EFFECTIVENESS OF SIGNAL COORDINATION
AS AN EMISSION REDUCTION
MEASURE FOR
VEHICLES

by

RAJASHI I PARIKH

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN CIVIL AND ENVIRONMENTAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON
AUGUST 2006

DEDICATED TO MY LATE FATHER INDRAVADAN NAVLAKHA AND MOTHER SULOCHANA WITH ALL MY LOVE

"Always keep your dreams alive. Understand that to achieve anything requires faith and belief in oneself, vision, hard work, determination, and dedication.
Remember all things are possible for those who believe."

ACKNOWLEDGEMENTS

A thesis is an opportunity to be thankful to friends, teachers and colleagues for all their support and encouragement with a heart full of gratitude. A graduate degree is a process that often develops character and engraves a permanent mark in the memory of a student, especially when the degree is pursued thousands of miles away from one’s home country, family and friends.

First of all I would like to take this opportunity to thank my advisor Dr. Melanie L. Sattler for her constant support. She is a brilliant mentor and an incredible teacher of countless new concepts and ideas. She is a kind and friendly person and has always been there in my times of need. She has taught me the essence of research and helped me channel my energies towards my work.

I would like to mention a special thanks to Dr. Stephen P. Mattingly, who has been of great help throughout my thesis. He is a very ebullient professor full of energy. His analytical and statistical skills always have been awe inspiring.

The thesis would have been impossible without their support. They have contributed silently and fundamentally to achieve the objective of my thesis. They have always appreciated my work and encouraged me by giving constructive feedbacks right through the completion of my work.

I am grateful to my other committee member Dr. Andrew Kruzic for imparting a keen sense of learning in me and passing on loads of information throughout the past couple of years. I would also like to thank my academic professors Dr. Sayed R. Qasim and Dr. Mustafa Gandhehari for enhancing my knowledge in areas other than air pollution.

My special and sincere thanks go to my research group members Benjamin, Gus, Vye, Shruthi and Shriharsha. We had a great time working together. I will always remember those moments when we drove around DFW for data collection and also those healthy discussions on a variety of different topics. They helped me regularly with my data questions and also solved many problems related to data analysis.

I thank the people working at the physical plant in UTA for helping us in solving any problem with our vehicle promptly and efficiently. I thank the Civil and Environmental Engineering Department at UTA for giving me an apt opportunity of working with many brilliant minds, and admire everything that I have gained here.

I would also like to thank my dearest friend Nishad, who has played a pivotal role throughout my thesis. I do not have enough words to thank him for being there without any hesitation, providing me encouragement and moral support throughout my study. I would also like to thank my other friends Vivek, Komal, Shobha, Arpita, Harshal, Dhaval, and others for their support throughout my work. I want to thank my uncles and aunts living in Dallas and Houston for supporting me. They have fulfilled all my needs throughout my graduate program.

And last but not the least my mother and two sisters Bhavita and Rachana who are the most important people in my life. I would like to thank them for their support and love in these two years far away from home. It is because of my mother’s encouragement and perseverance that I have been able to achieve all my dreams.

ABSTRACT

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Publication No. _______

Rajashi I. Parikh, MS.

The University of Texas at Arlington, 2006

Supervising Professor: Dr. Melanie L. Sattler, Dr. Stephen P. Mattingly

Air Pollution is a significant health and environmental concern. Vehicular emissions are major contributors to many air pollution problems. There is growing interest in reducing carbon dioxide emission because of the alarming increase in the pollution caused by petroleum resulting global warming issue. Various studies have found that U.S vehicles emit half of the CO_2 emitted from vehicle all over the world. Dallas Fort Worth is a non-attainment area for ozone and it is required to achieve NAAQS standards by 2010. NOx and VOCs from the automobile are a major precursor of ozone formation in the atmosphere. Traffic signal retiming has prove to be a beneficial measure for improving traffic flow conditions and reducing fuel consumption. This research focuses on measuring CO_2 and NOx from light duty vehicles to verify the effectiveness of traffic signal synchronization as measure for reduction of emissions.

Data for this research were collected using the On-Board Emission Measurement System OBS-1300. The OBS-1300 facilitates real-time collection of field data for second-by-second measurement of tailpipe emissions. The Chevy Astro Van was used as the study vehicle to collect on-road emission data on Cooper Street and involved four different drivers. The effect of signal coordination on CO_2 and NOx pollutants and the relationship between different driving modes were investigated using statistical and graphical approaches.

Rigorous statistical analysis has shown that the average emission rate for CO_2 collected on peak hour on Wednesday was increased by 15.4% after signal retiming, emissions at other times did not significantly change. After dividing emissions into different velocity clusters for each mode, CO_2 emissions were observed to increase for most of the velocity clusters after signal retiming. The analysis conducted for NOx emissions showed that after signal retiming, the emissions decreased for most of the velocity clusters. Since emissions by velocity cluster are a function of engine parameters only for a given velocity and acceleration, there should have been no difference in before vs. after. Ambient humidity or temperature could have caused the changes. The emission rates for CO_2 in g/mile were highest for acceleration, followed by deceleration and then by cruise. In the case of NOx, the average emissions were highest for acceleration, followed by deceleration and then by cruise.

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CHAPTER 1

INTRODUCTION

Air pollution is one of the most important sources of environmental degradation. Air pollution may be extremely harmful to living beings and in certain cases may result in severe disorder or death. The number of vehicles and the miles traveled are increasing rapidly each year. These mobile sources release millions of tons of pollutants into the air. Of all the environmental externalities of transportation, air pollution costs are perhaps the most extensive. Most of the transport problems occur when transport systems, for a variety of reasons, are unable to satisfy the numerous requirements of mobility. Severe traffic congestion and the accompanying air quality problems are making it essential for cities to be more innovative in managing traffic as populations grow.

1.1 The Mobile-Source Air Pollution Problem

Congress enacted the Clean Air Act Amendments of 1990 to ensure clean air for all Americans. The Environmental Protection Agency (EPA) sets limits for specific pollutants which are known as National Ambient Air Quality Standards. EPA and State and local agencies institute monitoring networks to gauge the concentration of pollutants in the air. The monitored data is analyzed to verify if the standards are met. If concentrations of any pollutant breach the standards, then EPA, along with the State, declares the area as non-attainment. For the past decade and a half, DFW has been unable to meet the National Ambient Air Quality Standard for ozone and hence has been classified as an ozone non-attainment area by the EPA. The Metroplex is facing increased health costs if the compliance mandates are not met. There are two major pollutants, nitrogen oxides (NOx) and volatile organic compounds (VOCs), responsible for ozone formation. These sources are classified as On-Road, Non-Road, Point and Area and Miscellaneous sources. Transportation, industrial processes and heat and energy generation are the primary contributors of these pollutants.

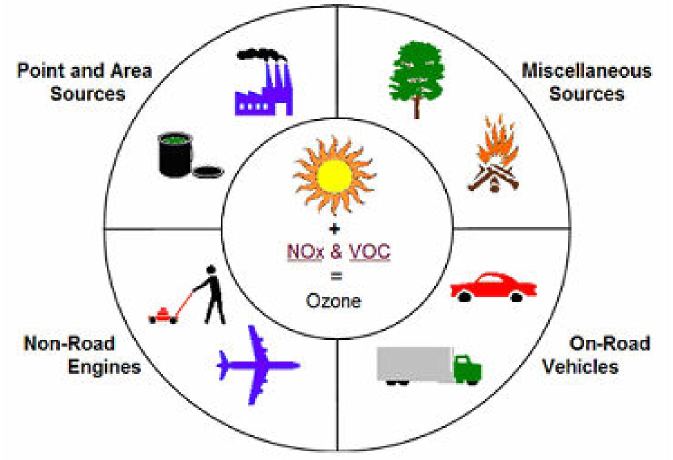

Figure 1.1 Sources forming Ozone
Source: NCTCOG Transportation Department, December 2005

Motor vehicles contribute the largest amount of ozone precursors like VOCs and NOx. They also produce nearly two third of all CO emissions. The contributions of each of these source classifications for NOx and VOCs are shown in Figure 1.2.

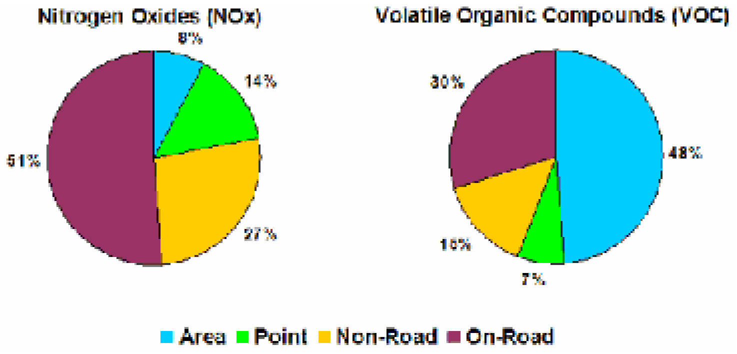

Figure 1.2 Pollutant Source Contribution for Dallas-Fort worth
Source: NCTCOG Transportation Department, December 2005

As evident from the Figure 1.2, on- road vehicular emissions is a foremost cause of the formation of ozone in DFW. On-road mobile vehicles emit more than half of the ozone precursor NOx pollution in North Central Texas. In order to meet the national ambient air quality standard for ozone, it is necessary to address major contributing factors to on-road mobile emissions like high emitting vehicles, cold starts, hard accelerations, excessive idling, high speeds, low speeds, vehicle engines and vehicle miles traveled.

1.2 Different Emission Measurement Methods

The EPA has developed a Mobile Source Emission Factor Model (MOBILE). The MOBILE and other emission models are based upon dynamometer testing, where emissions from vehicles are measured under laboratory conditions. It is a very expensive method and does not provide real world data. Vehicle testing in a laboratory setting does not take into account the effect of traffic and climatic conditions, aggressive driving, highly transient and high speed operation, and use of air conditioning and local roads.

Remote sensing is another method for measuring vehicle emissions. It uses infrared to measure the concentration of CO and CO_2 pollutants and ultra violet to measure NOx pollutant in exhaust emissions as the on-road vehicle passes a sensor on the roadway. It gives an instantaneous estimate of emissions at a specific location.

On-board emissions measurement is widely recognized as a desirable approach for monitoring second-by-second emission from vehicles. The device can gives readings for HC, CO, CO_2, and NOx emissions. The driving path of the vehicle can be traced using the in-built Global Positioning System (GPS) unit. The disparities in vehicle emissions depend on various factors like variation in roadway characteristics, vehicle location, vehicle operation, driver, or other factors. These can be represented and analyzed more reliably using on-board emissions measurement than by any other method.

1.3 Mobile Source Emission Reduction Strategies

Due to the increased motorization in America, air quality is undergoing an increased deterioration. This has required the development of strategies and action plans to achieve an effective improvement of the air quality. Following are different control strategies to improve air quality. Mobile source emission reduction can be achieved using Transportation Control Measure (TCM), Voluntary Mobile Emission Reduction Programs (VMEP) and Transportation Emission Reduction Measures (TERM).

1.3.1 Transportation Control Measures

TCM are project, program and related activities that are designed to achieve on-road mobile source emission reduction and are included as control measures in the State Implementation Plan (SIP). TCMs are strategies that reduce vehicle use or change the traffic flow and congestion conditions to reduce vehicular emissions. A few examples of TCMs include mass transit improvements, ridesharing arrangements, telecommuting and work schedule changes, parking management, and roadway tolls.

1.3.2 Voluntary Mobile Emission Reduction Programs

VMEPs compliment existing regulatory programs through voluntary changes in transportation choices and activities. These alternatives to traditional emission reduction strategies reduce mobile source emissions by engaging communities, employers, and residents in air quality initiatives.

1.3.3 Transportation Emission Reduction Measures

TERMs are transportation projects and related activities that are designed to achieve on-road mobile source emission reduction but not included in State Implementation Plan (SIP). The emission reductions are implemented in DFW through a Thoroughfare Assessment Program, which reduces congestion and improves air quality by enhancing traffic flow on the arterial street network using signal coordination, intersection improvements; extension of HOV facilities, new rail transit routes, grade separations, park and ride facilities, vanpools, and intelligent transportation system.

1.4 Research Objective

The primary purpose of the study is to collect real world on-road NOx and CO_2 emissions on Cooper Street in Arlington, Texas using the on-board measurement system (OBS-1300) to analyze the effect of signal coordination on carbon dioxide emissions from light duty vehicle and conduct modal analysis for NOx and CO_2.

1.5 Research Outline

The next chapter in this thesis is a literature review of similar studies that have been conducted using on-road emission measurement. Various new ideas that came up during the review of these studies will be discussed in this chapter. Chapter 3 will cover the methodology implemented to attain the research objectives. Chapter 4 will deal with the data collected, its analysis and depicting the results statistically. Chapter 5 will talk about the conclusions that are drawn from the analyzed data in Chapter 4. Aspects like recommendations and future scope of work will be discussed in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

This section presents a literature review that was performed for the pertinent research. Initially some background information on vehicle emissions is provided. The chapter also gives some information on regulations impacting vehicle emissions. A discussion on general approaches used in vehicle emissions measurement and modeling is provided. The chapter ends with a review of previous on-road emission measurement studies.

2.1 Introduction

One of the major factors that contribute to the success of a country is its transportation system. It helps to build up the economic condition of a country, fosters social growth and fortifies its defense systems. Unfortunately the advancement of the transportation system has adverse impact on natural and human environment. The fundamental technology used in transportation results in emission of pollutants which have been proven to or are supposed to cause harm to human health and plant life and to imbalance the sensitive ecosystem. The manner in which the present and future transportation system meets transportation demand will have significant implications for air quality.

2.1.1 Motor Vehicles and Emissions

In the U.S., the largest sources of air pollution, in order of importance are: 1) transportation, which includes all light and heavy duty vehicles; 2) electric power plants that burn coal or oil; and 3) industries, like steel mills, metal smelters, oil refineries, and paper mills. Motor vehicles are the most significant contributors to air pollution in U.S. The emissions from the vehicles include pollutants, such as carbon monoxide and particulate matter; those that react to form pollutants, such as nitrogen oxide (NOx) and volatile organic compounds (VOCs), both of which can lead to ozone formation; and numerous other hazardous air pollutants, like benzene and butadiene.

Nitrogen oxides and carbon monoxide are formed during the combustion process and are emitted only from the tailpipe. Hydrocarbons and air toxics may originate both from the tailpipe in the form of unburned or partially burned fuel, as well as in the form of evaporative emissions from the fuel tank, fuel lines and losses during the refueling process. Carbon dioxide is formed due to complete combustion process. There is growing interest in reducing CO_2 emissions because of the alarming increase in the pollution caused by petroleum and resulting global warming issue. As CO_2 emissions occur whenever a carbon-based fuel is burned, these emissions are deeply related to international energy issues. “The USA is the biggest emitter of greenhouse gases world wide. US emissions have increased to 7 billion tons of CO_2 in 2004, 16% higher than emissions in the late 90’s” (Cars and Pollution EPA Fact Sheet OMS-5). As per the study conducted by Environmental Defense, nearly half of all greenhouse gases emitted by automobiles globally is contributed by U.S automobiles and light trucks (http://www.ens-newswire.com/ens/jun2006/2006-06-28-03.asp). In the year 2004, light duty vehicles emitted the highest percentage of carbon dioxide when compared to emissions from other types of vehicles. Table 2.1 summarizes various types of motor vehicle pollution emissions and their impacts.

Table 2.1 Vehicle Pollution Emission

Emissions	Description	Sources	Harmful Effects	Scale
Carbon dioxide	A byproduct of combustion.	Fuel production and engine	Climate change.	Global
Carbon monoxide (CO)	A toxic gas that undermines blood's ability to carry oxygen.	Engine.	Human health, Climate change.	Very local
CFCs	Durable chemical harmful to the ozone layer and climate.	Older air conditioners.	Ozone depletion.	Global
Fine particulates (PM10; PM2.5)	Inhaleable particles consisting of bits of fuel and carbon.	Diesel engines and other sources.	Human health, aesthetics.	Local and Regional
Hydrocarbons (HC)	Unburned fuel. Forms ozone.	Fuel production and engineers.	Human health, ozone precursor.	Regional
Lead	Element used in older fuel additive.	Fuel additives and batteries.	Circulatory, reproductive and nervous system.	Local
Methane (CH4)	A gas with significant greenhouse gas properties2.	Fuel production and engines.	Climate change.	Global
Nitrogen oxides (NOx)	Various compounds. Some are toxic, all contribute to ozone.	Engine.	Human health, ozone precursor, ecological damages.	Local and Regional
Ozone (O2)	Major urban air pollution problem resulting from NOx and VOCs combined in sunlight.	NOx and VOCs.	Human health, plants, aesthetics.	Regional
Road dust	Dust particles created by vehicle movement.	Vehicle use.	Human health, aesthetics.	Local

Table 2.1 Continued

Sulfur oxide (SOx)	Lung irritant, and causes acid rain.	Diesel engines.	Human health risks, acid rain.	Local and Regional
Volatile organic hydrocarbons (VOCs)	A variety of organic compounds that from aerosols.	Fuel production and engines.	Human health, ozone precursor.	Local and Regional
Toxic	VOCs those are toxic and carcinogenic.	Fuel production. and engines.	Human health risks.	Very local

Courtesy: 1USEPA, Indicators of the Environmental Impacts of Transportation, USEPA (www.itre.ncsu.edu/cte), 1999; ORNL, Transportation Energy Data Book ORNL, (www.ott.doe.gov), 2000
2SCAQMD, Multiple Air toxic Exposure study (MATES-II), South Coast Air Quality Management District (www.aqmd.gov/matesiidf), 2002

2.1.2 Air Quality Standards

Emissions of air pollutants play an important role in a number of air quality issues. About 160 million tons of pollutants are emitted into the atmosphere each year in the United States[1]. These emissions typically contribute to the formation of ozone and particulate matter, the deposition of acids, and visibility impairment.

The Clean Air Act (CAA), which was last amended in 1990, requires the Environmental Protection Agency (EPA) to prescribe national primary ambient air quality standards (NAAQS) for certain air pollutants, which are known as criteria pollutants. These pollutant levels were chosen to protect the health of the most prone individuals in a population, including children, the aged and those with chronic respiratory ailments. A secondary standard is also set to protect human welfare like visibility, crop damage, and building damage. Based upon the levels of air pollutants, geographic areas are classified by EPA as attainment or non-attainment areas. A geographic region meeting or having pollutant levels below the NAAQS is called an attainment area. An area with continual air quality problems is assigned as a non-attainment area. Table 2.2 below shows the air pollution concentrations required to exceed the NAQQS.

Table 2.2 Air Pollution Concentrations Required to Exceed NAAQS

Pollutant	Average Period	NAAQS Violation Determination3	Primary Standard	Secondary standard
Particulate Matter (PM10)	Annual average	Never expected to be exceeded in any calendar year.	50 µg/m3	Same as Primary
	24-hour	Never expected to be exceeded more than once in any calendar year.	150µg/m3	Same as Primary
Particulate Matter (PM2.5)	Annual average	3-year average of the annual arithmetic mean.	15µg/m3	Same as Primary
	24- hour	98th percentile of the 24-hour values determined for each year. 3-year average of the 98th percentile values.	65µg/m3	Same as Primary
Carbon Monoxide	1-hour	Not to be exceeded more than once per year.	35 ppm (40,000µg/m3)	None
	8-hour	Not to be exceeded more than once per year.	9 ppm (10,000 µg/m3)	None
Nitrogen Dioxide (NO2)	Annual	Annual arithmetic mean	0.053 ppm (100µg/m3)	Same as Primary
Sulfur Dioxide (SO2)	Annual arithmetic mean	Not to be exceeded in any calendar year.	0.03 ppm (80µg/m3)	---------
	24-hour	Not to be exceeded more than once in any calendar year.	0.14 ppm (365µg/m3)	------------
	3-hour	Not to be exceeded more than once in any calendar year.	--------	0.5 ppm (1,300µg/m3)
Ozone (O3)	8-hour	Average of 4th highest max daily 8-hour average, over 3 consecutive years.	0.08 ppm (157µg/m3)	Same as Primary
Lead (Pb)	Calendar quarter	Not to be exceeded in any quarter of any calendar year.	1.5 µg/m3)	Same as Primary

1. http://www.epa.gov/airtrends/non.html
2. http://www.deq.state.id.us/air/data_reports/monitoring/overview.cfm
3. An exceedance of the NAAQS does not necessarily mean a violation has occurred, which would result in a re-designation of an area. Violation of the NAAQS are used to determine attainment/non-attainment status for an area where monitoring is being conducted)

µg/m3= microgram per cubic meter
ppm = parts per million

2.1.3 Dallas/ Fort Worth Air Quality

In accordance with the 1990 Clean Air Act, EPA designated the Dallas/ Fort Worth (DFW) area as a moderate non-attainment area and it required to demonstrate attainment of the 1-hour ozone standard by November 15, 1996. The DFW area was unable achieve the standards by the given deadline. In 1998 the EPA reclassified the DFW area as a serious non-attainment area and set a deadline of November 15, 1999. But the DFW area failed to reach attainment by that deadline as well.

In the attainment demonstration State Implementation Plan (SIP), adopted by the Texas Commission on Environmental Quality (TCEQ) in April 2000, the importance of local nitrogen oxides (NOx) reductions as well as the transport of ozone and its precursors from the Houston-Galveston-Brazoria (HGB) area were taken into account. Based on photochemical modeling, it was demonstrated that transport from the HGB area was impacting DFW's air quality. It was also demonstrated that a combined reduction in NOx and VOCs would be effective in reducing ozone formation. From 15th June, 2005 onwards, EPA began the implementation of a new ozone standard with an 8-hour averaging time. As per the 8-hour standard, the DFW region, which is designated as "moderate" non-attainment area for ozone, is developing a new 8-hour SIP that is more stringent than the 1-hour 2000 SIP.

2.1.4 Emission Measurement Methodologies

Vehicle emissions are measured and their reductions are predicted to ensure the greater 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 excessively stringent and costly SIP. However, if these emission reductions are overestimated, it results in the SIP falling short of achieving required compliance. The following are the different ways of measuring or modeling vehicular emissions.

2.1.4.1 Dynamometer

Dynamometer testing involves measurement of emissions from vehicles by using standard driving cycles, under controlled conditions. A driving cycle is composed of a unique profile of stops, starts, constant speed cruises, accelerations and decelerations and is normally characterized by an overall time-weighted average speed.

The data resulting from driving cycles are further used to develop emission estimation models, such as EMFAC7F, MOBILE6, MEASURE, and CMEM. The main limitation is the inability to measure vehicles under real driving conditions and particularly the impractical nature of applying the method to a large number of vehicles in a reasonable time.

Figure 2.1 Dynamometer
Source: Class notes (UTA, spring 2006)

2.1.4.2 Remote Sensing Device (RSD)

In this method the pollutant level in a vehicle's exhaust is measured while the vehicle is in motion on the road. Remote sensing devices use infrared (IR) to measure CO, CO_2 and use ultraviolet (UV) to measure concentration of NO. The foremost advantage of remote sensing is that it is possible to measure a large volume of on-road vehicles. The major drawbacks of remote sensing are that it only gives an instantaneous estimate of emissions at a specific location, and cannot be used across multiple lanes of heavy traffic. Figure 2.2 shows the how the RSD works.

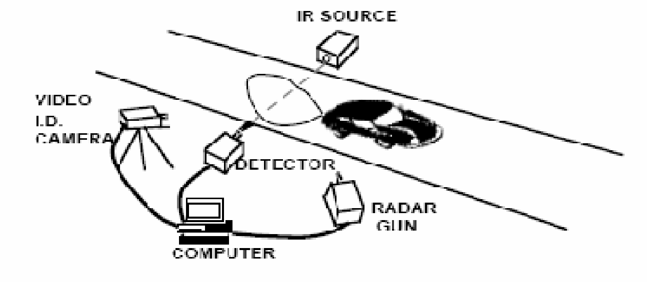

Figure 2.2 RSD Set-Up
Source: Fact sheet OMS-15 August, 1993

2.1.4.3 On-Board Emission Measurement Device

On-board emissions measurement is commonly recognized as a sought-after approach for quantifying emissions from vehicles since data in this method are collected under real-world conditions at any location traveled by the vehicle. Figure 2.3 shows the On-Board Emission Measurement System (OBS) used for second-by-second data collection.

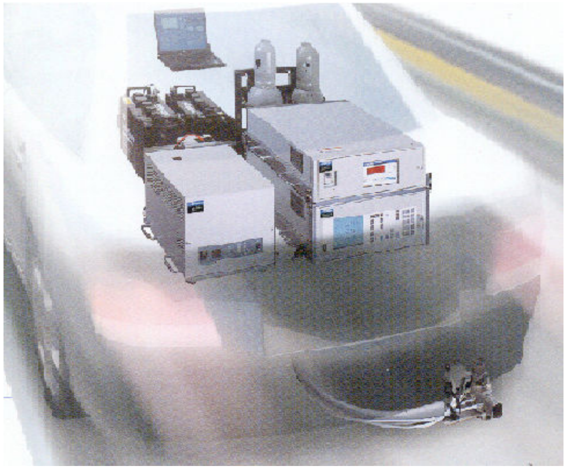

Figure 2.3 On-Board Emission Measurement Devices
Source: class notes (UTA, spring 2005)

The inconsistency in vehicle emissions as a result of variation in roadway characteristics, vehicle location, vehicle operation, driver, or other such factors can be represented and analyzed more reliably with on-board emissions measurement than with any other methods. This is because measurements are obtained during real world driving conditions, eliminating the concern about non-representativeness that is frequently an issue with dynamometer testing, and, at any location, doing away with the siting restrictions innate in remote sensing.

2.1.5 Transportation Control Measure

A Transportation Control Measure (TCM) "is any measure that is specifically identified and committed to, in an applicable implementation plan that is either one of the types listed in section 108 of CAA, or any other measure for the purpose of reducing emissions or concentrations of air pollutants from transportation sources by reducing vehicle use or changing traffic flow or congestion conditions" (UC Davis- Caltrans Air Quality Project Final Report, August 2004). In the United States, traffic signal synchronization is a very widely used TCM to deal with congestion management issues. The signal improvements can be made for an individual roadway or along an entire corridor network. It helps to reduce traffic congestion, increases safety and improves response times for emergency vehicles.

Among all the measures included in the 2000 DFW SIP, Transportation Control Measures (TCMs) play a major role in reducing 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 occupancy-vehicle (HOV) lanes.

* Appendix G, Transportation Control Measures, Dallas/Fort worth Attainment Demonstration, April 2000 revision.

2.1.6 Thoroughfare Assessment Program

The North Central Texas Council of Governments (NCTCOG) has developed a Thoroughfare Assessment Program (TAP) as a Transportation Control Measure (TCM) put forward in Transportation Conformity. In accordance with this program, the timing of almost 725 of the 1300 signalized intersections in the DFW Metroplex will be modified. The objectives of TAP are to lessen emissions and improve air quality as well as reduce congestion and improve traffic flow in the DFW Metroplex region via signal synchronization and low-cost operational improvements to comply with NAAQS for ozone. This will have a supplementary advantage of reducing overall driver delays at signalized intersections. It was anticipated that improved signal synchronization would result in reduced travel times and fewer collisions since there will be smoother traffic flow and fewer stops. “Environmentally, these improvements will result in less idling by vehicles, reduced air pollution, less gas consumption and cost savings.” (NCTCOG, 2004)

Earlier, NCTCOG used the Mobile Source Emission Reduction System (MOSERS) for air quality benefit calculations. MOSERS was based on assumptions which do not take into account the different driving modes at the intersections. The basis of the assumptions was that, due to signal re-timing and moderate upgrades, delay decreases and speed increases equally at all intersections irrespective of intersection performance and traffic volume, which was not very realistic. Therefore, NCTCOG has developed a new method for post processing SYNCHRO output to calculate air quality benefits under the TAP program. This methodology gives due considerations to account delay, queue length, stops and speed at each intersection approach.

The TAP development occurred in two phases:

1. Pilot Phase: This phase was conducted on a small scale taking into consideration all the parameters affecting air quality. The data collection was conducted for 49 signalized

intersections. The phase pointed out different parameters affecting vehicular emissions for a detailed study.

2. Production Phase: This phase was comprised of a detailed study covering 44 corridors, which included 835 signalized intersections throughout the DFW Metroplex area. The traffic counts for A.M; midday and P.M peak hours were obtained from SYNCHRO Model in before and after signal retiming scenarios. There was a post-processing approach of calculating emission reductions in NO_x, CO_2, and VOCs (g/mile) from different traffic parameters made available by 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 for NO_x and VOCs were obtained from the EPA emissions model MOBILE5. Although the post-processing approach is an improved 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.

2.2 Literature Review

Numerous studies have been conducted using on-road emission measurements with focus on various parameters and various fueled vehicles. Researchers have also set up different emission measurement kits to measure the concerned pollutants for their region. A number of researches conducted on the related theme are discussed in detail below. These aim to measure vehicular emissions and consider various factors affecting mobile source emissions.

2.2.1 Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions – NCSU, 2003

This study was undertaken at the North Carolina State University to evaluate the effect of traffic signal timing and coordination on vehicle emissions by comparing vehicle activity and emissions data collected before and after signal synchronization. The study was conducted by four drivers using eight gasoline fueled light-duty vehicles, on two signalized arterials, Walnut Street and Chapel Hill Road in Cary, North Carolina. The device OEM-2100^{TM} was used for the on-road data collection for a second-by second measurement of pollutant concentration of NOx, CO and HC. A data collection protocol was developed by graphical, statistical and theoretical approaches. It was observed that coordinated signal timing resulted in improved traffic flow on Walnut Street, which in turn led to a reduction in vehicle emissions. Chapel Hill Road being at capacity lacked any significant reduction in vehicle emissions. Emissions of NOx, CO, and HC were higher in the congested case compared to the uncongested case.

The comparison of signal timing and coordination demonstrated that the way the vehicles are driven is important. Modal analyses suggested that emissions were highest during acceleration and were least for idle mode. The rates varied substantially for specific periods during the day and the direction of travel, when comparing before and after results.

2.2.2 A Methodology for Modeling and Measuring Traffic and Emission Performance of Speed Control Traffic Signals – Margarida C. Coelho, Tiago L. Farias and Nagoui M. Rouphail

The article deals with a study conducted on Highway N6 connecting the cities of Lisbon and Cascais in Portugal where, to control speeds, 14 traffic control devices were installed. The main purpose of the research was to explain the interaction between the signal control variables and improved driver behavior. For this research, three cases were considered depending on the controller setting. The first case suggested that any additional "high speed calls" received during the minimum green time could be ignored. The second case suggested that "high speed calls" could trigger the start of a new cycle as soon as the current cycle has elapsed. The third case suggested that "high speed calls" which occurred within a certain amount of time after the previous speed violator has actuated the system resulted in an extension of the red time by a fixed amount for each other "high speed calls".

The author could not locate any real world situation where Case B was implemented. The experimental data for the model was collected by the means of video cameras at two different locations covering the signal system for the first and third cases. It was assumed that each driving mode generates a fixed emission rate for pollutants. The experiments concluded that using the speed control device, there was a significant reduction of average traffic speed. The results proved that the numerical model prediction was in accordance with the experimental data. They also concluded that speed control violators often increase traffic delays, which results in local pollutant emissions. Most importantly, the presence of signals showed that an increase in CO emissions of 15%, while NO emissions went up by 10% and HC emissions increased about 40%.

2.2.3 A Comparison Of Real-World And Modeled Emissions Under Conditions Of Variable Driver Aggressiveness – Edward K. Nam, Christine A. Gierczak, James W. Butler, 2003

The paper firstly talks about the Portable Real time Emissions Vehicle Integrated Engineering Workstation (PREVIEW), on-board, real-time, emissions measurement instrumentation developed at Ford. The data was collected from a PREVIEW system in Southfield, Michigan. Parameters like emissions, travel time and power during “normal” and “aggressive” driving styles were compared. The paper also discussed a microscopic traffic model (VISSIM) that was integrated with the load based Comprehensive Modal Emissions Model (CMEM). A virtual vehicle was simulated in VISSIM having similar characteristics as the instrumented vehicle. The virtual vehicle was inserted into the traffic model in which the southeast Michigan road network was coded. All of the applicable modeled variables are compared with measured quantities, with due consideration to driver aggressiveness.

The results showed that the magnitude of the emissions was relatively low for both normal and aggressive driving. The results from the network run and instrumented vehicle were compared, and it was observed that the generated driving pattern of the simulated vehicle was different from the measured patterns, while variables such as travel time and aggressivity compared well. The emissions simulated as function of aggressivity showed that aggressive driving caused significantly higher emissions. The article recommended that “the aggressivity number may be employed as an explanatory variable for emissions in future studies, as well as a means for comparing drive cycles.”

2.2.4 Vehicle Emissions and Traffic Measures: Exploratory Analysis of Field Observations at Signalized Arterials - Rouphail, et. al.

The primary purpose of this research was to study the effects of traffic flow on real-world vehicle emissions and to probe the relationship between vehicle emissions and control delay. Data for this research were collected in real-time through the use of portable, On-board Emission Measurement unit (OEM 2100^{TM}). The emissions data included second-by-second data for CO, NO, HC, CO_2 and O_2 and vehicle operation. Emissions for different driving modes were evaluated. Highest emissions during acceleration and least during idle modes were observed.

The results showed that emissions from the vehicle were two times higher during control delay than when not in delay. Statistical analysis showed that CO had the highest relative variability, with the standard deviation often exceeding the average, which in turn implied that CO is more dependent on other variables, such as engine condition, driver aggressiveness and outside weather conditions than the other two gases measured. Finally, a relationship between control delay and vehicle emissions was developed, which would give traffic analysts the option of minimizing vehicle emissions in designing a roadway or timing a signal system.

2.2.5 Emission Model Development Using In-Vehicle On-Road Emission Measurements - Rakha, Ahn, El-Shawarby, and Jang

This paper presents the microscopic emission model development using the VT-Micro framework and modal validation. It also demonstrates the applicability of on-road emission-measurement data and the larger cost savings that are associated with on-road testing in comparison to chassis dynamometer. For developing the microscopic emissions models, data were collected with OEM unit. The second-by-second data were collected on the Virginia Smart Road, which is an uncongested road, with a wide range of speed and acceleration. Driver aggressiveness was accounted for during the modeling procedures and results.

The proposed model was a nonlinear regression model utilizing a multi-dimensional polynomial model structure. These model predictions were also compared against models like MOBILE5a and MOBILE6, the CHEM model, the EMIT model, and the VT-Micro model. The study showed that the VT-Micro framework was better suited to capture differences in vehicle emissions across the various drive cycles. MOBILE5a and MOBILE6 models were incapable of doing the same, while the CHEM and EMIT models were too sensitive to minor differences in the drive cycles. The research concluded by mentioning that several areas of research were required to expand the applicability of the emission models. It also recommended that the effect of ambient temperature, relative humidity, vehicle type, and driving behavior on vehicle emissions be characterized.

2.2.6 Modal Analyses of Vehicle Emission Factors – Stefano Cernuschi, Michele Giugliano, Andrea Cemin

The study was conducted with the AMES (Advanced Monitoring Environmental System) research project, funded by ENI with the objective of analyzing emissions from light duty vehicles using a modal approach. Base emission data were obtained from the chassis dynamometer by performing an on-road measurement operation in the Milan urban area. These were subdivided into acceleration ranges and analyzed in terms of their dependence on speed, deriving relationships between emissions, speed and acceleration for CO, VOC and NOx. The emission maps generated from the dynamometer for 10 light duty vehicles represented the actual circulating fleet and identified emission factors for different driving modes. Base emission data were obtained by reproducing urban driving cycles with vehicles circulating in the Milan area and equipped with time-speed recorders. The relationship between emissions and the kinematics characteristics of the mode were represented by polynomial functions.

They have observed that for higher velocities CO and VOC emission decrease and NOx emission increases with the speed. For diesel engines some significant difference in emissions arising mainly from the weight of the vehicle was observed. NOx emission was observed to be higher from light-duty vehicles compared to the other study vehicles. CO and VOC are lower for diesel passenger car than the catalyzed gasoline vehicle. CO and VOC emission factors were found to be in fair agreement over the entire range of the experimental study, whereas NOx estimated values showed minor overestimations for the slowest cycle and a few underestimations for the fastest driving cycles.

2.2.7 Characterizing the Effects of Driver Variability on Real-World Vehicle Emissions – Britt A. Holmen and Debbie A. Niemeieir

The study was conducted with hypothesis that the different drivers and driving cycles associated with individual drivers will cause significant differences in measured emissions. The main objective of the study was to evaluate the hypothesis and identify and quantify the driving parameters that contribute to this variability. The study was carried out with 24 drivers on Davis Route in CA under low traffic conditions using on-board exhaust emission and engine operating data analyzers. The data were analyzed to test significant differences in CO and NOx emissions between drivers.

The results showed significant difference for CO and NOx emissions for different drivers and gave no significant difference for frequency of driving modes. The researchers have suggested that the intensity of vehicle operation within the given mode, not the modal frequency, explains the emissions variability between drivers. Future research should be aimed to develop statistically robust models that include this variability in addition to other currently used variables contributing towards urban air pollution.

2.3 Research Objective

The DFW Metroplex, being a non- attainment zone, is a major area for conducting studies to understand the emission patterns and try and provide solutions to overcome the same. As a part of this, the Texas Air Research Center (TARC) has assigned a project to the University of Texas at Arlington to verify the effect of signal coordination as a vehicular emission reduction measure. Work on a few corridors has already been completed and research is still in progress to cover other corridors. One of the studies was on the Great Southwest Parkway corridor where data were collected with on-board emission measurement system OBS-1300 for vehicular NOx emission. The data was analyzed statistically using ANOVA, for comparing the various factors such as driver behavior, AM Peak/PM Peak, Peak/Off-Peak, driving direction, and day of week, by one of the researchers Ms. Rupangi Munshi. From the research it was concluded that on-board data reveals the importance of real-world conditions and helps to develop more accurate traffic and air quality management policies and procedures.

Another research was carried out by Kamesh Vyethavya Sista where the corridor under focus was the Cooper Street from Park Row Drive up to Debbie Lane to verify the effect of signal retiming for vehicular NOx. This study used the same methodology and statistical approach as the previous study and observed that there was a significant reduction in the emissions of NOx for both peak and off-peak hours after signal retiming. The key objective of this research is to find the impact of signal coordination for vehicular CO_2 emission and also to develop a relationship between the various driving modes and average emission rate for CO_2 and NOx.

CHAPTER 3

METHODOLOGY

This chapter talks about the data collection corridor; equipment used (OBS 1300) including its specifications, installation and maintenance; and the data collection procedure.

3.1 Data Collection Corridor

The emission data were collected on Cooper Street, which is one of the most active traffic zones located in the Arlington area of the Dallas/Fort Worth Metroplex. Many important structures including the University Of Texas at Arlington (UTA), Parks Mall and Wal-Mart are in the vicinity of Cooper Street. UTA, with more than 25,000 students, is a major source of traffic on Cooper Street, along with thousands of other visitors to the Mall and Wal-Mart. Eastbound and westbound Interstate highway 20 (I-20), which connects to Dallas and Fort Worth, also intersects with Cooper Street, which further increases traffic volume. The corridor of study was 9.5 miles long, stretching from Park Row Street to the intersection of FM. 157 and Debbie Lane in Mansfield. It has 3 lanes each northbound and southbound, along with a buffer lane in the middle. The corridor under study has about 15 signalized intersections with no stop signs. The corridor close to UTA, north of Park Row Street, and that between Mayfield Street and Oak Village Blvd., are observed to be critical traffic zones for the study.

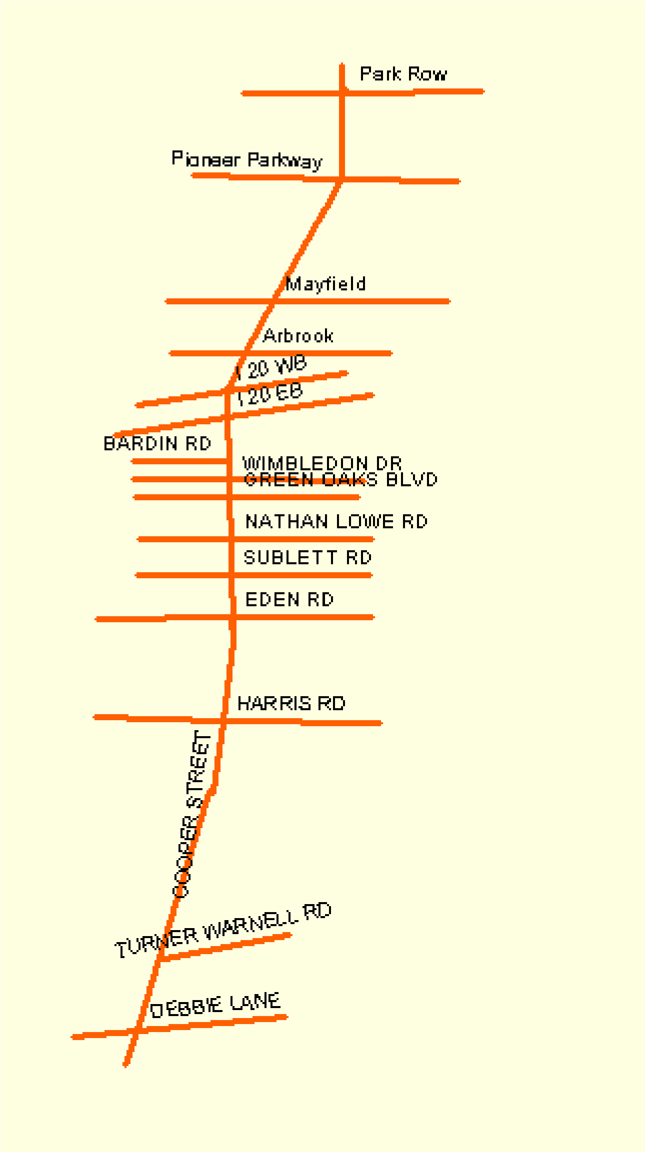

Figure 3.1 Cooper Street – Park Row to F.M 157 – Debbie Lane
Source: Synchro

3.2 Data Collection Equipment

The goals set for this research were achieved by conducting an extensive on-board emission measurement study using the experimental setup consisting of an On-Board System (OBS-1300) obtained from Horiba Instruments, Inc. The setup using OBS-1300, along with the study vehicle, a Chevrolet Astro Van provided by the Civil Engineering Department, was located at the University of Texas at Arlington.

The study vehicle is shown in Figure 3.2, and the characteristics of the study vehicle are mentioned in Table 3.1 below.

Figure 3.2 Study Vehicle (Chevrolet Astro Van)

Table 3.1 Study Vehicle Characteristics

Parameter	Value
Model Year	1999
Engine	4.3L V6
Power	142 kW, 190 HP @ 4400 rpm
Fuel tank capacity	95 liters
Injection system	Multi-point

3.3 Basic Description of OBS-1300 System

The OBS-1300 is designed to measure vehicle mass exhaust emissions under actual real-world driving conditions. This is achieved using the vehicle and engine operation data and concentrations of pollutants in exhaust gas sampled from the tailpipe. It is set up in the rear of the study vehicle as shown in Figure 3.3 and provides various parameters every second, like concentrations of NOx, HC, CO, CO_2, engine rpm, vehicle speed, temperature, position data with GPS unit and other parameters.

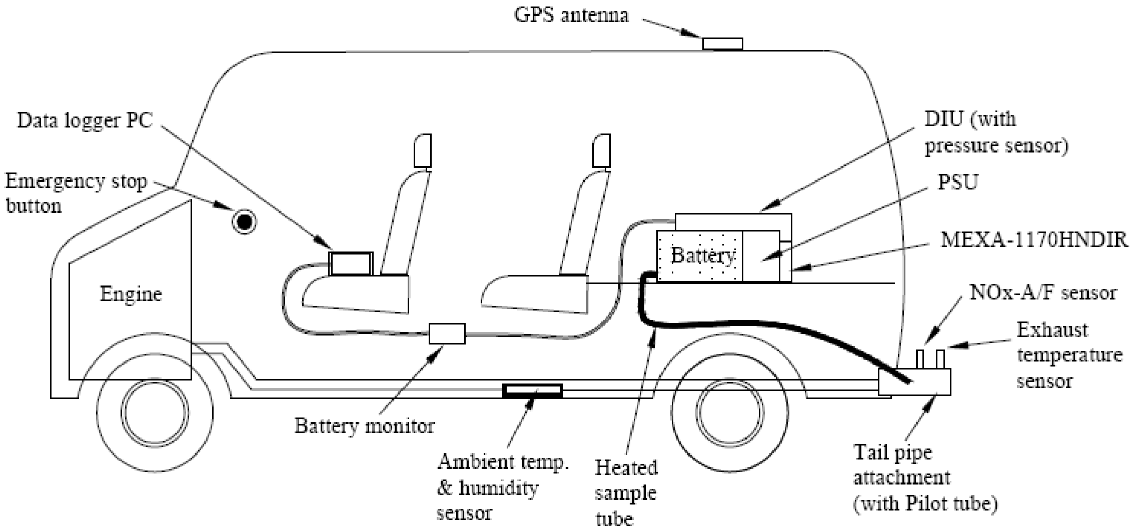

Figure 3.3 System Set up

The exhaust of the sample lines is routed through the window and fastened to the exhaust system using hose clamps. For in-vehicle installation, a power cable is connected to the power port, and engine data link connected to the OBD link and an emissions sampling probe inserted into the tailpipe. The connections are fully reversible and do not require any modifications to the vehicles. Figure 3.4 illustrates the placement of the OBD-1300 instrument on the vehicle floor.

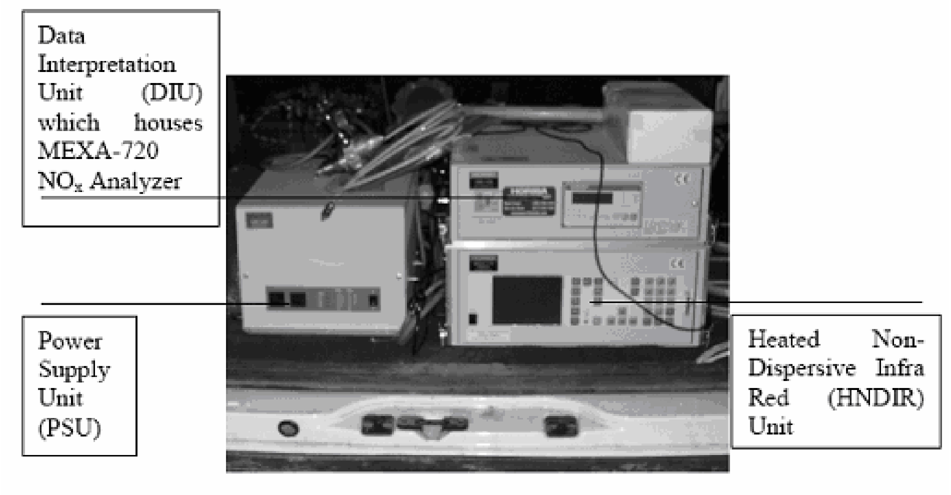

Figure 3.4 OBS -1300 Unit

The emission sampling probe and hose are routed into the vehicle and to the instrument. Grade probes and sample lines are used to sample undiluted exhaust gas from the tailpipe. The concentrations of HC, CO, CO_2 and NOx in the exhaust gas are determined by a gas analyzer system. Vehicle speed, intake air mass flow, temperature and other engine operation parameters are collected using an on-board diagnostics sensor array system. Multiplying the exhaust mass flow by the concentration of different pollutants yields grams per second emission data.

3.3.1 OBS 1300 Features and Specifications

The OBS 1300 is easy to install, connect, and remove individual components. It does not require gas line for operation and hence provides safety and economy. The dimensions of OBS 1300 are such that it can be installed in 1 square meter of space in the vehicle. The dimensions of the various units are as follows: HNDIR analyzer 510 x 190 x 690 mm (20.1 x 7.5 x 27.2 in), Data logger PC 250 x 40 x 260 mm, DIU 510 x 140 x 600 mm, PSU 300 x 250 x 400 mm and Battery monitor 170 x 100 x 230 mm. Cables and the sensor array also occupy some space. The sensors for analyzers are designed for vibration robustness. The system has an independent power supply with rechargeable battery packs for stable measurement. The weight of the batteries is approximately 80 kg with power of 12V DC. The equipment outputs second by second with 1.5-2.0 seconds initial delay.

The system computer uses PCMCIA card to perform analog to digital conversion. The user interface is designed as the keyboard/keypad. All the software is included in the computer. Real-time text information is displayed and the ASCII comma-delimited text file is generated, which is used for further analysis. The data logging computer makes a log of the following parameters: concentration of pollutants, exhaust temperature, exhaust pressure, ambient temperature, ambient pressure, ambient humidity, GPS signals, vehicle velocity, engine revolutions, exhaust flow rate, and time-trend profile.

The operating temperature and humidity are 0-40°C and under 80% RH for ambient conditions, respectively. The equipment can be operated in any type of on-road production gasoline or diesel engine vehicles. The instrument is not designed for rough off-road driving or such vehicles as performance driving on a racetrack, backhoes, bulldozers, locomotives, and marine vessels.

The typical installation time is 20 to 30 minutes. The warm-up time of the equipment is approximately 45 minutes and 15 minutes is required for the calibration of sensors. There are several parts of the unit, including the global positioning system (GPS), the heated sample line, the pitot tube, the exhaust pressure sensor, ambient humidity and temperature sensors, and NOx-A/F sensors.

3.3.2 Installation Requirement for OBS-1300

A warning from Horiba Instruments, Inc. mentions that OBS-1300 is designed for vehicular on-board use only. Any exhaust from MEXA-1170-HNDIR analyzer used in OBS-1300 should be released outside the vehicle. The lines contain various gases such as engine emissions and standard gas, which may be harmful to living beings.

3.3.3 System Operation

Successful operation of the OBS 1300 necessitates understanding the system, entering correct setup parameters, periodically checking that data are in reasonable ranges during real time operation, periodically calibrating the equipment, checking all connections for leaks and frequently assuring that the installed hardware has not shifted or been damaged during the on-road data collection.

The OBS 1300 is composed of an on board gas analyzer, as well as a personal computer equipped with data logging software. The OBS 1300 has various functional units such as Data Interpretation Unit (DIU), MEXA-1170 HNDIR Unit, Power Supply Unit (PSU), Data Logger PC, Battery, Tailpipe Attachment, a Remote Control and GPS unit. Each of these units is described below.

3.3.3.1 Data Integration Unit

As shown in Figure 3.4, the Data Integration Unit includes the MEXA 720 NOX analyzer and the main power breaker switch to the analyzer. The rear end of the unit has high and low differential pressure ports, an exhaust pressure port and an ambient pressure port. The unit also has ports for connecting to temperature and humidity sensors, and the NOX sensor. The RS-232C port connects to the computer used for data logging.

3.3.3.2 MEXA-1170 HNDIR Unit

This unit houses a power switch to boot up the system. The rear of the unit provides outlet for the exhaust gas, inlet for the sample, calibration and purge gas, and filter box. There is a provision for connecting remote control, heated sampling tube and connectors for leak check.

3.3.3.3 Power Supply Unit

This unit provides AC power output, providing supply to the Data Integration Unit by the means of an inverter power switch. It also has provisions for connecting battery terminals, emergency switch, and a main power breaker switch. Its basic function is to convert AC input power to DC current to serve as a battery charger.

3.3.3.4 Data Logger PC

The data logger contains an Analog to Digital conversion card inserted into the PC card slot (PCMCIA Card). It also provides a serial port for receiving the signals from the GPS unit.

3.3.3.5 Battery

Figure 3.5 shows two deep cell type batteries (12 V each) used as power supply to all units. They are connected to the Power Supply Unit.

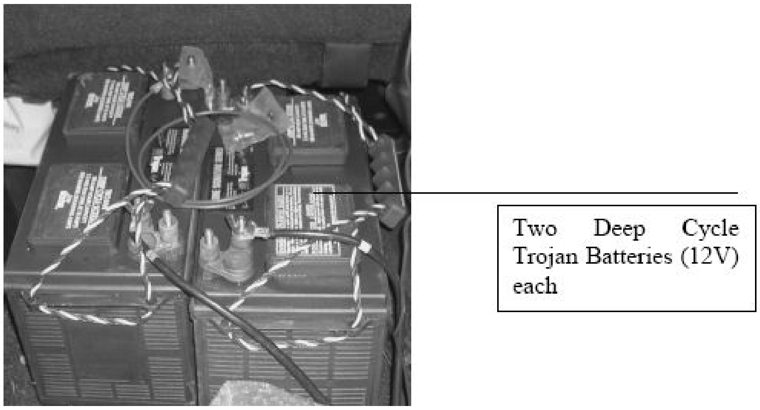

Figure 3.5 Batteries for Supplying Power

3.3.3.6 Tailpipe Attachment

The tailpipe attachment shown below has provisions for connecting various sensors and analyzers that obtain samples from the exhaust and measures the level of the pollutant. The measurements are logged to the data logging computer via the MEXA-1170-HNDIR and the Data Integration Unit.

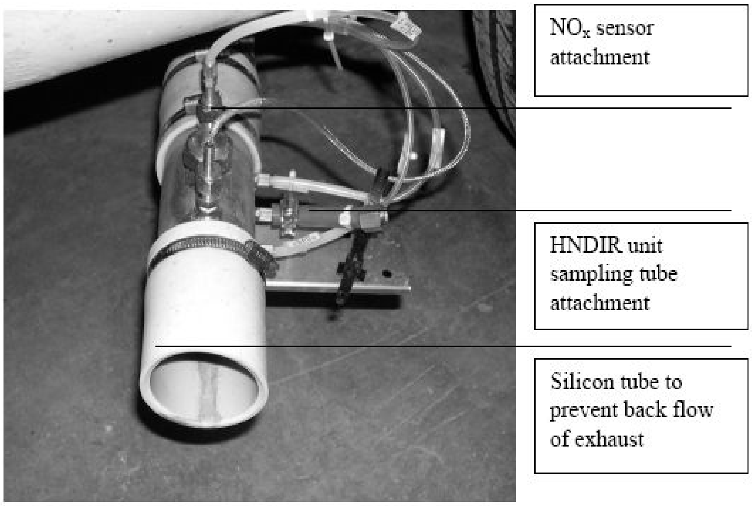

Figure 3.6 Tail Pipe Attachments

3.3.3.7 Remote Controller

The remote controller shown in Figure 3.7 below is an optional device for controlling the MEXA-1170-HNDIR unit. It can control operations using buttons on the remote which are also present on the front panel of the HNDIR unit. As an example, the 'Measure' button is used to start the sample intake into the sampling tube and the 'Reset' button is used to stop the operation. Various other buttons are provided which can handle purging and calibration.

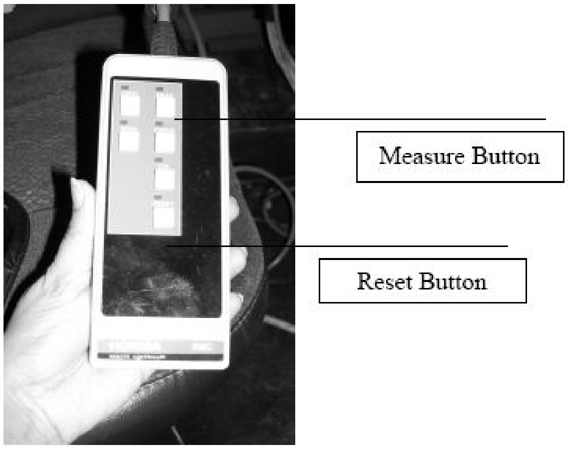

Figure 3.7 Remote Control

3.3.3.8 GPS Unit

As shown in Figure 3.8, a magnetic antenna, i.e. the GPS antenna, is used to determine the velocity, altitude and positioning of the vehicle on the road. This data is sent to the data logging computer for analysis.

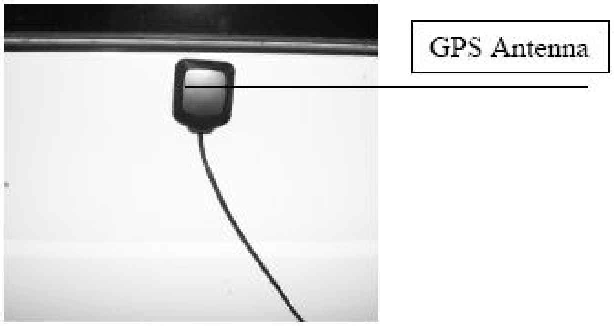

Figure 3.8 Geographic Positioning System

3.3.4 System Maintenance

In order to maintain high accuracy of gas concentration measurements, proper safety measures must be exercised when servicing internal parts of the unit. Before conducting maintenance, adequate training must be provided. In order to ensure consistent operation of the system and guarantee that the data obtained are of the highest quality and accuracy, periodic maintenance should be performed. System maintenance includes the cleaning of the sample filtering system, the sample system leak test, the gas analyzer calibration, the replacement of NOX sensor, the cleaning of HNDIR (Heat Non-Dispersive Infra-Red spectroscopy) and some other standard procedures.

Motor vehicle exhaust contains a large amount of water which needs to be removed prior to entering the analyzers. The external sample filtering system, located on the back of the unit, should be checked every week. The sampling system should be checked for leaks, as they tend to degrade the analyzer response time, and are detrimental to the accuracy of the measurement.

The data depends on the reliability of the NOx sensor and hence it is necessary to calibrate NOx sensor every week. The set up of the calibration unit and NOx sensors are as shown in Figure 3.9 and described below.

The NOx sensor must 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 must be filled in the calibration unit through the water inlet. The calibration gas cylinder is connected to the calibration unit via a regulator valve. The calibration gas used for this calibration 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.

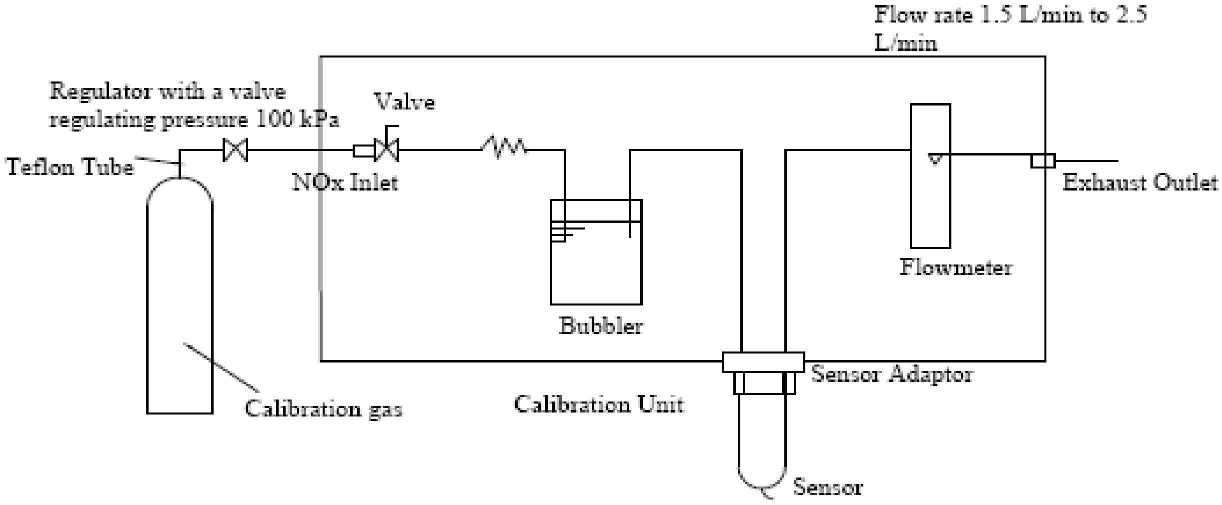

Figure 3.9 NOx Sensor Calibration Setup

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 NOx analyzer is switched on and needs to be calibrated by setting the values defined in the Horiba manual.

For setting the NOx concentration, CAL/SET key is pressed and held for approximately three seconds and the mode of the analyzer switches to the setting mode.

Channel number (ch000) then appears on display. Enter the value of concentration displayed on calibration gas label (in this case, 2000 ppm). This concludes the calibration process. Table 3.2 shows the daily maintenance items necessary for OBS 1300. (Ref. HORIBA Manual)

Table 3.2 The daily maintenance items for OBS-1300

Item	Recommended interval	Required tools	Remark
Battery charging and replacement	Every 4-hour operation		Required time for charging: 5 hours
	Every year of every 300 cycles of charge/discharge		Always use the included cable without adding any extension cables.
Cleaning of tail pipe attachment	Every working week	General tools: soft cloth water.	
Purge and replacement of pressure monitor tubing	Every working week	Purge gas	
	Semi-annually	Teflon tube	
GPS Setting			Only when required

3.4 Data Collection

The data collection was carried out after the installation of OBS 1300 in the study vehicle with the help of Horiba's technical representative. To ensure proper functionality of the setup, test runs were performed after installation and the data was analyzed to check for errors. On completion of the test runs, a data collection schedule was set up, taking into account time of the day, day of the week and the driver. Three different times during the day were decided upon, conforming to the information given by Kimley-Horn and Associates (consultants hired by NCTCOG), in order to accumulate data.

A.M Peak (7:00 AM – 9:00 AM)

Off Peak (9:00 AM – 4:00 PM)

PM Peak (4:00 PM – 6:30 PM)

Data collection was employed before and after signal retiming, so that the two situations could be compared. The data collection before signal retiming was carried out during the period of January-March 2005 and during August-September 2005 using OBS-1300. The data collection after signal retiming was carried out during the period of January-February 2006 using the same set up.

3.4.1 Factors Affecting Data Collection

3.4.1.1 Time of Day

Data was collected on Monday through Friday, as the traffic volume tends to remains more stable on weekdays. Data was separated into peak and off-peak data depending on the time of data collection.

3.4.1.2 Weather

Data collection was not possible on rainy days owing to the risk of damaging the sensors due to splashing of water. Also it was ensured that the vehicle was not driven through stagnant water on the road. To avoid direct contact of sunlight with the analyzers, the vehicle was parked in an enclosed parking area.

3.4.1.3 Vehicle Speed

The vehicle speed should be maintained at nearly the same rate as the other vehicles on the road in order to ensure that the emissions data would be representative to the maximum possible extent.

3.4.1.4 Driver

The driving habits of the drivers like tendency to accelerate break and, approach signals and intersections need to be similar to ensure consistent data collection.

3.4.1.5 Calibration

The calibration of sensors is one of the most important factors affecting accurate data collection.

3.4.1.6 Battery Power

Before the start of every data collection, it was ensured that all the batteries had enough power. A voltage drop below 21 V was unacceptable, as it resulted in erratic data.

3.4.1.7 Data Logging Software

Various parameters on the Analog to digital converter (ADC) setup need to be configured by going to the main screen of software. This shows a screen wherein all the parameters are displayed with a selectable range of values as listed in Table 3.3

Table 3.3 Parameters configured In ADC Set Up

Parameters	Rang of Values	Unit
NOx	0.00 – 3000	Ppm
Air to Fuel Ratio (AFR)	0.00 – 100	
Exhaust Temperature	0.00 – 1000	Degree C
Exhaust Pressure	0.00 – 200	k-Pa
Ambient Temperature	0.00 – 150	Degree C
Ambient Pressure	0.00 – 100	k-Pa
Ambient Humidity	0.00 – 100	%
Velocity	0 – 500	Kmph
Revolution	0 – 5000	Rpm

NOx concentration is measured taking into account a time delay for converting the sensor measured concentration from analog to digital form and logging the results in the data logging software. This time, determined by HORIBA Instruments, was about 1.5-2.0 seconds.

3.5 Data Collection Procedure

The steps below demonstrate the methodical procedure for data collection, preceded by the warm-up and calibration procedure.

- Charge 2, 12 Volt deep cycle batteries completely before every data collection schedule.
- Turn on DIU using AC power and start HNDIR unit and warm up the system for 45 minutes.

- Turn OFF DIU and HNDIR and switch their source to DC Power.
- Now turn ON the DIU and the HNDIR units at a one minute interval from each other (in the same order).
- Now turn ON the DIU and the HNDIR units at a one minute interval from
- each other (in the same order).
- Purge the HNDIR unit using ‘Zero’ gas and allow the process to run for 5 minutes.
- Press ‘RESET’.
- Press ‘ZERO’ and wait for 90 seconds followed by ‘RESET’ again.
- Input span gas from the cylinder and press ‘SPAN’ button and wait for 90 seconds.
- Press ‘RESET’ followed by the ‘CAL’ button and the system will perform zero and span calibration and then reset.
- At the starting point turn the vehicle ignition OFF and ensure zero calibration of the instrument.
- Press CAL’ for calibration of the pitot tube.
- Press ‘RESET’ followed by ‘PURGE’ to start the purging of the instrument.
- While purging turn vehicle ignition ON, and also the logging computer.
- Press “MEASURE’ button after 90 seconds of purging and ‘START LOGGING’ when a signalized intersection is reached.

The next chapter will talk about the results obtained using OBS-1300 for data collection and the inferences that can be made about the emission parameters after signal coordination.

CHAPTER 4

ANALYSIS AND RESULTS

4.1 Data Collection and Interpretation

This chapter deals with the analysis and evaluation of the collected emission data. First the data processing procedure will be provided. Then a statistical approach is presented for finding out whether a significant difference in CO_2 emissions between before and after signal synchronization occurred. This is followed by the modal analysis for CO_2 and NOx emission data.

4.1.1 Data Collection

The emission data collected on the Cooper corridor was second-by-second. The data collected using OBS-1300 was analyzed using the parameters logged into the computer. Table 4.1 shows those parameters.

Table 4.1 Parameters logged into the computer

Date and Time	Velocity (km/hour)
NOx concentration (ppm)	Latitude (degree)
CO_2 concentration (% vol)	Longitude (degree)
Air to Fuel Ratio (AFR)	Altitude (m)
Exhaust Flow Rate (L/min)	GPS velocity (km/hour)
Exhaust Temperature (○ C)	No. of Satellites
Exhaust Pressure (kpa)	North/South (GPS information for location on the globe)
Humidity (%)	West/East (GPS information for location on the globe)

The data collected on different days, times and drivers was saved in a ".txt" file. A specific template was made in Microsoft Excel to calculate and analyze emission data. Table 4.2 summarizes the number of runs made on Cooper corridor for Carbon dioxide emission during AM Peak, Off Peak and PM Peak.

Table 4.2 Number of Data Collection Runs for CO_2

Number of Runs					
Before			After		
AM Peak	Off Peak	PM Peak	AM Peak	Off Peak	PM Peak
19	23	1	8	16	30

Table 4.3 shows the number of runs made for NOx emission data

Table 4.3 Number of Data Collection Runs for NOx

Number of Runs					
Before			After		
AM Peak	Off Peak	PM Peak	AM Peak	Off Peak	PM Peak
50	43	28	8	17	30

The number of runs for data collection of NOx were greater than the number of data collection run for CO_2 because variety of problems. A part of the reason was the improper calibration of CO_2 sensors and the other part being the fact that the sensor used for CO_2 was different from the one used for NOx.

4.1.2 Data Interpretation

The objective of the study was determined whether there is a significant difference in emissions between before and after signal synchronization. The data was compared in mean g/mile for CO_2 as well as for NOx. The instantaneous NOx and CO_2 emissions data were in the units of parts per million and % Vol, respectively. In order to achieve concentration of NOx and CO_2 in μg/m^3 and then in μg/sec, the following formulas were employed.

Calculation for NOx and CO_2 concentrations in μg/m3 are shown below.

NOx in μg/m3 unit :

$$Cmass_1 = \frac{1000 * M.W * Cppm * P}{R * T}$$

CO_2 in μg/m^3 unit:

$$Cmass_2 = \frac{1000 * M.W * (10000 * C\%vol) * P}{R * T}$$

Where,

$Cmass_{1\text{-}2}$ = Instantaneous Concentration of NOx and CO_2 in μg/m3 unit.

M.W. = Molecular weight of pollutant of concern

Molecular Weight of NOx assuming 90% NO and 10%

NO_2 = 31.60 g/g-mole

Molecular weight of CO_2 is 28 g/mole

C_{ppm} = Concentration of NOx in ppm

$C_{\%vol}$ = Concentration of CO_2 (%vol)

P = Exhaust Pressure in atm

T = Exhaust Gas Temperature in o K

R = Ideal gas constant = 0.08206 atm-L/g-mole-K

In order to convert the NOx and CO_2 concentration from μg/m^3 to μg/sec, the concentration of both pollutants (μg/m^3) is multiplied by the exhaust flow rate (L/min). The exhaust flow rate used was 11,240 L/min. The exhaust flow rate was collected for only two days during the data collection and an average value between the two was calculated. The average NOx and CO_2 (g/mile) is achieved by the following formula:

$$\text{E.F (g/mile)} = \frac{\text{Average (NOx or } CO_2\text{) concentration (g/sec)}}{\text{Average GPS velocity (miles/sec)}}$$

The velocity was averaged over each run because the instantaneous CO_2 and NOx emission factor (g/mile) were also averaged out for each run. As discussed earlier in Chapter 3, numerous factors such as the day of the week, the time of the day, the direction of run, and the driver behavior were considered thoroughly by using several statistical approaches as discussed in the following section.

4.2 Before Vs, After Data Analysis for CO_2 and NOx

A statistical approach is one that involves collecting, interpreting and manipulating numerical information in the form of data to determine group trends and operations, and make inferences about their characteristics and correlate between data sets by assuming that the results of the analysis of a particular data set would yield similar results for any other data set under similar given conditions.

In this study, statistical tests were performed on the data collected before and after signal co-ordination on Cooper Street. Depending upon the results obtained, a prediction of the trend of CO_2 emissions could be made for other corridors with similar conditions. Two approaches were adopted in this study: 1) Comparing data for variability, using the analysis of variance (ANOVA); 2) Comparing data from before and after signal retiming by testing for any significant differences.

4.2.1 Analysis of Variance (ANOVA): What factors produce significantly different CO_2 emissions?

Prior to combining two identical groups of data together, it is necessary to check whether there is a significant difference between two categories or not. To perform this, preliminary analysis ANOVA was performed. ANOVA has two kinds of analysis.

1) One-way ANOVA – only one basic variable is being studied
2) Two-way ANOVA – Two types of independent variables are investigated.

In this analysis, one-way ANOVA was used to determine the impact of the following variables on CO_2 emissions:

- North – South Direction
- AM Peak – PM Peak
- Peak – Off Peak
- Drivers
- Day of the Week

The results for the ANOVA tests performed on the above variables are summarized in Table 4.4 and 4.5.

Table 4.4 ANOVA Results for Peak and Off Peak
ANOVA Single factor

Summary						
Groups	Count	Sum	Average	Variance		
Column 1	58	143316	2470	179899		
Column 2	39	86752.9	2224	75668.9		
Source of Variation	SS	Df	MS	F	P-value	Fcrit
Between Groups	1417391	1	1417391	10.25	0.00185	3.9412
Within Groups	1312964	95	138207			
Total	1454703	96				

Table 4.5 ANOVA Result for Different Days
ANOVA Single factor

Summary						
Groups	Count	Sum	Average	Variance		
Column 1	51	12946	2538	112617		
Column 2	45	98163	2181	133227		
ANOVA						
Source of Variation	SS	Df	MS	F	P-value	Fcrit
Between Groups	3049251	1	3049251	24.94	2.72E-06	3.94
Within Groups	1312964	95	138207			
Total	14542111	95				

The ANOVA was conducted by comparing every day with each of the other day and it was found that Wednesday data was significantly different than the Tuesday and Thursday data. The analysis showed a significant difference for Peak and Off Peak and for Wednesday in comparison to the rest of the days in the week. It can be seen that $F_{critical}$ is less than $F_{calculated}$. This implied that these factors have an impact on CO_2 emissions. The ANOVA results between North and South, AM Peak and PM Peak and between drivers are summarized below. Detailed ANOVA results are presented in Appendix B.

Table 4.6 ANOVA between North and South Directions
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	47	111943	2382	169700		
Column 2	49	115684	23601	140114		
ANOVA						

Table 4.6 Continued

Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	104450	1	10450	0.067597	0.79544	3.942
Within Groups	1453166	94	15459			
Total	14542111	95				

Here the Fcal<Fcritcial which implied there is no significant difference exist between North and South emission data.

Table 4.7 ANOVA Result between all Drivers Involved
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	43	97822	2275	138926		
Column 2	23	55644	2419.	160754		
Column 3	27	66652	2469	13100		
Column 4	4	9952	2488	33573		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	762384	3	254128	1.71451	0.1694	2.7025
Within Groups	13784651	93	148222			
Total	14547036	96				

Here the F_{cal}<$F_{critcial}$ which implied no significant difference between involved drivers.

Table 4.8 ANOVA between AM Peak Vs PM Peak
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	27	63635	2357	20701		
Column 2	31	79681	2570	140469		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	657933	1	65793	3.8394	0.0550	4.0130
Within Groups	9596294	56	17136			
Total	10254227	57				

Here the $F_{cal} < F_{critcial}$ which implied no significant difference between AM Peak and PM Peak.

4.2.2 Hypothesis Testing: Did CO_2 emissions before vs. after retiming differ significantly for the corridor?

The study was conducted with the hypothesis that ‘there will be significant difference in emissions for before and after signal synchronization’. Hypothesis testing was carried out for the before and after signal coordination emission data.

The ANOVA results showed that there was significant difference for North and South, Different Drivers, AM Peak and PM Peak emission data. All these data sets were combined since the ANOVA test showed there is no significant difference between these variables, Wednesday was kept separately and the rest of the day were combined. Hypothesis test was performed on before and after peak emission data on Wednesday, and before and after peak on Monday, Tuesday, Thursday and Friday. Similarly the test was conducted for off Peak emission data. Table 4.9 shows how the hypothesis test is carried out and the rejection criteria involved.

Table 4.9 Hypothesis Test and Rejection Criteria

Hypothesis	Rejection Criteria	Results
H0: $\mu_1 = \mu_2$ H1: $\mu 1 \neq \mu 2$	$\lvert tcal \rvert > t_{crit}$	Reject null hypothesis
H0: $\mu_1 = \mu_2$ H1: $\mu_1 > \mu_2$	$t_{cal} > t_{crit}$	Reject null hypothesis
H0: $\mu_1 = \mu_2$ H1: $\mu_1 < \mu_2$	$t_{cal} < - t_{crit}$	Reject null hypothesis

Where, μ_1 = Mean of CO_2 EFs before traffic signal retiming for a given condition

μ_2 = Mean of CO_2 EFs after traffic signal retiming for a given condition

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

$t_{cri}t$ = T-value derived from the t-distribution table for a given confidence level and type of t-test

The study was conducted with the null hypothesis that ‘there is no significant difference in CO_2 concentration for before and after signal retiming’. The analysis was performed with a 95% of confidence level and for one and two tail types of t-test. If the null hypothesis is rejected, it is implied that there is significant difference between concentrations. To calculate tcal with unequal numbers of samples the following equation was used.

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

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

Where S = Standard deviation between sample means

N_1= Number of sample in before data set

N_2= Number of sample in after data set

t = Calculated t-value

X_1 = Mean of before data set

X_2 = Mean of after data set

With a significance level of 0.05 and degree of freedom as N1+N2-2, t_{cal} was calculated for the Peak for before and after signal retiming on Wednesday and Peak for before and after signal retiming on the rest of the days. Also the same procedure was carried out for Off peak. All the t-test results are attached in Appendix B. The test results are summarized in Table 4.10.

Table 4.10 T-test Results

	Wednesday		Rest of the Days		Significant Difference	
	$t_{calculated}$	$t_{critical}$	$t_{calculated}$	$t_{critical}$	Wed	Rest of the days
Peak	-2.231	1.706	0.9700	1.701	Yes	No
Off Peak	-0.1738	1.706	0.3186	1.701	No	No

The shading number indicates t_{cal} and $t_{critical}$ for before and after signal retiming on Wednesday and also for the rest of the days in week. The T-test result shows that there is a significant difference for Peak data for Wednesday for carbon dioxide concentration. The table 4.11 shows the significant difference for CO_2 (g/miles).

Table 4.11 Significant Difference

Peak – Wednesday Mean CO_2 g/mile	
Before	After
2077	2398
15.5% increased after signal retiming	

The shaded numbers in the above table indicates before and after average g/mile carbon dioxide emissions and % increased in emission after retiming. The above result shows that the CO_2 emission is increased by 15.5% after signal coordination. There are a number of variables which may have an impact on the emissions, like average speed, temperature, humidity, control delay and number of stops. Emissions would not, however be expected to increase from a signal retiming perspective. Signal retiming should reduce the time spent in acceleration mode. Since the load on the engine is greater during acceleration mode, more fuel is fed to the engine and more combustion occurs. If the combustion is complete, then more CO_2 would be expected to be produced during acceleration. If time spent in the acceleration mode is reduced via signal coordination, emissions would be expected to decrease.

A before vs. after comparison for NOx emissions for the corridor was conducted by Sista, (2006). He found a 36.1% decrease in NOx emissions after signal retiming on Peak hour and 28.4% decrease in NOx emissions after retiming on Off Peak hour.

4.2.3 Hypothesis testing: Did CO_2 and NOx emissions before vs. after retiming differ significantly by velocity category?

On-road driving is an arbitrary combination of four standard driving modes. It is of immense interest to characterize the emissions behavior at different driving modes. The modal analysis approach is used for NOx and CO_2 emissions from the study vehicle. The second-by-second data were divided into acceleration, deceleration, cruise and idle mode and the emissions rates for each mode were calculated. The data were divided into different modes by instantaneous acceleration in m/sec^2. For the acceleration mode, instantaneous acceleration value must be equal to or greater than 0.1 m/sec^2, the deceleration mode is defined in similar manner as acceleration, except the criteria for deceleration are based upon negative acceleration rates. The idle mode is defined as less than 1 mph speed and zero acceleration. All other events not classified as idle, acceleration or decelerations are classified as cruising. The instantaneous acceleration in miles/ sec^2 and m/ sec^2 was calculated from the following equation.

- Instantaneous acceleration in $miles/sec^2$

$$= \frac{G_2 - G_1 * 0.6213}{T_2 - T_1 * 3600}$$

- Instantaneous acceleration in m/sec^2

= Instantaneous acceleration ($miles/sec^2$)* 1609.3

Where, G_1 = GPS velocity at that instant

G_2 = GPS velocity at the next instant

T_1 = Time at 1st instant

T_2 = Time at next instant

The data was divided into velocity clusters having an interval of 1 mile/hr for each driving mode. The average and standard deviation for NOx and CO_2 emissions in g/mile were calculated for each velocity cluster for different modes. With the average and standard deviation for each velocity cluster, the t-test with 95% confidence interval and one-tail type was performed between before and after signal retiming data for acceleration, deceleration and cruising. Table 4.12 shows the t- test results for acceleration mode for CO_2 pollutant. Detailed results are attached in Appendix D.

Table 4.12 T-test for Acceleration Mode for CO_2

Average Velocity Miles/hr	t_{cal}	t_{crit}	Significant increase
0.35	0.38	1.64	No
1.49	-1.05	1.64	Yes
2.52	-2.17	1.64	Yes
3.48	-1.01	1.29	No
4.54	-1.99	1.65	Yes
5.51	-0.25	1.65	No
6.53	-2.14	1.65	Yes
7.49	-1.72	1.65	Yes
8.52	-3.41	1.65	Yes
9.47	-2.40	1.64	Yes
10.51	-3.58	1.64	Yes
11.53	-5.09	1.64	Yes
12.52	-3.88	1.64	Yes
13.52	-4.18	1.64	Yes
14.50	-4.08	1.64	Yes
15.49	-5.21	1.64	Yes
16.51	-4.61	1.64	Yes
17.50	-5.12	1.64	Yes
18.48	-6.08	1.64	Yes
19.49	-7.63	1.64	Yes
20.51	-8.72	1.64	Yes
21.52	-7.43	1.64	Yes
22.52	-8.07	1.64	Yes
23.55	-9.08	1.64	Yes
24.53	-10.10	1.64	Yes
25.50	-7.93	1.64	Yes

Table 4.12 Continued

26.50	-10.93	1.64	Yes
27.49	-9.72	1.64	Yes
28.53	-8.77	1.64	Yes
29.49	-11.94	1.64	Yes
30.47	-10.62	1.64	Yes
31.45	-12.14	1.64	Yes
32.50	-11.53	1.64	Yes
33.54	-9.98	1.64	Yes
34.52	-11.14	1.64	Yes
35.50	-11.91	1.64	Yes
36.50	-14.12	1.64	Yes
37.48	-14.84	1.64	Yes
38.50	-14.84	1.64	Yes
39.49	-16.30	1.64	Yes
40.49	-16.91	1.64	Yes
41.47	-17.24	1.64	Yes
42.46	-17.69	1.64	Yes
43.49	-18.74	1.64	Yes
44.53	-19.67	1.64	Yes
45.52	-18.43	1.64	Yes
46.51	-17.88	1.64	Yes
47.50	-20.05	1.64	Yes
48.48	-19.91	1.64	Yes
49.47	-18.85	1.64	Yes
50.46	-19.30	1.64	Yes
51.48	-17.61	1.64	Yes
52.47	-16.00	1.64	Yes
53.50	-13.12	1.64	Yes
54.51	-10.92	1.64	Yes
55.49	-10.61	1.64	Yes
56.46	-8.81	1.64	Yes
57.44	-8.65	1.64	Yes
58.45	-4.77	1.66	Yes
59.48	-1.90	1.66	Yes
60.37	-2.36	1.68	Yes
61.35	-4.89	1.68	Yes
62.08	-2.30	1.69	Yes

From the t-test results, it can be concluded that the there is a significant increase in emissions of CO_2 for all the velocities except <1 mile/hr, 1-2 miles/hr and 5-6 miles/hr after signal retiming for acceleration mode. Table 4.13 shows t-results with a significant difference for different velocities for average CO_2 emissions after retiming for deceleration and cruising.

Table 4.13 t-test Results for Deceleration and Cruise for CO_2

Speed Range	Deceleration	Cruise
miles/hr	Significant increase in CO_2 for particular speed (miles/hr)	Significant increase in CO_2 for particular speed (miles/hr)
0-5	0.5	3.5,4.5
5-10	-	6.5,7.5
10-15	-	-
15-20	-	16.5,19.5
20-25	20.5	21.5
25-30	28.5,29.5	25.5,29.5
30-35	32.5,34.5	-
35-40	36.5,37.5,38.5,39.5	38.5,39.5
40-45	All	40.5,42.5,43.5,44.5
45-50	All	All
50-55	All	All
55-60	55.5,56.5,57.5,58.5	55.5,56.5,57.5,58.5
60-65	-	-

The above table shows that for the higher velocities the CO_2 emissions increased after signal coordination for deceleration and cruise mode. Thus, at speeds above 20 mph, CO_2 emissions increased after signal retiming for all three modes. This helps explain why signal coordination, which it was hypothized would reduce CO_2 emissions, did not. However, an increase in CO_2 emissions by velocity cluster after signal retiming is not what would be expected. Emissions from a vehicle traveling in cruise mode (acceleration= 0) at 40 mph before signal retiming would be expected to be the same as emissions from a vehicle traveling in cruise mode at 40 mph after signal retiming. Instantaneous emissions from a vehicle at a given velocity and acceleration are a function of engine parameters and other vehicle parameters, independent of what is happening on the surrounding roadway. Signal coordination impacts the amount of time a vehicle spends at different acceleration/velocity combinations, not the emissions at a given combination. Ambient temperature and humidity impact emissions at a given velocity/acceleration combination, and could perhaps explains the increase in CO_2 emissions after signal retiming. The other potential explanations are that the other potential explanations are that the analyzer was calibrated incorrectly before and/or after signal coordination, or that using average flow rate value to convert ppm to g/sec was not valid. The impact of using average flow rate will be analyzed shortly.

The Tables 4.14 summarizes the result for NOx for all three modes.

Table 4.14 t-test results for NOx for all modes

Speed Range	Deceleration	Cruise	Acceleration
miles/hr	Significant decrease in NOx for particular speed (miles/hr)	Significant decrease in NOx for particular speed (miles/hr)	Significant decrease in NOx for particular speed (miles/hr)
0-5	All	All	Except 3.5,4.5,5.5
5-10	All	All	Except 6.5
10-15	All	All	All
15-20	All	All	All
20-25	All	All	All
25-30	All	All	All
30-35	All	All	All
35-40	All	All	All
40-45	All	All	All
45-50	All	All	All
50-55	All	Except 50.5 and 54.5	-
55-60	All	Except 59.5	-
60-65	-	-	-

From the above results, it can be concluded that NOx emissions decreased after signal retiming for all three modes. This may have been due to various factors such as ambient temperature and humidity, since again; it is not what would have been expected. Signal coordination alone should not cause emissions at a given speed and acceleration to decrease, since second-by-second emissions are a function of only vehicle engine parameter, velocity, acceleration, and ambient temperature and humidity. The impact of ambient temperature/humidity will be addressed in the following section.

4.2.4 Did use of constant flow rate value cause NOx and CO_2 emissions to vary before vs. after?

To test whether the use of the constant flow rate assumed earlier, the use of constant exhaust flow rte may have caused the CO_2 emission to increase before vs. after signal retiming for the velocity cluster analysis. Similarly, the use of the constant exhaust flow rate could have caused the NOx emissions to decrease. Additional analysis was conducted for cruise mode using a varying flow rate for NOx as well as for CO_2. The analysis was conducted for velocity clusters before and after signal retiming for NOx and CO_2 using the cruise mode average flow rate for that velocity cluster that was obtained from the after market Retrofit Technology and Fuel additive Research Program study, conducted on a different route using same the equipment. The t-test results of cruise mode for NOx and CO_2 showed no difference from the previous results. If a velocity showed a significant difference with the constant flow rate data, it showed a significant difference with the varying flow rate data. This makes sense, because even with the varying flow rate data, a constant values was used within the velocity cluster. The before and after ppm values were each multiplied by this new constant to obtain g/sec and g/mile values. Since the before and after values were multiplied by the same constant, one would expect a significant difference to still exist where there was one before. Use of flow rate values varying second by second, rather than using an average for a velocity cluster, may still eliminate the before vs. after emissions differences for CO_2 and NOx by velocity cluster. The results are attached in appendix E.

4.2.5 Did ambient temperature and humidity cause NOx emissions by velocity category to decrease after signal retiming?

To explain why NOx emissions may have decreased after signal retiming, ambient temperature and humidity were examined. Early research suggested that humidity and temperature impacts emissions from vehicles (Munshi, et. al, 2005). The data were collected in different years: before signal retiming data were collected in January, February, March 2005, whereas the after data were collected in January and February 2006. The humidity and temperature were different for these months. Table 4.15 and 4.16 shows the humidity and temperature data for those months.

Table 4.15 Average % Humidity before and after signal retiming

	High		Average		Low	
	2005	2006	2005	2006	2005	2006
Jan	86	68	70	46	50	25
Feb	90	78	69	60	46	41

Table 4.16 Average temperature before and after signal retiming

	Min temp	Min temp
January	2005	2006
Max	36^{o}F	53^{o}F
Mean	30^{o}F	46^{o}F
Min	25^{o}F	30^{o}F

The above tables show that the humidity and temperature are different in 2005 and 2006 which might be affecting NOx emissions.

A data analysis was conducted to check the temperature and humidity impacts on the velocity cluster before and after signal retiming. For this analysis, the average emissions of NOx in ppm were used for specific velocity clusters. The analysis was conducted for velocity clusters of 38- 45 miles/hr. The temperature and humidity data obtained from instrument was used. The temperature and humidity data were also averaged for that velocity cluster. The humidity and temperature corrected NOx was calculated using the equation developed by Rupangi Munshi is shown below.

$\Delta NO_x = -0.76\,(t_b - t_a) - 0.57(h_a - h_b)$

Where ΔNOx = Calculated difference in NOx = NOx before – NOx after

t_b = Ambient temperature in deg C (before signal retiming)

t_a = Ambient temperature in deg C (after signal retiming)

h_a = Ambient humidity in % (before signal retiming)

h_b = Ambient humidity in % (after signal retiming)

Table 4.17 summarizes the temperature and humidity impact on NOx emissions for particular velocity clusters.

The observed ΔNOx values are positive, since (NOx) before > (NOx) after. However, the calculated ΔNOx values are negative, considering temperature and humidity effects and considering humidity effect only. This means that based on temperature and humidity differences between the before and after data collection months, NOx emissions would have been expected to increase, not decrease.

Table 4.17 Impact of Temperature and Humidity on NOx Emissions

Nox (ppm)	Amb temp (degC)	Amb humidity (%)	GPS Vel (mile/hr)	NOx (ppm)	Amb temp (degC)	Amb humidity (%)	GPS Vel (mile/hr)	Cal ΔNOx	Observed ΔNOx	Cal ΔNOx considering humidity only
BEFORE				AFTER						
107.24	16.58	47.82	38.48	68.70	17.45	29.84	38.51	-9.59	38.54	-10.25
104.02	16.59	47.93	39.49	69.34	16.73	28.27	39.47	-11.11	34.68	-11.21
102.31	16.16	49.06	40.50	78.34	16.79	28.98	40.49	-10.97	23.97	-11.45
102.97	16.17	47.85	41.48	83.78	17.09	28.07	41.47	-10.58	19.19	-11.28
109.20	16.14	48.64	42.46	89.01	17.06	32.66	42.51	-8.40	20.19	-9.10
105.44	15.82	48.06	43.46	66.65	16.56	29.21	43.50	-10.19	38.79	-10.75
116.15	17.10	49.13	44.49	79.18	16.63	24.87	44.50	-14.18	36.97	-13.83
111.69	17.09	50.66	45.52	78.58	16.03	29.39	45.51	-12.94	33.11	-12.13

Since humidity decreased during after data collection, humidity cannot explain the decrease in NOx emissions after retiming (a decrease in humidity would have caused an increase in emissions). Although an increase in temperature would decrease NOx emissions, according to Munshi's equation, the temperature was not significantly different for before and after data collections. Hence the temperature would not be the factor that impacts the NOx emissions.

Since temperature and humidity do not explain the decrease in NOx emissions by velocity category after signal retiming, we can conclude that either 1) the NOx analyzer was improperly calibrated before and/or after signal retiming, or 2) use of the average flow rate value to convert emissions from ppm to g/sec was not valid; second by second values should have been used instead.

4.3 Analysis for different modes for CO_2 and NOx

4.3.1 ANOVA among modes for CO_2

Analysis of Variance for CO_2 was performed between all modes after combining before and after signal retiming data in g/sec to determine whether there was a significant difference between modes and also in g/mile for acceleration, deceleration and cruising mode. ANOVA was also used to conduct inter-modular analysis. The results of ANOVA for all modes in g/sec and g/mile for CO_2 are shown in Tables 4.18 and 4.19, respectively. Other detailed results are attached in Appendix C.

Table 4.18 ANOVA between all modes for CO_2 in g/sec
ANOVA Single Factor (g/sec)

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	38414	819717	21.34	6.05		
Column 2	16054	340334	21.20	8.40		
Column 3	9960	225908	22.68	7.88		
Column 4	32089	687294	21.48	12.91		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	16529	3	5509.56	617.73	0	2.605
Within Groups	860796	96512	8.92	617.74		
Total	877325	96516				

Table 4.19 ANOVA between all modes for CO_2 in g/miles

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	3.84E+04	6.51E+08	1.69E+04	1.24E+10		
Column 2	1.61E+04	3.64E+07	2.27E+03	1.66E+07		
Column 3	3.21E+04	2.57E+08	8.00E+03	2.62E+09		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	2.87E+12	2.00E+00	1.43E+12	2.21E+02	1.33E-96	3.00E+00
Within Groups	5.61E+14	8.66E+04	6.48E+09			
Total	5.63E+14	8.66E+04				

Since F> F_{criti} for both Tables 4.18 and 4.19, there is a significant difference among modes for g/sec and g/mile.

Previous studies for NOx (Christopher Frey, Naugi Rouphail, et al.) have shown that emissions are greatest for the acceleration mode, followed by deceleration and cruise mode. We could not find any previous studies of CO_2 emissions by mode. As discussed earlier, it is hypothesized that CO_2 emissions for the acceleration mode would be greatest.

4.3.2 NOx and CO_2 emissions vs. velocity for acceleration, deceleration and cruise mode

Figure 4.1-4.8 shows average emissions in g/mile vs. average velocity in mile/hour for acceleration, deceleration and cruise modes for both pollutants after combining the data obtained for before and after signal retiming.

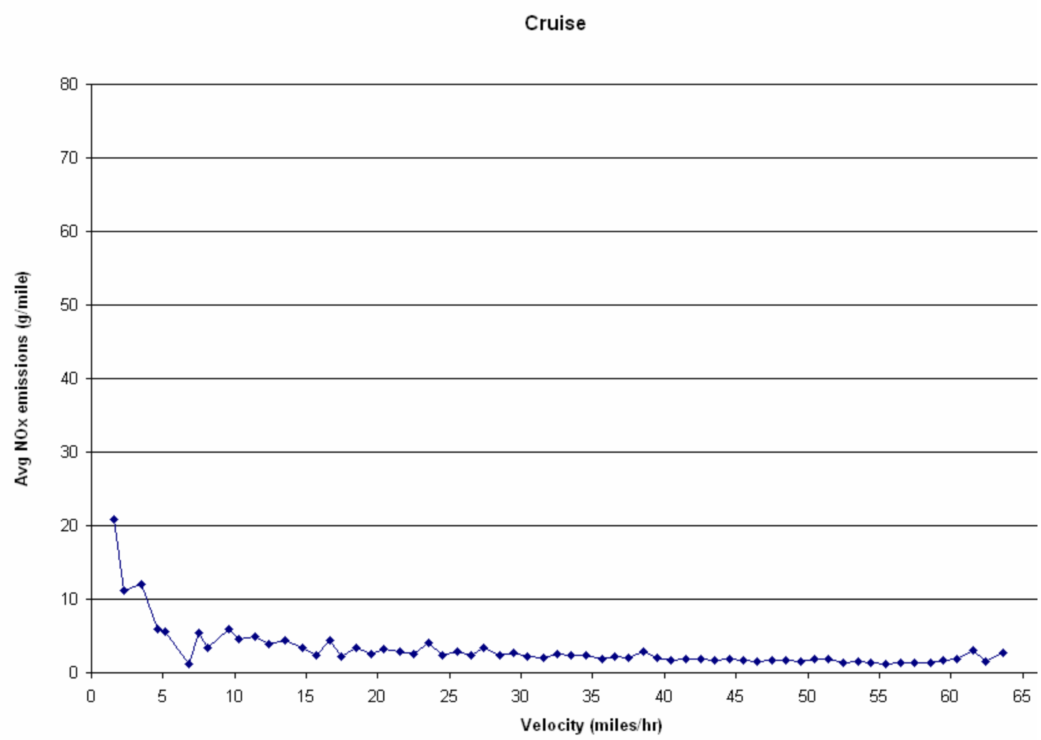

Figure 4.1 Graph for Cruise Mode of NOx

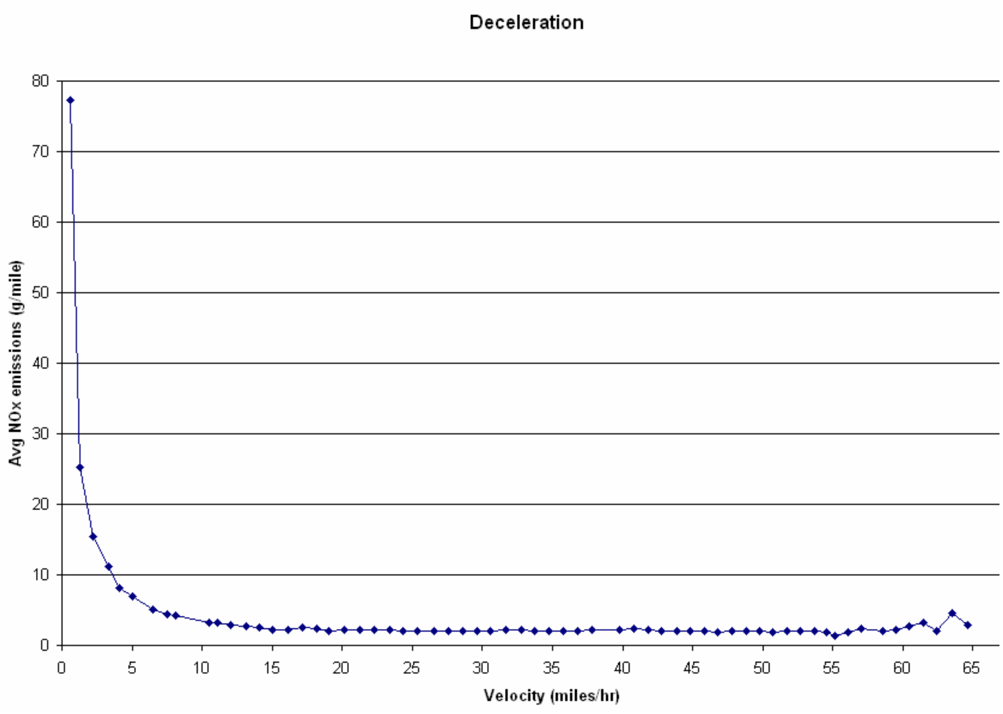

Figure 4.2 Graph for Deceleration Mode of NOx

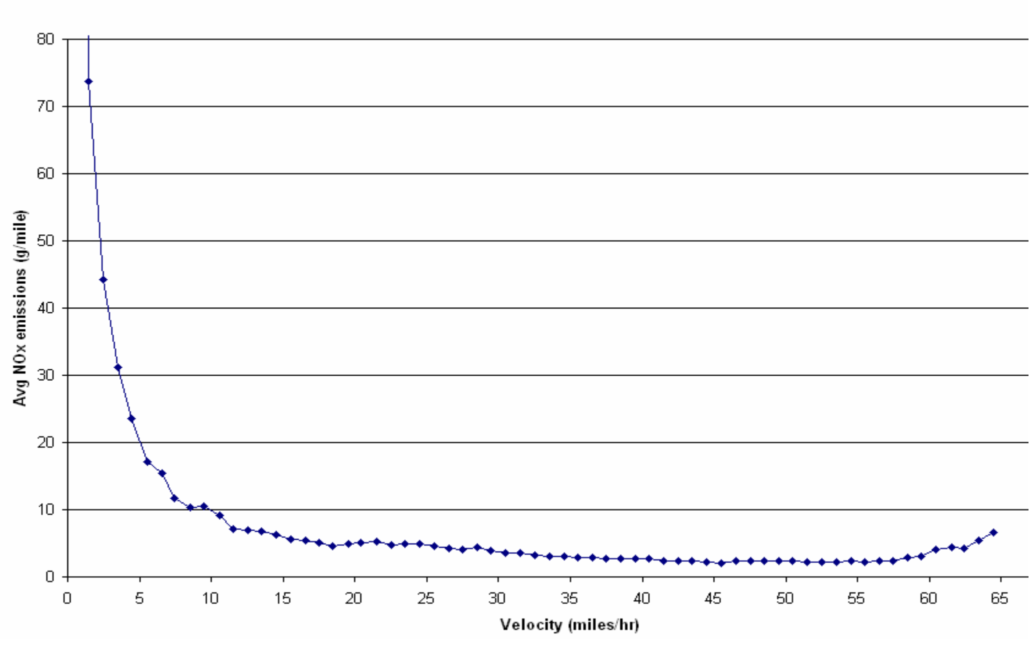

Figure 4.3 Acceleration Mode of NOx

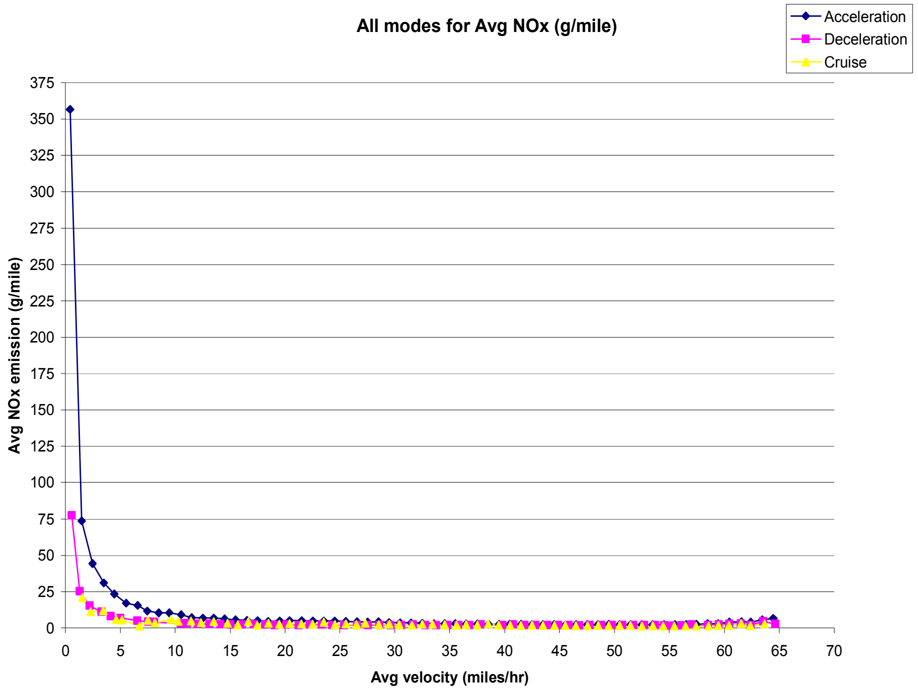

Figure 4.4 Superimposed emissions for three modes for NOx

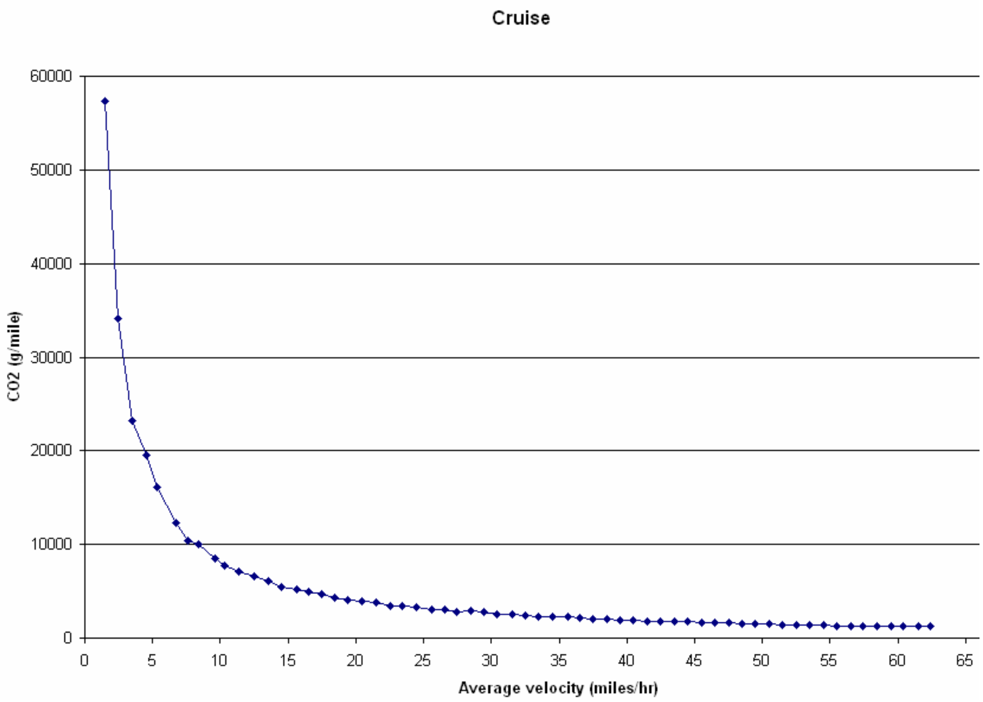

Figure 4.5 Cruise Mode of CO_2

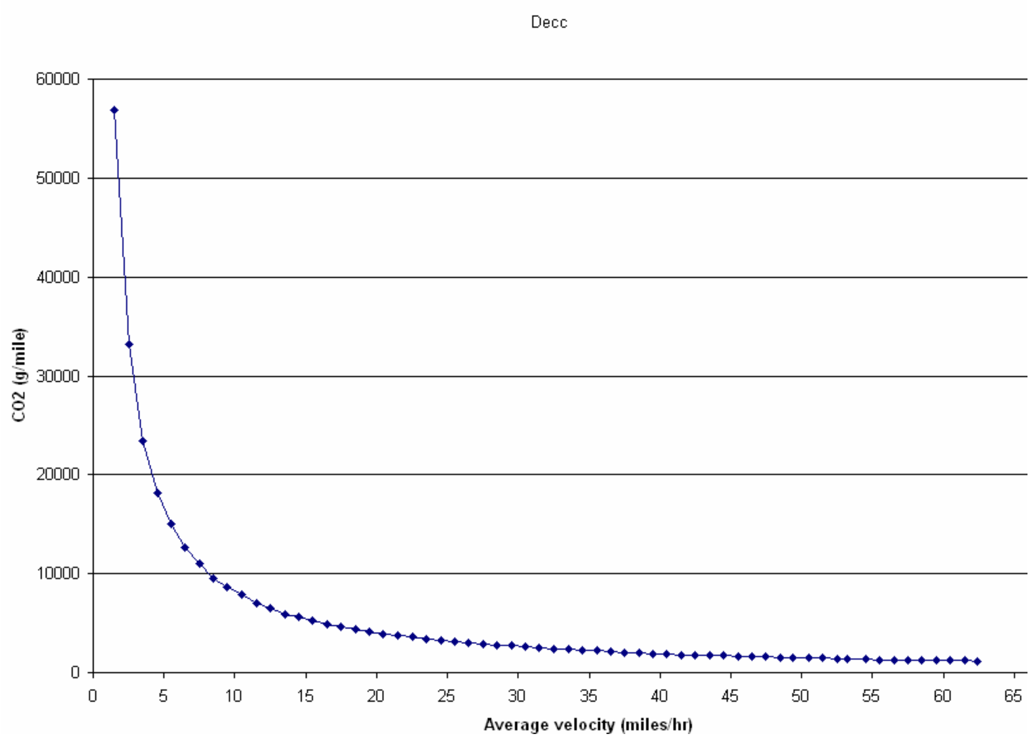

Figure 4.6 Deceleration Mode of CO_2

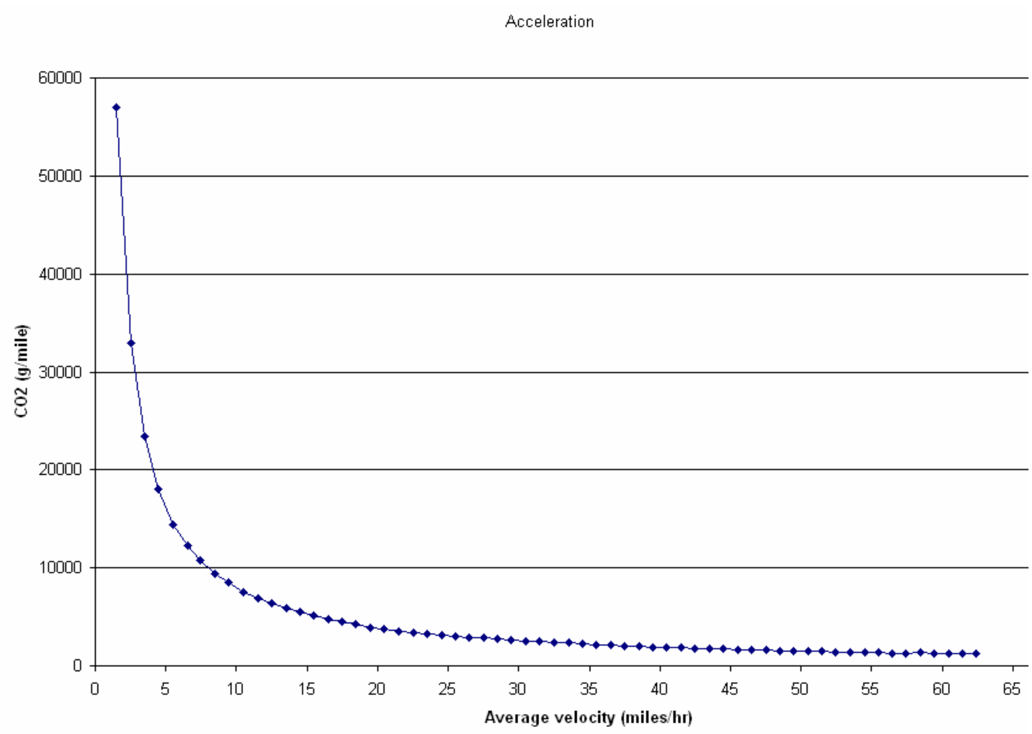

Figure 4.7 Acceleration Mode of CO_2

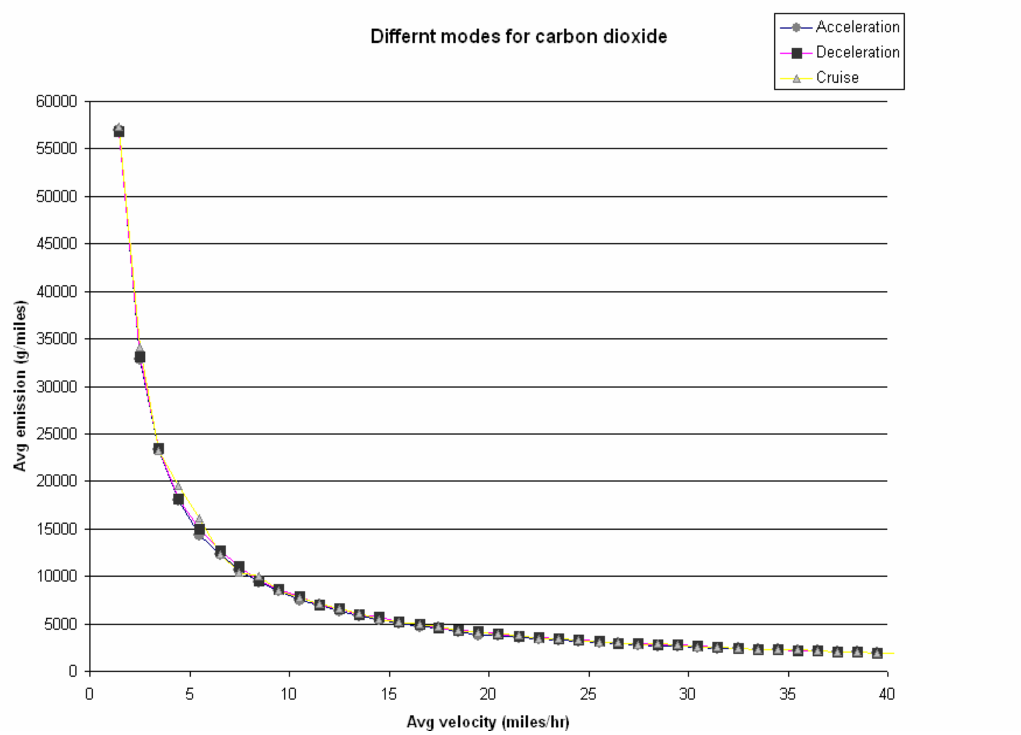

Figure 4.8 Superimposed emissions for the three modes for CO_2

From Figure 4.8, it can be observed that there is not much difference between each mode for carbon dioxide. This is contrary to the results that were expected from the ANOVA analysis presented in the previous section. The values used in the graph are taken after dividing into different velocity clusters and then the average emission for that particular velocity cluster was used, whereas in ANOVA analysis the values show overall average without dividing into different velocity clusters.

From Fig. 4.4, a difference is observed for all the driving modes of NOx. For NOx the average emission rate was highest during acceleration which is consistent with previous studies. Cruise and deceleration emissions were observed to be similar.

4.3.3 Different driving modes and the average % and comparisons ratio between acceleration, deceleration and cruise mode for NOx and CO_2

Table 4.20 and Table 4.23 summarize the average emissions for both the pollutants in g/sec, combing before and after signal retiming data. The acceleration, deceleration, and cruise mode average emission values were obtained for every velocity cluster in g/mile. By comparing the average emissions between acceleration and deceleration; and between acceleration and cruise modes the percentage difference was determined. Table 4.21 and 4.24 summarize the average % difference between mode results for NOx and CO_2. Table 4.22 and 4.25 shows the comparisons ratios between acceleration, deceleration and cruise mode for both pollutants.

Table 4.20 Average nitrogen oxide emissions for all modes, g/sec

Average Acceleration	Average Cruise	Average Deceleration	Average Idle
g/sec	g/sec	g/sec	g/sec
0.0130	0.0128	0.0105	0.0060

Table 4.21 Average NOx Emissions for acceleration, deceleration and cruise, g/mile

Average Acceleration	Average Cruise	Average Deceleration	% lower cruise than acceleration	% lower deceleration than acceleration
g/miles	g/mile	g/mile		
13.60	0.92	2.26	93	83

Table 4.22 Comparison ratios between acceleration, deceleration and cruise mode for NOx

Average Acceleration	Average Cruise	Average Deceleration	Acceleration to cruise ratio	Acceleration to deceleration ratio
g/mile	g/mile	g/mile		
13.60	0.92	2.26	15.00	6.00

Table 4.23 Average CO_2 emissions for all modes

Avg acceleration	Avg Cruise	Avg Deceleration	Avg Idle
g/sec	g/sec	g/sec	g/sec
21.34	21.20	21.42	22.68

Table 4.24 Average CO_2 Emissions for acceleration, deceleration and cruise, g/mile

Average Acceleration	Average Cruise	Average Deceleration	%lower cruise than acceleration	%lower deceleration than acceleration
g/mile	g/mile	g/mile		
16939	2270	8000	87	53

Table 4.25 Comparison ratios between acceleration, deceleration and cruise mode for CO_2

Avg Acceleration	Avg cruise	Avg Deceleration	Acceleration to cruise ratio	Acceleration to deceleration ratio
g/mile	g/mile	g/mile		
16939	2270	8000	7	2

Avg = Average

The graph 4.8 showed not much difference for CO_2 which is inconsistent with the Table 4.24. The inconsistency in the results is because the value used for the graph is the average emission for the particular velocity cluster, while the value used in Table 4.24 is the overall average of CO_2 emissions after combining before and after data. Different amounts of time would have been spent at different velocities before vs. after; this would have caused a difference in g/mile values for the overall averages, but not for the case where the data was divided by velocity cluster.

Considering emissions in g/mile, the order of emission from highest to lowest for the various modes was found to be different when compared to the order measured in g/sec. The CO_2 emissions were slightly higher during idle, followed by deceleration, acceleration and then cruise mode for g/sec. The CO_2 emissions in g/mile were highest during acceleration followed by deceleration and then to cruise. For NOx, emissions in g/sec were highest during acceleration, followed by cruise, deceleration and then idle. For NOx, emissions in g/mile were highest during acceleration, followed by deceleration and then cruise. The average acceleration emission to average deceleration emissions was six and average acceleration emissions to average cruise emissions ratio was fifteen in case of NOx. The average acceleration CO_2 emissions to average cruise emissions ratio was seven and average acceleration emissions to average deceleration emissions ratio was seven.

4.4 Time spent in each mode before vs. after coordination

Signal coordination impacts the time spent in each mode. Signal coordination should increase time spent in cruise mode and decrease time spent in acceleration, deceleration and idle modes. The data analyses were performed for peak and off peak, and for Wednesday and the rest of the days, to find whether there was significant increase or decrease in time spent in each mode after signal retiming. For each run the time spent in mode was determined. Overall the runs of a given category (Peak vs. Off Peak, Wed vs. Other days , before vs. after), averages and standard deviations of time spent per mode were found T-test were performed on the before and after mean. Table 4.26 and Table 4.27 summarize these results.

Table 4.26 t-test results of time spent in each mode for Peak on Wednesday and the Rest of the days before and after signal retiming for CO_2

	Wednesday		Rest of the days		Significant increase/decrease	
	t_{cal}	$t_{critical}$	t_{cal}	$t_{critical}$	Wed	Rest of the days
Acceleration	-0.387	1.71	1.501	1.701	No significant increase/decrease	Decrease
Cruise	0.83	1.71	1.702	1.701	No significant increase/decrease	No significant increase/decrease
Deceleration	-1.29	1.71	0.43	1.701	No significant increase/decrease	No significant increase/decrease
Idle	-0.98	1.71	2.5	1.701	No significant increase/decrease	Decrease

Table 4.27 t-test Results of time spent in each mode for Off Peak on Wednesday and the Rest of the days, before and after signal retiming for CO_2

	Wednesday		Rest of the days		Significant increase/decrease	
	t_{cal}	$t_{critical}$	t_{cal}	$t_{critical}$	Wed	Rest of the days
Acceleration	1.97	1.81	-1.98	1.72	decrease	Increase
Cruise	0.79	1.81	4.15	1.73	No significant increase/decrease	Decrease
Deceleration	-0.18	1.81	-1.31	1.73	No significant increase/decrease	No significant increase/decrease
Idle	0.27	1.81	-0.07	1.73	No significant difference	No significant difference

The results showed that for Peak time on Wednesday the average time spent in all modes did not increase or decrease after signal retiming, which was not expected as the signal coordination should reduce amount of time spent in acceleration, deceleration and cruise mode and increase average time spend in cruise mode. In section 4.2.2, emissions along the corridor in g/mile increased after signal retiming for Wed Peak. This must have been due to temperature and humidity effects, calibration error, or use of constant flow rate data, since the amount of time spent in acceleration did not change. For the Off Peak time on Wednesday only acceleration decreased, the average time spent in cruise, idle and deceleration mode did not increase or decrease after signal retiming. The decrease in average time spent in acceleration mode supports the absence of increase in emissions after signal retiming for Wednesday on Off Peak hour. For the Rest of the days on Peak time, the amount of average time spent in acceleration and idle modes decreased and there was no significant increase or decrease after signal retiming for cruise and deceleration modes. For the Rest of the days on Off Peak time the amount of average time spent in acceleration increased and the average time spent in cruise mode decreased. There was no significant increase or decrease after signal retiming for cruise and deceleration mode.

Similar hypothesis testing was conducted all the modes for NOx and CO_2 without separating into Peak/Off Peak and by days. The number of runs for data collection of NOx were greater than the number of data collection runs for CO_2. This results into two different tables; Table 4.28 presents the time spent in each mode for CO_2 whereas Table 4.29 presents the time spent in each mode for NOx.

Table 4.28 t-test results for time spent in each mode for CO_2

	t_{cal}	$t_{critical}$	Significant increase/decrease
Acceleration	0.05	1.701	No significant difference
Cruise	3.17	1.701	Decrease
Deceleration	-0.87	1.701	No significant difference
Idle	0.314	1.701	No significant difference

Table 4.29 t-test results for time spend in each mode for NOx

	t_{cal}	$t_{critical}$	Significant increase/decrease in time
Acceleration	0.79	1.70	No Significant increase or decrease
Cruise	3.14	1.70	Decrease
Deceleration	-0.72	1.70	No Significant increase or decrease
Idle	-7.41	1.70	Increase

Table 4.28 shows that the average time spent in cruise mode decreased, which is the opposite of what would be expected for signal retiming. Time spent in the other 3 modes was anticipated to decrease, but the statistical analysis showed no significant difference.

Table 4.29 shows that the average time spent in cruise is decreased, while the average time spent in idle mode increased after signal retiming. There was no significant increase or decrease in average time spent for acceleration mode and deceleration mode. It would have been anticipated that time spent in cruise mode would have increased rather than decrease, and that time spent in the other 3 modes would have decreased, rather than staying the same or increasing.

4.5 Summary

The analysis conducted for NOx emissions has shown that after signal retiming the emissions decreased for most of the velocity clusters; theoretically it would have stayed the same. Temperature and humidity impact did not explain the decrease. Either there was a calibration error with the NOx sensors, or second-by-second flow rate data a should have been used instead of average flow rate data.

NOx, emissions in g/sec were highest during acceleration, followed by cruise, deceleration and then idle. The NOx emissions in g/mile were highest during acceleration, followed by deceleration and then cruise. The average time spent in each mode shows that after signal retiming the time spent in cruise mode decreased, whereas the average time spent in idle mode increased after signal retiming. There was no significant increase of decrease in average time for acceleration and deceleration mode. This is not what was anticipated, suggesting that the signal retiming is not functioning as intended.

The overall impact on CO_2 emissions along the corridor before and after signal retiming analysis showed that the CO_2 emission increased by 15.5% after signal coordination for Peak times on Wednesday; for all other times, there was no significant change in emissions.. The before and after results by velocity clusters showed that for the higher velocities the CO_2 emissions increased after signal coordination for deceleration and cruise mode, and for almost all speeds for acceleration mode. Thus, at speeds above 20 mph, CO_2 emissions increased after signal retiming for all three modes. This helps explain why signal coordination, which it was hypothized would reduce CO_2 emissions, did not. The humidity and temperature may be impacting the results of increasing carbon dioxide emissions. For the carbon dioxide emissions, there was no significant difference in average time spent in each mode for over all impact on CO_2 emissions after signal retiming, for the Peak time on Wednesday the average time spent in acceleration, deceleration and idle mode.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The aim of the study was to evaluate the impact of traffic signal retiming on carbon dioxide and nitrogen oxide emissions from a light duty vehicle on Cooper Street. The following conclusions were derived after thorough statistical analysis of the data obtained.

5.1.1 Emissions Before vs. after Signal Retiming

- As discussed in Chapter 4, after conducting ANOVA for the different variables that could impact carbon dioxide emissions, the results showed no significant differences between the emission data for North and South directions, different drivers, and AM peak and PM peak. A few significant differences were observed between peak and off peak data and the data collected on Wednesday and rest of the days in the week. This implied that these variables impact on the carbon dioxide emissions and cannot be lumped together for further statistical analysis.
- Hypothesis testing with t-distribution was carried out to determine significant difference in emissions in g/mile before vs. after signal retiming, considering the variables which could affect the data. From the t-test, it was found that the peak as well as off peak data collected on Monday, Tuesday and Thursday had no significant difference in carbon dioxide emissions after signal retiming, whereas the peak data collected on Wednesday showed increased emissions after signal

retiming, but the off peak data had no significant difference. It had been anticipated that emissions in all cases would decrease.

- The carbon dioxide emission for the Peak data collected on Wednesday was increased by 15.4%.
- After combining before and after carbon dioxide and nitrogen oxide data in g/sec and g/mile for each mode and dividing into velocity clusters with interval of 1 mile/hr, the hypothesis test was conducted to determine whether there was a significant difference in emissions before vs. after, Theoretically, there should not have been a difference, since second-by-second emissions at a given velocity and acceleration depend on engine parameter not on traffic patterns. and it was found that for most of the velocities the emissions showed an increase for carbon dioxide and nitrogen oxide emissions was decreased after signal retiming. The various factors like ambient temperature and humidity may be responsible for the increased or decrease in emissions.
- The humidity and temperature impact on NOx emissions analysis showed that with an increase in humidity, the NOx emission increased, which is a contradictory result from the earlier researches. This suggests that humidity and temperature differences do not explain the decrease in NOx emissions.
- Since humidity and temperature impacts do not explain the decrease in NOx emissions, it suggests that there was calibration error with NOx the sensors or that second-by-second flow rate data needed to be used rather than an average value.
- The increase in CO_2 emissions found during the velocity cluster analysis may be due to humidity and temperature effects, calibration error or use of average rather

than second-by-second flow rate data. a correlation between the humidity and temperature and carbon dioxide emissions should be developed.

5.1.2 Differences in Emissions by Mode

- The modal analysis was conducted to determine which driving mode produces the greatest emissions. The preliminary statistical approach using ANOVA was performed for acceleration, deceleration, cursing, and idle mode. The ANOVA results for carbon dioxide emissions in g/sec, showed significant differences between all the modes. The results were similar for carbon dioxide emissions in g/mile.
- The graphs of emissions vs. velocity for acceleration, deceleration and cruise for CO_2 show that the emissions for each mode are not significantly higher from each other. Since average emissions were plotted for each velocity cluster, the amount of time spent at different velocities was not taken to account. This could explain why the graphs did not show a significant difference between modes, whereas the ANOVA analysis did.
- An overall analysis, considering the time spent at different velocities, showed that the emission rates for CO_2 in g/mile were highest for acceleration, followed by deceleration and then by cruise. The emission trend was different for g/sec and was highest during idle followed by deceleration, acceleration and then by the cruise mode, although the differences were slight. In g/mile the average acceleration emission is 87 % higher than average cruise mode emissions, while the average deceleration emission is 53% lower than the average acceleration emissions. . The average acceleration CO_2 emissions to average cruise emissions

ratio was seven and average acceleration emissions to average deceleration emissions ratio was seven.

- In case of NOx the graph of emissions vs. velocity show that emissions for each mode differ considerably from each other.
- An overall analysis, considering the time spent at different velocities, showed that NOx emission rates were highest for acceleration mode. In g/sec, emissions from highest to lowest were acceleration > cruise > deceleration > idle. In g/mile, the average emissions from highest to lowest were acceleration > deceleration > cruise. In g/mile the average acceleration emission is 93 % higher than the average cruise emission and 83 % higher than the average deceleration emission. The average acceleration emission to average deceleration emissions was six and average acceleration emissions to average cruise emissions ratio was fifteen in case of NOx.

5.1.3 Time Spent in Each Mode

- The hypothesis testing of the average time spent in each mode for carbon dioxide emissions for peak and off peak hour on Wednesday and the rest of the days was conducted. The results showed that for peak time on Wednesday, the average time spent in all modes did not increase or decrease after signal retiming. For the Off Peak time on Wednesday only acceleration decreased. The average time spent in cruise, idle and deceleration mode did not increase or decrease after signal retiming. For the Rest of the days on Peak time the amount of average time spent in acceleration and idle decreased and there was no significant increase or decrease after signal retiming for cruise and deceleration mode. For the Rest of the days on Off Peak time the amount of average time spent in acceleration increased and the average time spent in cruise mode decreased. There was no significant increase or decrease after signal retiming for cruise and deceleration mode. The anticipated results were that time spent in cruise mode would have increased, and time spent in the other modes would have decreased. Thus, traffic signal coordination is not performing as anticipated.

- Similar analysis hypothesis testing of the average time spent in each mode was conducted for carbon dioxide as well as nitrogen oxides, without separating the data by Peak/Off Peak and days of the week. For carbon dioxide pollutant the average time spent in cruise mode decreased, which is the opposite of what would be expected for signal retiming. Time spent in the other 3 modes was anticipated to decrease, but the statistical analysis showed no significant difference. For NOx the results showed that after signal retiming the average time spent in cruise is decreased, while the average time spent in idle mode increased after signal retiming. There was no significant increase or decrease in average time spent for acceleration mode and deceleration mode. These results are not what was anticipated.

5.2 Recommendations

5.2.1 Recommendations for Improving On-Road Emission Measurement

- Consider the different traffic variables like control delay, number of stops and driving cycle which could have a significant impact on emissions from vehicles.
- To obtain accurate data, the system should be calibrated properly. Improper calibration will result in data with substantial errors.

- Equal number of data sets will give more reliable statistical results. The equal number data should be collected for AM Peak, PM Peak, Off Peak, different days of week and different drivers. For comparison between before and after signal retiming the data should be of equal number.
- Maintain a log book to record entries of all the atypical behavior during the data collection. Such behavior includes but is not restricted to an accident or train delay, which results in a stop time which has not been considered in this study.
- Since the study vehicle is considered to be a representative sample, it is important to ensure that the speed of the vehicle is maintained in accordance with the average speed of the other vehicles on the road and any unwarranted accelerations and decelerations are avoided.

5.2.2 Recommendations for Future Research

- The signal synchronization is considered to improve traffic flow on the corridor but it does not consider the side street traffic and turning movements. It is important in future researches to evaluate all vehicular movements to understand the overall impact of signal coordination on vehicle emissions.
- Vehicle emissions are observed to be higher during cold-start when compared to hot-start trips. Modal analysis should consider cold-start as a separate mode of operation.
- On-board emissions measurement can be used to support the development of emission factors and can be used in the development of future emission factor models.

- On-board emissions measurement is a practical method for measuring real-world tailpipe emission data. The methods developed in this study should be applied to other research objectives, such as evaluation of other Transportation Control Measures, Transportation Improvement Projects, alternative routing, driver behavior, and other important factors that may significantly influence real-world emissions.
- Public awareness, on how the driving styles affect emissions of pollutants from vehicles, should be created.
- The study was conducted on a light duty vehicle; the analysis should be carried out for heavy-duty vehicles and also for different types of fuels.
- Determine the impact of signal synchronization on the on-road measurement of CO and HC emissions.
- Analysis on temperature and humidity impacts on carbon dioxide emissions.

APPENDIX A

DATA SUMMARY OF AVERAGE CARBON DIOXIDE IN G/MILE FOR BEFORE AND AFTER SIGNAL COORDINATION

Table A-1 Peak and Off Peak Data Collected on Different Dates, Day of week, with different Drivers before Signal Coordination

Date	Day	Direction for Peak	Direction for Off Peak	Driver	Peak Avg CO_2 g/mile	Off Peak Avg CO_2 g/mile
1/19/2005	Wed	S	N	aut	2442	2197
			S			2334
			N			1907
			S			2019
			N			2074
1/20/2005	Thus	S	N	aut	2691	2081
		N	S		3007	2272
		S	N		2376	2608
		N	S		2660	2234
			N			2622
			S			2383
1/25/2005	Tue	S	S	aut	3468	2497
		N	N		3043	2296
		S	S		2756	2290
		N	N		2595	2263
1/26/2005	Wed	S	N	aut	2401	1740
		N	S		2142	1962
		S	N		2363	2069
		N	S		1829	2145
		S	N		2066	2135
			S			2447
2/1/2005	Tue	S	N	aut	2202	1597
2/2/2005	Wed	S	S	aut	1839	2007
		N			1890	
		S			1950	
		N			1794	
		S			2131	

Table A-2 Peak and off Peak Data Collected on different Date, Day, with different Drivers after Signal Synchronization

Date	Day	Direction for Peak	Direction for Off Peak	Driver	Peak Avg CO_2 g/mile	Off Peak Avg CO_2 g/mile
1/30/2006	Mon	S	S	vye	2533	2290
		N	N		2621	2527
		S			2343	
		N			2569	
1/31/2006	Tue	S	N	ben	2452	2215
		N			2715	
		S			2938	
		N			2571	
		S			3357	
2/1/2006	Wed	S	S	Vye-peak ben- off peak	1729	1885
		N	N	vye	1947	1729
		S	S		2333	2035
		N	N		2140	2035
		S			2061	
		N			2061	
		S		Ben	1947	
		N			2333	
		S			2140	
		N			2061	
2/2/2006	Thus	S	S	Ben	2140	2180
		N	N		2607	2716
		S			2272	
		N			2616	
2/3/2006	Thus	S		Gus		
		N			3237	
2/9/2006	Thus	S	S	Ben	2626	2591
		N	N		2627	2656
		S			2773	
		N			3200	
3/22/2006	Wed	N	S	Vye	2761	2681
		S			2737	
		N			2907	
		S			2861	
		N			3089	
		S			3064	

TABLE A-2 Continued

Date	Day	Direction for Peak	Direction for Off Peak	Driver	Peak Avg CO_2 g/mile	Off Peak Avg CO_2 g/mile
		N			2591	
3/23/2006	Thus	S	S	gus-peak ben-off peak	2631	2157
		N	N		2161	2559
			S			2174
			N			2145

APPENDIX B

ANOVA AND HYPOTHESIS TEST RESULTS OF CARBON DIOXIDE FOR PEAK AND OFF PEAK ON DIFFERENT DAYS

Table B-1 ANOVA between Monday, Tuesday, Wednesday, Thursday, Friday
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	6.00	14884	2481	17502		
Column 2	15.00	39658	2644	163391		
Column 3	45.00	98162	2181	133227		
Column 4	30.00	74923	2497	104088		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	3286582	3.00	1095527	8.95	0.00	2.70
Within Groups	11255529	92.00	122343			
Total	14542111	95.00				

Here the Fcal>Fcritcial, which implied there is significant difference between all the days in week.

Table B-2 ANOVA between Monday and Tuesday
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	6.00	14884	2481	17502		
Column 2	15.00	39658	2644	163391		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	114206	1.00	114206	0.91	0.35	4.38
Within Groups	2374986	19.00	124999			
Total	2489192	20.00				

Here the Fcal<Fcritcial, which implied there is no significant difference between Monday and Tuesday.

Table B-3 ANOVA between Monday and Wednesday

ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	6.00	14883.94	2481	17502		
Column 2	45.00	98162.49	2182	133227		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	474147	1.00	474147	3.91	0.05	4.04
Within Groups	5949512	49.00	121419			
Total	6423659	50.00				

Here the Fcal<Fcritcial, which implied there is no significant difference between Monday and Wednesday.

Table B-4 ANOVA between Monday and Thursday

ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	6.00	14884	2481	17502		
Column 2	30.00	74923	2497	104088		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	1405	1.00	1405	0.02	0.90	4.13
Within Groups	3106050	34.00	91354			
Total	3107455	35.00				

Here the Fcal<Fcritcial, which implied there is no significant difference between Monday and Thursday.

Table B-5 ANOVA between Tuesday and Wednesday
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	15.00	39659	2644	163391		
Column 2	45.00	98162	2181	133227		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	2406549	1.00	2406549	17.13	0.00	4.01

Table B-5 Continued

Within Groups	8149479	58.00	140508			
Total	10556028	59.00				

Here the Fcal>Fcritcial, which implied there is significant difference between Tuesday and Wednesday.

Table B-6 ANOVA between Tuesday and Thursday
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	15.00	39658.48	2644	163391		
Column 2	30.00	74922.64	2497	104087		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	214556	1.00	214556	1.74	0.19	4.07
Within Groups	5306017	43.00	123396			
Total	5520573	44.00				

Here the Fcal<Fcritcial, which implied there is no significant difference between Tuesday and Thursday.

Table B-7 ANOVA between Wednesday and Thursday
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	45.00	98162	2181	133227		
Column 2	30.00	74923	2497	104088		
ANOVA						

Table B-7 Continued

Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	1797781	1.00	1797781	14.78	0.00	3.97
Within Groups	8880543	73.00	121651			
Total	10678323	74.00				

Here the Fcal>Fcritcial, which implied there is significant difference between Wednesday and Thursday.

Table B-8 Hypothesis Test Results for Peak and Off Peak on Monday/Tuesday/Thursday Vs Wednesday

	Monday/Tuesday/Thursday		Wednesday	
	$t_{calculated}$	$t_{critical}$	$t_{calculated}$	$t_{critical}$
Peak	0.9700	1.701	-2.23096	1.706
Off Peak	-0.17382	1.706	-0.31858	1.701

APPENDIX C

ANOVA RESULTS FOR CO_2 MODAL ANALYSIS

Table C-1 ANOVA Result for Acceleration and Cruise Mode for CO_2 in g/mile
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	3.84E+04	6.51E+08	16940	1.24E+10		
Column 2	16054	36448482	2270	16569644		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	2.44E+12	1	2.44E+12	278	2.35E-62	3.8
Within Groups	4.77E+14	54466	8.75E+09			
Total	4.79E+14	54467				

Here, F>$F_{critcial}$ results in significant difference between this two modes.

Table C-2 ANOVA Result for Cruise and Deceleration Mode for CO_2 in g/mile
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	1.61E+04	3.64E+07	2.27E+03	1.66E+07		
Column 2	3.21E+04	2.57E+08	8.00E+03	2.62E+09		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	3.51E+11	1.00E+00	3.51E+11	2.01E+02	1.64E-45	3.84
Within Groups	8.42E+13	4.81E+04	1.75E+09			
Total	8.45E+13	4.81E+04				

$F > F_{critcial}$ thus a significant difference exist between these two modes.

Table C-3 ANOVA Result for Acceleration and Deceleration Mode for CO_2 in g/mile
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	3.84E+04	6.51E+08	1.69E+04	1.24E+10		
Column 2	3.21E+04	2.57E+08	8.00E+03	2.62E+09		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	1.40E+12	1.00E+00	1.40E+12	1.76E+02	4.45E-40	3.84
Within Groups	5.60E+14	7.05E+04	7.95E+09			
Total	5.62E+14	7.05E+04				

$F > F_{critcial}$ thus a significant difference exist between these two modes.

Table C-4 ANOVA Results for Acceleration and Cruise Mode for CO_2 in g/sec
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	3.84E+04	8.20E+05	2.13E+01	6.05		
Column 2	1.61E+04	3.40E+05	2.12E+01	8.40		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	2.21E+02	1.00	2.21E+02	3.27E+01	1.06E-08	3.84
Within Groups	3.67E+05	5.45E+04	6.74			
Total	3.68E+05	5.45E+04				

F>$F_{critcial}$ thus a significant difference exist between these two modes

Table C-5 ANOVA Result for Acceleration and Deceleration Mode for CO_2 in g/sec
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	3.84E+04	8.20E+05	2.13E+01	6.05		
Column 2	3.21E+04	6.87E+05	2.14E+01	1.29E+01		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	1.10E+02	1.00	1.10E+02	1.20E+01	5.34E-04	3.84
Within Groups	6.47E+05	7.05E+04	9.18			
Total	6.48E+05	7.05E+04				

F>Fcritcial thus a significant difference exist between these two modes

Table C-6 ANOVA Result for Acceleration and Idle Mode for CO_2 in g/sec
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	3.84E+04	8.20E+05	2.13E+01	6.05		
Column 2	9.96E+03	2.26E+05	2.27E+01	7.88		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	1.43E+04	1.00	1.43E+04	2.22E+03	0.00	3.84
Within Groups	3.11E+05	4.84E+04	6.43			
Total	3.25E+05	4.84E+04				

F>F$_{critcial}$ thus a significant difference exist between these two modes

Table C-7 ANOVA Result of Cruise and Idle Mode for CO_2 in g/sec
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	3.84E+04	8.20E+05	2.13E+01	6.05		
Column 2	9.96E+03	2.26E+05	2.27E+01	7.88		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	1.35E+04	1.00	1.35E+04	1.65E+03	0.00	3.84
Within Groups	2.13E+05	2.60E+04	8.20			
Total	2.27E+05	2.60E+04				

F>F$_{critcial}$ thus a significant difference exist between these two modes

Table C-8 ANOVA Result of Cruise and Deceleration Mode of CO_2 in g/sec
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	1.61E+04	3.40E+05	2.12E+01	8.40		
Column 2	3.21E+04	6.87E+05	2.14E+01	1.29E+01		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	5.13E+02	1.00	5.13E+02	4.49E+01	2.04E-11	3.84
Within Groups	5.50E+05	4.81E+04	1.14E+01			
Total	5.50E+05	4.81E+04				

$F > F_{critcial}$ there is significant difference exist between these two modes

Table C-9 ANOVA Result of Idle and Deceleration Mode for CO_2 in g/sec
ANOVA Single Factor

SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	9.96E+03	2.26E+05	2.27E+01	7.88		
Column 2	3.21E+04	6.87E+05	2.14E+01	1.29E+01		
ANOVA						
Source of variation	SS	Df	MS	F	P-Value	Fcrit
Between Groups	1.21E+04	1.00	1.21E+04	1.03E+03	5.20E-24	3.84
Within Groups	4.93E+05	4.20E+04	1.17E+01			
Total	5.06E+05	4.20E+04				

$F > F_{critcial}$ thus a significant difference exist between these two modes

APPENDIX D

T-TEST RESULTS FOR ACCELERATION, DECELERATION AND CRUISE FOR BEFORE AND AFTER SIGNAL COORDINATION

Table D-1 T-test Result for CO_2 Emissions Before and After signal coordination Cruise Mode for Various Average Velocity Clusters

Average Velocity Miles/hr	t_{cal}	t_{crit}	Significant increase
1.47	1.47	1.68	No
2.58	-0.23	1.68	No
3.48	2.43	1.70	Yes
4.47	2.36	1.70	Yes
5.44	0.35	1.94	No
6.60	29.25	1.66	Yes
7.61	2.27	1.74	Yes
9.59	1.11	1.78	No
10.30	0.55	1.78	No
11.35	0.59	1.71	No
12.78	-0.90	1.83	No
13.59	0.14	1.77	No
14.37	0.47	1.78	No
15.60	6.04	1.71	Yes
16.40	1.95	1.71	Yes
17.47	-0.09	1.73	No
18.44	-0.61	1.70	No
19.30	2.09	1.69	Yes
20.42	-0.81	1.70	No
21.52	1.72	1.68	Yes
22.55	-0.35	1.68	No
23.36	0.00	1.68	No
24.45	0.62	1.68	No
25.59	-2.00	1.67	Yes
26.64	0.06	1.67	No
27.52	1.03	1.66	No
28.51	-0.45	1.66	No
29.48	3.01	1.66	Yes
30.44	-1.78	1.65	No
31.51	0.55	1.65	No
32.43	0.32	1.64	No
33.54	-0.02	1.64	No
34.55	0.74	1.64	No
35.61	1.04	1.64	No
36.54	-0.64	1.64	No
37.51	-0.57	1.64	No
38.50	-3.45	1.64	Yes
39.46	-2.80	1.64	Yes
40.51	-1.88	1.64	Yes

Table D-1 Continued

Average Velocity Miles/hr	t_{cal}	t_{crit}	Significant increase
41.49	-0.87	1.64	No
42.44	-4.06	1.64	Yes
43.48	-5.97	1.64	Yes
43.48	-8.43	1.64	Yes
44.54	-7.39	1.64	Yes
46.52	-10.97	1.65	Yes
47.48	-8.47	1.64	Yes
48.52	-7.51	1.64	Yes
49.48	-7.44	1.64	Yes
50.49	-12.65	1.64	Yes
51.50	-14.12	1.64	Yes
52.47	-7.94	1.64	Yes
53.52	-6.01	1.64	Yes
54.55	-7.21	1.64	Yes
55.47	-7.56	1.64	Yes
56.53	-3.56	1.64	Yes
57.40	-4.36	1.65	Yes
58.39	-0.58	1.66	No
59.57	0.10	1.67	No
60.42	-1.49	1.69	No
61.37	-0.76	1.72	No
62.61	-8.43	1.64	No

Table D – 2 T-test Result for CO_2 Emissions Before and After Signal Coordination: Deceleration Mode for Various Average Velocity Clusters

Average Velocity Miles/hr	t_{cal}	t_{crit}	Significant increase
0.47	7.85	1.64	Yes
1.52	-1.14	1.64	No
2.51	1.04	1.64	No
3.52	-0.53	1.64	No
4.52	0.05	1.64	No
5.52	1.03	1.64	No
6.47	0.29	1.64	No
7.44	0.51	1.64	No
8.51	0.57	1.64	No
9.49	0.45	1.64	No
10.46	1.36	1.64	No
11.45	0.72	1.64	No
12.52	1.20	1.64	No
13.52	-0.90	1.64	No
14.49	1.26	1.64	No
15.52	0.53	1.64	No
16.52	0.65	1.64	No
17.52	-1.28	1.64	No
18.51	0.73	1.64	No
19.50	-1.14	1.64	No
20.45	-1.75	1.64	Yes
21.51	-0.35	1.64	No
22.51	-1.13	1.64	No
23.53	-0.16	1.64	No
24.51	-2.13	1.64	Yes
25.48	-0.66	1.64	No
26.50	-0.48	1.64	No
27.49	-1.56	1.64	No
28.49	-2.81	1.64	Yes
29.50	-2.52	1.64	Yes
30.53	-0.84	1.64	No
31.47	-1.30	1.64	No
32.54	-1.91	1.64	Yes
33.57	-0.57	1.64	No
34.52	-1.92	1.64	Yes
35.53	-0.80	1.64	No
36.51	-2.85	1.64	Yes
37.52	-2.27	1.64	Yes
38.51	-4.35	1.64	Yes

Table D-2 Continued

39.49	-4.43	1.64	Yes
40.47	-2.05	1.64	Yes
41.50	-3.01	1.64	Yes
42.46	-4.21	1.64	Yes
43.51	-5.38	1.64	Yes
44.52	-4.62	1.64	Yes
45.50	-4.84	1.64	Yes
46.51	-5.85	1.64	Yes
47.48	-7.61	1.64	Yes
48.50	-9.31	1.64	Yes
49.28	-7.56	1.64	Yes
50.48	-7.02	1.64	Yes
51.47	-6.27	1.64	Yes
52.48	-6.92	1.64	Yes
53.49	-5.26	1.64	Yes
54.52	-2.76	1.64	Yes
55.48	-3.86	1.64	Yes
56.50	-3.11	1.64	Yes
57.45	-3.95	1.64	Yes
58.41	-3.11	1.66	Yes
59.43	0.34	1.66	Yes
60.47	-0.60	1.67	No
61.49	0.13	1.67	No
62.47	-0.66	1.71	No

Table D-3 T-test Result for NOx Emissions Before and After Signal Coordination: Acceleration Mode for Various Average Velocity Clusters

Average Velocity Miles/hr	Tcal	tcrit	Significant decrease
0.47	9.49	1.64	Yes
1.52	3.39	1.64	Yes
2.51	1.06	1.64	No
3.52	-0.21	1.64	No
4.52	-1.42	1.64	No
5.52	-0.75	1.64	No
6.47	-0.16	1.64	No
7.44	1.77	1.64	Yes
8.51	1.21	1.64	No
9.48	1.40	1.64	No
10.53	2.38	1.64	Yes
11.53	4.08	1.64	Yes
12.51	2.61	1.64	Yes
13.50	3.63	1.64	Yes
14.49	1.86	1.64	Yes
15.48	0.72	1.64	No
10.53	2.42	1.64	Yes
11.53	2.66	1.64	Yes
12.51	1.94	1.64	Yes
13.50	0.83	1.64	No
14.49	2.60	1.64	Yes
15.48	3.77	1.64	Yes
16.51	3.41	1.64	Yes
17.49	4.40	1.64	Yes
18.48	4.88	1.64	Yes
19.47	5.81	1.64	Yes
20.49	5.62	1.64	Yes
21.52	3.53	1.64	Yes
22.53	4.48	1.64	Yes
23.54	4.75	1.64	Yes
24.52	3.97	1.64	Yes
25.51	5.64	1.64	Yes
26.51	5.80	1.64	Yes
27.49	5.79	1.64	Yes
28.50	5.35	1.64	Yes
29.49	5.49	1.64	Yes
30.49	5.63	1.64	Yes
31.47	6.47	1.64	Yes

Table D-3 Continued

32.51	5.80	1.64	Yes
33.53	5.79	1.64	Yes
34.52	5.35	1.64	Yes
35.51	5.49	1.64	Yes
36.51	5.63	1.64	Yes
37.50	6.47	1.64	Yes
38.50	5.55	1.64	Yes
39.49	4.43	1.64	Yes
40.49	6.54	1.64	Yes
41.48	7.24	1.64	Yes
42.47	6.03	1.64	Yes
43.49	7.42	1.64	Yes
44.53	7.40	1.64	Yes
45.51	4.16	1.64	Yes
46.51	4.45	1.64	Yes
47.49	4.11	1.64	Yes
48.48	2.76	1.64	Yes
49.48	5.01	1.64	Yes
50.46	4.37	1.64	Yes
51.47	3.41	1.64	Yes
52.46	0.34	1.64	No
53.50	-0.18	1.64	No
54.51	-2.17	1.64	No
55.51	-1.67	1.64	No
56.48	-0.14	1.64	No
57.48	0.23	1.64	No
58.46	0.26	1.64	No
59.42	-0.40	1.65	No
60.45	-1.64	1.66	No
61.44	-0.45	1.67	No
62.33	-0.89	1.68	No
63.10	-0.58	1.69	No
64.00	0.11	1.69	No

Table D-4 T-test Result for NOx Emissions Before and After of Cruise Mode for Various Average Velocity Clusters

Average Velocity Miles/hr	Tcal	tcrit	Significant decrease
0.55	1.45	1.64	No
1.51	1.17	1.66	No
2.51	0.72	1.66	No
3.50	2.37	1.67	Yes
4.47	0.48	1.72	No
5.52	2.23	1.66	Yes
6.49	0.90	1.70	No
7.49	0.82	1.74	No
8.49	3.06	1.70	Yes
10.50	0.34	1.72	No
11.51	1.72	1.71	Yes
12.50	2.24	1.73	Yes
13.52	0.74	1.71	No
14.49	0.08	1.70	No
15.50	0.66	1.68	No
16.51	0.57	1.69	No
17.51	1.20	1.68	No
18.50	0.34	1.69	No
19.47	6.54	1.67	Yes
20.47	1.47	1.67	No
21.49	0.88	1.66	No
22.51	2.24	1.66	Yes
23.51	2.51	1.67	Yes
24.51	2.88	1.66	Yes
25.48	0.06	1.66	No
26.49	3.51	1.66	Yes
27.49	3.41	1.65	Yes
28.49	4.61	1.66	Yes
29.48	2.68	1.65	Yes
30.48	5.59	1.64	Yes
31.49	4.41	1.64	Yes
32.52	3.96	1.64	Yes
33.55	5.31	1.64	Yes
34.53	5.34	1.64	Yes
35.52	3.85	1.64	Yes
36.50	-0.77	1.64	No
37.51	1.39	1.64	No
39.49	4.32	1.64	Yes

Table D-4 Continued

40.48	2.19	1.64	Yes
41.49	6.26	1.64	Yes
42.47	4.41	1.64	Yes
43.50	6.31	1.64	Yes
44.52	4.62	1.64	Yes
45.51	2.53	1.64	Yes
39.49	2.37	1.64	Yes
40.49	5.30	1.64	Yes
41.48	2.67	1.64	Yes
42.47	2.51	1.64	Yes
43.49	-20.33	1.64	No
44.53	2.86	1.64	Yes
45.51	3.56	1.64	Yes
46.51	2.54	1.64	Yes
47.50	-1.15	1.64	No
48.49	3.28	1.64	Yes
49.47	3.61	1.64	Yes
50.48	3.91	1.64	Yes
51.51	1.51	1.64	Yes
52.48	-2.76	1.66	No
53.50	2.01	1.67	Yes
54.51	-9.43	1.70	No
55.50	2.19	1.64	Yes
56.58	6.26	1.64	Yes
57.46	4.41	1.64	Yes
58.46	6.31	1.64	Yes
59.42	4.62	1.64	Yes
60.43	2.53	1.64	Yes
61.43	2.37	1.64	Yes
62.51	5.30	1.64	Yes

Table D-5 T-test Result for NOx Emissions Before and After Signal Coordination: Deceleration Mode for Various Average Velocity Cluster of Average

Average Velocity Miles/hr	t_{cal}	t_{crit}	Significant decrease
1.48	7.06	1.64	Yes
2.52	4.98	1.64	Yes
3.54	6.36	1.64	Yes
4.46	5.97	1.64	Yes
5.45	4.99	1.64	Yes
6.48	4.39	1.64	Yes
7.52	4.56	1.64	Yes
8.44	6.31	1.64	Yes
9.47	6.15	1.64	Yes
10.41	5.79	1.64	Yes
11.49	6.26	1.64	No
12.60	5.26	1.64	Yes
13.57	5.84	1.64	Yes
14.51	6.60	1.64	No
15.58	6.12	1.64	Yes
16.44	7.44	1.64	Yes
17.49	5.57	1.64	Yes
18.50	6.21	1.64	Yes
19.36	5.97	1.64	No
20.46	6.77	1.64	Yes
21.51	6.84	1.64	Yes
22.50	6.03	1.64	Yes
23.49	5.77	1.64	Yes
24.42	1.04	1.64	No
25.59	6.89	1.64	Yes
26.66	7.04	1.64	Yes
27.49	7.51	1.64	Yes
28.50	7.64	1.64	Yes
29.49	8.09	1.64	Yes
30.49	7.53	1.64	Yes
31.48	6.43	1.64	Yes
32.51	7.56	1.64	Yes
33.50	8.63	1.64	Yes
34.55	7.50	1.64	Yes
35.57	7.83	1.64	Yes
36.52	7.19	1.64	Yes

Table D-5 Continued

37.4935	7.88	1.64	Yes
38.4826	8.58	1.64	Yes
39.49	7.80	1.64	Yes
40.50	5.54	1.64	Yes
41.48	6.34	1.64	Yes
42.45	7.25	1.64	Yes
43.49	7.17	1.64	Yes
44.51	6.49	1.64	Yes
45.53	5.78	1.64	Yes
46.53	7.27	1.64	Yes
47.48	6.65	1.64	Yes
48.50	6.03	1.64	Yes
49.48	4.82	1.64	Yes
50.49	4.08	1.64	Yes
51.48	4.15	1.64	Yes
52.48	5.04	1.64	Yes
53.49	3.65	1.64	Yes
54.55	3.19	1.64	Yes
55.50	3.10	1.64	Yes
56.51	1.16	1.64	No
58.40	1.89	1.64	Yes
59.40	1.73	1.65	Yes
60.38	0.90	1.66	No
61.35	0.28	1.67	No
62.62	-0.16	1.69	No

APPENDIX E

T-TEST RESULTS FOR CRUISE MODE AFTER CHANGING FLOW RATE

Table E-1 t-test Results of CO_2 Emissions for Cruise Mode After Changing Flow Rate

Average Velocity Miles/hr	t_{cal}	t_{crit}	Significant increase
1.47	0.44	1.68	No
2.58	-2.32	1.68	Yes
3.48	0.96	1.70	No
4.47	0.39	1.70	No
5.44	0.35	1.94	No
6.60	29.25	1.66	No
7.61	1.06	1.74	No
9.59	1.11	1.78	No
10.30	-0.30	1.78	No
11.35	0.25	1.71	No
12.78	-0.91	1.83	No
13.59	0.14	1.77	No
14.37	0.45	1.78	No
15.60	6.04	1.71	No
16.40	1.95	1.71	No
17.47	-0.09	1.73	No
18.44	-0.61	1.70	No
19.30	2.09	1.69	No
20.42	-0.81	1.70	No
21.52	1.72	1.68	No
22.55	-0.35	1.68	No
23.36	0.00	1.68	No
24.45	0.62	1.68	No
25.59	-2.00	1.67	Yes
26.64	0.06	1.67	No
27.52	1.03	1.66	No
28.51	-0.45	1.66	No
29.48	3.01	1.66	Yes
30.44	-1.78	1.65	Yes
31.51	0.55	1.65	No
32.43	0.32	1.64	No
33.54	-0.02	1.64	No
34.55	0.74	1.64	No
35.61	0.26	1.64	No
36.54	-0.64	1.64	No
37.51	-0.57	1.64	No
38.50	-3.45	1.64	Yes
39.46	-2.80	1.64	Yes

Table E-1 Continued

40.51	-1.88	1.64	Yes
41.49	-0.87	1.64	No
42.44	-4.06	1.64	Yes
43.48	-5.97	1.64	Yes
43.48	-8.43	1.64	Yes
44.54	-8.73	1.64	Yes
46.52	-7.39	1.64	Yes
47.48	-10.97	1.65	Yes
48.52	-8.47	1.64	Yes
49.48	-10.14	1.64	Yes
50.49	-7.44	1.64	Yes
51.50	-12.65	1.64	Yes
52.47	-14.12	1.64	Yes
53.52	-10.00	1.64	Yes
54.55	-6.01	1.64	Yes
55.47	-7.42	1.64	Yes
56.53	-7.56	1.64	Yes
57.40	-3.56	1.64	Yes
58.39	-4.36	1.65	Yes
59.57	-0.58	1.66	No
60.42	0.10	1.67	No
61.37	-1.49	1.69	No
62.61	-0.76	1.72	No

Table E-2 t-test Results of NOx emissions for Cruise Mode After Changing Flow Rate

Average Velocity Miles/hr	t_{cal}	t_{crit}	Significant decreased
1.47	1.45	1.64	No
2.58	1.20	1.66	No
3.48	0.84	1.66	No
4.47	6.95	1.67	Yes
5.44	0.53	1.72	No
6.60	2.33	1.66	Yes
7.61	2.13	1.70	No
9.59	0.55	1.74	No
10.30	3.57	1.70	Yes
11.35	0.39	1.72	No
12.78	1.23	1.71	No
13.59	1.56	1.73	No
14.37	0.11	1.71	No
15.60	1.99	1.70	Yes
16.40	1.33	1.68	No
17.47	-0.57	1.69	No
18.44	0.89	1.68	No
19.30	0.95	1.69	No
20.42	5.60	1.67	Yes
21.52	1.66	1.67	No
22.55	4.18	1.66	Yes
23.36	1.90	1.66	Yes
24.45	3.41	1.67	Yes
25.59	2.34	1.66	Yes
26.64	3.29	1.66	No
27.52	1.85	1.66	Yes
28.51	4.28	1.65	Yes
29.48	4.03	1.66	Yes
30.44	3.94	1.65	Yes
31.51	9.35	1.64	Yes
32.43	4.97	1.64	Yes
33.54	4.47	1.64	Yes
34.55	4.83	1.64	Yes
35.61	8.82	1.64	Yes
36.54	4.53	1.64	Yes
37.51	4.27	1.64	Yes
38.50	1.20	1.64	No
39.46	1.39	1.64	No

Table E-2 Continued

40.51	2.83	1.64	Yes
41.49	3.54	1.64	Yes
42.44	6.78	1.64	Yes
43.48	6.28	1.64	Yes
43.48	6.85	1.64	Yes
44.54	2.94	1.64	Yes
46.52	3.92	1.64	Yes
47.48	3.16	1.64	Yes
48.52	6.60	1.64	Yes
49.48	4.27	1.64	Yes
50.49	1.72	1.64	Yes
51.50	6.21	1.64	Yes
52.47	4.54	1.64	Yes
53.52	3.49	1.64	Yes
54.55	308.12	1.64	Yes
55.47	10.94	1.64	Yes
56.53	0.12	1.64	No
57.40	5.11	1.64	Yes
58.39	2.05	1.64	Yes
59.57	-0.01	1.66	No
60.42	0.60	1.67	No
61.37	2.81	1.70	Yes
62.61	-507.90	1.73	No

REFERENCES

Munshi, Rupangi P., (2005). Impacts of Signal Synchronization on Vehicular Emissions – An On-Board Measurement Case Study. M.S. thesis, University of Texas at Arlington.

Sista, Kamesh Vyethavya., (2006). Effects of Traffic Signal Re-timing On Vehicular Nitrogen Oxide Emissions. M.S. thesis, University of Texas at Arlington.

Tong, Hing Yan, (2001). Vehicular Emissions and Fuel Consumption At Urban Traffic Signal Controlled Junctions. Ph.D. Dissertation, Hong Kong Polytechnic University.

Unal, Alper, (2002) On-Board Measurement and Analysis of On-Road Vehicle Emissions. Ph.D. Dissertation, North Carolina State University.

Andrew, James, Kean, (2002). Effect of Vehicle Speed and Engine Load on Emissions from In-use-Light-Duty vehicles. Ph.D. Dissertation, University of California, Berkley.

Lei, Yu, Fengaxiang, Qiao, (2004) Collection and Evaluation of On-Road Vehicle Emission and Activity Data. Texas Southern University.

Unal, Alper, Rouphail, Nagui M.; Frey, Christopher H.; (2003*).* Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions, North Carolina University.

Coelho, Margarida C., Farias, Tiago L.,(2003). A Methodology for Modeling and

Measuring Traffic and Emission Performance of Speed Control Traffic Signals.

Edward K. Nam, Christine A. Gierczak, James W. Buttler, (2003). A Comparison of Real-World and Modeled Emissions under Conditions of Variable Driver aggressiveness. Ford Scientific Research Laboratory.

Frey, Christopher H.; Unal, Alper; Rouphail, Nagui M.; & Colyar, James D., (200o). Vehicle Emissions And Traffic Measures: Exploratory Analysis of Field Observations at Signalized Arterials. North Carolina State University.

Rakha, Ahn, El-Shawarby, and Jang, (2004). Emission Model Development Using In- Vehicle On- Road Emission Measurement.

United States Environmental Protection Agency Air and Radiation EPA420-F-97-021 December 1997.

Dallas/Fort Worth Attainment Demonstration, April 2003 Accessed in June 2006.

Sattler, Melanie L., University of Texas at Arlington, “Transportation and Air Quality”, Class notes, Spring 2006.

North Central Texas Council of Governments, www.nctcog.org, Accessed in May 2006.

Transportation Cost and Benefit Analysis – Air Pollution Costs Victoria Transportation

Policy Institute, October 2005.

Texas Commission Of Environmental Quality www.tceq.org Accessed in June 2006.

Environmental Protection Agency, www.epa.gov Accessed in June 2006.

BIOGRAPHICAL INFORMATION

Born on December 21st 1981 in the city of Vadodara, in India, Rajashi Indravadan Parikh earned her Bachelor of Civil Engineering degree from the Maharaja Sayajirao University, India in August 2003. After graduation, she worked as an engineer with Multimentech International Pvt. Limited for six months before coming to the US for pursuing her Master of Science degree.

She earned her Masters of Science in Civil Engineering degree 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 "Effect of signal co-ordination as an emission reduction measure for vehicles". The study dealt with evaluating the effects of signal co-ordination for on-road NOx and CO_2 emissions. The research involved extensive statistical analysis for various modes of driving for different times during the day.

During the course of her Masters, she also worked as an Engineering Intern with PBS&J at their Dallas/Forth office. She has also been an active member of the Air and Waste Management Association chapter at The University of Texas at Arlington, during 2005-2006.