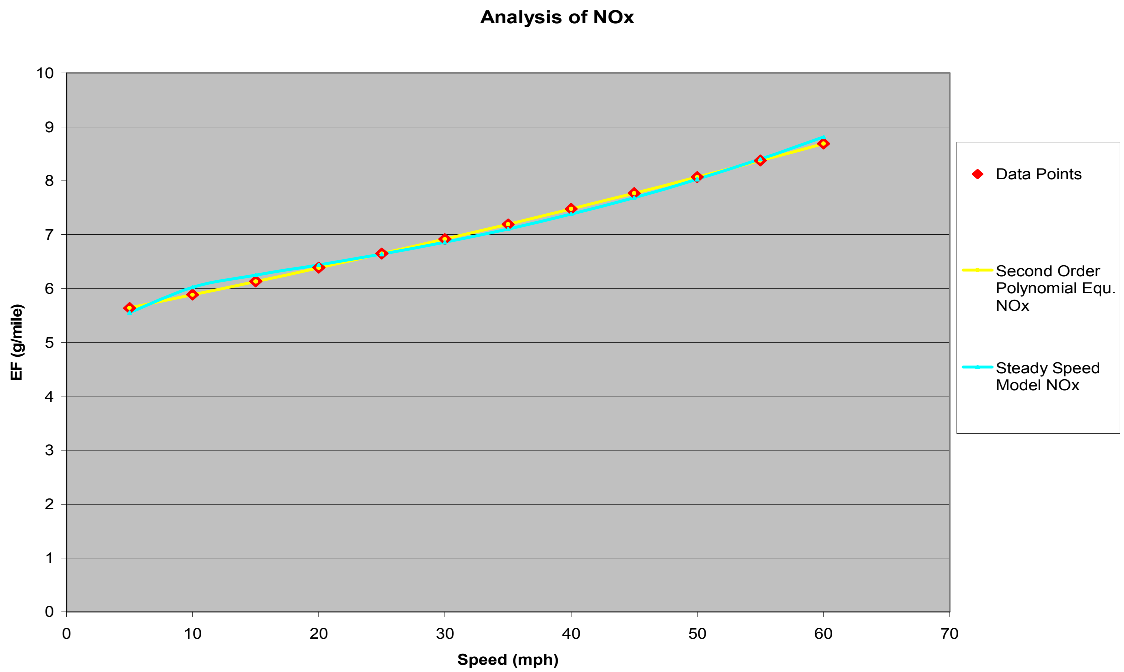

Figure B.75 Emission Trend of NO_x for Different Freeway Speeds

26. Diesel Transit and Urban Buses (HDDBT)

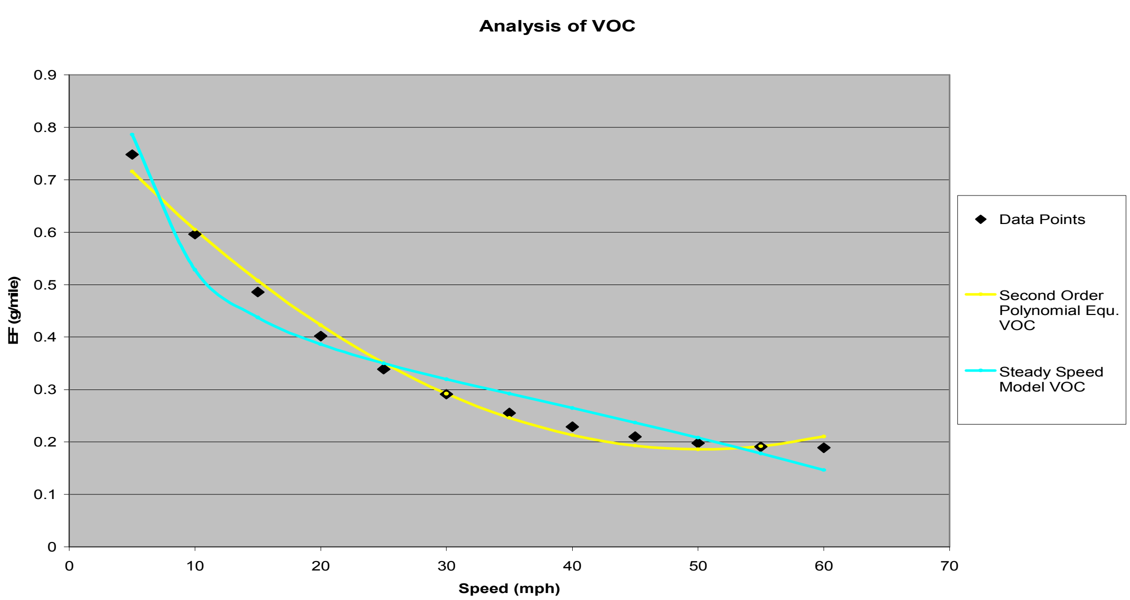

Figure B.76 Emission Trend of HC for Different Freeway Speeds

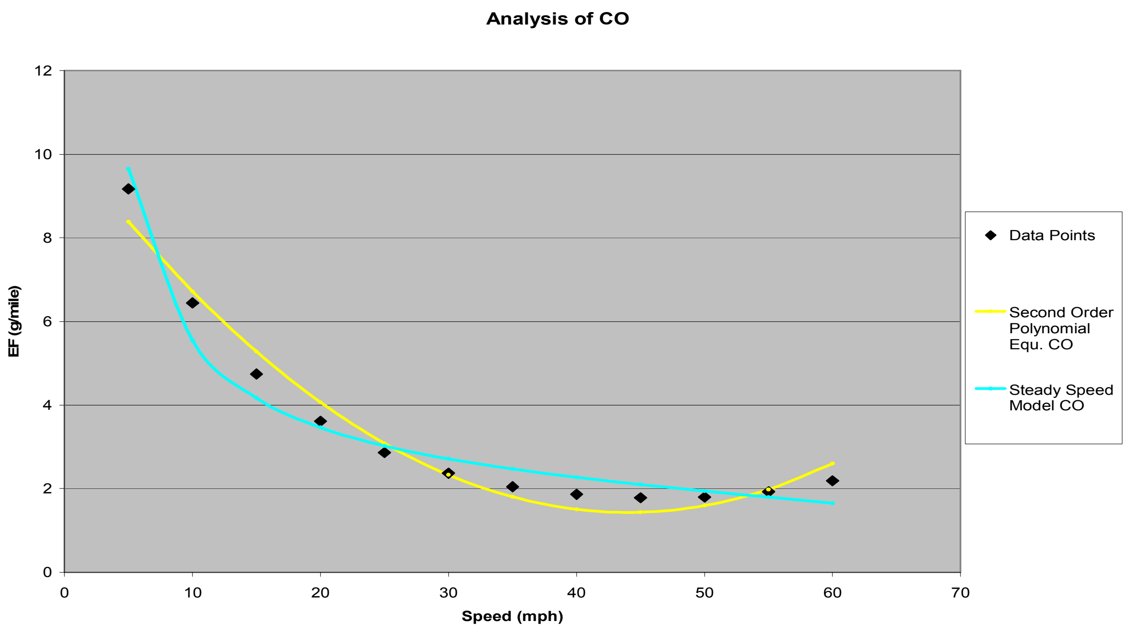

Figure B.77 Emission Trend of CO for Different Freeway Speeds

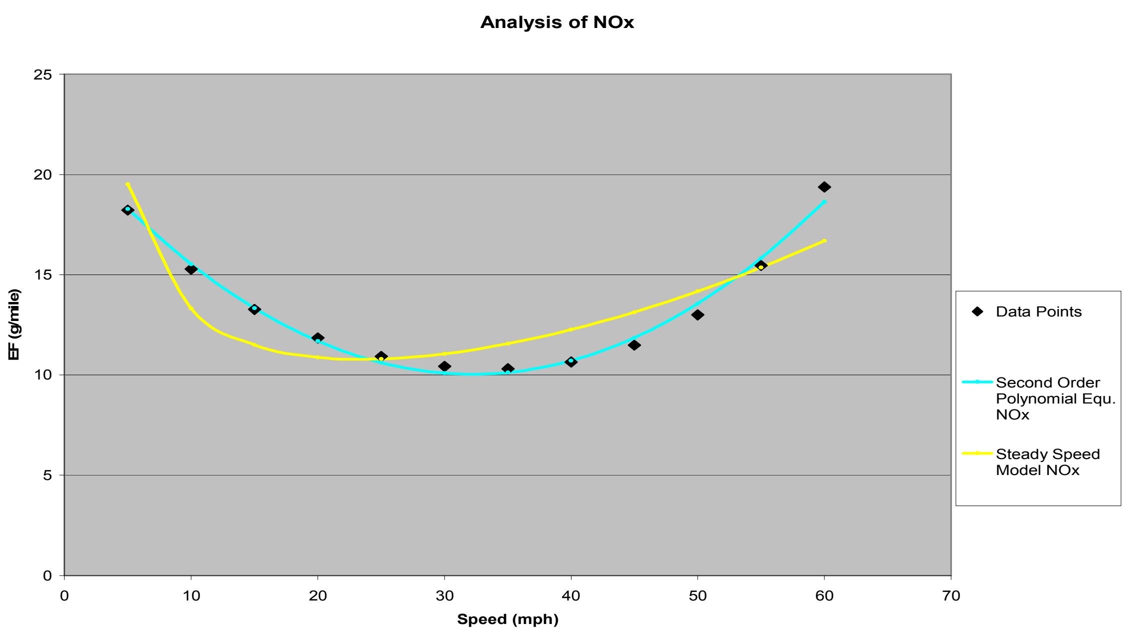

Figure B.78 Emission Trend of NO_x for Different Freeway Speeds

27. Diesel School Buses (HDDBS)

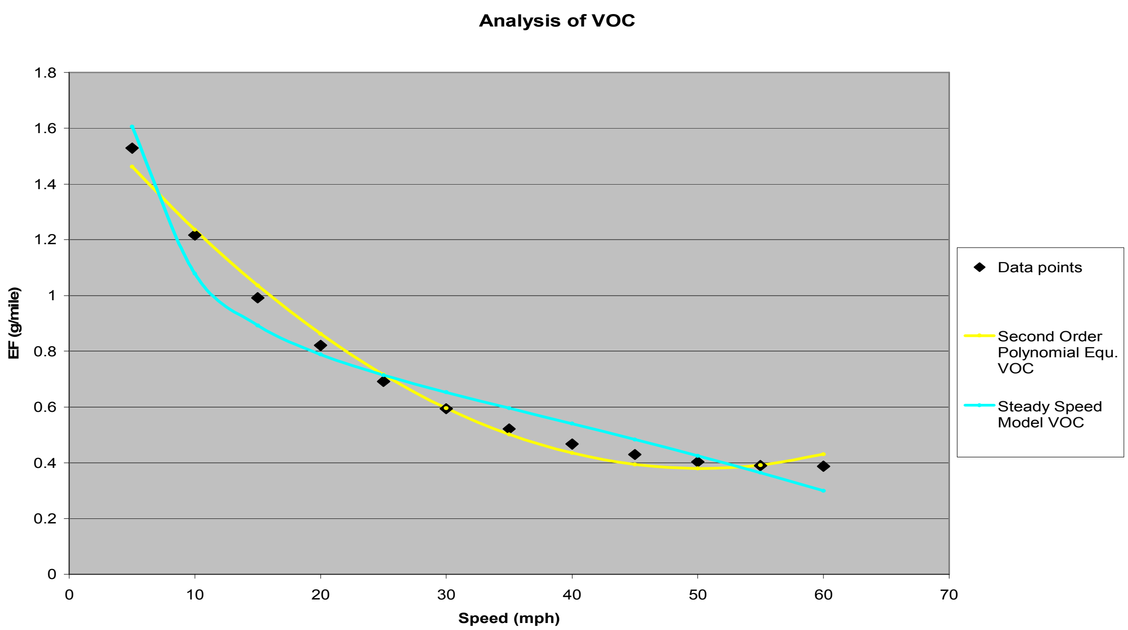

Figure B.79 Emission Trend of HC for Different Freeway Speeds

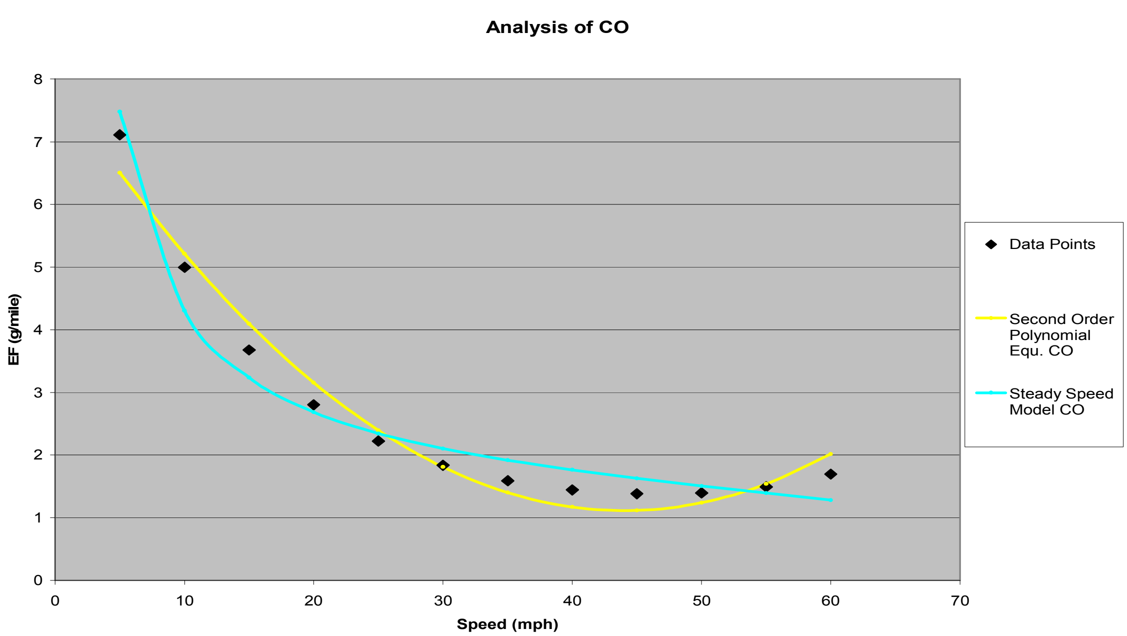

Figure B.80 Emission Trend of CO for Different Freeway Speeds

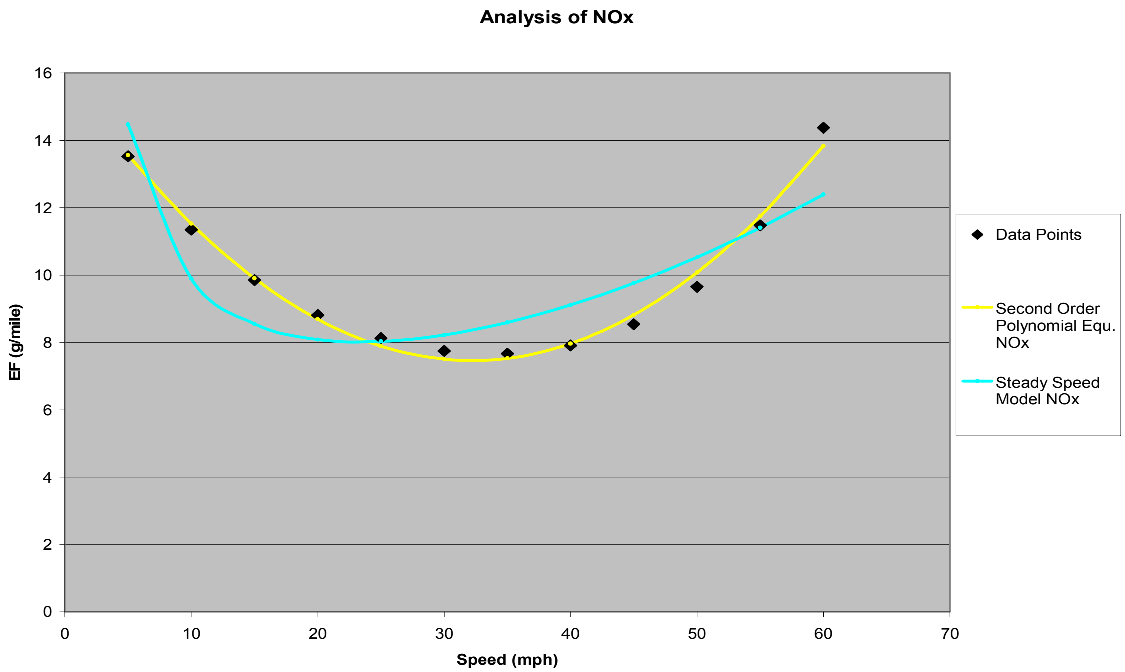

Figure B.81 Emission Trend of NO_x for Different Freeway Speeds

28. Light Duty Diesel Trucks 3 and 4 (LDDT 34)

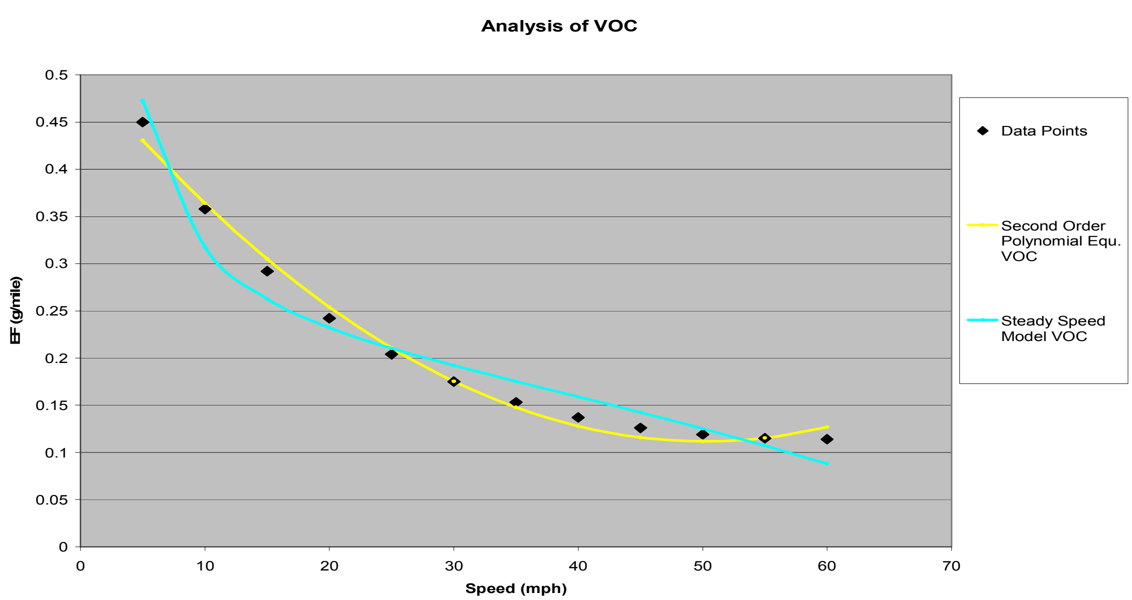

Figure B.82 Emission Trend of HC for Different Freeway Speeds

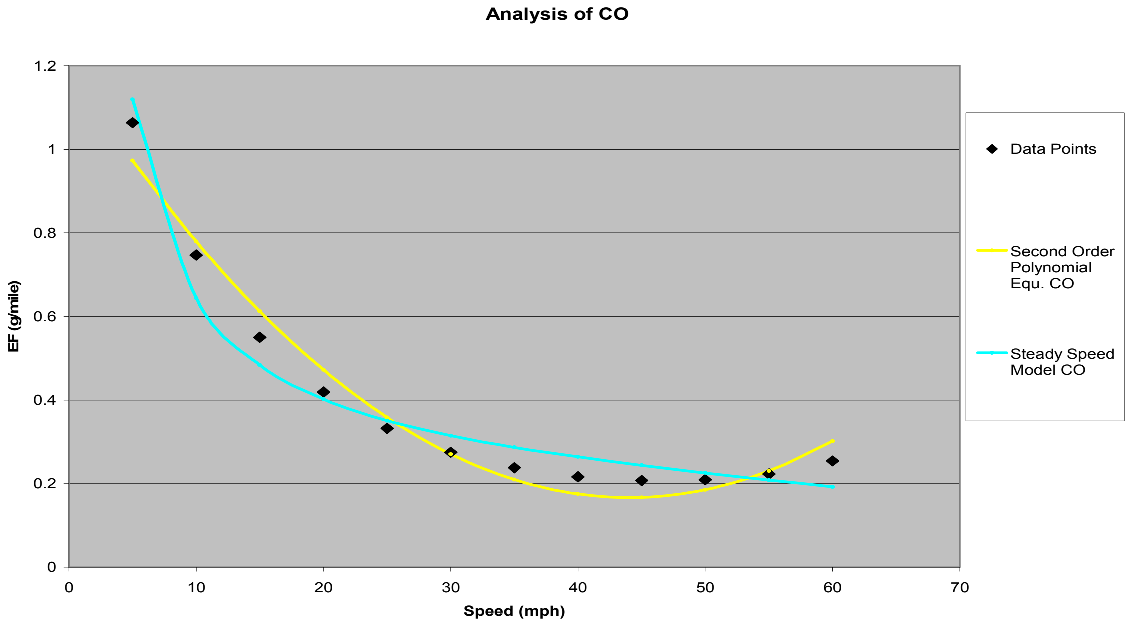

Figure B.83 Emission Trend of CO for Different Freeway Speeds

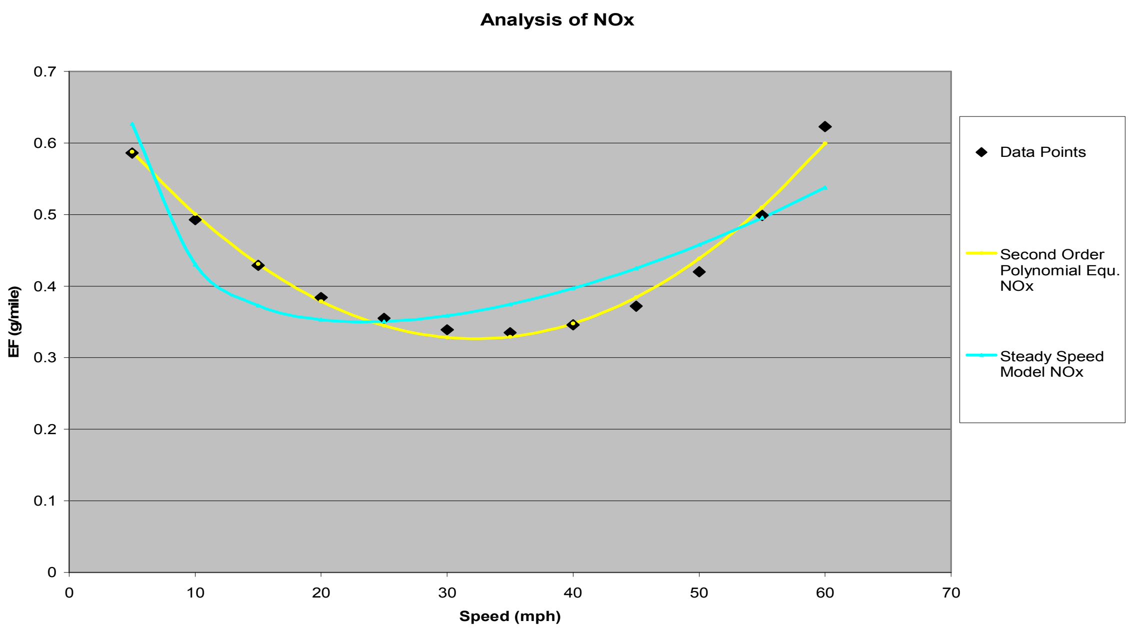

Figure B.84 Emission Trend of NO_x for Different Freeway Speeds

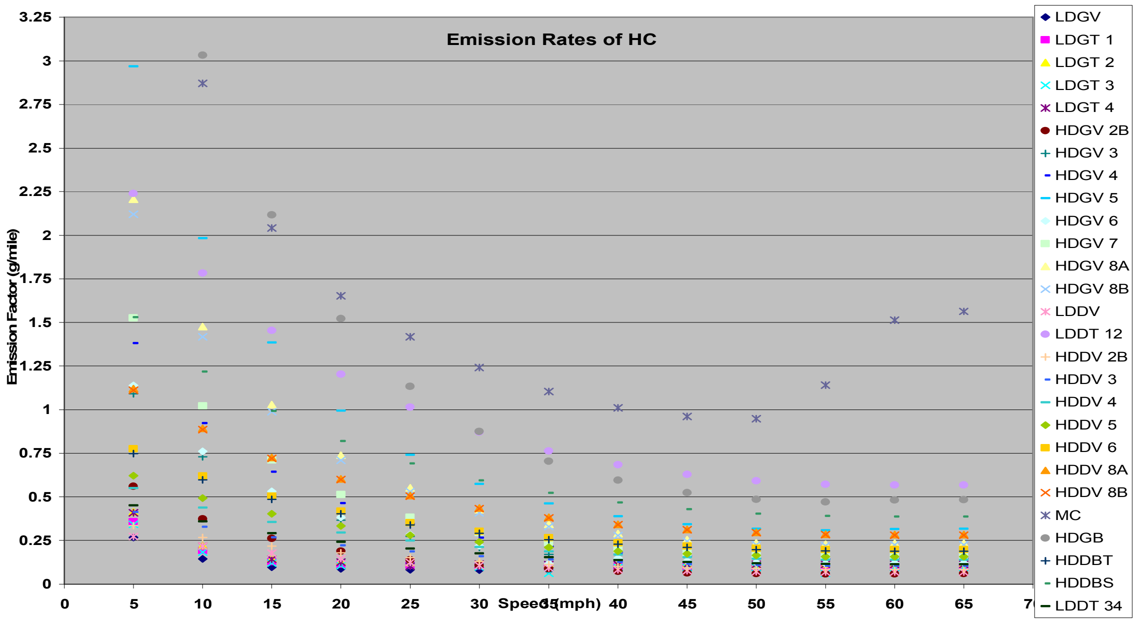

Figure B.85 Emission Trend of HC for Different Classes of Vehicles

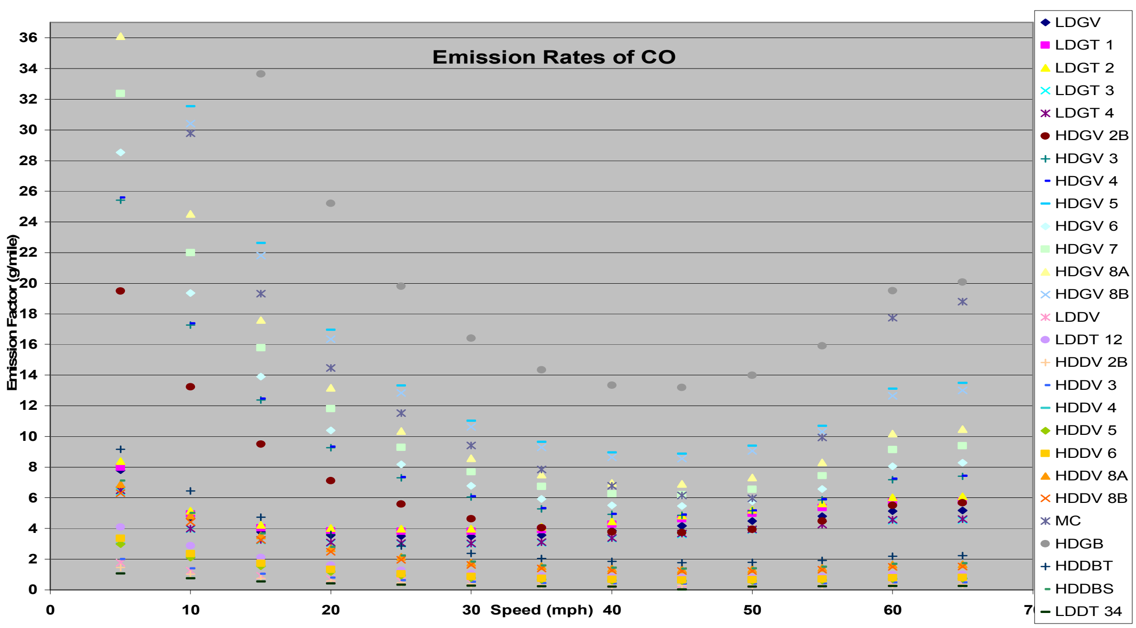

Figure B.86 Emission Trend of CO for Different Classes of Vehicles

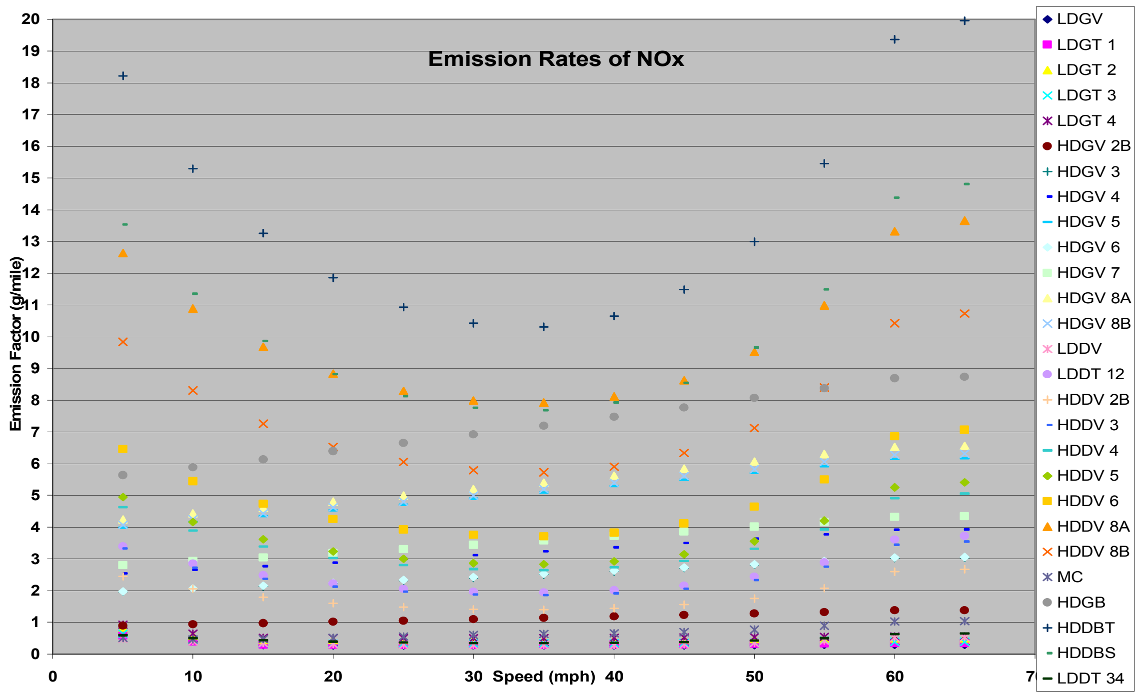

Figure B.87 Emission Trend of NO_x for Different Classes of Vehicles

REFERENCES

[1]. J. D. Colyar (2001) "An Empirical Study of the Relationships between Macroscopic Traffic Parameters and Vehicle Emissions," North Carolina State University, Raleigh, NC.

[2]. T. Tang, M. Roberts, and C. Ho, "Sensitivity Analysis of Mobile6," The Federal Highway Administration (FHWA).

[3]. K. Post, J.H. Kent, J. Tomlin and N. Carruthers (1983) "Fuel Consumption and Emission Modeling by Power Demand and a Comparison with other Models," Transportation Research-A Volume 18A, No. 3, pp. 191-213, 1984, Department of Mechanical Engineering, University of Sydney.

[4]. D. B. Jodray and C. Edwards (2005), "Transportation Conformity Determination for the Dallas-Fort Worth Non-Attainment Area that Includes Mobility 2025: The Metropolitan Transportation Plan, Amended April, 2005 and 2006-2008 Transportation Improvement Program," Transportation Department-North Central Texas Council of Governments.

[5]. K. Ahn (1998), "Microscopic Fuel Consumption and Emission Modeling," Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

[6]. S. Satyanarayan (2006), "Trends of Vehicular Emissions due to the Effect of Ethos as Fuel Additive," University of Texas, Arlington, TX.

[7]. I. Formunung, S. Washington, and R. Guensler (1999), "A Statistical Model for Estimating Oxides of Nitrogen Emissions from Light Duty Motor Vehicles," Transportation Research Part D 4, pp. 333-352, Georgia Institute of Technology, Atlanta, Georgia.

[8]. S. Washburn and F. Mannering (2003), "Statistical Modeling of Vehicle Emissions from Inspection/Maintenance Testing Data: An Exploratory Analysis reply," Transportation Research Part D 8, pp. 73-74, University of Florida, Gainesville, FL and Purdue University, West Lafayette, IN.

[9]. M. R. Bloomberg (2007), "Inventory of New York City Greenhouse Gas Emissions," City of New York.

[10]. Office of Integrated Analysis and Forecasting, EI-81 (2007), "U.S. Carbon-dioxide Emissions from Energy Sources 2006 Flash Estimate," U.S. Department of Energy.

[11]. "Greenhouse Gas Emissions from the U.S. Transportation Sector, 1990-2003", (2006) U.S. Environmental Protection Agency and Office of Transportation and Air Quality.

[12]. "Automobile Emissions: An Overview," (1994) U.S. Environmental Protection Agency Office of Mobile Sources.

[13]. "Evaluation of Mobile Vehicle Emission Model," (1994) the Bureau of Transportation Statistics Research and Innovative Technology Administration.

[14]. H. C. Frey, N. M. Rouphail, A. Unal, and J. D. Colyar (2001), "Measurement of On-Road Tailpipe CO, NO and HC Emissions using a Portable Instrument," Air and Water Management Association, North Carolina State University, Raleigh, NC.

[15]. "User's Guide to Mobile6.1 and Mobile6.2," (2003) U.S. Environmental Protection Agency.

[16]. M. L. Sattler (2006), "Transportation and Air Quality (Class Notes)," University of Texas at Arlington, TX.

[17]. S. A. Ardekani (2007), "UTA Managed Lane Toll Pricing Model (Draft)," University of Texas at Arlington, TX.

[18]. S. A. Ardekani (2007), "Fuel Consumption Models, (Class Notes)," University of Texas at Arlington, TX.

[19]. "EMFAC2007 Version 2.30 User's Guide," (2007) the Air Resource Board, California.

[20]. C. D. Cooper and F. C. Alley (2002), *Air Pollution Control*, University of Central Florida and Clemson University, Waveland Press, Illinois.

[21]. D. P. Bowyer, R. Akcelik, and D. C. Biggs (1984), "Guide to Fuel Consumption Analysis for Urban Traffic Management," ARRB Internal Report-AIR 390-9.

[22]. Office of Transportation and Air Quality "Brief History of the Mobile Highway Vehicle Emission Factor Model," (2004) U. S. Environmental Protection Agency.

[23]. EPA's Mobile review committee, Transportation Research Board, National Research Council, *Modeling Mobile-Source Emissions* (2000), National Academy Press, Washington, D.C.

[24]. Cambridge Systematics, Inc. "A sampling of Emission Analysis Techniques for Transportation Control Measures," (2000) Federal Highway Administration.

BIOGRAPHICAL INFORMATION

Abhishek Yerramalla was born on 15th January 1983. He hails from Hyderabad, India. He completed his Bachelors in Civil Engineering from Osmania University in 2005 During this period he also worked as an intern for Aarvee Associates where he contributed towards a project titled "Golden Quadrilateral" which mainly dealt with a feasibility study and detailed project for expanding the 2-lane National Highway 7 to a 4-lane.

He completed his Masters in Civil Engineering from the University of Texas at Arlington in Summer 2007. In Summer 2006 Walter P Moore company hired him as an engineering intern. He assisted in Traffic Impact studies and also a ATMS data base project for TX DOT in El Paso. Dr. Siamak A Ardekani appointed him as a graduate teaching assistant for the Spring and Summer of 2007. He attended the Institute of Transportation Engineers meetings at both state and international levels. His Masters thesis was titled "Vehicular Emissions Models using Mobile6.2 and field data". The focus of his thesis was to develop regression models to estimate the vehicular emission rates for major pollutants CO, CO_2, HC and NO_x. He has volunteered for the TX DOT Adopt a Highway program in 2005 and 2006.