IMPACTS OF SIGNAL SYNCHRONIZATION ON VEHICULAR EMISSIONS
- AN ON-BOARD MEASUREMENT CASE STUDY

by

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A SINCERE DEDICATION TO MY PARENTS

“wind beneath my wings”

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ABSTRACT

IMPACTS OF SIGNAL SYNCHRONIZATION ON VEHICULAR EMISSIONS - AN ON-BOARD MEASUREMENT CASE STUDY

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Nearly 56% of total nitrogen oxide (NO_x) emissions are produced by mobile sources in United States. Transportation and air quality managers at the state and regional level have the responsibility of developing and evaluating Transportation Control Measures (TCMs) and Transportation Improvement Plans (TIPs) to improve regional air quality. Signal synchronization is considered to be an effective TCM to reduce corridor congestion and maintain air quality in the region. This research was conducted to determine the impacts of signal synchronization on real-world, on-road emissions. A portable instrument, OBS-1300 manufactured by Horiba Instruments Inc., was used to measure on-road tailpipe emissions of NO_x on a second-by-second basis during actual driving. Data was collected in a light-duty 1999 Chevy Astro van. The focus of data collection was measuring emissions before and after signal synchronization on Great Southwest Parkway, Grand Prairie, Texas.

The collected data was analyzed using a series of statistical tests. The results determined that there was no significant change in NO_x emissions after signal retiming. Therefore, various variables were analyzed to check for their effect on emissions. It was observed that with the signal retiming, the average speed increased, which is directly proportional to NO_x emissions. Also, the parameters like ambient temperature, driver behavior, peak conditions and days of the week significantly impact real-world NO_x emissions. The instantaneous model also indicated that engine parameters significantly impact NO_x emissions in addition to instantaneous velocity and acceleration.

Thus, on-board data demonstrate the importance of real-world conditions and help develop more accurate traffic and air quality management policies.

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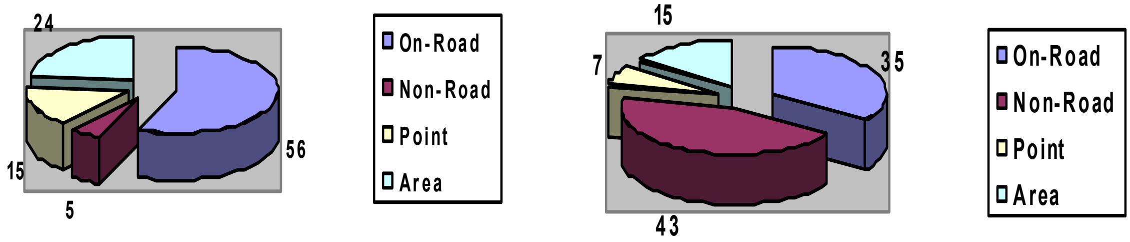
CHAPTER 1

INTRODUCTION

1.1 Air Quality and Transportation

“Nearly 103 million Americans in 119 metropolitan areas breathe air that does not meet National Ambient Air Quality Standards (NAAQS), according to the U.S. Environmental Protection Agency (EPA). Mobile sources account for more than half of air pollutants (56% approximately) in many urban areas” (Smith *et al*., 2001). Vehicular emissions contribute a major share of the total emissions for nitrogen oxide (NO_x), carbon monoxide (CO), hydrocarbons (HC/VOCs), particulate matter (PM) and carbon dioxide (CO_2). Figure 1-1 shows that for Dallas/Fort Worth (DFW), on-road sources contribute 56% and 35% of NO_x and VOC emissions, respectively (NCTCOG, 2005). These pollutants are highly detrimental for human health and environment.



NO_x Emissions (year 2002)

2002 VOC Emissions

Figure 1.1 NO_x and VOC emissions for DFW by various sources (NCTCOG, March 2005)

Transportation and air quality managers at the state and regional level have the responsibility of developing and evaluating Transportation Control Measures (TCMs) and Transportation Improvement Plans (TIPs) to improve air quality of the region. These measures accrue benefits at micro level such as individual signalized intersections, traffic-control devices, improvements of roadway facilities (e.g., ramps, roundabouts) and improved incident response and management. For congestion management in United States, signal synchronization is a widely used practice. Signal timing improvements can be simple changes in timing plans or complex, computer-controlled signal coordination along an entire corridor. When effective, signal improvement can reduce congestion, increase safety and improve response times for emergency vehicles.

1.2 Various Methods of Vehicular Emissions Measurement

There are different ways of measuring vehicular emissions as listed in Table 1-1:

Table 1.1 Different methods of emission measurement

Technique	Shortcoming
Dynamometer	Based on standard driving cycles, which may not replicate real-world conditions.
Remote Sensing	Provides a “snapshot” emissions reading at a single time and space.
Macroscopic Emission Models (like MOBILE6)	Based on standardized driving cycles; therefore, cannot account for increased/decreased numbers of accelerations.
Emission Models	May not be very accurate, especially if not calibrated for local conditions.

1.2.1 Why On-Road Tailpipe Emission Measurement?

- It measures real-world emissions from various driving patterns – (accelerations and decelerations), in comparison to the laboratory simulated emissions measured by dynamometer testing.
- It can measure emissions at various times continuously second by second at different places, rather than snap-shot remote sensing.
- "It evaluates 'micro' scale impacts: improvements at individual intersections too small to observe in a macroscopic model but significant when aggregated" (Sattler Melanie, 2004).
- It measures real-world emissions for actual driving conditions rather than modeling simulated conditions, which proves advantageous over micro scale modeling.

Many studies have been conducted for on-road emission measurements focusing on various parameters and using different fueled vehicles. Also, these researches deployed different emission measurement kits to measure the concerned pollutants for their region.

1.2.2 Why NOx Emissions Measurement?

As per 2001 State Implementation Plant (SIP) revisions, the Dallas/Fort Worth Metroplex is designated as a serious "non-attainment" zone for ozone per the one-hour standard. The precursors of ozone are NO_x and VOCs. Since DFW is declared as a NO_x limited zone, overall reductions in NO_x would highly reduce the formation of ozone. Thus, this study focuses on on-road tailpipe NO_x emission measurement since transportation is a major contributor of NO_x emissions.

1.3 Research Objective:

The primary goal of this study was to measure real world on-road NO_x emissions on Great Southwest Parkway in Grand Prarie, Texas. The objectives of this research project were as follows:

1. To evaluate the effect of signal synchronization with respect to vehicular emissions on a selected corridor on the basis of field data collection.
2. To determine whether signal synchronization significantly reduces emissions in terms of g/mile during peak and off peak travel times using statistical tests.
3. To develop an aggregate model, or corridor-level model, to predict emissions on a macro level.
4. To develop a disaggregate model to predict instantaneous emissions on a micro level.

1.4 Overview of Research Report:

Table 1.2 gives the overall organization of the thesis.

Table 1.2 Overall thesis report organization

Chapters	Contents
2	This chapter consists of a literature review of the similar studies that have been conducted using “on-road emission measurements”.
3	This chapter discusses the process deployed in conducting measurements.
4	This chapter discusses the analysis and results deduced from the data collection.
5	This chapter discusses the conclusions deduced from the analysis.
6	This chapter contains recommendations and the future scope of research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

2.1.1 Background

Transportation infrastructure is considered to be the backbone of a country and essential for its economic development, social growth and national defense. It reflects the economical and technological development of the nation. But at the same time, the adverse effects of the transportation sector on environmental degradation are well known. It consumes high levels of non-renewable sources like energy and fossil fuel. It is also a major contributor to air pollutant emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x) and volatile organic compounds (VOC), all of which have negative impacts at local and often at regional levels. Also, it is associated with adverse noise and land use impacts.

2.1.2 Air Quality Standards

As mentioned above, mobile sources contribute substantially to emissions of CO, VOCs, NO_x and Particulate Matter (PM). These are some of the primary criteria pollutants which are highly hazardous to human health and environment. NO_x and VOCs (hydrocarbons) contribute in the formation of ground level ozone (O_3) that is highly detrimental to the environment and health. NAAQS and Clean Air Act Amendments (CAAA) have divided the nation into two classes based on the air quality for all the six criteria pollutants (CO, Pb, NO_x, O_3, PM and SO_x):

1. Attainment Zone – An area that complies with a NAAQS is generally known as an "attainment area," although this is not an official classification under the Federal Clean Air Act.
2. Non-attainment Zone – Under the Federal Clean Air Act, any area that violates National Ambient Air Quality Standards (NAAQS) for any of the six criteria pollutants as few times as once per year and as often as four times over a three-year period is classified as a "nonattainment" area, as shown in Table 2.1.

Table 2.1 Air pollution concentrations required to exceed NAAQS (TCEQ, 2005)

Pollutant	Averaging Period	Standard	Primary NAAQS	Secondary NAAQS
Ozone	1-hr	Not to be at or above this level on more than three days over three years.	125 ppb	125 ppb
	8-hr	The average of the annual fourth highest daily eight-hour maximum over a three-year period is not to be at or above this level.	85 ppb	85 ppb
Carbon Monoxide	1-hr	Not to be at or above this level more than once per calendar year.	35.5 ppm	35.5 ppm
	8-hr	Not to be at or above this level more than once per calendar year.	9.5 ppm	9.5 ppm
Sulfur Dioxide	3-hr	Not to be at or above this level more than once per calendar year.	–	550 ppb
	24-hr	Not to be at or above this level more than once per calendar year.	145 ppb	–
	Annual	Not to be at or above this level.	35 ppb	–
Nitrogen Dioxide	Annual	Not to be at or above this level.	54 ppb	54 ppb

Table 2.1 Continued

Pollutant	Averaging Period	Standard	Primary NAAQS	Secondary NAAQS
Respirable Particulate Matter (10µ or less) (PM10)	24-hr	Not to be at or above this level on more than three days over three years with daily sampling.	155 µg/m^3	155 µg/m^3
	Annual	The three-year average of annual arithmetic mean concentrations at each monitor within an area is not to be at or above this level.	51 µg/m^3	51 µg/m^3
Respirable Particulate Matter (2.5µ or less) (PM2.5)	24-hr	The three-year average of the annual 98th percentile for each population-oriented monitor within an area is not to be at or above this level.	66 µg/m^3	66 µg/m^3
	Annual	The three-year average of annual arithmetic mean concentrations from single or multiple community-oriented monitors is not to be at or above this level.	15.1 µg/m^3	15.1µg/m^3
Lead	Quarter	Not to be at or above this level.	1.55 µg/m^3	1.55µg/m^3

Notes:

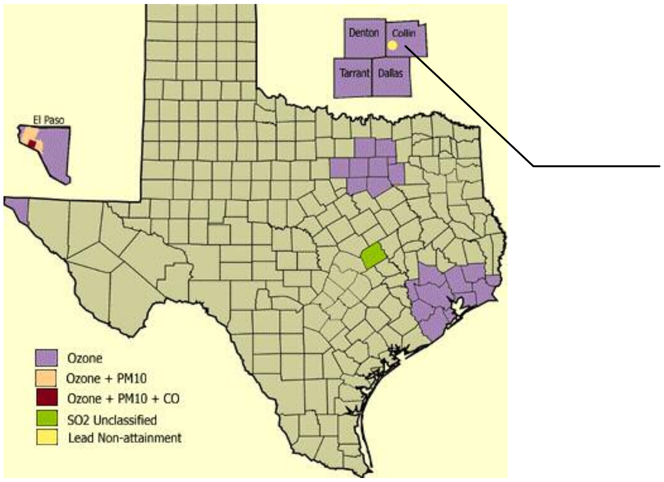
Primary NAAQS: the levels of air quality that the EPA judges necessary, with an adequate margin of safety, to protect the public health.

Secondary NAAQS: the levels of air quality that the EPA judges necessary to protect the public welfare from any known or anticipated adverse effects.

2.1.3 Brief History of Air Quality In Dallas/Fort Worth Metroplex

According to 1990 Federal Clean Air Act Ammendments (FCAAA), the Dallas Fort Worth (DFW) Metroplex was classified as a moderate ozone nonattainment area. As a moderate nonattainment area, DFW was required to demonstrate attainment of the 1-hour ozone standard by November 15, 1996.

In 1994, photochemical modeling was submitted with the State Implementation Plan (SIP) which showed that ozone attainment would be achieved by VOC reduction only. But as shown in Figure 2.1, the data from the DFW area ambient air quality monitors from the years 1994-96 showed that the 1-hour NAAQS for ozone was exceeded more than one day per year over this three year period. Since the region failed to comply with NAAQS, the Environmental Protection Agency (EPA) reclassified DFW as a “serious” non-attainment zone.



DFW Metroplex – Four Counties designated as Non Attainment Zone according to 1-hour Ozone standard. (TCEQ, April 2005)

Figure 2.1 Air quality in DFW metroplex according to 1-hour ozone standard

Also, EPA required a SIP to be resubmitted by March 20, 1999. This time, the photochemical modeling investigated the effect of NO_x and VOCs in the formation of ozone. The results concluded that combined reduction in NO_x and VOCs would be effective in reducing ozone formation. The 1999SIP submitted was incomplete but a complete SIP was submitted in April 2000. The April 2000 SIP included the following issues (TCEQ, 2005):

- Photochemical modeling of specific control strategies and future state and national rules for attainment of the 1-hour ozone standard in the DFW area by the attainment deadline of November 15, 2007.
- A modeling demonstration that shows that the air quality in the DFW area is influenced at times by transport from the Houston Galveston area (HGA).
- Identification of the level of reductions of VOC and NO_x emissions necessary to attain the 1-hour ozone standard by 2007.
- Control strategies developed by the State of Texas involving controls on stationary sources.
- Control strategies selected by the NCTCOG North Texas Clean Air Steering Committee.
- A 2007 mobile source budget for transportation conformity.
- A commitment to perform and submit a mid-course review by May 1, 2004.

DFW has been implementing the 2000 1-hour SIP although it was never approved by EPA because the federal courts struck down transport arguments in other states. The courts held that EPA cannot approve a SIP with an extended compliance deadline based on pollution transport from another region with a later deadline. As of 15th June, 2005 EPA began implementing a new ozone standard with an 8-hour averaging time. As per 8-hour standards, the DFW region, which is designated as a “moderate” non-attainment zone is developing a new 8-hour SIP that is more stringent than 1-hour 2000 SIP.

2.1.4 Transportation Control Measures

Since NO_x and VOCs are the precursors of harmful ozone and the DFW Metroplex is designated as NO_x limited zone, NO_x reduction would highly reduce the formation of ground level ozone (O_3). Thus, the measures that reduce emissions by even small percents can substantially improve air quality. Measures that reduce emissions (and typically traffic congestion) by improving transportation operations are called Transportation Control Measures (TCMs).

Among all the measures included in the 2000 SIP, Transportation Control Measures (TCMs) play a major role in reducing NO_x emissions caused by vehicles. Different TCMs applied to the DFW Metroplex include:

1. Sequencing traffic signals,
2. Improving intersections,
3. Widening streets,
4. Adding protected left-turn lanes and
5. Designating high occupany-vehicle (HOV) lanes.

In United States, signal synchronization has been widely used TCM to deal with congestion management issue. The signal improvements can be made for an individual roadway or along an entire corridor network. It reduces traffic congestion, increases safety and improves response times for emergency vehicles.

2.2 Vehicle Emissions

Vehicle emissions are measured and the reductions are estimated to ensure the air quality in the region. Quantitative emission reductions are required to be estimated in the SIP submitted by the region or state to the EPA. If these emission reductions are underestimated, it results in an overly stringent and costly SIP. However, if these emission reductions are overestimated, it results in the SIP falling short of achieving required compliance. There are different ways of measuring or modeling vehicular emissions as described below:

1. Dynamometer:

In dynamometer testing, emissions are measured in lab controlled conditions wherein a specified driving cycle simulates vehicle road operation. A vehicle is driven on a simulated cycle involving stops, starts, acceleration, deceleration, constant speed and idling. All these driving modes are characterized by an overall time-weighted average speed.

Since dynamometer testing was not designed to replicate real world emissions, it is not beneficial in quantifying TCM emission benefits. Figure 2.2 shows a typical chasis dynamometer. (Mustangdyne, March 2005)

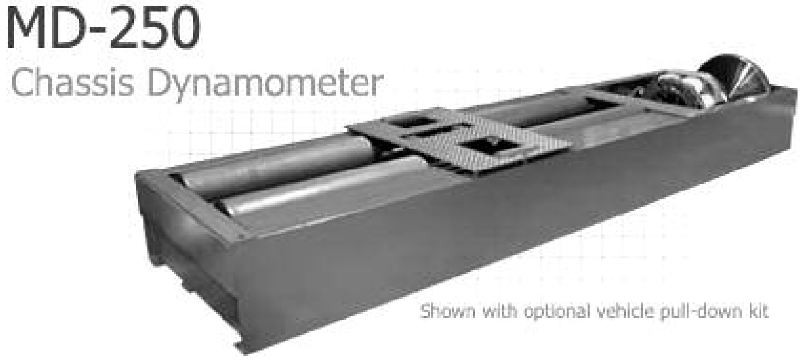


Figure 2.2 Chassis dynamometer

2. Remote Sensing:

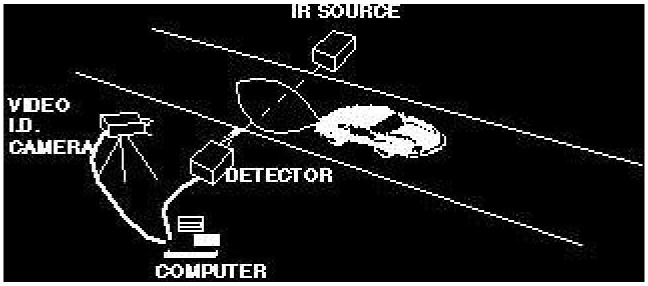


Figure 2.3 Remote Sensing (City of Albuquerque, “Remote sensing” March 2005)

Remote sensing is a method to measure pollutant levels in a vehicle's exhaust while the vehicle is traveling down the road. Unlike most equipment used to measure vehicle (RSDs) do not need to be physically connected to the vehicle. It facilitates collection of trend data for entire vehicle populations, identifies gross polluters between inspection cycles, and allows for the emissions monitoring of commuter vehicles that are registered outside the boundaries of the test area.

As shown in Figure 2.3 above, the RSD system uses an infrared (IR) absorption principle to measure emissions. The system operates by projecting a beam of IR radiation across a roadway continuously. Two scenarios may be observed:

- When the RSD's detectors are receiving infrared light signals through the air with no vehicle emissions in the path, the signals are strong.
- If there is some amount of CO, CO_2, HC, or NO_x present in the path, it will absorb a portion of the light for the pollutant's unique wavelength, thus weakening the signals.

“In the case of NOx, the RSD uses an ultraviolet (UV) light source in addition to the infrared beam. This is due to the fact that NO_x absorption characteristics are stronger and more selective in the ultraviolet light spectrum. RSD systems also employ a freeze-frame video camera and equipment to digitize a color image of the rear of the tested vehicle, including the license plate. This allows the system to store emissions information for each monitored vehicle, based on the license plate number." (City of Albuquerque, "Remote sensing" March 2005)

Although remote sensing can be used to examine a large number of vehicles, it only provides a "snapshot" of emissions reading at a particular time and location. In the case of TCMs such as signal synchronization, emissions need to be quantified for the entire length of the corridor and thus remote sensing is not well-suited for evaluation of TCM emission benefits.

3. Macroscopic Emission Models (eg: MOBILE6)

The macroscopic modeling component consists of a model that has been developed for freeway and arterial road networks for the whole region. There are various macroscopic models, however this research focuses on MOBILE6 and SYNCHRO which are adapted by North Central Texas Council of Governments (NCTCOG) for estimating DFW mobile source emission reductions associated with the Thoroughfare Assessment Program (TAP). These emissions benefits are quantified by NCTCOG in the transportation conformity.

Unlike many traffic models (Transyt-7F, Passer II-90, HCS and SIGNAL 97), MOBILE6 estimates on-road vehicle emissions under various conditions. MOBILE6 is widely used because it is more efficient and detailed compared to other models. It gives better understanding of emissions and facilitates input of latest and updated data available. In MOBILE6, emission rates can be combined with activity (vehicle miles traveled or VMT) from a travel demand model to develop highway emission inventories expressed in tons per time period. Further, it calculates region-wide emission factors (EF) in grams/mile for arterials, free-ways, ramps and other minor road connectors.

Another macroscopic model, SYNCHRO calculates fuel consumption based on vehicle miles, total control delay and total number of stops. In its basic approach, fuel consumption is then multiplied by an adjustment factor to estimate vehicle emissions. (Rouphail et al., 2001)

Although these region-wide models predict emissions, they are not designed to be effective in quantifying TCM emission benefits. The reason is that benefits of TCMs such as signal synchronization accrue at the "micro" level. To evaluate air quality benefits of such TCMs, it is necessary to evaluate localized emission changes at a fixed location.

4. Microscopic Emission Models:

Several microscopic sub-models also exist that simulate traffic on different roadway facility types such as freeway segments, freeway on-ramps, arterial intersections, and rural highways.

For example, the microscopic model CORSIM was developed for the Federal Highway Administration. The computer model consists of two principal modules, a pre-processor and simulator. It uses vehicle emission rates from dynamometer testing. An urban street is represented as a set of nodes and directed links. Total emissions on each link are determined by applying default emission rates (based on speed and acceleration from look-up tables) to each driving vehicle second by second traveling on the link. CORSIM can accommodate a range of traffic control scenarios, including fixed time and fully actuated control. Each vehicle as it is enters the network is stochastically assigned a set of performance characteristics, which include a vehicle type as well as driver behavior characteristics.

Microscopic models are more accurate than region-wide macroscopic models but may still be inaccurate if not calibrated for local conditions. Also, vehicle operating history can impact emissions, but speed-acceleration table cannot account for this. Microscopic models, however, represent the best strategy for estimating benefits pre-implementation.

5. On-Board Emission Measurement:

On-board emission measurement is a widely used “micro-scale” approach for quantifying vehicular emissions since the data is collected under real-world conditions at any point of time and location where the vehicle is driven. It measures real-world emissions from various driving patterns (accelerations and decelerations), in comparison to the laboratory simulated emissions measured by dynamometer testing. Also, it proves advantageous over RSDs since remote sensing gives an instantaneous estimate of emissions at a specific location and cannot be used across multiple lanes of heavy traffic. Improvements at individual intersections which are too small to observe in a macroscopic model but are significant when aggregated, can be measured using on-board systems. Also, it measures real-world emissions for actual driving conditions rather than model simulated conditions which prove advantageous over micro scale modeling. Variability in vehicular emissions as a result of variation in road characteristics, vehicle location, vehicle operation, driver behavior are accurately represented and analyzed in on-board emission measurement as compared to other methods.

2.3 Literature Review

Many studies have been conducted using on-road emission measurements, focusing on various parameters and using different fueled vehicles. Also, these researches deployed different emission measurement kits to measure the concerned pollutants for their region. A number of ongoing researches are listed in Table 2.2, which aim to measure vehicular emissions and consider various factors affecting mobile source emissions.

Table 2.2 Different details regarding the ongoing researches in the related field:

Sr. No.	Author	Agency	Vehicles tested	Parameters measured	Sensor / Analyser	Kind of Test	Sources/ Remarks
1	Christopher Frey, Nagui Rouphail, et al.	NCSU, 2001	11 vehicles – 1998 Plymouth Breeze Sedan, 1999 Ford Taurus Sedan, 1998 Ford Club Wagon, 1998 Toyota Camry Sedan, 1996 Dodge Caravan, 1997 Jeep Cherokee sport utility vehicle,1998 Chevy Venture, 1996	CO, NO and HC	OEM 2100 $^{\text{TM}}$	On-board measurement and analysis of on-road vehicle emissions	Studies parameters like traffic signals, road conditions, traffic congestion and driving behavior were studied that influence motor vehicle emissions in real world.
2	Matthew Smith, Kent Johnson, *et.al*	UC-Riverside, CE-CERT, 2001	Class 8 Tractor with common Detroit Diesel, Caterpillar or Cummins Engine.	PM and other gaseous emissions	Dynamometer	Develop on-Road system for HDT emission measurement	Comparison between dynamometer and real world emissions.
3	Randall L. Guensler and Billy Williams	CEE, Georgia Institute of Technology	Majority were Atlanta vehicles (type and make not mentioned)	vehicles miles traveled (VMT) and model improvements	SEMTECH-G	The role of instrumented vehicle data in transportation decision making	Identify factors affecting crash risk & understand price elasticity of trip making behavior.

Table 2.2 Continued

4	H.Y. Tong and W.T. Hung, C.S. Cheung	Polytechnic University, Hong Kong, 2000	4 different vehicles: 1. Passenger Car 2. Petrol Van 3. Diesel Van 4. Double-decker	CO, CO_2, NO_x, O_2 and HC	Flux-2000 five gas analyzer	On-road motor vehicle emissions & fuel consumption in Urban driving conditions	Comparison of Emissions to various modes of driving.
5	Gibble, John Curtis	West Virginia University, 2003	Six different diesel powered vehicles.	NO_x and CO_2	Mobile Emissions Measurement System (MEMS)	Comparison of Heavy-duty diesel engine emissions between an on-road route & engine dynamometer simulated on-road	
6	Hawariko, Jason David	University of Alberta, Canada 2003	1992 GMC three-quarter ton regular cab pick-up	HC, CO and NO_x	Vetronix PXA-1100 Five gas analyzer	Modeling vehicle emission factors determined with an in-use and real-time emission measurement system	

Table 2.2 Continued

7	Mazzoleni, Claudio	University of Nevada, Reno, 2003	Vehicles in Clark County	PM	Vehicle Emission remote sensing system (VERSS)	On-road emission measurement by remote sensing	Comparison of PM emissions based on model year of vehicles in Clark county.
8	Kean, Andrew James	University of California, Berkerly, 2002		CO, NO_x, Non-methane Organic Compounds Ammonia (NH_3) & CO_2		Effects of vehicle speed and engine load on emissions from in-use light duy vehicles	correlation with the roadway characteristics and engine load.
9	Liao, Tsai-Yun	University of Texas-Austin, 1997		CO and CO_2	Analytical Fuel Consumption Model (ACFM)	Fuel consumption estimation and optimal traffic signal timing	Factors affecting emissions
10	Fomunung, Ignatius Wobyeba	Georgia Institute of Technology, 2000		HC, CO and NO_x	MEASURE	Predicting emission rates for Atlanta on-road light duty vehicular fleet as a function of operating modes, control technologies and engine characteristics	Updating MEASURE which can account for acceleration, deceleration and engine load

Table 2.2 Continued

11	Tong, Hing-Yan	Hong Kong Polytechnic University, 2001			TREFSIM	Vehicular emissions and fuel consumption at urban traffic signal controlled junctions	Microscopic Traffic simulation model - TREFSIM
12	Glynis C. Lough & James Schauer, Lonneman & Mark Allen	University of Wisconsin Milwaukee 2005	Vehicular fleet passing on testing days through two tunnels in Milwaukee	Nonmethane hydrocarbons (NMHCs) and PM	Gas Chromatography	Summer and winter NHMC from on-road motor vehicles in Midwestern USA	

Remarks for above sources:

1. In this NCSU research study, the parameters that influence motor vehicle emissions in the real world, like traffic signals, road conditions, traffic congestion and driving behavior were studied. The emissions were measured by On-board Emission Measurement (OEM) repeatedly and then by logging the measurements on computer (data acquisition system), the spreadsheets were prepared. These data were analyzed statistically by using ANOVA for detailed analysis of factors affecting emissions. The data of pollutants vs. time indicate that emissions rates differ during different driving modes (acceleration, deceleration, cruise and idling). Average emissions of HC, NO and CO are significantly higher in acceleration than in other driving modes. Also, taking before and after signal coordination data samples, modal emission rates for HC in idle and deceleration, NO idle and acceleration and CO idle and acceleration were similar before and after signal coordination. The data suggest that efforts aimed at reducing only stop time may not always be successful in achieving overall reductions in emissions of air pollution. Also, this study concluded that for congested roadways, there was no significant reduction in emissions after signal coordination because the congestion did not improve and thereby there was no emission reduction.

   This study also studied all driving modes and their effect on emissions. It concluded that acceleration produces maximum emissions followed by deceleration and cruise. This means that synchronizing signals reduces accelerations and decelerations and thereby may reduce vehicle emissions.

2. CE-CERT, UC Riverside constructed an emissions laboratory within a 53-foot container trailer to study a tractor's emissions under actual driving conditions. This laboratory was designed to replicate a traditional engine/chasis heavy-duty emissions laboratory configuration as closely as possible. However, it operated while in motion, with the laboratory itself served as the load for heavy-duty tractor to pull. The laboratory captured the truck's PM and other gaseous emissions and compared them with on-board instrumentation in real time. These real-world emissions data was further used as input into emissions inventories and atmospheric models. This provided accurate data that can predict overall emissions and future air quality. The source of this research as of 31st May 2001 did not provide final results, as it says that CE-CERT had not accumulated sufficient data to draw comparisons between dynamometer and real world emissions data.
3. The research is focused on the importance of the role of instrumented vehicles in transportation decision making. The detailed use of various data streams in transportation model development and calibration, transportation control measure evaluation, congestion studies and vehicle emission modeling are outlined. The research team uses a SEMTECH-G analyzer to collect accurate, high-resolution emission measurements in parallel with engine and vehicle activity. These datasets will facilitate development of more accurate regional and micro scale emission modeling capabilities to satisfy long-term conformity reviews and short-term project evaluation.

4. This research focuses on influences of instantaneous vehicle speed on emissions and fuel consumption. This study concluded that the fuel-based emission factors varied much less than the time-based and distance-based emission factors as instantaneous speed changed. The study suggested that great emphasis should be placed on minimizing vehicle stops in urban areas to speed traffic and to smooth acceleration and deceleration since these driving modes produce more emissions compared with cruise.
5. The study aimed to examine the accuracy of the West Virginia University Mobile Emissions Measurement System (MEMS). On-road emission tests were performed with six different diesel powered vehicles. MEMS measured exhaust pollutants like NO_x and CO_2, which were thereafter, used an input in the development of simulated in-use dynamometer cycle. The system was compared against an engine dynamometer laboratory.
6. This research has multiple objectives that were achieved at different phases of the project. The research concluded that the all emission factors increased with decreasing ambient/initial engine temperatures. It also found that typical magnitude increases between the cold-start pre and post light-off emission factors were 100, 60 and 10 for emissions of HC, CO and NO_x, respectively.
7. This research is based on PM emission measurements via remote sensing. A new Vehicle Emission Remote Sensing System (VERSS) has been developed for measurement of PM emission factors. This system captures the vehicle's rear license plate and thereby the researchers acquired data for each vehicle such as

model year, vehicle weight category, and engine ignition type. This enables development of a correlation between vehicle characteristics and PM emissions. VERSS also measures speed and acceleration of the vehicles. Also, a commercial VERSS can be used to measure CO, HC and NO_x.

8. This study has some novel findings for the pollutants (CO, HC, NMOC, NH_3, CO_2 and NO_x) correlation to variations in roadway grade, vehicle speed, travel direction and engine load. In regard to engine load, CO emissions were constant till a certain value known as threshold and thereafter it increased drastically. NO_x emissions increased with operating engine load conditions. Emission factors for NH_3 and NO_x were observed to increase with increase in vehicle speed and engine load. These factors suggested that the development in vehicle emission control technology due to stringent governmental standards has led to improvement of air quality by reducing the emissions.
9. This research aims to develop a model that estimates fuel consumption and studies the effect of signal timing on fuel consumption. To achieve this, an Analytical Fuel Consumption Model (ACFM) was developed that is based on a conceptual framework to identify interrelationships among traffic characteristics, signal control strategies and roadway geometry conditions.
10. Georgia Tech uses the model MEASURE, which unlike other models addresses acceleration, deceleration and engine load. This research focused on updating MEASURE with algorithms that can give accurate emission predictions from vehicles. For this, statistical techniques such as Hierarchical Tree Based

Regression (HTBR) and Ordinary Least Squares Regression (OLSR) were developed to forecast emissions of HC, CO and NO_x from the current light duty vehicular fleet in Atlanta.

11. This research was intended to develop a microscopic traffic simulation model TREFSIM to estimate vehicle journey time, average speed, delay, fuel consumption and emissions in urban traffic signal controlled roads. It also incorporates NNDHM – a discharge headway model of individual vehicle queued at signal controlled junctions. TREFSIM is of the microscopic level and thereby it is sensitive to vehicular behavior at signals.
12. Many Nonmethane Hydrocarbons (NHMC) are classified as hazardous air pollutants by EPA due to their effects on human health. NHMCs also contribute to the formation of ground-level ozone and secondary organic aerosols. This research provides information about seasonal impacts on vehicular NHMC emissions from vehicles. The study showed a significant impact of seasonal differences on fuels and emissions. NHMC emissions were affected by vehicle condition and performance of catalytic converters in cold weather conditions. Thus, during cold starts, NHMC emissions are higher due to partial combustion. Therefore, effective air control strategies should be developed concerning fuel composition with respect to seasonal temperature changes to control NHMC and toxic air emissions.

2.4 Research Objectives

From the above literature and to best of my knowledge, this research covers additional aspects of on-road NO_x emission measurement. The previous on-road studies have shown the significance of average speed, humidity and modes of driving as the main parameters affecting NO_x emissions (NCSU, 2001). This research also considers parameters like ambient temperature and days of the week as the variables that would affect the variability in NO_x emissions.

Previous study at NCSU compared drivers for the variability in pollutant emissions (HC, CO and NO_x). The study concluded that there was no difference in emissions with the drivers (Frey *et al*. 2003). Since NO_x emissions are related to average speed and acceleration/decelerations, the research at UTA checks for the driving behavior as a significant parameter for NO_x emissions.

This research also develops an aggregate regression model considering a wide variety of variables including average ambient humidity, ambient temperature, number of stops and average speed. The aggregate model also introduces driver as a dummy variable. Furthermore, an instantaneous model is developed to predict NO_x emissions using second by second on-road data for instantaneous speed, acceleration and NO_x emissions.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 General

3.1.1 NCTCOG's Transportation Control Measure

As discussed in Chapter 2, North Central Texas Council of Governments (NCTCOG) has developed a Thoroughfare Assessment Program (TAP) as a Transportation Control Measure (TCM) submitted in the transportation conformity. The goals of TAP are to reduce emissions and improve air quality as well as reduce congestion and improve traffic flow in the DFW region through signal synchronization and low-cost operational improvements. Signal synchronization facilitates better traffic flow and thereby minimizes congestion at the signals. Previously, NCTCOG was using Mobile Source Emission Reduction System (MOSERS) for air quality benefit calculations. MOSERS was based on assumptions which do not account for accelerations and decelerations at the intersections. It was based on the assumptions that, due to signal retiming and moderate upgrades, delay decreases and speed increases equally at all intersections irrespective of intersection performance and traffic volume. Due to this assumption, detailed data was not considered for all intersections at the microscopic level. Therefore, NCTCOG has developed a new method for post processing SYNCHRO output to calculate air quality benefits under the TAP program. This methodology takes into account delay, queue length, stops and speed at each intersection approach.

The TAP was developed in two phases:

1. Pilot Phase: This phase was conducted on a small scale for method development considering all the parameters affecting air quality. The data collection was conducted for 49 signalized intersections. This phase identified different parameters affecting vehicular emissions for a detailed study.
2. Production Phase: This phase consisted of a detailed study covering 44 corridors, including 835 signalized intersections throughout the DFW Metroplex. The traffic counts for am, midday and pm peak hours were obtained from SYNCHRO Model in before and after signal retiming scenarios. There was a post-processing approach of calculations of emission reductions of NO_x and VOCs (g/mile) from different traffic parameters available from SYNCHRO listed below:
    - Link Speed (miles per hour)
    - Traffic Volume (vehicles per hour)
    - Stops (vehicles per hour)
    - Signal Delay/Vehicle (sec/vehicle)
    - Internal Link Distance (ft)
    - Queue Length 50th (ft)

    The emission factors (EF) for NO_x and VOCs were obtained from the EPA emissions model MOBILE5.

Although the post-processing approach has a better approach for calculating emissions as compared to other models, it does not account for zero speed, as MOBILE5 does not have EF for zero speed. Thus, an equivalent speed of 2.5 mph is assumed for stopped vehicles.

3.1.2 Research Objective of This Study

The objective of this study is based on the following hypothesis:

1. Emissions will decrease with the signal synchronizations. That means the emissions in terms of g/mile will decrease after signal retiming for Great Southwest Corridor.
2. Real world emissions tend to be different than modeled emissions.

3.1.3 Great Southwest Parkway

Great Southwest (GSW) Parkway is a road in the city of Grand Prairie, Texas. The stretch of Great Southwest Parkway under study is from the signalized intersections of GSW and Abram Street to GSW and Fairmont Street. This stretch of road has multiple facets such as a school zone, two railroad crossings, commercial zone and residential neighborhood. It also runs perpendicular to an approach road of I-20 at one signalized intersection. These facets impact the flow of traffic and thereby the traffic volume is unique at each signalized intersection. For example, at the intersection connecting to I-20, the traffic volume is higher compared with the GSW intersections connecting to residential neighborhoods. Also, the school zone lowers the speed limit for a small stretch of GSW from the normal speed limit of 45 mph to 20 mph. A detailed map of the Great South West Parkway between the signalized intersections under study is shown in Figure 3.1:

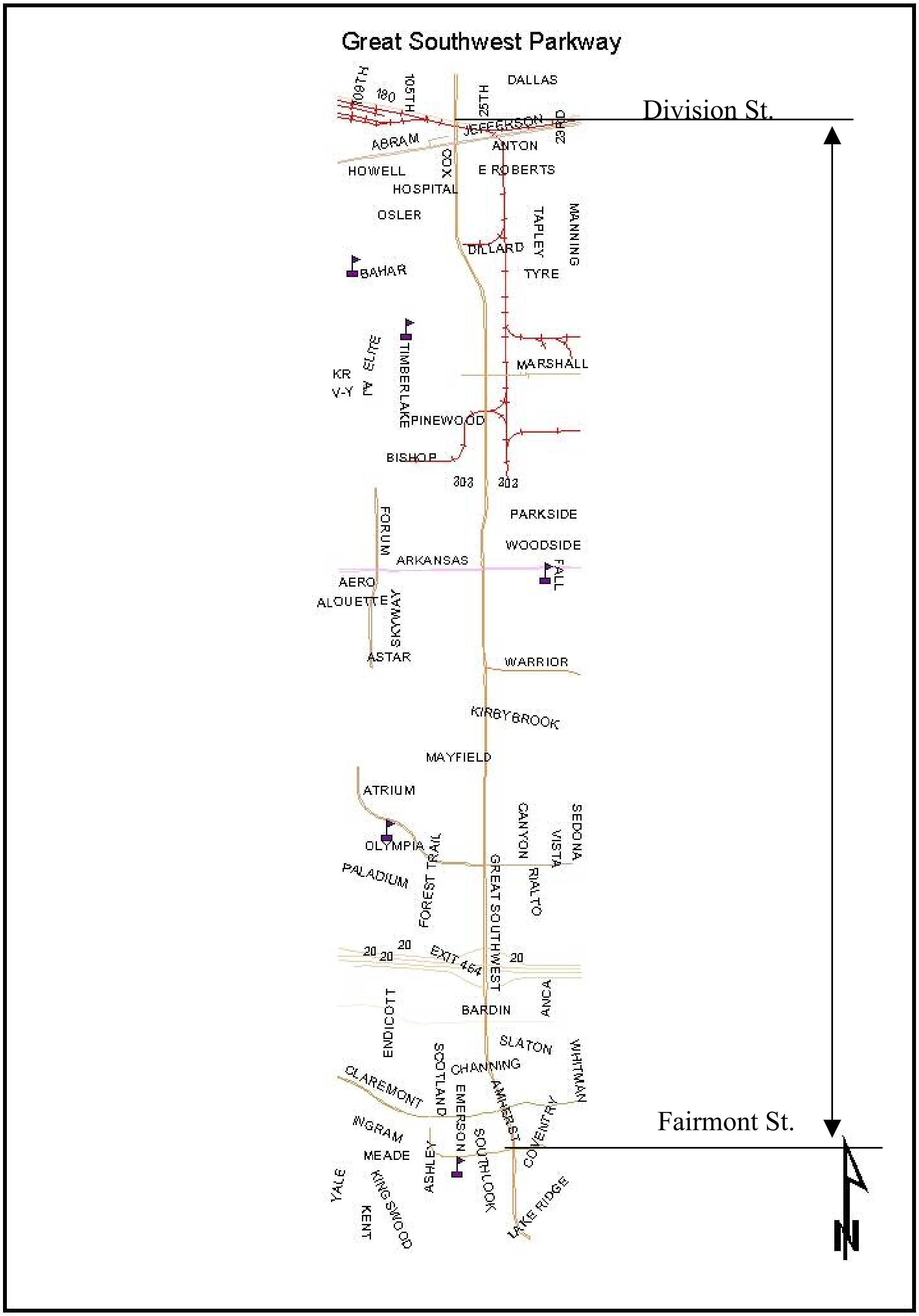


Figure 3.1 Layout of Great Southwest Parkway between study signals (NCTCOG, June 2005)

3.2 Data Measurement Setup

The research objectives were achieved by conducting an extensive on-board emission measurement study. The experimental setup consisted of a data sampling kit containing an On-Board System (OBS-1300) obtained from Horiba Instruments Inc. for emission measurement. The OBS 1300 included all the accessories that measured NO_x emissions as well as selected vehicle and tail pipe characteristics that can be checked for their correlation to emissions. The whole setup was installed in the University of Texas at Arlington (UTA) Civil Engineering (CEE) department Chevrolet Astro (model year 1999) van as shown above in Figure 3.2. The vehicle characteristics are listed in Table 3.1 below:

Figure 3.2 Chevrolet Astro Van (study vehicle)

Table 3.1 Chevrolet Astro characteristics

Parameters	Value
Engine	4.3L V6
Power	142 kW, 190 HP @ 4400 rpm
Fuel tank capacity	95 liters
Injection system	Multi-point

Since the model year is later than 1996, this vehicle has an On-board Diagnostic (OBD) system installed in the vehicle itself.

The OBS 1300 is an on-board emission measurement system used to perform simple analysis of exhaust gases from a vehicle driven on the road. It is composed of on-board gas analyzers as well as a personal computer (PC) equipped with data logging software. It is comprised of two main units, as shown in Figure 3.3 below:

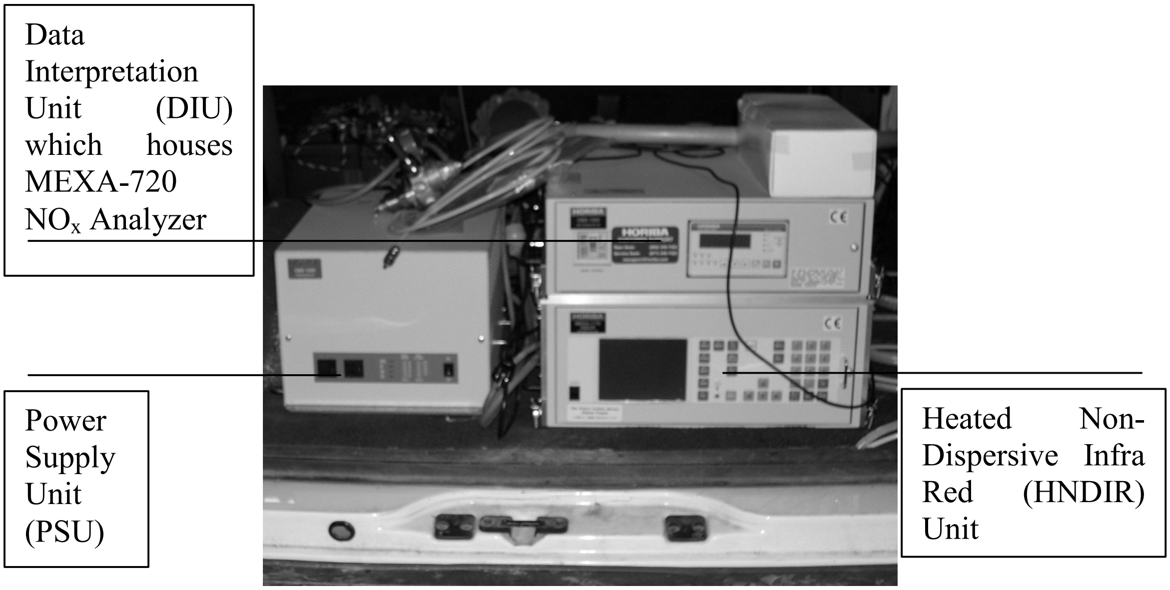


Figure 3.3 OBS 1300 Unit

Components of the OBS-1300 are now explained in more detail.

1. **Data Interpretation Unit (DIU):** This is an interface unit for each sensor, analyzer and the data logger PC. It houses pressure sensors and the MEXA-720 NO$_x$ analyzer. The MEXA 720 NO$_x$ analyzer is a non-sampling type zirconia analyzer that is connected to a sensor probe to the exhaust attachment, as shown in Figure 3.4 below.

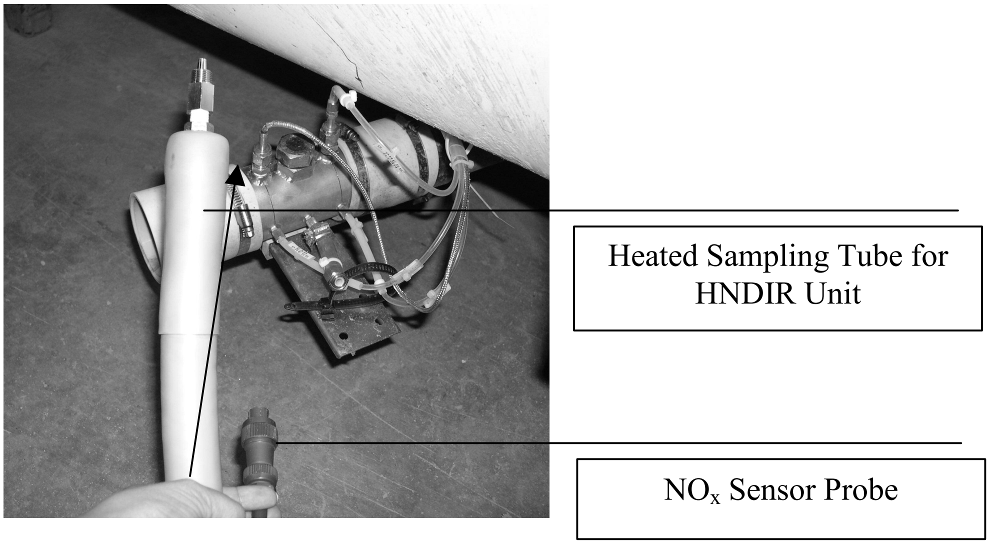


Figure 3.4 NO$_x$ Sensor and Sampling tube attached to the tail pipe attachment

2. **MEXA-1170 HNDIR Unit:** This unit used a Heated Non-Dispersive Infrared (HNDIR) technique to measure CO, HC and CO$_2$ emissions. The HNDIR unit has a heated sampling tube connected to the tail-pipe attachment as shown in Figure 3.4 above. It also connects the analog output of data to DIU.
3. **Power Supply Unit (PSU):** As shown in Figure 3.3 above, the power supply unit converts the battery output power (24 V DC) to AC current and supplies it to all the units. It also converts AC power to DC current for charging the battery. This unit is connected to the battery, DIU and external power supply

provided from batteries. A battery monitor is provided to display the voltage level of the battery.

4. **Data logger PC:** A DELL laptop is provided with the OBS 1300 for data logging. The software that is used in conjunction with OBS logs the pollutant emissions, A/F ratio, exhaust pipe temperature and ambient temperature and ambient humidity data.
5. **Battery**: As shown in Figure 3.5 below, two Deep Cell type batteries (24 V-12 V each) obtained from Trojan Batteries are used for the power supply to all the units. These batteries are connected to the PSU. The batteries should maintain their power for approximately four hours after they are fully charged.

Two Deep Cycle Trojan Batteries (12V) each

Figure 3.5 Batteries

6. **Tail pipe attachment:** An attachment is provided for the exhaust pipe to hold the tubing and wiring that connects to MEXA-1170 HNDIR and DIU, as shown in Figure 3.6.

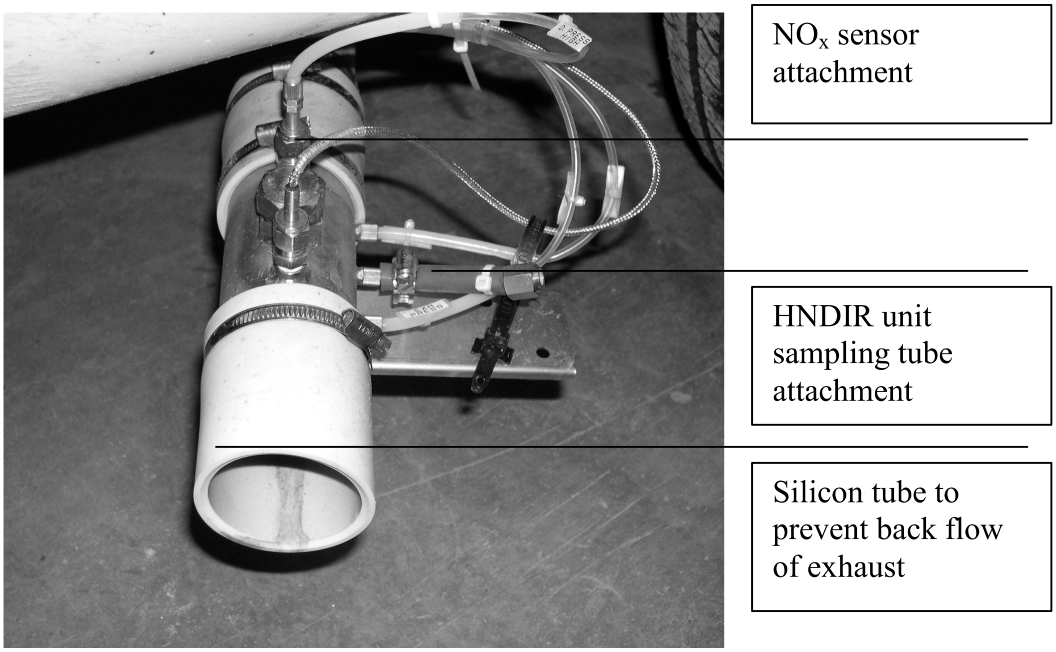


Figure 3.6 Tail pipe attachments

7. A **remote controller** is provided for controlling the MEXA-1170 HNDIR unit. It performs the HNDIR unit functions such as starting the sample intake into the sampling tube by pressing the “Measure” button on remote, which is also provided on the display panel in the HNDIR unit, as shown in Figure 3.7 below. When the data logger wishes to stop the sample intake, he/she can use the “Reset” button and the suction stops. Also, the HNDIR unit can be purged and calibrated (zero and span by different gases) using the buttons on the remote.

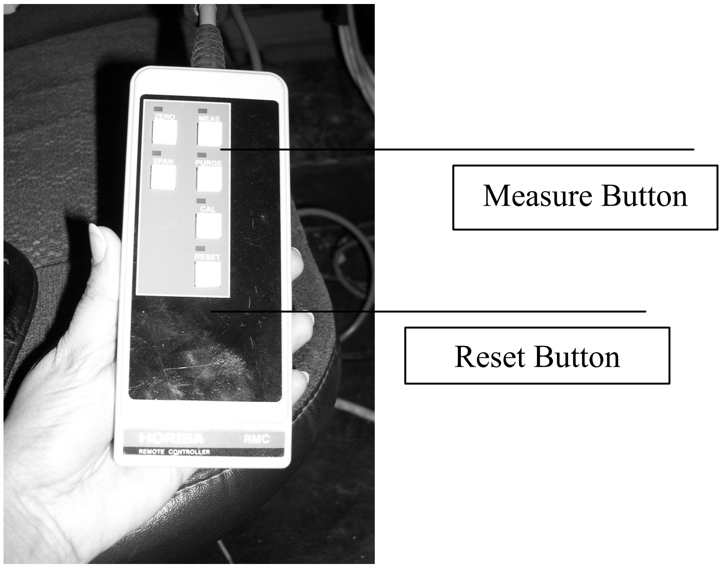


Figure 3.7 Remote controller

As shown in Figure 3.8, a **Geographic Positioning System (GPS)** antenna is used to measure velocity, altitude and positioning of vehicle on the roadway.

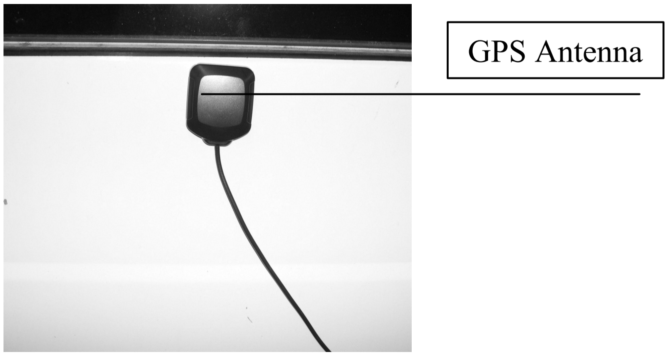


Figure 3.8 GPS Antenna

The entire setup of the OBS-1300 components is installed in the Chevy-Astro van as shown in the following schematic diagram (Figure 3.9):

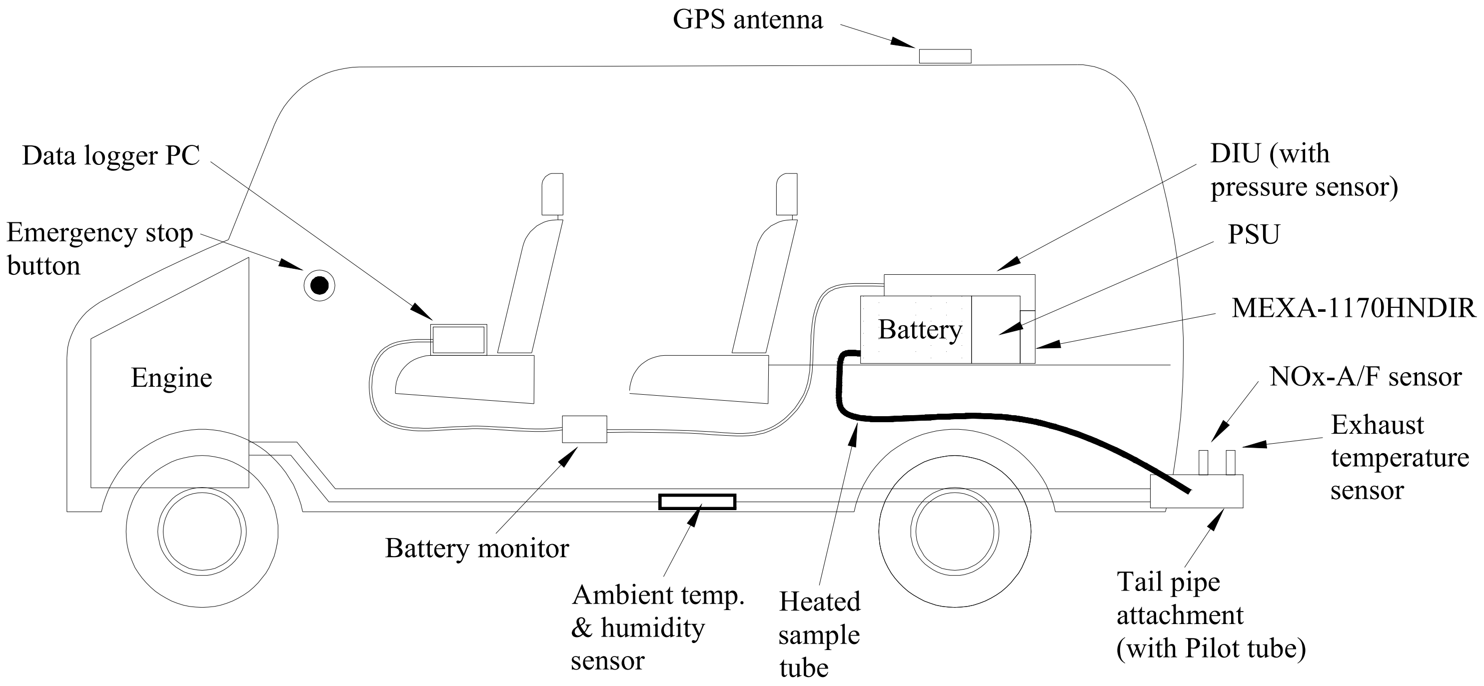


Figure 3.9 OBS-1300 setup in Chevy Astro van

3.3 Data Collection Procedure

3.3.1 General Setup

The OBS-1300 and its accessories were installed in the Chevy Astro van with help from Horiba technical representatives. Some test runs were made to ensure the system worked properly and a data check was also conducted. After the pilot runs, detailed data collection began. Runs were made for three different traffic conditions:

1. AM Peak – 7:00 to 8:30 AM
2. Off-Peak – 8:30 to 11:00 AM and 4:00 to 4:30 PM
3. PM Peak – 4:30 to 6:30 PM

The peak hours were determined by Kimley Horn and Associates Inc. from the traffic count data. These runs were made before and after signal retiming. The signal retiming was implemented by Kimley-Horn Associates Inc., a consulting firm hired by NCTCOG. The before signal retiming runs were made in December and January, which are considered to be winter months, and the after signal retiming runs were made in April and May, which are spring months.

3.3.2 Factors Considered in Data Collection

There were many factors taken into consideration during data collection:

- Data was collected on Tuesdays, Wednesdays and Thursdays because the traffic volume remains more stable on these weekdays.
- No runs were made on days with rain.
- The study vehicle was driven on average speed maintained by the cars on the corridor.

- The vehicle was warmed up when data collection was started, so cold starts did not impact the data.

3.3.3 Data Logging Software Configuration

Different parameters need to be configured in the software by going to ADC setup on the main screen of software. This produces a screen wherein all the parameters are displayed with a selectable range of values as listed in Table 3-3:

Table 3.2 Parameters configured in ADC Setup

Parameters	**Range of Values**	**Unit**
NO_x	0.00 – 3000	ppm
Air to Fuel Ratio (AFR)	0.00-100	
Exhaust Temperature	0.00-1000	Deg. C
Exhaust Pressure	0.00-200	kPa
Ambient Temperature	0.00-150	Deg. C
Ambient Pressure	0.00-100	kPa
Ambient Humidity	0.00-100	%
Velocity	0-500	kmph
Revolution	0-5000	rpm

NO_x concentration is measured with a delay time which is required for the sensor measured concentration to be converted from analog to digital output and logged in the data software. This time was determined by HORIBA Instruments to be 1.5-2.0 seconds. Figure 3.10 shows the procedure followed on each data collection run.

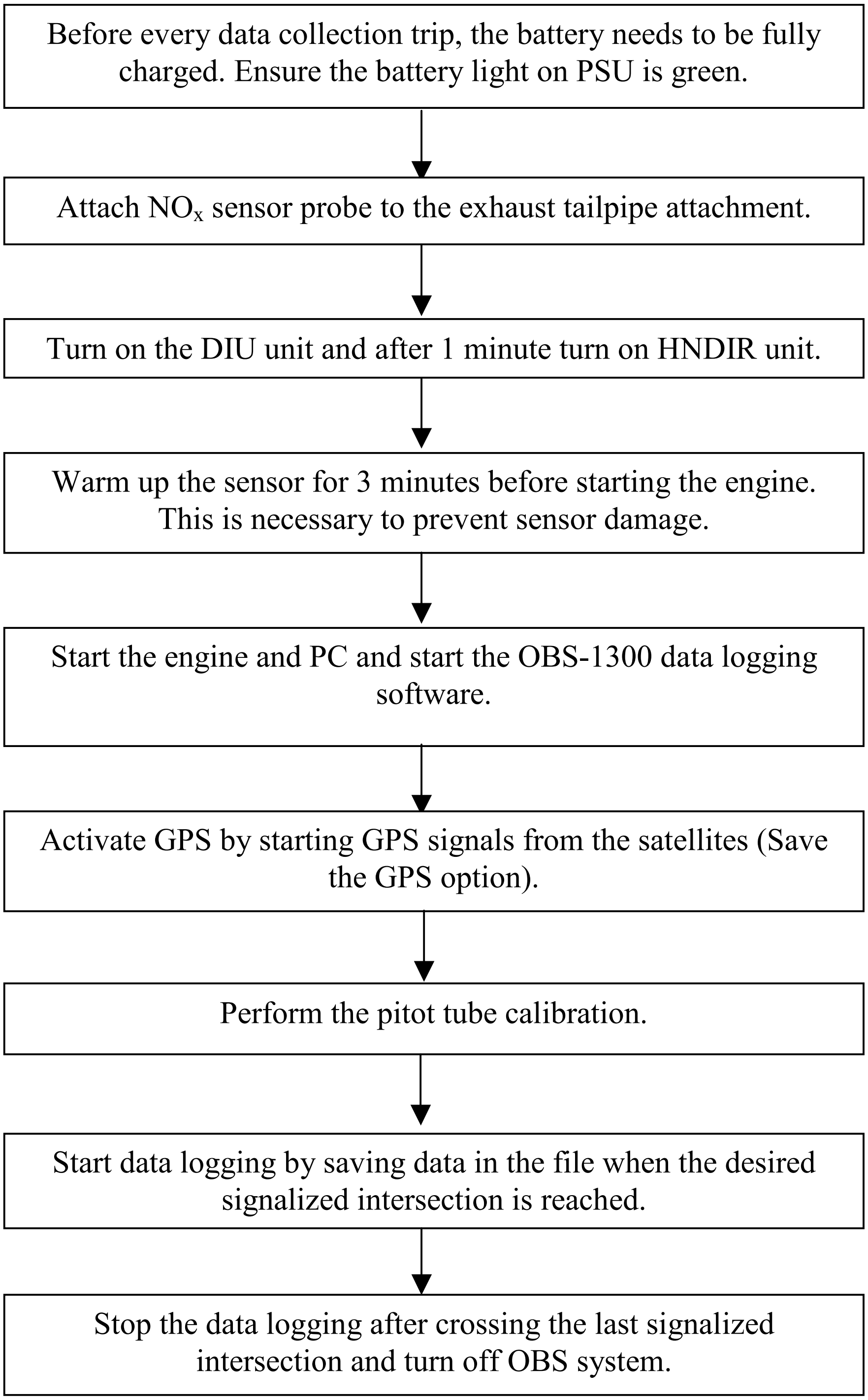


Figure 3.10 OBS-1300 Data Collection Procedure

3.3.4 NO_x Sensor Calibration

Apart from the data collection, there is a calibration of the NO_x sensor which was performed every week. This involved a set up of the calibration unit and NO_x sensor as shown in the Figure 3.11 and described below:

Calibration Setup:

- The NO_x sensor has to be fixed in the sensor adaptor of the calibration unit. The calibration unit consists of a flow meter, bubbler, sensor adaptor and water inlet.
- Distilled water has to be filled in the calibration unit through the water inlet.
- The calibration gas cylinder is connected to the calibration unit through a regulator valve.
- The calibration gas used for this process is O_2 free N_2, which was obtained from Scott Specialty Gases.
- The exhaust outlet of the calibration unit is connected to a long Teflon tube, through which the calibration gas is safely discharged outside the building.

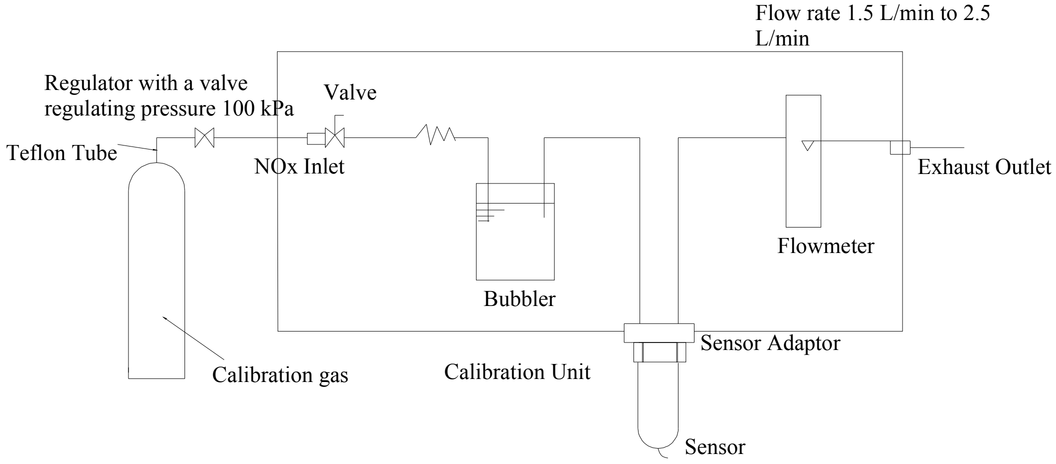


Figure 3.10 NO_x Sensor Calibration Setup

- After the calibration set up, the calibration gas is allowed to flow at a sufficient rate (1.5 L/min to 2.5 L/min) so that the ball in the flow meter positions in between the two levels indicated in the flow meter.
- After the required gas flow is achieved, the NO_x analyzer is switched on and needed to be calibrated by setting the values defined in the Horiba manual.
- For setting NOx concentration, press and hold CAL/SET key for approximately three seconds and mode of analyzer switches to setting mode. Channel number (ch000) appears on display.
- Input the value of concentration displayed on calibration gas label (in this case, 2000 ppm). This finishes the calibration process.
- Check the value that was displayed previously. If the value was 1997 ppm, the sensor showed an error of 10%.

The calibration of sensor is an important process and thus recommended to be done once a week.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Data Analysis

4.1.1 Introduction

As discussed in Chapter 3, NO_x emissions data was collected before and after signal synchronization on Great Southwest Parkway. Instantaneous emissions measured by OBS-1300 were logged in the computer along with various second by second engine and meteorological parameters as shown in Table 4.1:

Table 4.1 OBS-1300 parameters:

1. Date and time	2. NO_x concentration (ppm)
3. Air to Fuel Ratio (AFR)	4. Exhaust flow rate (L/min)
5. Exhaust Temperature (°C)	6. Exhaust Pressure (kPa)
7. Ambient Temperature (°C)	8. Ambient Pressure (kPa)
9. Humidity (%)	10. Velocity (km/hour)
11. Latitude (degree)	12. Longitude (degree)
13. Altitude (m)	14. GPS Velocity (km/hour)
15. North/South	16. East/West
17. No of Satellites	

The database was saved in a specific format with the name of driver, date and peak/off-peak details for future reference.

4.1.2 Data Interpretation

Instantaneous NO_x emissions were obtained from the database in the units of parts per million (ppm). The final objective is to calculate on-road NO_x emission factors in grams/mile. Thus, the first step of post-processing the raw data for each run was calculating instantaneous NO_x emissions in $\mu g/m^3$ using the following formulae:

$$C_{mass} = \frac{1000*MW*C_{ppm}*P}{RT}$$

Where C_{mass} = Instantaneous NO_x Concentration ($\mu g/m^3$)

MW = NO_x Molecular weight is 31.6 g/gmole (assuming 90% NO and 10% NO_2)

C_{ppm} = Instantaneous NO_x concentrations measured by OBS-1300

P = Instantaneous Ambient Pressure (atm)

T = Instantaneous Ambient Temperature (Kelvin)

R = 0.08206 atm-l/gmol-K

Finally, the instantaneous NO_x Concentration ($\mu g/m^3$) is converted into an emission factor (gram/mile) by the following formula:

$$\text{E.F. (g/mile)} = \frac{C_{mass}*\text{Exhaust flow rate } (m^3/\text{min})}{\text{Velocity (mile/min)}}$$

Here, the exhaust flow rate used was an instantaneous value, but the velocity was averaged over the run, since the instantaneous velocity was sometimes zero. This instantaneous NO_x emission factor (g/mile) is then averaged out for each run with other parameters like average trip duration (sec), average speed (mile/hr), total no. of stops, control delay (seconds). In this study, control delay is assumed as the time period in which vehicle is driving at speed <10 miles/hour.

4.1.3 Averaging Data

The above mentioned parameters were determined for each run classified by the day, direction and AM peak/offpeak/PM peak for before and after signal retiming scenarios as shown in a typical Table 4.2:

Table 4.2 Typical summary data sheet for each day

Date:	11/16/2004	
Day of week: Tuesday	AM	PM
Driver:	Driver 3	---
Before signal Retiming	☑	

	AM Peak	Off-Peak
No of Runs in North	2	3
No of Runs in South	2	3
Trip Duration	3054	4185

AM Peak Run	**N**	**S**	**N**	**S**
Parameters	**Run1**	**Run2**	**Run3**	**Run4**
Trip Duration (Seconds)	686	768	776	824
Average Speed (miles/hour)	28.24	25.24	24.96	23.42
Control Delay (Seconds)	133	140	197	198
Total No. of stops per run	5	6	6	7
NOx Emissions (g/mile)	0.88	0.62	0.88	0.66

Off-Peak Run	**N**	**S**	**N**	**S**	**N**	**S**
Parameters	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**	**Run6**
Trip Duration (Seconds)	686	686	755	686	686	686
Total Speed in mile/hours	30.20	35.31	25.53	31.48	32.26	30.98
Control Delay (Seconds)	110	53	177	111	77	66
Total No. of stops per run	3	2	6.00	1.00	4	6
NOx Emissions (g/mile)	0.95	0.62	0.69	0.62	0.75	0.68

All these input average datasheets are attached in Appendix A. The following variables are studied for their effect on NO_x emissions:

a. Day of the week – The days of week (Tuesday, Wednesday and Thursday) are considered to have stable traffic. The assumption is checked by analyzing the collected data.

b. Peak/Off-peak – The variations in NO_x emissions are studied for peak and off-peak conditions.

c. Travel Direction – North and South directions are checked for the data variations.

d. Driver behavior – The effect of driver on the patterns of accelerations, decelerations and driving are considered to be different and thereby affect the NO_x emissions. More rapid accelerations would be expected to increase NO_x emissions.

e. Indirect variables – Ambient humidity and temperature are also studied. A research at NCSU has found that NO_x emissions decreased with increase in relative humidity.

Firstly, based on the data output, traffic variables were analyzed to check whether there is any significant change with signal synchronization. These variables are dependent on time of the day. Thus, the data output is divided into am peak, off-peak and pm peak timing scenario as listed in Table 4.3 below.

Table 4.3 Traffic variables variations in AM, PM and Off-Peak scenarios:

Parameters	**Before**	**After**	**Change**	**% Change**
AM PEAK				
Trip duration (seconds)	773	709	- 63	8 ↓
Total speed (mph)	25.49	29.76	4.27	17 ↑
Control delay (seconds)	180	111	-69	38 ↓
Total no. of stops per run	6.00	5.2	-0.8	13 ↓
Total running time (seconds)	593	598.6	-5.6	1 ↑
OFF-PEAK				
Trip duration (seconds)	722.4	696.6	-25.8	4 ↓
Total speed (mph)	29.14	31.24	2.1	7 ↑
Control delay (seconds)	133.5	107.7	-25.8	19 ↓
Total no. of stops per run	4.50	4.50	0	0
Total running time (seconds)	589	589	0	0
PM PEAK				
Parameters	**Before**	**After**		**% Change**
Trip duration (seconds)	793.0	705.5	-87.5	11 ↓
Total speed (mph)	25.71	29.41	3.7	14 ↑
Control delay (seconds)	229.5	134	-95.5	42 ↓
Total no. of stops per run	4.8	4.1	-0.7	15 ↓
Total running time (seconds)	563.6	571. 6	8	1.41 ↑

As seen in the above table, in all the three scenarios, overall average speed (mph) increased with signal synchronization. The “rule of thumb” assumes a projected increase of three mph average speed with moderate level signal synchronization, but the data shows a speed increase of 4.7, 2.1 and 3.7 mph in am peak, off-peak and pm peak cases, respectively. With signal retiming, control delay (seconds) significantly reduced by 38, 19 & 42% in am peak, off-peak pm peak, respectively. Also, trip duration and no. of stops were reduced in peak cases, whereas there was no change in off-peak case. The total running time increased with signal synchronization. All of these trends would be expected and indicate that signal retiming does benefit motorists. Also, from the peak and off-peak cases, it can be inferred that retiming makes more of a difference when traffic volumes are greater.

4.2 Statistical Analysis

4.2.1 Introduction to Statistics

Statistics can be used to analyze the relationship between two or more variables. It can be used for quantitative prediction or forecasting, particularly using a small sample to forecast the behavior of the larger population. Relationships between dependent variables and one or more independent variables can be estimated so that a dependent variables value can be estimated based on the values of the independent variables.

4.2.2 Statistical Approach

The statistical approach in this study was a three-step statistical process. A number of statistical tests were conducted to establish the relationship between various parameters and NO_x emissions.

4.2.2.1 Preliminary Analysis - ANOVA

Analysis of Variance (ANOVA) is a tool wherein the data is compared between two categories which might show a significant statistical variation. This test decides whether statistically indifferent categories can be lumped together or should be kept separate for further analysis. In this case, ANOVA is used to identify variables that can help explaining the emissions variability. There are two kinds of ANOVA used:

a. One-way ANOVA - Only one basic variable is being studied.

b. Two-way ANOVA - Two types of independent variables are investigated.

ANOVA is not concerned with analyzing variances but rather analyzing variation in means. In this research, one-way ANOVA is used to determine if the following variables impact the measured NO_x emissions:

1. North-South
2. AM-PM Peak
3. Peak – Off-peak
4. Driver
5. Day of the week

All of these factors were tested using ANOVA and the test result sheets are attached in Appendix B. These tests determined that:

- The direction of travel and AM or PM peak is not statistically significant with respect to NO_x emissions, as shown in Table 4.4:

Table 4.4 ANOVA results for insignificantly varying factors

Source of Variation	**Degrees of Freedom**	**F**	**P-value**	**F critical**
North-South direction comparison				
Between Groups	1	1.810	0.180	3.906
Within Groups	145			
Total	146			
AM – PM Peak comparison				
Between Groups	1	2.897	0.092	3.949
Within Groups	88			
Total	89			

- In both the cases, the P value is greater than 0.05 and also F > F critical. Thus, the north-south direction and AM-PM peak data can be lumped together for further statistical testing.
- As shown in Table 4.5 below, there is a statistically significant difference in NO_x emissions for the peak and off-peak scenarios. The emissions are also dependent on driving behavior and day of the week.

Table 4.5 ANOVA results for significantly varying factors

Source of Variation	Degree of Freedom	F	P-value	F critical
Peak-Off-peak Comparison				
Between Groups	1	18.054	3.82E-05	3.906
Within Groups	145			
Total	146			
Driver comparison				
Between Groups	2	55.30	1.02E-18	3.056
Within Groups	150			
Total	152			
Days of week (Tuesday, Wednesday) Comparison				
Between Groups	2	14.63	1.53E-06	3.054
Within Groups	154			
Total	156			

As shown in the above three cases, the P value is less than 0.05 and also $F < F_{critical}$. Thus, it can inferred that the peak and off-peak data, driver's behavior and day of the week significantly impact the NO_x emissions and therefore cannot be lumped together for further statistical testing.

4.2.2.2 Hypothesis Testing (T-distribution)

After the ANOVA was conducted, the data was tested for the hypotheses as stated in Table 4.6 below. The mean NO_x concentrations were compared for before and after signal timing for a specific driver, day of the week and peak/off-peak conditions.

Table 4.6 Hypothesis testing criteria: (assuming T-distribution)

Hypothesis	Rejection Criteria	
$H_0: \mu_1 = \mu_2$ $H_1: \mu_1 \neq \mu_2$	$\lvert t_{cal} \rvert > t_{Crit}$	reject the null hypothesis
$H_0: \mu_1 = \mu_2$ $H_1: \mu_1 > \mu_2$	$t_{cal} > t_{Crit}$	reject the null hypothesis
$H_0: \mu_1 = \mu_2$ $H_1: \mu_1 < \mu_2$	$t_{cal} < -t_{Crit}$	reject null hypothesis

where:

μ_1 = before signal retiming NO_x emissions mean for a given condition

μ_2 = after signal retiming NO_x emissions mean for a given condition

t_{cal} = T-value calculated from the given data

$t_{critical}$ = T-value derived from the t-distribution table for a given level of confidence (95%) and type of t-test.

Since there are an unequal number of data samples, following set of formulae are used to calculate t-value:

$$S_{\overline{X}_1-\overline{X}_2} = \sqrt{\frac{(N_1-1)S_1^2+(N_2-1)S_2^2}{(N_1+N_2-2)}\left(\frac{1}{N_1}+\frac{1}{N_2}\right)}$$

$$t = \frac{\overline{X}_1-\overline{X}_2}{S_{\overline{X}_1-\overline{X}_2}}$$

where s = standard deviation between sample means

N_1 = Number of samples in data set 1

N_2 = Number of samples in data set 2

t = calculated t-value

$\overline{X}_1$ = mean of Sample 1

$\overline{X}_2$ = mean of Sample 2

In the first hypothesis test, $t_{critical}$ was based on a two-sided t-test; whereas in the following two tests, $t_{critical}$ was based on a one-sided t-test. The above means were compared for before and after signal timing for a specific driver, day of the week and peak/off-peak conditions. All of the t-test results are attached in Appendix C. The tests results are summarized in Table 4.7.

Table 4.7 T-test results

Drivers	NO_x emissions	Tuesday		Wednesday		Thursday	
		Before	After	Before	After	Before	After
1	Peak	-	-	-	-	0.86	0.97
	Off-peak	-	-	-	-	0.69	1.51
2	Peak	1.30	1.69	1.45	1.43	1.26	-
	Off-peak	1.73	1.45	-	1.22	1.36	-
3	Peak	0.76	-	0.97	1.35	1.12	-
	Off-peak	-	-	-	-	-	-

Table 4.7 Continued

Drivers	Variables	Tuesday	Wednesday	Thursday
1	Peak	--	--	No significant difference
	Off-Peak	--	--	No significant difference
2	Peak	Before emissions are less than after emissions	No significant difference	--
	Off-Peak	No significant difference	--	--
3	Peak	--	Before emissions are less than after emissions	--
	Off-Peak	--	--	--

where -- indicates that no runs were conducted for that driver/day of week/peak-off-peak combination.

For Driver 1:

The tests show that there is no significant statistical difference between before and after NO_x emissions.

For Driver 2:

In two cases, there is no significant statistical difference between before and after NO_x emissions.

In one case, NO_x emissions for before case are significantly less than those for the after case.

For Driver 3:

Statistically, the NO_x emissions before signal retiming are less than those after retiming, but in this case, there was only data set representing the before case. Therefore, these results should not presented as a generalizing conclusion.

Thus, in the majority of the cases, it can be inferred from hypothesis testing that there is no significant statistical difference in NO_x emissions between the before and after signal trials. In other cases, where before emissions are less than after NO_x emissions, there are a number of variables changing that can cause an increase in emissions, such as average speed, temperature, humidity, control delay and number of stops.

4.2.2.3 Regression Analysis

Thus, the final step is to determine the significant variables and their impact on NO_x emissions. This is achieved with the help of regression analysis using SPSS (Statistical Package for Social Sciences). There are two levels of regression analysis in this research study:

i. Aggregate Model # 1: In this model, the following independent variables are aggregated per run and compared on a macro-level with NO_x emissions (ppm):

    1. Average speed (miles/hour)
    2. Control delay (seconds)
    3. No. of stops
    4. Ambient humidity (%)
    5. Ambient temperature (deg. C)

These variables are checked for their correlation and significance with respect to NO_x emissions variability, as shown in Tables 4.8 and 4.9 below:

Table 4.8 Model summary for aggregate model # 1

Model	R	**R Square**	Adjusted R Square	Std. Error of the Estimate
1	0.632(a)	**0.400**	0.380	17.5

where:

a = Predictors: (Constant), no. of stops, ambient humidity, ambient temperature, control delay, GPS velocity

Table 4.9 Aggregate model coefficients for aggregate model # 1

Model		Unstandardized Coefficients		Standardized Coefficients	t	Significance
		B	Std. Error	Beta		
1	(Constant)	7.97	12.4		.64	.523
	Amb temp	-0.76	.26	-.201	-2.9	.004
	Amb humidity	-0.57	.07	-.519	-7.4	.000
	Average speed	11244	1288	.634	8.7	.000
	No. of Stops	1986	631	.213	3.1	.002

a = Dependent Variable: NO_X

Thus,

$NO_x = 7.97 - 0.76t - 0.57h + 11244v + 1986s$……………………………….(1)

where t = Ambient temperature (deg. C)

h = Ambient humidity (%)

v = Average speed (miles/sec)

s = Number of stops

Since the significance value of control delay in greater than 0.05 in Table 4.9, control delay is not significant and thus does not impact the NO_x emissions variability. Thus, it is not incorporated into the above equation.

This model gives R-square value of 0.400 and thus it can be inferred the combination of all the above variables account for 40% NO_x emission variability. The above equation shows that NO_x emissions increase as ambient humidity and temperature decrease since the coefficients are negative. Frey et al. (2001) also found that NO_x emissions increase as ambient humidity decreases.

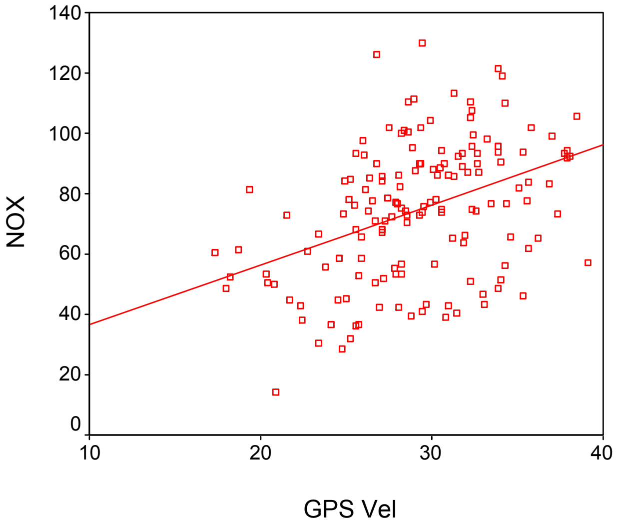


Figure 4.1: Average speed (mph) vs. NO_x (ppm)

Also, as shown in Figure 4.1, NO_x emissions increase with an increase in average speed. Thus, after signal retiming, although the number of accelerations/decelerations was reduced because of the reduced no. of stops, the average speed increased and thereby may have increased NO_x emissions. Thus, there is no significant statistical difference in before and after NO_x emissions.

In the case of number of stops, as stops increases, NO_x emissions increase as expected. However, the standard error is too high, showing that the values of stops are randomly distributed over a wide confidence interval. Thus, even though the coefficient of stops is so high, independently this variable does not impact significantly on NO_x emissions.

ii. Aggregate Model # 2: The above aggregate model is proposed for a general relation among these variables and does not account for driving behavior. Therefore, another aggregate model was developed wherein driver behavior is considered in estimating NOx emission variability. Here, driver is introduced as a dummy variable to consider the driving behavior as a significant variable in estimating average NOx emissions (ppm).

Table 4.10 Model summary for aggregate model # 2

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.760(a)	0.58	0.567	14.6

where:a = Predictors: (Constant), no. of stops, ambient humidity, ambient temperature, control delay, GPS velocity, Driver 1 and Driver 2.

Table 4.11 Aggregate model coefficients for aggregate model # 2

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	84.7	5.5		15.4	.000
	Amb humidity	-.26	.065	-.235	-4.0	.000
	Control Delay	-90.0	13.2	-.380	-6.8	.000
	DRIVER1	.76	4.1	.012	.19	.852
	DRIVER2	26.2	3.2	.555	8.18	.000

a Dependent Variable: NO_X

Thus,

NO_x = 84.7 – 0.26h -90c + 26.2d_2……………………………………(2)

where h = Ambient humidity (%)

c = Control delay (seconds)

d_1 = Driver 1

d_2 = Driver 2

Here, ambient temperature, average speed, driver 1 and no. of stops are not significant and thus do not impact the NO_x emissions. Thus, they are not incorporated in the above equation. This model has an R-square value of 0.58, and thus it can be inferred the combination of all the above variables accounts for 58% NO_x emission variability.

The above equation shows that NO_x emissions increase with a decrease in ambient humidity and control delay. Since this observation does not make physical sense (a decrease in control delay should decrease NO_x emissions), this model is likely not valid. This model also indicates the importance of driving behavior in estimating NO_x emissions variability since driver shows up as a significant variable.

<u>Aggregate Model # 3</u>: An aggregate model is developed that takes into account peak and off-peak along with driver as dummy variables. This model develops a relation of these dummy variables in addition to average values of ambient humidity.

Table 4.12 Model summary for aggregate model # 3

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.797(a)	0.64	0.612	13.8

where:a = Predictors: (Constant), no. of stops, ambient humidity, ambient temperature, control delay, average speed, Driver 1,Driver 2, D1P, D2P and peak.

b = dependent variable: NO_x

Table 4.13 Aggregate model coefficients for aggregate model # 3

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	55.568	25.778		2.156	0.033
	Ambient humidity	-0.173	0.076	-0.157	-2.260	0.025
	Peak	16.968	5.296	0.379	3.204	0.002
	Driver 2	33.617	5.333	0.712	6.304	0.000

where

a = Dependent Variable: NO_X

D1P = Driver1-peak interaction

D2P = Driver 2-peak interaction

Thus,

$NO_x = 55.57 – 0.17h + 16.97p + 33.6d_2$……………………..……………………………(3)

where h = Ambient humidity (%)

p = peak time

d_2 = Driver 2

This model has R-square value of 0.64, and thus it can be inferred the combination of all the above variables accounts for 64% NO_x emission variability. The above model determines that ambient temperature, no. of stops, average speed and driver 1 do not impact NO_x emissions. It also indicates that ambient humidity, driver 2 and peak time impacts variations in NO_x emissions. The model states that NO_x emissions increase in peak hours as compared to off-peak hours.

iii. Disaggregate Model: The final analysis is to validate an instantaneous (second by second) model wherein NO_x emissions (ppm) are compared against a number of instantaneous independent variables:

1. Ambient humidity (%)
2. Ambient temperature (deg. C)
3. Instantaneous speed (miles/sec)
4. Instantaneous acceleration (miles/sec^2)

Most of the emission factors used in models depends on the average values of variables (e.g. average speed). However, current studies indicate that there is a difference in emission factors in average model and instantaneous model. Such differences occur when the amount of fluctuation of instantaneous speed with respect to average travel speed. The studies also show that 50% of all emissions are emitted during peak hours (Haan *et. al*, 2000). The studies also indicate that instantaneous models are very case-specific for every vehicle and driver behavior.

Table 4.14 Model summary for disaggregate model

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.3 (a)	0.09	0.09	91.75

where:
a = Predictors: (Constant), Amb_humidity, S2, A3, A2S, AMB_TEMP, AS2, A2, S, A, A3S3, A2S2, AS, S3, AS3, A3S, A2S3, A3S2 (S = instantaneous velocity, A = Instantaneous acceleration)
b = dependent variable: NO_x

Table 4.15 Aggregate model coefficients for disaggregate model

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	101	4.216		23.868	.000
2	A	55.5	2.464	.677	22.527	.000
3	A2	5.34	.620	.106	8.608	.000
4	A3	-2.7	.417	-.203	-6.647	.000
5	S	-34.2	1.288	-.633	-26.550	.000
6	S2	4.0	.612	.155	6.616	.000
7	S3	1.73	.165	.401	10.481	.000
8	AS	-23.0	1.259	-.903	-18.296	.000
9	AS3	.86	.080	.400	10.679	.000
11	A3S	1.02	.128	.237	7.993	.000
12	Ambient temperature	-.53	.172	-.022	-3.087	.002
13	Ambient humidity	-.51	.027	-.134	-18.733	.000

Where S = Instantaneous velocity
A = Instantaneous acceleration

Thus,

$$NO_x = 101 + 55.5A + 5.34\ A^2 - 2.7\ A^3 - 34.2\ S + 4\ S^2 + 1.73S^3 - 23\ AS + 0.86AS^3 + 1.02\ A^3S - 0.53t - 0.51h \ldots\ldots(4)$$

where S = Instantaneous velocity (mph)

A = Instantaneous acceleration (ft/min^2)

t = Ambient temperature (deg. C)

h = Ambient humidity (%)

The above equation shows that NO_x emissions depend on instantaneous acceleration and velocity. This model has R-square value of 0.09, and thus it can be inferred the combination of all the above variables accounts for 9% NO_x emission variability. The above model is not best-fit for instantaneous variables. Previous studies have indicated that engine parameters like power, engine load, fuel consumption and type of the vehicle affects NO_x emissions. This research did not collect these parameters and hence did not incorporate in the instantaneous modeling. Therefore, this model failed to show a strong relationship because of some missing significant variables.

The following figures show the relationship between instantaneous acceleration and instantaneous NOx emissions for various ranges of instantaneous velocity. The figures below indicate that for initial values of velocities, NO_x emissions are high on zero acceleration, whereas in velocity range of 20-30 mph, NO_x emissions are high at acceleration 5 ft/sec^2. On higher values of velocities ranging from 30-50 mph, NO_x emissions increase at constant velocities.

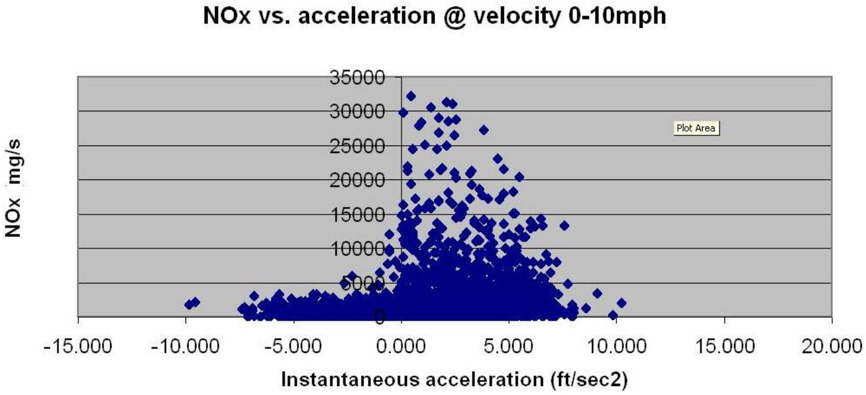


Figure 4.2 NO_x vs. acceleration @ velocity 0-10 mph

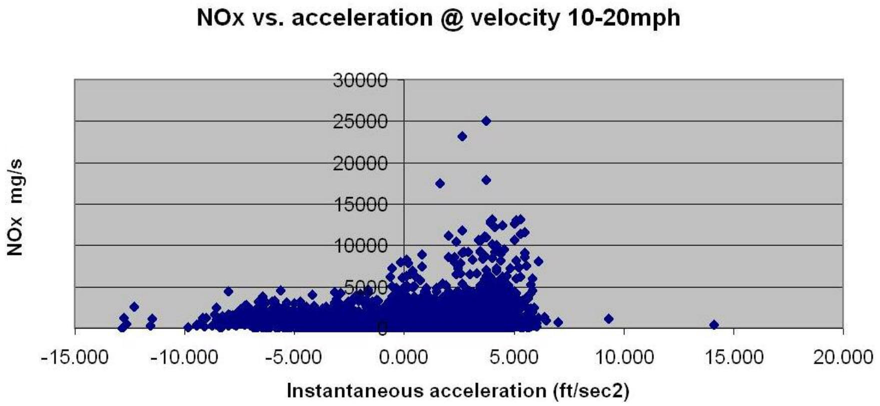


Figure 4.3 NO_x vs. acceleration @ velocity 10-20 mph

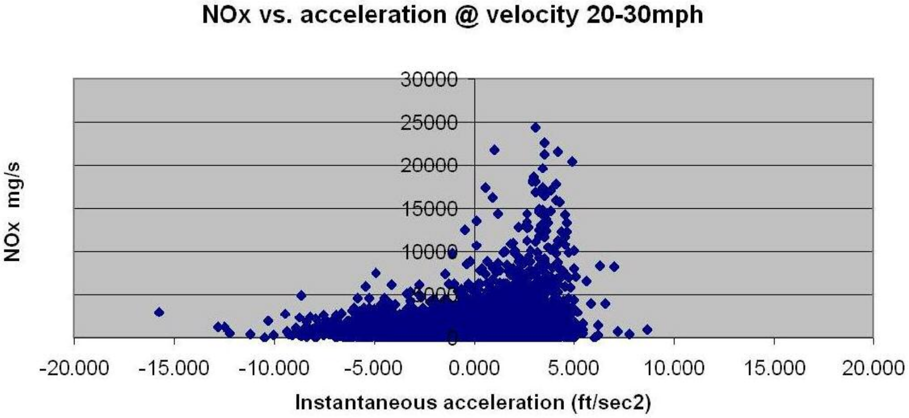


Figure 4.4 NO_x vs. acceleration @ velocity 20-30 mph

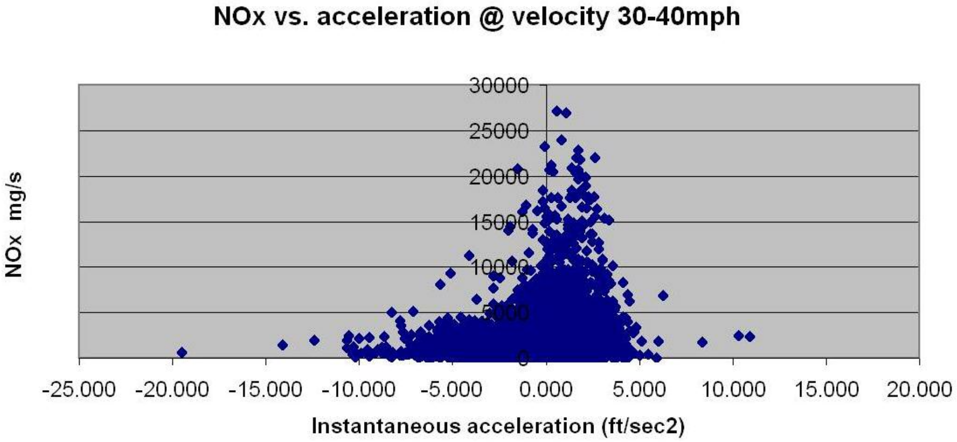


Figure 4.5 NO_x vs. acceleration @ velocity 30-40 mph

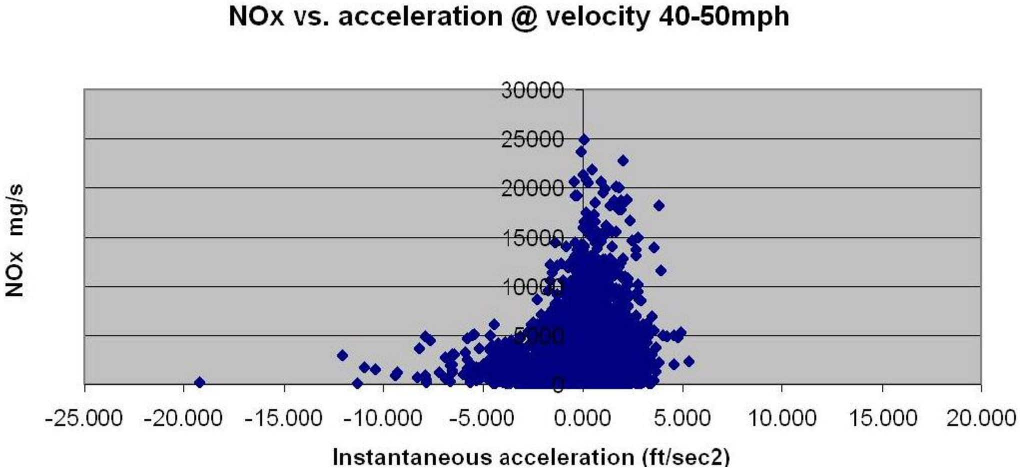


Figure 4.6 NO_x vs. acceleration @ velocity 40-50 mph

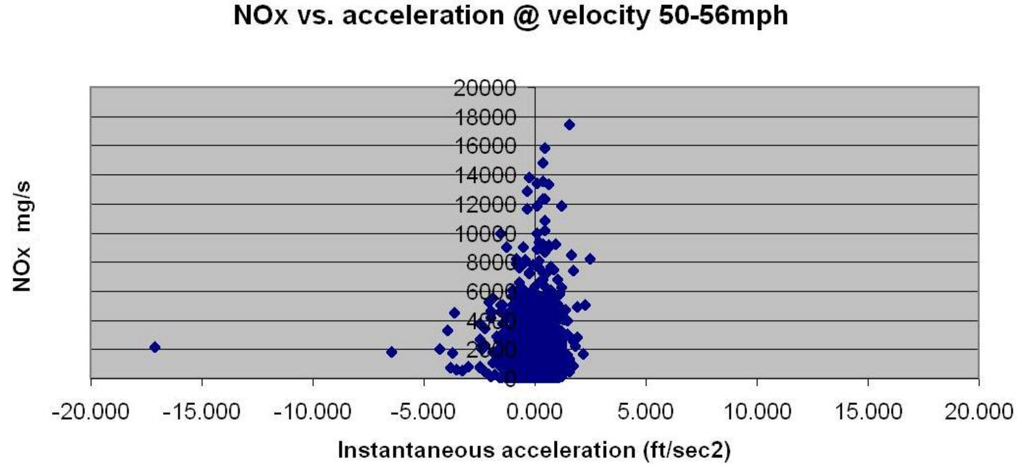


Figure 4.7 NO_x vs. acceleration @ velocity 50-56 mph

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research was aimed at on-road NO_x emission measurement and various variables affecting the emissions variability. A series of statistical analyses were conducted that lead to the following conclusions:

- As presented in Chapter 4, in all the three scenarios (am peak, off-peak and pm peak), average speed (mph) increased with signal synchronization. For Great Southwest Parkway, the "rule of thumb" assumes an increase of 3 mph average speed associated with moderate level signal synchronization which is used by NCTCOG in their Thoroughfare Assessment Program (TAP), but the on-road measurement data shows a speed increase of 4.7, 2.1 and 3.7 mph in am peak, off-peak and pm peak cases, respectively. With signal retiming, trip duration, control delay and no. of stops decreased with the signal retiming. Also, the running time and speed increased with the signal synchronization. Thus, we can conclude that signal synchronization helped in dealing with traffic parameters.
- From ANOVA, we can conclude that the north-south direction and AM-PM peak data has no significant variations in NOx emissions. Also, it can be inferred that the peak and off-peak data, driver's behavior and days of the week

significantly impact the NO_x emissions variability and therefore cannot be lumped together for further statistical testing.

- From the hypothesis testing using t-distribution, it was found that for most of the cases, there is no significant statistical difference between before and after signal timing NO_x emissions. In other cases, where before emissions are less than after NO_x emissions, there are a number of variables that can affect the increase in emissions.
- According to the aggregate model regression analysis, the average speed, no. of stops, ambient humidity and temperature significantly impact NO_x emissions. The linear regression results suggest that NO_x emissions increase with decrease in humidity and temperature. Also, NO_x emissions increase with the increase in average speed and no. of stops. The R-square value of 0.400 suggests that these variables can impact 40% variation in NO_x emissions. The R-square is low because the drivers are not accounted for in this regression. Further, an aggregate regression with driver behavior concluded that driver 2 is a significant variable impacting NO_x emissions and driver 1 is insignificant and therefore, driver behavior is to be considered while modeling the NO_x emissions.
- A thorough regression analysis was made to study the significance of various variables on NO_x emissions. Different types of regression models were developed for achieving desired results:

a. Aggregate model:

$NO_x = 7.97 – 0.76t – 0.57h + 11244v + 1986s$……………………………(1)

where t = Ambient temperature (deg. C)

h = Ambient humidity (%)

v = Average speed (miles/sec)

s = Number of stops

b. Aggregate model (with driver behavior):

Here driver behavior is introduced as a dummy variable and checked for its significance in estimating NO_x emissions.

$NO_x = 84.7 – 0.26h -90c + 26.2d_2$………………………………………(2)

where h = Ambient humidity (%)

c = Control delay (seconds)

d_2 = Driver 2

In case of driver 2,

$NO_x = 84.7 – 0.26h -90c + 26.2d_2$

In case of driver 3,

$NO_x = 84.7 – 0.26h -90c$

The above model (b) gives R-square value of 0.58 and thus it can be inferred the combination of all the above variables account for 58% NO_x emission variability. The above equation shows that NO_x emissions increase with decrease in ambient humidity and control delay. This model also indicates the importance of driving behavior in estimating NO_x emissions variability.

c. Aggregate model with peak/off-peak and driver as dummy variables:

$NO_x = 55.57 – 0.17h + 16.97p + 33.6d_2$……………………………………………………(3)

where h = Ambient humidity (%)

p = peak time

d_2 = Driver 2

This model has R-square value of 0.64 since it takes into account a significant parameter – peak conditions. The model states that NO_x emissions increase in peak hours as compared to off-peak hours. It also indicates that ambient humidity, driver 2 impacts variations in NO_x emissions.

d. Disaggregate model:

$NO_x = 101 + 55.5A + 5.34\ A^2 – 2.7\ A^3 – 34.2\ S + 4\ S^2 + 1.73S^3 – 23\ AS + 0.86AS^3 + 1.02\ A^3S – 0.53t – 0.51h$ ……………………………………(4)

where S = Instantaneous velocity (mph)

A = Instantaneous acceleration (ft/min^2)

t = Ambient temperature (deg. C)

h = Ambient humidity (%)

This model has R-square value of 0.09 which means that it is not best-fit for instantaneous variables. The reason is that this research did not collect parameters like power, engine load, fuel consumption and type of the vehicle that affect NO_x emissions and hence did not incorporate in the instantaneous modeling. Therefore, this model failed to show a strong relationship because of some missing significant variables.

5.2 Recommendations

5.2.1 Recommendations for Improving On-Road Emission Measurement

- Conduct a pilot study and analysis before a detailed study to determine the significant variables affecting emissions of respective pollutants.
- Calibrate the system regularly to avoid any system error in data collection.
- Take an equal amount of data for am, pm peak and off-peak cases. Also, get the equal number of data sets for each driver.
- Maintain a log book of all the abnormal mishaps on the data collection. For example, an accident or train delay is considered to be abnormal driving and the resultant stop time is not considered in this kind of study.
- Since the study vehicle is considered to be a representative sample, maintain the speed of the vehicle fleet and do not make any jack-rabbit accelerations and decelerations.
- Collect the data of engine parameters during study trips to perform disaggregate regression analysis.

5.2.2 Recommendations for Further Research

- Compare the real-world NO_x emissions with modeled NO_x emissions and check for the compatibility.
- Determine the impact of signal synchronization on the on-road measurement of CO, CO_2, and HC emissions.

- Compare the NO_x emissions variability on a number of roadways and thereby compare the effect of corridor congestion on NO_x emissions.
- Test different types of vehicles (model and alternate fueled) to determine the engine and fuel parameters affecting NO_x emissions.

APPENDIX A

SUMMARY DATA SHEETS AVERAGE PER DAY

Table A-1 Before Signal Retiming Input tables (Parameters averaged per run)

	Parameters	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
11/16/04 Driver 3	Average speed(mile/hour)	26.6	24.3	29.3	32.6	--	--
	Average Trip Duration (Sec/run)	731	796	709	686	--	--
	Control Delay (hour)	0.05	0.05	0.03	0.02	--	--
	Total Stops per run	5.5	6.5	4.3	3.0	--	--
	NO_x Emissions(g/mile)	0.9	0.6	0.8	0.6	--	--
	NO_x Emissions (Grams)	4.7	3.45	4.3	3.5	--	--
	Parameters	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
11/18/04 Driver 1	Average speed(mile/hour)	26.7	23.7	30.1	33.6	--	--
	Average Trip Duration (Sec/run)	751	825	691	686	--	--
	Control Delay (hour)	0.05	0.06	0.03	0.02	--	--
	Total Stops per run	5.3	7	4.2	3.5	--	--
	NO_x Emissions(g/mile)	0.7	1.1	0.4	0.3	--	--
	NO_x Emissions (Grams)	3.8	5.7	2.3	1.7	--	--
12/01/04 Driver 3	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
	Average speed(mile/hour)	22.9	24.1	27.9	--	--	--
	Average Trip Duration (Sec/run)	844	794	698	--	--	--

Table A-1 Continued

	Control Delay (hour)	0.06	0.05	0.04	--	--	--
	Total Stops per run	6.5	5	4	--	--	--
	NO$_x$ Emissions(g/mile)	0.95	1.02	0.97	--	--	--
	NO$_x$ Emissions (Grams)	5.1	5.5	5.2	--	--	--
12/02/04 Driver 3	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
	Average speed(mile/hour)	27.8	20.9	--	--	22.1	27.4
	Average Trip Duration (Sec/run)	686	978	--	--	893	728
	Control Delay (hour)	0.04	0.09	--	--	0.09	0.05
	Total Stops per run	4.00	8.00	--	--	5.67	3.67
	NO$_x$ Emissions(g/mile)	0.94	0.36	--	--	1.19	1.04
	NO$_x$ Emissions (Grams)	5.05	1.92	--	--	6.41	5.60
12/14/04 Driver 2	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
	Average speed(mile/hour)	--	--	28.2	30.5	26.1	27.9
	Average Trip Duration (Sec/run)	--	--	686	686	797	712
	Control Delay (hour)	--	--	0.03	0.04	0.06	0.05
	Total Stops per run	--	--	4.00	4.00	5.00	3.00
	NO$_x$ Emissions(g/mile)	--	--	2.02	1.43	1.30	1.29
	NO$_x$ Emissions (Grams)	--	--	10.8	7.67	7.01	6.92
12/15/04 Driver 2	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**

Table A-1 Continued

	Average speed(mile/hour)	--	--	--	--	25.8	22.9
	Average Trip Duration (Sec/run)	--	--	--	--	766	876
	Control Delay (hour)	--	--	--	--	0.05	0.09
	Total Stops per run	--	--	--	--	4.40	5.00
	NO_x Emissions(g/mile)	--	--	--	--	1.46	1.45
	NO_x Emissions (Grams)	--	--	--	--	7.83	7.79
12/16/04 Driver 2	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
	Average speed(mile/hour)	--	--	27.3	28.6	23.8	30.1
	Average Trip Duration (Sec/run)	--	--	731	710	897	705
	Control Delay (hour)	--	--	0.05	0.04	0.09	0.03
	Total Stops per run	--	--	4.80	5.50	8.00	5.33
	NO_x Emissions(g/mile)	--	--	1.36	1.37	1.55	1.08
	NO_x Emissions (Grams)	--	--	7.32	7.35	8.32	5.79

Table A-2 After Signal Retiming Input tables (Parameters averaged per run)

	Parameters	AM Peak		Off-Peak		PM Peak	
		North	South	North	South	North	South
04/12/05 Driver 2	Average speed(mile/hour)	28.8	26.7	33.6	33	--	--
	Average Trip Duration (Sec/run)	701	789	686	686	--	--
	Control Delay (hour)	0.03	0.05	0.02	0.02	--	--
	Total Stops per run	5.33	5.00	4.00	5.00	--	--
	NO_x Emissions(g/mile)	1.96	2.00	1.57	1.30	--	--
	NO_x Emissions (Grams)	10.5	10.8	8.42	7	--	--
	Parameters	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
04/13/05 Driver 2 Driver 3	Average speed(mile/hour)	31.2	28.5	31	35.4	27.1	30.9
	Average Trip Duration (Sec/run)	686	712	686	686	722	687
	Control Delay (hour)	0.02	0.03	0.04	0.01	0.05	0.03
	Total Stops per run	5	4	5	4	4	4.7
	NO_x Emissions(g/mile)	1.46	1.58	1.28	1.01	1.37	1.32
	NO_x Emissions (Grams)	7.84	8.50	6.89	5.43	7.39	7.09
	Parameters	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
04/14/05 Driver 1	Average speed(mile/hour)	--	--	29	--	25.9	29.3
	Average Trip Duration (Sec/run)	--	--	686	--	757	686

Table A-2 Continued

	Control Delay (hour)	--	--	0.03	--	0.06	0.04
	Total Stops per run	--	--	3.00	--	6.33	5.00
	NO_x Emissions(g/mile)	--	--	1.51	--	0.92	1.01
	NO_x Emissions (Grams)	--	--	8.13	--	4.95	5.45
04/26/05 Driver 2	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
	Average speed(mile/hour)	--	--	33.9	21.5	34.3	30.7
	Average Trip Duration (Sec/run)	--	--	686	894	686	686
	Control Delay (hour)	--	--	0.02	0.10	0.01	0.04
	Total Stops per run	--	--	4.00	3.00	2.00	3.00
	NO_x Emissions(g/mile)	--	--	1.71	1.60	1.69	1.43
	NO_x Emissions (Grams)	--	--	9.19	8.61	9.09	7.70
04/27/05 Driver 2	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
	Average speed(mile/hour)	30.5	33	33.1	33.2	25.7	--
	Average Trip Duration (Sec/run)	700	686	686	686	751	--
	Control Delay (hour)	0.03	0.02	0.02	0.03	0.07	--
	Total Stops per run	6.25	2.75	4.17	4.20	6.00	--
	NO_x Emissions(g/mile)	1.50	1.41	1.32	1.30	1.63	--
	NO_x Emissions (Grams)	8.08	7.61	7.09	7.00	8.75	--
05/03/05 Driver 2	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**

Table A-2 Continued

	Average speed(mile/hour)	28.1	26.9	--	29.5	--	--
	Average Trip Duration (Sec/run)	722	731	--	686	--	--
	Control Delay (hour)	0.04	0.04	--	0.03	--	--
	Total Stops per run	6.33	5.67	--	3.00	--	--
	NO_x Emissions(g/mile)	1.46	1.51	--	1.22	--	--
	NO_x Emissions (Grams)	7.86	8.10	--	6.54	--	--
05/04/05 Driver 2	**Parameters**	**AM Peak**		**Off-Peak**		**PM Peak**	
		North	**South**	**North**	**South**	**North**	**South**
	Average speed(mile/hour)	32.7	32.5	--	--	27.8	30.8
	Average Trip Duration (Sec/run)	686	686	--	--	696.5	692
	Control Delay (hour)	0.03	0.02	--	--	0.05	0.04
	Total Stops per run	7.00	5.00	--	--	5.50	6.50
	NO_x Emissions(g/mile)	1.48	1.44	--	--	1.49	1.02
	NO_x Emissions (Grams)	7.98	7.72	--	--	8.01	5.48

APPENDIX B

ANOVA TEST RESULTS

TABLE B-1 NORTH SOUTH ANOVA COMPARISON

NO_X EMISSIONS DATA

North data	South data
0.88	0.62
0.88	0.66
0.97	1.22
0.58	0.92
0.60	1.73
1.66	2.14
1.87	2.13
2.35	1.61
1.68	1.69
1.45	1.43
1.21	0.99
1.49	1.91
1.16	1.67
1.84	1.08
1.64	1.73
1.36	1.52
1.51	1.26
1.62	1.45
1.26	1.43
1.49	0.89
1.68	1.04
1.29	1.19
0.97	1.45
1.41	1.35
0.77	1.06
1.39	1.47
1.22	1.65
1.35	1.44
1.34	1.44
1.74	1.24
1.42	1.08
1.29	0.94
1.33	1.71
1.50	1.20
1.39	1.31
1.71	1.35

1.55	1.29

Table B-1 Continued

North data	South data
1.17	1.43
1.40	1.63
1.24	1.24
1.14	1.04
0.38	0.62
1.44	1.16
1.54	1.16
1.69	0.88
0.95	0.62
0.69	0.62
0.75	0.68
0.74	0.60
0.78	0.68
0.63	0.69
0.67	0.66
0.66	0.78
1.09	0.71
0.81	0.89
0.94	1.15
1.83	0.36
1.91	1.37
1.23	1.34
1.29	1.06
1.10	1.43
1.20	0.83
1.28	1.12
1.21	1.28
1.62	0.93
1.51	1.02
1.71	0.86
1.29	1.60
1.21	1.16
1.35	1.70
1.27	1.10
1.47	1.27
1.33	1.28
	1.22

Table B-1 Continued

Anova: Single Factor SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	73	93.37	1.28	0.14
Column 2	74	88.46	1.19	0.14

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.25	1	0.25	1.810	0.180	3.90
Within Groups	20.6	145	0.142			
Total	20.85	146				

Conclusion:
Here F<Fcritical, there is no significant difference.

TABLE B-2 AM-PM PEAK ANOVA COMPARISON

NO_X EMISSIONS DATA

AM	PM
0.88	0.97
0.88	1.41
0.97	0.77
0.58	1.39
0.60	1.22
0.62	1.35
0.66	1.34
1.22	1.74
0.92	1.42
1.66	1.29
1.87	1.33
2.35	1.50
1.68	1.39
1.45	1.71
1.21	0.89
1.49	1.04
1.16	1.19
1.84	1.45
1.64	1.35
1.36	1.06
1.51	1.47
1.62	1.65
1.26	1.44
1.49	1.44
1.68	1.24
1.29	1.08
1.73	0.94
2.14	1.71
2.13	1.20
1.61	1.55
1.69	1.17
1.43	1.40
0.99	1.24
1.91	1.14
1.67	0.38

1.08	1.44

Table B-2 Continued

AM	**PM**
1.73	1.54
1.52	1.69
1.26	1.31
1.45	1.35
1.43	1.29
	1.43
	1.63
	1.24
	1.04
	0.62
	1.16
	1.16
	0.88

Anova: Single Factor SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	41	57.66	1.406341	0.183219
Column 2	49	62.64	1.278367	0.078656

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.3655794	1	0.365579	2.897185	0.092265	3.949321
Within Groups	11.104221	88	0.126184			
Total	11.4698	89				

Conclusion:
Here F<Fcritical, there is no significant difference.

TABLE B-3 PEAK – OFF-PEAK ANOVA COMPARISON

NO$_X$ EMISSIONS DATA

Peak	Off-Peak
0.88	0.95
0.88	0.69
0.97	0.75
0.58	0.74
0.60	0.78
0.62	0.63
0.66	0.67
1.22	0.66
0.92	1.09
1.66	0.81
1.87	0.94
2.35	0.62
1.68	0.62
1.45	0.68
1.21	0.60
1.49	0.68
1.16	0.69
1.84	0.66
1.64	0.78
1.36	0.71
1.51	0.89
1.62	1.15
1.26	0.36
1.49	1.83
1.68	1.91
1.29	1.23
1.73	1.29
2.14	1.10
2.13	1.20
1.61	1.28
1.69	1.21
1.43	1.62
0.99	1.51
1.91	1.71
1.67	1.29

1.08	1.21

Table B-3 Continued

Peak	Off-Peak
1.73	1.35
1.52	1.27
1.26	1.47
1.45	1.33
1.43	1.37
0.97	1.34
1.41	1.06
0.77	1.43
1.39	0.83
1.22	1.12
1.35	1.28
1.34	0.93
1.74	1.02
1.42	0.86
1.29	1.60
1.33	1.16
1.50	1.70
1.39	1.10
1.71	1.27
0.89	1.28
1.04	1.22
1.19	
1.45	
1.35	
1.06	
1.47	
1.65	
1.44	
1.44	
1.24	
1.08	
0.94	
1.71	
1.20	
1.55	
1.17	

1.40	
1.24	

Table B-3 Continued

Peak	**Off-Peak**
1.14	
0.38	
1.44	
1.54	
1.69	
1.31	
1.35	
1.29	
1.43	
1.63	
1.24	
1.04	
0.62	
1.16	
1.16	
0.88	

Anova: Single Factor SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	90	120.3	1.336667	0.128874
Column 2	57	61.53	1.079474	0.126244

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.308438	1	2.308438	18.05463	3.82E-05	3.906392
Within Groups	18.53948	145	0.127859			
Total	20.84792	146				

Conclusion:

Here F>Fcritical, there is significant difference.

TABLE B-4 DRIVERS ANOVA COMPARISON

NO_X EMISSIONS DATA

Driver 1	Driver 2	Driver 3
0.97	2.02	0.88
1.22	1.43	0.62
0.58	1.62	0.88
0.92	1.30	0.66
0.60	1.06	0.95
0.60	1.20	0.62
0.74	1.23	0.69
0.68	1.76	0.62
0.78	1.39	0.75
0.69	1.20	0.68
0.63	1.50	1.09
0.66	1.22	0.89
0.67	1.45	0.81
0.78	1.35	1.15
0.66	1.35	0.94
0.71	1.34	0.36
1.51	1.06	0.97
1.24	1.74	1.41
1.24	1.47	0.89
1.04	1.42	0.77
1.14	1.65	1.04
0.62	1.29	1.39
0.38	1.44	1.19
1.16	1.33	1.55
	1.44	1.31
	1.50	1.17
	1.24	1.35
	1.08	1.40
	1.39	1.29
	0.94	
	1.71	
	1.20	
	1.66	
	1.73	
	1.87	
	2.14	
	2.35	

Table B-4 Continued

Driver 1	Driver 2	Driver 3
	2.13	
	1.68	
	1.61	
	1.45	
	1.69	
	1.21	
	1.43	
	1.49	
	1.16	
	0.99	
	1.84	
	1.91	
	1.64	
	1.67	
	1.36	
	1.08	
	1.51	
	1.73	
	1.62	
	1.52	
	1.26	
	1.26	
	1.49	
	1.68	
	1.45	
	1.29	
	1.43	
	1.83	
	1.37	
	1.91	
	1.34	
	1.23	
	1.06	
	1.29	
	1.43	
	0.83	
	1.10	
	1.12	

	1.20	

Table B-4 Continued

Driver 1	Driver 2	Driver 3
	1.28	
	1.28	
	0.93	
	1.21	
	1.02	
	1.62	
	0.86	
	1.71	
	1.60	
	1.29	
	1.16	
	1.21	
	1.70	
	1.35	
	1.10	
	1.27	
	1.27	
	1.47	
	1.28	
	1.33	
	1.22	
	1.7	
	1.4	
	1.63	

Anova: Single Factor SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	20.21055972	0.842107	0.079269
Column 2	100	142.264396	1.422644	0.0811
Column 3	29	28.32642988	0.976773	0.090659

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9.137255616	2	4.568628	55.30806	1.02E-18	3.056366
Within Groups	12.39049355	150	0.082603			
Total	21.52774917	152				

Conclusion:

Here F>Fcritical, there is significant difference.

TABLE B-5 DAYS OF WEEK ANOVA COMPARISON

NO$_X$ EMISSIONS DATA

Tuesday	Wednesday	Thursday
0.88	1.09	0.97
0.62	0.89	1.22
0.88	0.81	0.58
0.66	1.15	0.92
0.95	0.97	0.60
0.62	1.74	0.60
0.69	1.47	0.74
0.62	1.42	0.68
0.75	1.65	0.78
0.68	1.29	0.69
2.02	1.44	0.63
1.43	1.33	0.66
1.22	1.44	0.67
1.45	1.50	0.78
1.35	1.24	0.66
1.35	1.68	0.71
1.34	1.61	0.94
1.06	1.45	0.36
1.66	1.69	1.41
1.73	1.21	0.89
1.87	1.43	0.77
2.14	1.49	1.04
2.35	0.83	1.39
2.13	1.10	1.19
1.83	1.12	1.62
1.37	1.20	1.30
1.91	1.28	1.06
1.34	1.28	1.20
1.23	0.93	1.23
1.06	1.21	1.76
1.29	1.02	1.39
1.43	1.62	1.20
1.71	0.86	1.50
1.60	1.55	1.08
1.7	1.31	1.39

1.4	1.17	0.94
1.51	1.35	1.71

Table B-5 Continued

Tuesday	Wednesday	Thursday
1.73	1.40	1.20
1.62	1.29	1.51
1.52	1.16	1.24
1.26	0.99	1.24
1.26	1.84	1.04
1.49	1.91	1.14
1.22	1.64	0.62
	1.67	0.38
	1.36	1.16
	1.08	
	1.29	
	1.16	
	1.21	
	1.70	
	1.35	
	1.10	
	1.27	
	1.27	
	1.47	
	1.28	
	1.33	
	1.63	
	1.68	
	1.45	
	1.29	
	1.43	
	1.44	
	1.16	
	1.54	
	0.88	

Anova: Single Factor
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	44	59.94617858	1.362413	0.19791
Column 2	67	89.09730825	1.329811	0.064647
Column 3	46	46.78055972	1.016969	0.123137

Table B-5 Continued

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.47959681	2	1.739798	14.62652	1.53E-06	3.054771
Within Groups	18.3180227	154	0.118948			
Total	21.7976195	156				

Conclusion:
Here F>Fcritical, there is significant difference.

APPENDIX C

HYPOTHESIS (T-DISTRIBUTION) TEST RESULTS

TABLE C-1 T-Tests for Driver 1

Driver 1 - Peak NO_x data for Thursday

Before	After
0.97	1.24
1.22	1.24
0.58	1.04
0.92	1.14
0.60	0.62
	0.38
	1.16

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	0.86	0.97
Variance	0.07	0.11
Observations	5.00	7.00
Pooled Variance	0.10	
Hypothesized Mean Difference	0.00	
df	10.00	
t Stat	-0.63	
P(T<=t) one-tail	0.27	
t Critical one-tail	1.81	
P(T<=t) two-tail	0.54	
t Critical two-tail	2.23	

Hypothesis Testing

Hypothesis	Rejection Criteria		
$H_0: \mu_1 = \mu_2$ $H_1: \mu_1 \neq \mu_2$	$\lvert t_{cal} \rvert > t_{Crit}$	$t_{Cal} = -0.63$ $t_{Crit} = 2.23$	Fail to reject the null hypothesis
$H_0: \mu_1 = \mu_2$ $H_1: \mu_1 > \mu_2$	$t_{cal} > t_{Crit}$	$t_{Cal} = -0.63$ $t_{Crit} = 1.81$	Fail to reject the null hypothesis
$H_0: \mu_1 = \mu_2$ $H_1: \mu_1 < \mu_2$	$t_{cal} < -t_{Crit}$	$t_{Cal} = -0.63$ $t_{Crit} = 1.81$	Fail to reject the null

			hypothesis

This means that this before and after data is not significantly different for any statistical conclusion.

Driver 1 – Off-peak NO_x data for Thursday

Before	After
0.60	1.51
0.74	
0.68	
0.78	
0.69	
0.63	
0.66	
0.67	
0.78	
0.66	
0.71	

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	0.69	1.51
Variance	0.00	#DIV/0!
Observations	11.00	1.00
Pooled Variance	0.00	
Hypothesized Mean Difference	0.00	
df	10.00	
t Stat	-13.63	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.81	
P(T<=t) two-tail	0.00	
t Critical two-tail	2.23	

Hypothesis Testing

Hypothesis	Rejection Criteria		
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 \neq \mu_2$	$\lvert t_{cal} \rvert > t_{Crit}$	$t_{Cal} = -13.63$ $t_{Crit} = 2.23$	Fail to reject the null hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 > \mu_2$	$t_{cal} > t_{Crit}$	$t_{Cal} = -13.63$ $t_{Crit} = 1.81$	Fail to reject the null hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 < \mu_2$	$t_{cal} < -t_{Crit}$	$t_{Cal} = -13.63$ $t_{Crit} = 1.81$	Fail to reject the null hypothesis

This means that this before and after data is not significantly different for any statistical conclusion.

Driver 1 – Off-peak NO_x data for Wednesday

Before	After
	0.83
	1.10
	1.12
	1.20
	1.28
	1.28
	0.93
	1.21
	1.02
	1.62
	0.86
	1.29
	1.16
	1.21
	1.70
	1.35
	1.10
	1.27
	1.27
	1.47
	1.28
	1.33

We do not have after data for statistical comparison.

Driver 1 – Off-peak NO_x data for Thursday

Art - Off-peak data for Thursday

Before	After
1.62	
1.30	
1.06	
1.20	
1.23	
1.76	
1.39	
1.20	
1.50	

We do not have after data for statistical comparison

TABLE C-2 T-Tests for Driver 2

Driver 2 - Peak NO_x data for Tuesday

Before	After
1.22	1.7
1.45	1.4
1.35	1.66
1.35	1.73
1.34	1.87
1.06	2.14
	2.35
	2.13
	1.51
	1.73
	1.62
	1.52
	1.26
	1.26
	1.49

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	1.30	1.69
Variance	0.02	0.10
Observations	6.00	15.00
Pooled Variance	0.08	
Hypothesized Mean Difference	0.00	
df	19.00	
t Stat	-2.93	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.73	
P(T<=t) two-tail	0.01	
t Critical two-tail	2.09	

Hypothesis	Rejection Criteria		
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 \neq \mu_2$	$\lvert t_{cal} \rvert > t_{Crit}$	$t_{Cal} = -2.93$ $t_{Crit} = 2.09$	reject the null hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 > \mu_2$	$t_{cal} > t_{Crit}$	$t_{Cal} = -2.93$ $t_{Crit} = 1.729$	reject the null hypothesis

Thus, before NO_x emissions are less than after NO_x emissions in this case.

Driver 2 - Peak NO_x data for Wednesday

Before	After
1.74	1.55
1.47	1.31
1.42	1.17
1.65	1.35
1.29	1.40
1.44	1.29
1.33	1.68
1.44	1.61
1.50	1.45
1.24	1.69
	1.21
	1.43
	1.49
	1.16
	0.99
	1.84
	1.91
	1.64
	1.67
	1.36
	1.08
	1.63
	1.68
	1.45
	1.29
	1.43
	1.44
	1.16
	1.54
	0.88

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	1.45	1.43
Variance	0.02	0.06
Observations	10.00	30.00
Pooled Variance	0.05	
Hypothesized Mean Difference	0.00	
df	38.00	

t Stat	0.31	
P(T<=t) one-tail	0.38	
t Critical one-tail	1.69	
P(T<=t) two-tail	0.76	
t Critical two-tail	2.02	

Hypothesis Testing

Hypothesis	Rejection Criteria		
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 \neq \mu_2$	$\lvert t_{cal} \rvert > t_{Crit}$	$t_{Cal} = 0.31$ $t_{Crit} = 2.02$	Fail to reject the null hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 > \mu_2$	$t_{cal} > t_{Crit}$	$t_{Cal} = 0.31$ $t_{Crit} = 1.69$	Fail to reject the null hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 < \mu_2$	$t_{cal} < -t_{Crit}$	$t_{Cal} = 0.31$ $t_{Crit} = 1.69$	Fail to reject the null hypothesis

Driver 2 - Peak NO_x data for Thursday

Before	After
1.08	
1.39	
0.94	
1.71	
1.20	

We do not have after data for statistical comparison

Driver 2 – Off-Peak NO_x data for Tuesday

Before	After
2.02	1.83
1.43	1.37
	1.91
	1.34
	1.23
	1.06
	1.29
	1.43
	1.71
	1.60
	1.22

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	1.73	1.45
Variance	0.17	0.07
Observations	2.00	11.00
Pooled Variance	0.08	
Hypothesized Mean Difference	0.00	
df	11.00	
t Stat	1.22	
P(T<=t) one-tail	0.12	
t Critical one-tail	1.80	
P(T<=t) two-tail	0.25	
t Critical two-tail	2.20	

Hypothesis Testing

Hypothesis	Rejection Criteria		
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 \neq \mu_2$	$\lvert t_{cal} \rvert > t_{Crit}$	$t_{Cal} = 1.22$ $t_{Crit} = 2.2$	Fail to reject the null hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 > \mu_2$	$t_{cal} > t_{Crit}$	$t_{Cal} = 1.22$ $t_{Crit} = 1.80$	Fail to reject the null hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 < \mu_2$	$t_{cal} < -t_{Crit}$	$t_{Cal} = 1.22$ $t_{Crit} = 1.80$	Fail to reject the null

			hypothesis

This means that this before and after data is not significantly different for any statistical conclusion.

Driver 2 – Off-Peak NO_x data for Wednesday

Before	After
	0.83
	1.10
	1.12
	1.20
	1.28
	1.28
	0.93
	1.21
	1.02
	1.62
	0.86
	1.29
	1.16
	1.21
	1.70
	1.35
	1.10
	1.27
	1.27
	1.47
	1.28
	1.33

We do not have after data for statistical comparison.

Driver 2 – Off-Peak NO_x data for Thursday

Before	After
1.62	
1.30	
1.06	
1.20	
1.23	
1.76	

1.39	
1.20	
1.50	

We do not have after data for statistical comparison.

TABLE C-3 T-Tests for Driver 3

Driver 3 –Peak NO_x data for Tuesday

Before	After
0.88	
0.62	
0.88	
0.66	

This means that this we do not have any significant data for any statistical conclusion.

Driver 3 –Peak NO_x data for Wednesday

Before	After
0.97	1.55
	1.31
	1.17
	1.35
	1.40
	1.29

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	0.97	1.35
Variance	#DIV/0!	0.02
Observations	1.00	6.00
Pooled Variance	0.02	
Hypothesized Mean Difference	0.00	
df	5.00	
t Stat	-2.78	
P(T<=t) one-tail	0.02	
t Critical one-tail	2.02	
P(T<=t) two-tail	0.04	
t Critical two-tail	2.57	

Hypothesis Testing

Hypothesis	Rejection Criteria		
H_0: $\mu_1 = \mu_2$	$\left\|t_{cal}\right\| > t_{Crit}$	$t_{Cal} = -2.78$	reject the null

H_1: $\mu_1 \neq \mu_2$		$t_{Crit} = 2.57$	hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 > \mu_2$	$t_{cal} > t_{Crit}$	$t_{Cal} = -2.78$ $t_{Crit} = 2.02$	Fail to reject the null hypothesis
H_0: $\mu_1 = \mu_2$ H_1: $\mu_1 < \mu_2$	$t_{cal} < -t_{Crit}$	$t_{Cal} = -2.78$ $t_{Crit} = 2.02$	reject the null hypothesis

This means that before NO_x emissions are less than after NO_x emissions.

Driver 3 –Peak NO_x data for Thursday

Before	After
1.41	
0.89	
0.77	
1.04	
1.39	
1.19	

This means that this we do not have any significant data for any statistical conclusion.

Driver 3 –Off-Peak NO_x data for Wednesday

Before	After
	0.83
	1.10
	1.12
	1.20
	1.28
	1.28
	0.93
	1.21
	1.02
	1.62
	0.86
	1.29
	1.16
	1.21

	1.70
	1.35
	1.10
	1.27
	1.27
	1.47
	1.28
	1.33

This means that this we do not have any significant data for any statistical conclusion.

Driver 3 –Off-Peak NO_x data for Thursday

Before	After
1.62	
1.30	
1.06	
1.20	
1.23	
1.76	
1.39	
1.20	
1.50	

We do not have sufficient data for statistical comparison

APPENDIX D

REGRESSION ANALYSIS

TABLE D-1 Aggregate Model # 1 results:

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	No. of Stops, Amb humidity, Amb temp, Control Delay, GPS Vel(a)	.	Enter

a All requested variables entered.
b Dependent Variable: NO_X

Model Summary(b)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.628 (a)	.394	.3378	17.57

a Predictors: (Constant), No. of Stops, Amb humidity, Amb temp, Control Delay, GPS Velocity
b Dependent Variable: NO_X

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	31098.728	4	7774.682	25.174	.000(a)
	Residual	47870.170	155	308.840		
	Total	78968.898	159			

a Predictors: (Constant), No. of Stops, Amb humidity, Amb temp, Control Delay, GPS Vel
b Dependent Variable: NO_X

Table D-1 Continued:

Coefficients(a)

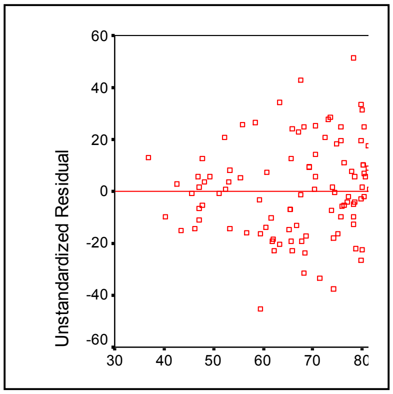
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.968	12.434		.641	.523
	Amb temp	-.764	.263	-.201	-2.903	.004
	Amb humidity	-.569	.076	-.519	-7.448	.000
	GPS Vel	11244.472	1288.370	.634	8.728	.000
	No. of Stops	1985.992	630.731	.213	3.149	.002

a Dependent Variable: NO_X

Residuals Statistics (a)

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	36.79084	100.87985	74.61119	14.092057	160
Residual	-45.10374	51.61967	.00000	17.264810	160
Std. Predicted Value	-2.684	1.864	.000	1.000	160
Std. Residual	-2.571	2.942	.000	.984	160

a Dependent Variable: NO_X



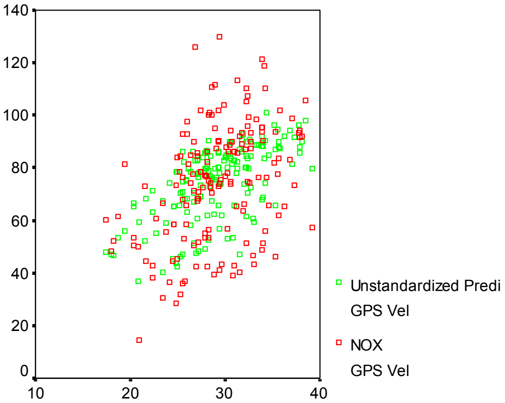


Figure D-1 Unstandardized Residual vs. Unstandardized Predicted values for aggregate model # 1

TABLE D-2 Aggregate Model # 2 results (considering driver as a dummy variable)

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	DRIVER2, Control Delay, DRIVER1, Amb humidity,	No. of Stops, Amb temp, GPS Vel(a).	Enter

a All requested variables entered.
b Dependent Variable: NO_X

Model Summary(b)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.767(a)	.58	.567	14.6

a Predictors: (Constant), DRIVER2, Control Delay, DRIVER1, Amb humidity
b Dependent Variable: NO_X

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	46412.678	7	6630.383	30.956	.000(a)
	Residual	32556.220	152	214.186		
	Total	78968.898	159			

a Predictors: (Constant), DRIVER2, No. of Stops, Amb temp, Control Delay, DRIVER1, Amb humidity, GPS Vel
b Dependent Variable: NO_X

Table D-2 Continued

Coefficients(a)

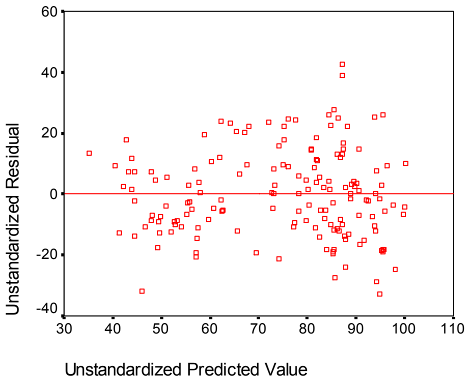
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	84.694	5.522		15.337	.000
	Amb humidity	-.258	.065	-.235	-3.989	.000
	Control Delay	-90.081	13.212	-.380	-6.818	.000
	Driver 2	26.186	3.200	.555	8.183	.000

a Dependent Variable: NO_X

Residuals Statistics(a)

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	35.17097	100.09501	74.61119	17.085188	160
Residual	-32.93358	42.65307	.00000	14.309301	160
Std. Predicted Value	-2.308	1.492	.000	1.000	160
Std. Residual	-2.250	2.914	.000	.978	160

a Dependent Variable: NO_X



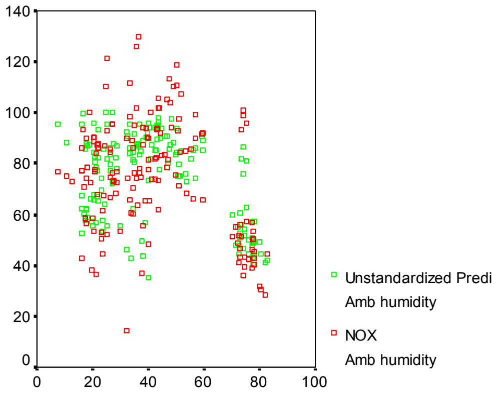


Figure D-2 Unstandardized Residual vs. Unstandardized Predicted values for aggregate model # 2

TABLE D-3 Aggregate Model # 3 results
(considering driver and peak/off-peak as dummy variables)

Variables Entered/Removed (b)

Model	Variables Entered	Variables Removed	Method
1	D2P, Control _delay, Amb_humidity, D1P, STOPS, AMB_TEMP, DRIVER2, DRIVER1, PEAK, GPS_velocity(a)	.	Enter

a All requested variables entered.
b Dependent Variable: NOX

Model Summary(b)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.797(a)	0.636	0.612	13.8

a Predictors: (Constant), D2P, Control _delay, Amb_humidity, D1P, STOPS, AMB_TEMP, DRIVER2, DRIVER1, PEAK, GPS_velocity
b Dependent Variable: NO_X

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	50725.612	10	5072.561	26.545	.000(a)
	Residual	29046.483	152	191.095		
	Total	79772.094	162			

a Predictors: (Constant), D2P, Control _delay, Amb_humidity, D1P, STOPS, AMB_TEMP, DRIVER2, DRIVER1, PEAK, GPS_velocity
b Dependent Variable: NO_X

Table D-3 Continued

Coefficients (a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	55.568	25.778		2.156	0.033
	Amb_humidity	-0.173	0.076	-0.157	-2.260	0.025
	PEAK	16.968	5.296	0.379	3.204	0.002
	DRIVER2	33.617	5.333	0.712	6.304	0.000

a Dependent Variable: NO_X

Residuals Statistics(a)

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	33.92	103.98	74.906802	17.6952	163
Residual	-31.28	39.70	0.0000000	13.39026	163
Std. Predicted Value	-2.316	1.643	0.000	1.000	163
Std. Residual	-2.263	2.872	0.000	0.969	163

a Dependent Variable: NO_X

TABLE D-4 Disaggregate Model results

Variables Entered/Removed (b)

Model	Variables Entered	Variables Removed	Method
1	Amb_humidity, S2, A3, , AMB_TEMP, A2, S, A, AS, S3, AS3, A3S, (a)	A2S2, A2S3, A3S2, A2S, AS2, A3S3	Enter

a All requested variables entered.

b Dependent Variable: NO_X

Model Summary (b)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.30(a)	0.09	0.09	91.75

ANOVA (b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	19909688.666	11	1809971.697	215.002	.000(a)
	Residual	201191568.390	23899	8418.409		
	Total	221101257.056	23910			

Coefficients (a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	100.629	4.216		23.868	.000
	A	55.503	2.464	.677	22.527	.000
	A2	5.339	.620	.106	8.608	.000
	A3	-2.771	.417	-.203	-6.647	.000
	S	-34.205	1.288	-.633	-26.550	.000
	S2	4.051	.612	.155	6.616	.000
	S3	1.734	.165	.401	10.481	.000
	AS	-23.032	1.259	-.903	-18.296	.000
	AS3	.859	.080	.400	10.679	.000
	A3S	1.022	.128	.237	7.993	.000
	AMB_TEMP	-.531	.172	-.022	-3.087	.002

	Amb_humidity	-.509	.027	-.134	-18.733	.000

Table D-4 Continued

Residuals Statistics(a)

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	-10.22983	321.43637	73.8328	29.271700	23911
Residual	-268.10999	974.33105	.00000	91.599111	23911
Std. Predicted Value	-2.872	8.459	.000	1.000	23911
Std. Residual	-2.926	10.633	.000	1.000	23911

a Dependent Variable: NO_X

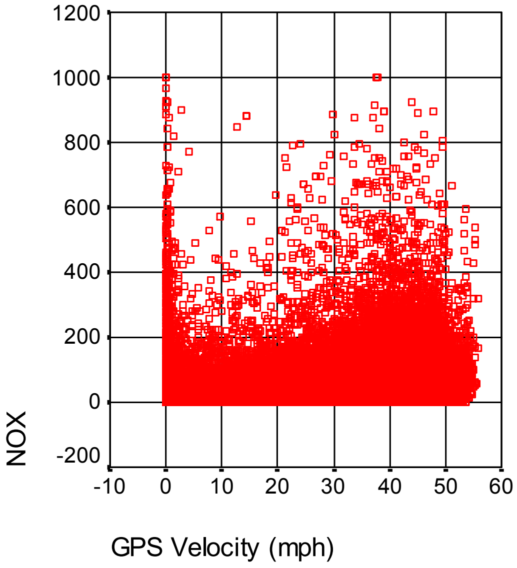


Figure D-3 NO_x vs. GPS Velocity (mph)

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BIOGRAPHICAL INFORMATION

Born on August 17th 1980, Rupangi Prakash Munshi earned her Bachelor of Civil Engineering from the Center for Environmental Planning and Technology (CEPT), India in August 2002. After graduation, she worked as a project management engineer with Project Consultancy Services (PCS) for a year (2002-2003).

The author has earned her Masters of Science in Civil Engineering from The University of Texas at Arlington with major concentration in Environmental Engineering. During her graduate studies, she was appointed as a research assistant by Dr. Melanie L. Sattler. Her master's research is focused on the "Impact of signal synchronization on vehicular emissions – an on-board measurement case study". The study dealt specifically with the impacts of signal synchronization on on-road NO_x emissions. Unlike the present trend of using modeled data to predict NO_x emissions, this study collected data under real world conditions taking into account all the parameters that could affect the NO_x emissions. This study was an example of novel researches in the field which made it more challenging. She also presented her research at the "2005 Summer TxITE (Texas Institute of Transportation Engineers) meeting" at Laredo, Texas.

During the course of her Masters, she also worked as an Engineering Intern with the Bridge Division at Texas Department of Transportation (TxDOT), Austin and Energy & Asset Management Division at Dallas/Forth Worth International Airport, Dallas. In

Spring 2005, she was also initiated into Chi Epsilon – The National Civil Engineer’s Honors Society.