TRENDS OF VEHICULAR EMISSIONS DUE TO THE EFFECT OF ETHOS® FR AS FUEL ADDITIVE

by

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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

December 2006

DEDICATED TO MY PARENTS AND MY PARENTS-IN-LAW

"For making everything worthwhile"

ACKNOWLEDGEMENTS

This Transportation and Air Quality project was easier said than done. I started this endeavor with not knowing much except for few things I learned from the little reading, which one day triggered me to accomplish this research.

Firstly, I would like to convey my sincere regards to my advisor Dr. Melanie Sattler, who has been a motivation throughout my graduate program. I owe a debt of overwhelming gratitude to her for all the persistent support and immense help to complete this challenging project. She truly is a blend of all the desired qualities one could ever ask for. I am very grateful to her for believing in my capabilities and entrusting me with this research.

I would like to express my profound gratitude to dynamic personality, Dr. Stephen Mattingly, for his undeterred support all through the research. He is an inexhaustible source of ideas and suggestions and possesses analytical and statistical skills that are always awe inspiring.

I would like to sincerely thank Dr. Max Spindler for his able guidance throughout my graduate program.

I am thankful to the Civil and Environmental Engineering department at UTA for providing me the platform to pursue my higher education. It was a bridge between my professional and technical world and helped make things tangible.

I would also like to thank Paul Shover and the physical plant for their cooperation and helping with technical aspects of the van.

My special thanks to my research team – Benjamin, Vyethavya, Sriharsha, Rajashi, Gus and Jaya, who assisted me throughout the research. I would like to express my deep appreciation to my good friends Hari, Kapil, Nandita, Haritha, Hetal, Neelesh and my roommates for their unconditional support. I would also like to thank all my xrelatives and friends for their encouragement.

Above all, I would like to express my heartfelt gratitude to my husband Harsha, my parents and parents-in-law to whom all my success is dedicated. Words are inadequate to express how indebted I am to them.

It would be simple to list out the names of everyone who pitched in, but will be hard to thank them enough.

November 7, 2006

ABSTRACT

TRENDS OF VEHICULAR EMISSIONS DUE TO THE EFFECT OF ETHOS® FR AS FUEL ADDITIVE

Publication No. ______

Shruthi Satyanarayan, M.S.

The University of Texas at Arlington, 2006

Supervising Professors: Dr. Melanie L. Sattler, Dr. Stephen Mattingly

The main objective of this research was to observe if the addition of the fuel additive Ethos® Fuel Reformulator significantly reduced the emissions of CO, CO_2, HC and NO_X from a light duty vehicle. The research was conducted by the Department of Civil and Environmental Engineering at The University of Texas at Arlington as part of North Central Texas Council of Governments (NCTCOG) Aftermarket Technology and Fuel Additive Research Program. Ethos® fuel reformulator is non-toxic, non-hazardous and free from carcinogens. Ethos® is not a derivative of petroleum, it utilizes cleaning and lubricating synthetic esters suspended in a mineral oil base.

The research was carried out on a light duty gasoline vehicle, a 2000 Chevrolet Astro van, a Horiba On Board system OBS-1300 analyzed second by second concentrations of CO, CO_2, and HC and NO_X as the van traveled on-road. The fuel tank had to be completely drained for the Ethos® to be added. 5 oz. of Ethos® FR per 10 gallons of fuel and 1 oz. of Ethos® FR per quart of oil (per oil change) were added for the first two fuel tanks, later 1 oz. of Ethos® FR per 10 gallons of fuel was added.

The data collection was carried out before and after the application of Ethos® FR. The data was collected driving in peak and off-peak traffic conditions, on highway and arterial test track. The data analysis was conducted and the following results were observed.

1. There was a significant reduction in NO_x emission concentrations with application of Ethos® in all modes (acceleration, deceleration, cruise and idle), the maximum reduction being 45% in the Idling mode for the arterial test track.
2. A reduction in CO and CO_2 concentrations was observed in most of the modes; however, there was a slight increase in CO and CO_2 emissions for the highway test track.
3. An increase in the emissions of HC was observed in all the modes except on the highway test track during peak conditions.

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CHAPTER 1

INTRODUCTION

1.1 Air Quality

Air contains elements that are vital to life on Earth. Pollution is an undesirable change in the physical, chemical and/or biological components. In the external atmosphere, it is the presence of one or more pollutants or their combination in such quantities and duration that may be hazardous to human health or property, plant or animal life. Degradation of the environment has made air pollution one of the major concerns, despite the essential components of air.

Air pollution can be classified into the following source groups, with examples of each:

1. Point sources: Cement and power plants
2. Area sources: Dry cleaners, bakeries
3. Non-road sources: Construction equipments, aircrafts, lawn mowers
4. On-road sources: Cars, trucks and buses.

“According to the World Health Organization (WHO), 4-8% of deaths occurring annually in the world are related to air pollution.**”** *(Kathuria, 2002)*

1.2 Types of Pollutants

The US Environmental Protection Agency (EPA) has set National Ambient Air Quality Standards (NAAQS) that consider the following as six criteria pollutants, which may cause damage to human health and property or unreasonably interfere with the conduct of life.

- Ozone (O_3)
- Nitrogen Oxides (NO_X)
- Carbon Monoxide (CO)
- Sulfur dioxide (SO_2)
- Lead (Pb)
- Particulate Matter (PM)

Ozone is a colorless gas composed of three atoms of oxygen. It occurs in two layers; the stratospheric O_3 extends from 10 to 30 miles above the Earth's atmosphere and acts as a protective shield from the Ultraviolet ray and is beneficial to the life on Earth. The tropospheric O_3 is one of the criteria pollutants contributing to the photochemical smog and is detrimental to human health. Ambient exposures are associated with reduced baseline lung function, exacerbation of asthma and premature mortality, while evidence from chronic exposure studies indicates progressive and persistent structural abnormalities.

NO_X and Volatile Organic Compounds (VOC's) are the precursors for the formation of the tropospheric O_3 under high temperature (>85^0F) and sunlight.

Photochemical smog occurs when nitrogen oxides and hydrocarbons react chemically under the influence of sunlight:

$$NO_X + VOC \rightarrow O_3$$

Figure 1.1 shows a simplified version of how nitrogen oxides and hydrocarbons react to form photochemical smog. The actual process involves dozens of VOC's and hundred of reactions.

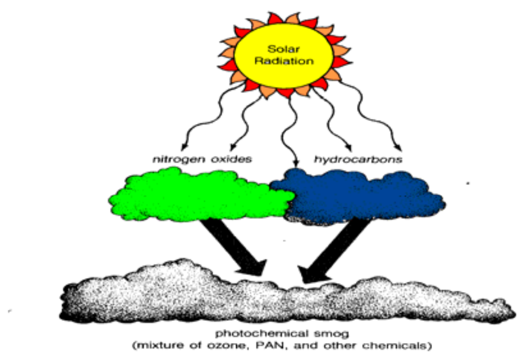


Figure 1.1 Formation of photochemical smog

(Source: Miller, 1979)

The term NO_X refers to both nitric oxide (NO) and nitrogen dioxide (NO_2), since both of these compounds are always found together in the atmosphere. NO_X is one of the main ingredients involved in the formation of ground-level ozone; it also reacts to form nitrate particles, acid aerosols and NO_2 which can trigger serious respiratory problems. NO_X also contributes to the formation of acid rain. The **Vehicular emissions** contribute **56%** of NO_X; the rest are from industries, utilities and other sources. Figure 1.2 shows the various sources of NO_X.

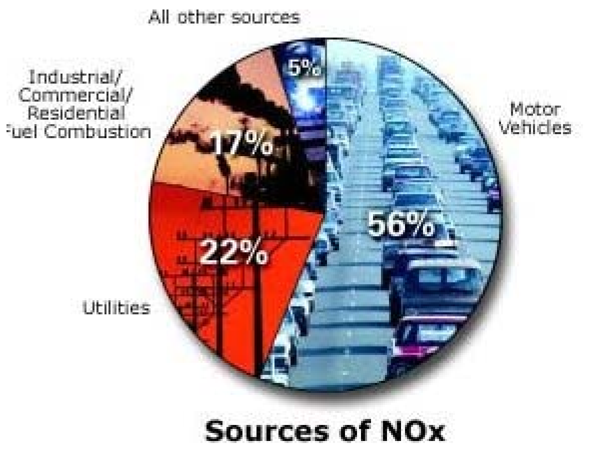


Figure 1.2 Various sources of NO_X

(http://www.epa.gov/oar/oaqps/gooduphigh/bad.html)

Volatile Organic Compounds include all organic compounds with appreciable vapor pressures. Some VOC's are hydrocarbons (HC) containing only hydrogen and carbon. Among the VOC's, some are reactive whereas others are inert. Figure 1.3 shows various sources of VOC.

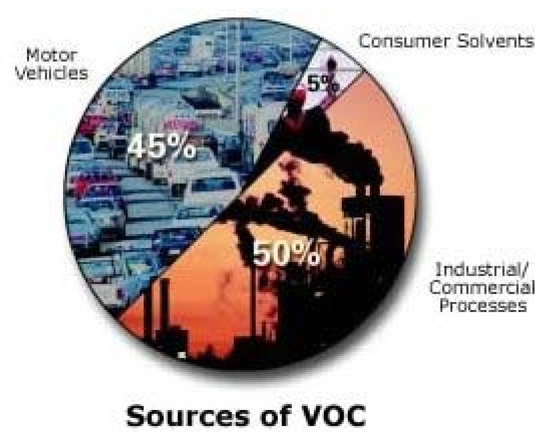


Figure 1.3 Various sources of VOC

(http://www.epa.gov/oar/oaqps/gooduphigh/bad.html)

Exposure to higher levels of CO is known to poison the hemoglobin as it enters the bloodstream through the lungs and also cause respiratory disorders like asthama and bronchitis. Sulfuric acid (H_2SO_4) is the major constituent of acid deposition caused by SO_2. The other effects include acidification of lakes, disruption of terrestrial ecosystems, corrosion of steel and damage to historical aircrafts. Pb causes possible direct or indirect effects on human health and Particulate Matter (PM) causes respiratory disorders since the particle size is small and gets into the lungs through the nostrils when inhaled.

In addition to criteria pollutants, transportation sources emit carbon dioxide. Atmospheric CO_2 is transparent to incoming short-wave solar radiation, and is opaque to outgoing long-wave radiation radiated back to space by Earth. Thus CO_2 contributes to greenhouse gasses which has the ability to trap heat in the atmosphere, resulting in heating up of earth's surface causing global warming.

A State Implementation Plan (SIP) is a strategy employed by the state to reduce emissions of the six criteria pollutants in order to comply with NAAQS. The state submits a plan (SIP) to EPA to tell how it will achieve or maintain NAAQS.

1.3 Control Strategies

Various control strategies are employed with an objective to meet the standards of NAAQS.

- Engine Design
- Alternate fuels

- Transportation System Management
- Travel Demand Management
- Others
    1. Gasoline Composition Changes (Oxygenated, Reformulated)
    2. Add on Controls (Catalytic Converter)
    3. Gas Tax
    4. Corporate Average Fuel Economy (CAFÉ) Standards
    5. Stringent Inspection / Maintenance I/M

Gasoline composition changes is the modifications in constituent of the fuels like use of fuel additives. The scope of this research is based on the application of Ethos® FR as a fuel additive.

1.4 Research Objective

The main objective of this research was to observe if the addition of the fuel additive Ethos® Fuel Reformulator significantly reduced the emissions of CO, CO_2, HC and NO_X.

The research was conducted by the Department of Civil and Environmental Engineering at The University of Texas at Arlington which for the North Central Texas Council of Governments (NCTCOG) that administers the Aftermarket Technology and Fuel Additive Research Program.

This research was focused on air quality in the Dallas-Fort Worth (DFW) Metroplex, designated as a ‘moderate’ non-attainment area for ground-level ozone according to the 8-hour ozone NAAQS. The DFW Metroplex is a NO_x limited region, which means that NO_x emissions need to be reduced in order to reduce ozone.

1.5 Ethos® Fuel Reformulator

Ethos® fuel reformulator is non-toxic, non-hazardous and free from carcinogens. Ethos® is not a derivative of petroleum; it utilizes cleaning and lubricating synthetic esters suspended in a mineral oil base. An ester can be defined as a group of liquid or solid compounds formed due to the reaction of an acid and an alcohol with the elimination of water.

Ethos® FR reformulates gasoline fuel, which causes two important benefits. ***ONE*** The synthetic esters add lubrication properties to the engine oil, which keeps the metals in the engine from wearing as quickly, which in turn lengthens the life of the engine. ***TWO*** The synthetic esters bond to the metal on a molecular level, causing any carbon deposits to fall off. Table1.1 provides an overview of subsequent chapters of the report.

1.6 Report Overview

Table 1.1 Thesis report Overview

Chapter No.	Chapters	Contents
2	**Literature Review**	This chapter consists of background information of similar studies conducted.
3	**Materials and Methodology**	This chapter reviews the methodology of the data collection and analysis.
4	**Results and Discussion**	This chapter discusses the results of the data analysis.
5	**Conclusion and Recommendation**	This chapter presents the conclusions drawn from the analysis and suggestions for future scope of study.

CHAPTER 2

LITERATURE REVIEW

2.1 Vehicular Sources and their Impacts

Advancement in the transportation system is one of the major factors to contributing to the economy, trade, commerce, social growth and infrastructure of the country. However, their adverse effect has led to interference in the conduct of life. Many US cities are on the threshold of environmental crisis due to the growing air pollution and greenhouse gas emissions caused by fuels used in vehicles. Table 2.1 summarizes types of emissions and their adverse effects.

Table 2.1 Vehicle pollution emissions

Emissions	Description	Sources	Harmful Effects	Scale
Carbon dioxide	A byproduct of combustion.	Fuel production and engines.	Climate change.	Global
Carbon monoxide (CO)	A toxic gas that undermines blood's ability to carry oxygen.	Engines.	Human health.	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 engines.	Human health, ozone precursor.	Regional

Table 2.1 – continued

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.	Engines.	Human health, ozone precursor, ecological damages.	Local and Regional
Ozone (O_3)	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
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: USEPA, 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

The air pollution problems and priorities will differ from one city to another depending on their emission sources, meteorological conditions like prevailing winds and climate. In the Dallas Fort Worth metroplex, ground level-ozone is a harmful pollutant. Ozone pollution is a concern during the summer season due to strong sunlight and hot weather, resulting in harmful ozone concentrations in the air. Many other urban and suburban areas throughout the United States have high levels of "bad" ozone; however, many rural areas of the country are also subject to high ozone levels as winds carry emissions hundreds of miles away from their original source.

The following are possible health problems and plant and ecosystem damage ozone can cause:

1. Ozone can irritate lung airways and cause inflammation much like sunburn. Other symptoms include wheezing, coughing, pain when taking a deep breath and breathing difficulties during exercise or outdoor activities. People with respiratory problems are most vulnerable, but even healthy people that are active outdoors can be affected when ozone levels are high.

2. Repeated exposure to ozone pollution for several months may cause permanent lung damage. Anyone who spends time outdoors in the summer is at risk, particularly children and other people who are active outdoors.

3. Even at very low levels, ground-level ozone triggers a variety of health problems including aggravated asthma, reduced lung capacity, and increased susceptibility to respiratory illnesses like pneumonia and bronchitis.

4. Ground-level ozone interferes with the ability of plants to produce and store food, which makes them more susceptible to disease, insects, other pollutants, and harsh weather.

5. It damages the leaves of trees and plants, ruining the aesthetic appearance of cities, national parks, and recreation areas. It reduces crop and forest yields and increases plant vulnerability to disease, pests, and harsh weather.

(Source: http://www.tceq.state.tx.us/compliance/monitoring/air/monops/naaqs.html)

2.2 Air Quality Standards and Transportation Emission Reduction Measures

2.2.1 National Ambient Air Quality Standards

The Clean Air Act (CAA), which was last amended in 1990, requires the U.S. Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS) for the pollutants which cause damage to public health and the environment. The levels of air quality that the EPA judges necessary, with an adequate margin of safety to protect from known and anticipated adverse effects, can be classified as follows:

- Primary NAAQS that protect public health, including the highly sensitive population such as people with breathing disorders, elderly and children.
- Secondary NAAQS that protect public welfare, including the protection against decreased visibility and damage to animals, vegetation, crops and buildings.

As mentioned earlier, EPA has established NAAQS to protect the public from exposure to harmful amounts of pollutants. According to federal regulations, an area is said to be **"attainment"** for a particular pollutant when the pollutant levels in that area complies with the NAAQS. When the pollutant levels in an area have caused a violation of a particular standard, the area is classified as **"non-attainment"** for that pollutant, EPA then imposes federal regulations on pollutant emissions and designates a time period in which the area must again attain the standard.

A State Implementation Plan (**SIP**) is an enforceable plan developed at the state level that explains how the state will comply with air quality standards according to the federal CAA. A SIP must be submitted by the state government of any state that has nonattainment of federal air quality standards.

The federal CAA is the legal foundation for the national air pollution control program. The CAA requires each state to produce and regularly update the SIP. The CAA also requires that SIPs include a description of control strategies, or measures to deal with pollution, for areas that fail to achieve NAAQS.

The CAA grants the EPA power to establish NAAQS and to approve or reject SIPs. Table 2.2 shows the air pollution concentrations required to exceed NAAQS.

Table 2.2 Air pollution concentrations required to exceed the NAAQS

Pollutant	Averaging Period	Standard	Primary NAAQS	Secondary NAAQS
Ozone	8-hr	The average of the annual fourth highest daily eight-hour maximum over a three-year period is not to be at or above this level.	85 ppb	85 ppb
Carbon Monoxide	1-hr	Not to be at or above this level more than once per calendar year.	35.5 ppm	35.5 ppm

Table 2.2 - continued

	8-hr	Not to be at or above this level more than once per calendar year.	9.5 ppm	9.5 ppm
Sulfur Dioxide	3-hr	Not to be at or above this level more than once per calendar year.	–	550 ppb
	24-hr	Not to be at or above this level more than once per calendar year.	145 ppb	–
	Annual	Not to be at or above this level.	35 ppb	–
Nitrogen Dioxide	Annual	Not to be at or above this level.	54 ppb	54 ppb
Respirable Particulate Matter (10 microns or less) (PM_{10})	24-hr	Not to be at or above this level on more than three days over three years with daily sampling.	155 µg/m^3	155 µg/m^3
	Annual	The three-year average of annual arithmetic mean concentrations at each monitor within an area is not to be at or above this level.	51 µg/m^3	51 µg/m^3
Respirable Particulate Matter (2.5 microns or less) ($PM_{2.5}$)	24-hr	The three-year average of the annual 98th percentile for each population-oriented monitor within an area is not to be at or above this level.	66 µg/m^3	66 µg/m^3
	Annual	The three-year average of annual arithmetic mean concentrations from single or multiple community-oriented monitors is not to be at or above this level.	15.1 µg/m^3	15.1 µg/m^3
Lead	Quarter	Not to be at or above this level.	1.55 µg/m^3	1.55 µg/m^3

(http://www.tceq.state.tx.us/compliance/monitoring/air/monops/naaqs.html)

2.2.2 Air quality in Dallas Fort Worth

The more stringent 8-hour ozone NAAQS replaced the1-hour ozone in 2004. An area is said to reach non-attainment when the annual fourth highest daily maximum 8-hour ozone NAAQS, averaged over three years, at an individual monitor exceeds 0.08 ppm or 84 ppb.

The DFW Metroplex is designated as "moderate" non-attainment area for the 8-hour ozone standard and must comply with NAAQS by June 15th, 2010. The Clean Air Act Amendments (CAAA) specifies a deadline for the DFW region to develop a SIP that demonstrates how the ozone standard will be achieved.

2.2.3 Various strategies to reduce emissions

As mentioned earlier various control strategies are employed with an objective to meet the standards of NAAQS.

- Engine design
- Alternate fuels
- Transportation System Management
- Travel Demand Management
- Others

Engine Design: The engine is designed in such a way that it emits lower emissions. The following are some of the changes made in the engine to produce lower emissions.

1. Avoiding stoichiometric combustion to lower NO_X , through:

a. Air to Fuel Ratio

b. Stratified charge engine

c. Extra lean burn engine

2. Lowering combustion temperature to lower NO_X, through:

   a. Exhaust gas recirculation

   b. Water injection

   c. Changing engine cycle

   d. Fuel injection system modification

3. Ensuring complete combustion to lower HC and VOC, through:

   a. Reduced flame quenching

   b. Speeding the warm up

Alternate Fuels: The demand for travel has lead to exhaustive consumption of fuels (conventional gasoline) and hence natural resources. This fact has lead to fuels being outsourced. Alternate fuel options include the following:

1. Alkanes (CNG, LPG)
2. Alcohols (Methanol and Ethanol)
3. Electric Vehicles
4. Hydrogen Fuel Cell Vehicles
5. Hybrid Vehicles

Transportation System Management (TSM): TSM includes measures that impact operation of the transportation system, typically improving traffic flow and thereby reducing emissions. TSM measures include:

1. Speed Limit Reduction
2. Intersection improvements
    a. Turning lanes
    b. Grade separation
    c. Pavement striping
    d. Signage and lighting
    e. Bus turnouts, and
    f. Channelization of traffic
3. Signalization improvements
    a. Signal timing optimization
    b. Signal equipment upgrades
    c. System interconnection
4. Bottleneck removal
5. Intelligent transportation systems
6. Special events management strategies
7. Extended idling reductions
8. Driver Behavior Education

Travel Demand Management (TDM): TDM takes into account the measures for managing the demand for travel. In other words, it reduces the number of vehicles on the road, especially during peak times; TDM also accommodates more people who travel to the same place. Options include:

1. Mass transit
2. Carpooling / Vanpooling
3. Introducing High Occupancy Vehicle (HOV) / High Occupancy Toll (HOT) lanes
4. Compressed work weeks
5. Telecommuting
6. Bicycle / pedestrian transit

Others: Other measures for reducing emissions from vehicle include:

1. Gasoline Composition Changes (Oxygenated, Reformulated)
2. Add On Controls (Catalytic Converter)
3. Gas Tax
4. Corporate Average Fuel Economy (CAFÉ) Standards
5. Stringent Inspection / Maintenance (I/M)

Gasolines are blends of various paraffins, olefins, naphthalenes, and aromatics, compounded to give desired characteristics when burned in automobile engines, with varying composition from one geographical region to another. Extensive tests show that different gasolines when burned in a given engine will yield different unburned hydrocarbon exhaust products. A catalytic converter is a device which makes use of catalyst platinum to oxidize CO and HC to CO_2 and rhodium to reduce NO_X to N_2 and O_2. By increasing the gas tax, people have an incentive to drive less and hence reduce emissions; also, revenue is raised for the transport and improving mass transit. CAFÉ standards reduce dependency on foreign gas and reduce emissions. Ensuring emissions meet the air pollution standards by stringent inspection is also one of the keys to maintain low emissions.

(Adapted from Dr. Sattler, Transportation and Air Quality course, UTA, fall 2005/2006)

2.3 Emission Measurements

2.3.1 Emissions from internal combustion engines

Combustion taking place in an automobile engine gives rise to tailpipe emissions. Combustion is an exothermic process which burns fuel with the presence of air and at high temperature. The following is the basic short-hand equation for ideal Combustion:

$$HC + O_2 \rightarrow CO_2 + H_2O \qquad \rightarrow \text{eqn 1}$$

$$HC + O_2 \rightarrow CO + H_2O \qquad \rightarrow \text{eqn 2}$$

In actuality, the process of combustion is more complicated and involves many free radical reactions. Equation 1 represents complete combustion with Carbon-dioxide, water and heat as products, and Equation 2 represents incomplete combustion with Carbon-monoxide and water.

NOx is formed by the thermal oxidation of N_2 and O_2 at high temperatures:

$$N_2 + O_2 \rightarrow NOx \qquad \rightarrow \text{eqn 3}$$

The pollutants HC, CO, CO_2 and NO_X are the four major pollutants from tailpipes, formed by the above three reactions in an engine.

2.3.2 Importance of emission measurement

From an air quality management perspective, it is important to aggregate emission values of the pollutants, using their appropriate toxicity levels in the atmosphere. Their relative toxicity weights are uncertain and a subject of professional debate, as these factors need to be estimated empirically for a given area under study on the macro (regional) scale, as explained below:

1. SIP's require quantitive estimates of emission reduction.
2. NO_X and VOC emissions are input into a regional photochemical model to predict Ozone concentrations, this photochemical model accounts for meteorology (wind speed and direction, temperature etc.) and chemistry (several reactions between NO_X and VOCs)
3. Ozone concentrations are predicted before and after controls, to ensure that controls are efficient strategies to bring the region into compliance with CAA standards. If the emissions are underestimated, it results in being expensive with too many controls. When emissions are overestimated, it results in very few controls and pollutants may exceed the limits.

Note: Accurate emission estimates are thus critical to achieve air quality compliance cost effectively. A macro scale emission model is used to estimate emission factors. Also a **Macro scale emission model** is used to estimate emission factors and a **travel demand model** is used to estimate Vehicle Miles Traveled (VMT).

Emissions = **Emission factor** * Activity level.

2.3.3 Methods of measuring emissions

Methods of measuring vehicle emissions include dynamometer testing, remote sensing, and On Board measurement Systems.

Dynamometer testing:

The dynamometer applies various loads on the engine and measures the engine's ability to move the load. The dynamometer is connected to a computer which calculates the output of the engine. The engine is run from idle to its maximum speed and the output is measured and plotted on a graph. Although a dynamometer has an advantage of being accurate and reliable, it's main shortcoming that it may not simulate real world driving conditions and it underepresents short term events that cause high emissions. Figure 2.1 represents dynamometer testing of a car.

Fig 2.1 Dynamometer
(http://www.gatewaycleanair.com/images/dyno.jpg)

Remote sensing:

The remote sensing device (RSD) employs infrared or Ultraviolet (UV) absorption, a source which continuously emits IR or UV radiation, RSD detector which receives IR or UV signals, is placed across the roadway. The signals are strong if there are no vehicle emissions; otherwise, the tailpipe plume absorbs a portion of light for pollutants with unique wavelength. As the vehicle passes through the beam, the device stores readings and performs electronic calibration. As the vehicle exits the beam, the system takes measurement at the rate of 100 per second and adjusts them for ambient conditions. Using IR light, RSD uses the before measurements of the ambient conditions as a base and calculates the vehicles CO emission rate by combustion. Exhaust HC is calculated in a similar manner by comparing the total carbon content of exhaust HC, CO, CO_2 to the total carbon content of the gasoline the car burns. In the case of NO_X, the RSD uses UV light source in addition to infrared. Although it provides real world data, RSD just provides a snap shot of emission at particular time and space; in addition RSD cannot give an accurate result when many vehicles are moving on parallel lanes. Figure 2.2 represents the method of measuring emissions by remote sensing method.

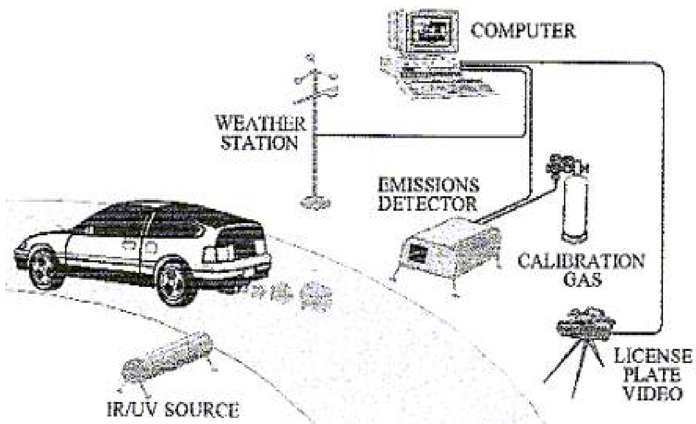


Fig 2.2 Remote sensing
(http://www.dmvnv.com/images/smogremote.jpg)

On-Board Measurement:

In this research, a portable On-Board measurement System (OBS) was deployed to collect vehicle emissions and engine data driven under real-world conditions. The system includes a five gas analyzer to measure volume percentage of CO, CO_2, HC, NO_X and O_2 in the vehicle exhaust. It has an engine diagnostic scanner that downloads second by second data.

The On-Board System is selected for this research since it measures the real world emissions under actual conditions. All the four driving modes, namely acceleration, deceleration, idling and cruising can be measured based on these actual conditions rather than a simulated condition. Although it is time sensitive and a little expensive, it has the advantage of measuring emissions from various driving pattern. Figure 2.3 shows the set up used for On Board Measurement system.

Fig 2.3 On-Board measurement System
(http://www.emd.horiba.com/engmeas/p_image/newsOBS_in_car_angle.jpg)

2.4 Related Studies

2.4.1 Aftermarket technology and fuel additive program

A similar case study was made using Aftermarket Technology and Fuel Additive Program's retrofit device. In this study, Sriharsha Kanukolanu attempted to observe any significant reduction of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and nitrogen oxides (NO_X). S. Kanukolanu's thesis was concerned with the impact of a pre-combustion retrofit device on vehicular emissions. In this research, a pre-combustion retrofit device was installed on a light duty vehicle and was tested to study the impact of the device on the emissions coming out of the vehicle. An On-Board System (OBS-1300) was used to measure the second by second emissions of CO, CO_2, HC and NO_X, under on-road traffic conditions. Emission measurements were carried out of both 'before' and 'after' the installation of the device and on both arterial and highway test tracks. Data was collected for both peak and off-peak time intervals.

The device had a major impact on NO_X emission concentrations, with a maximum decrease of 26.2% occurring for the highway track's off-peak acceleration mode. A significant decrease in emission concentrations of CO_2 was also observed for all modes and both the time intervals on the arterial test track.

2.4.2 Previous research on fuel additives

The author did not identify any previous research related to applying Ethos® FR for reducing emissions in any of the search engines like Sci-finder, Science Direct and Engineering Village.

2.5 Working of Ethos® FR

Thousands of different kinds of esters are commercially produced for a broad range of applications. Within the realm of synthetic lubrication, relatively small but still substantial families of esters are very useful in environmental applications. Ethos® Fuel Reformulator contains two hundred and eighty and eighty (288) distinct cleaning and lubricating esters.

According to the product literature, Ethos® FR removes the carbon deposits that cause fuel to combust incompletely, which results in wasted fuel that creates toxic emissions. The combination of the cleaning and the lubricating esters in Ethos® FR stabilize the fuel without changing its specifications.

The carbon deposits lower the engine's performance which makes it less fuel efficient and causes it to exhaust raw fuel, which is the primary contributor to air pollution. The low molecular weight esters in Ethos® FR clean the dirty deposits formed by the fuels during the combustion process, while the high molecular weight esters lubricate the engine surface as the fuel runs through it. Their molecular structure is small enough to penetrate the metal and form a lubricating layer between the surfaces, which allows the moving components of the engine to operate smoother with less friction and heat. EPA registers additives which are derived from petroleum. Ethos® FR is a reformulator even though it is added to the fuel, it is not derived from petroleum.

In many ways, esters are very similar to more commonly known and used synthetic hydrocarbons, esters are synthesized from relatively pure and simple starting materials to produce predetermined molecular structures designed specifically for high performance lubrication. The synthetic base stocks are primarily branched hydrocarbons which are thermally and oxidatively stable, have high viscosity indices, and lack the undesirable and unstable impurities found in conventional petroleum based oils. The structure of the ester has the presence of linkages **(COOR), which impart polarity to the molecules. Table 2.3 shows how polarity affects the esters behavior.

Table 2.3 Effect of polarity on ester behavior

Polarity:	The polarity of the ester molecules causes them to be attracted to one another, and this intermolecular attraction requires more energy (heat) for the esters to transfer from a liquid to a gaseous state. Therefore, at a given molecular weight or viscosity, the esters will exhibit a lower vapor pressure, which translates into a higher flash point and a lower rate of evaporation for the lubricant.
Lubricity:	Polarity causes ester molecules to be attracted to the positively charged metal surfaces. As a result, the molecules tend to line up on the metal surface, creating a film which requires additional energy (load) to penetrate. The result is a stronger film, which translates into higher lubricity and lower energy consumption in lubricant applications.
Detergency / Dispersency:	The polar nature of esters also makes them good solvents and dispersants. This allows the esters to solubilize or disperse oil degradation by-products which might otherwise be deposited as varnish or sludge, and translates into cleaner operation and improved additive solubility in the final lubricant.
Biodegradability:	While stable against oxidative and thermal breakdown, the ester linkage provides a vulnerable site for microbes to begin their of

Table 2.3 - continued

	biodegrading the ester molecule. This translates into very high biodegradability rates for ester lubricants and allows more environmentally work friendly products to be formulated.

(http://www.ethosnw.com/ester.html)

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Standard Test Procedure

3.1.1 Application of Ethos® FR

The Ethos® FR was added to the fuel tank of the study vehicle using a funnel; it was ensured that tank was completely drained before the application of the fuel additive.

Initial application required greater dosage with an objective to accelerate the cleaning and lubricating purpose.

Initial Application was as follows:

- **5 oz. of Ethos® FR per 10 gallons of fuel,** this dose was continued for the first two fuel tanks.
- **1 oz. of Ethos® FR per quart of oil** (per oil change)

Subsequent Application was as follows:

- **1 oz. of Ethos® FR per 10 gallons of fuel.**

Figure 3.1 shows the method of application of Ethos® FR into the fuel tank of the study vehicle.

Figure 3.1 Application of Ethos® FR

3.1.2 Test procedure

The test procedure involves multi-phase testing of the product. This research is pertained to Phase-I testing. The research is carried out on a light duty gasoline Chevrolet Van. An On Board System (OBS) by Horiba Instruments Inc., is used to measure the real world emissions of CO, CO_2, HC and NO_X.

The Standard NCTCOG/UTA protocol procedure was followed. 40 hours of On-road testing in real world traffic conditions was calculated which included 20 hours of highway test track and 20 hours of arterial test track. In 20 hours of data collected on each test track, 10 hours was at peak time interval and the other 10 hours was during the off-peak time interval. Tests were conducted from Monday afternoon through Friday morning, with

- AM Peak: 6:30 - 9:00AM,
- PM Peak: 4:00 – 6:30PM,
- Off-peak: 9:00AM – 4:00PM.

The following is the path way of arterial test track and the highway test track.

- **Arterial Test Track:** From UTA Blvd., travel North on Cooper to Division. East on Division to Collins. South on Collins to Pioneer. West on Pioneer to Cooper. North on Cooper to UTA Blvd. Figure 3.2 shows the path of the arterial test track.

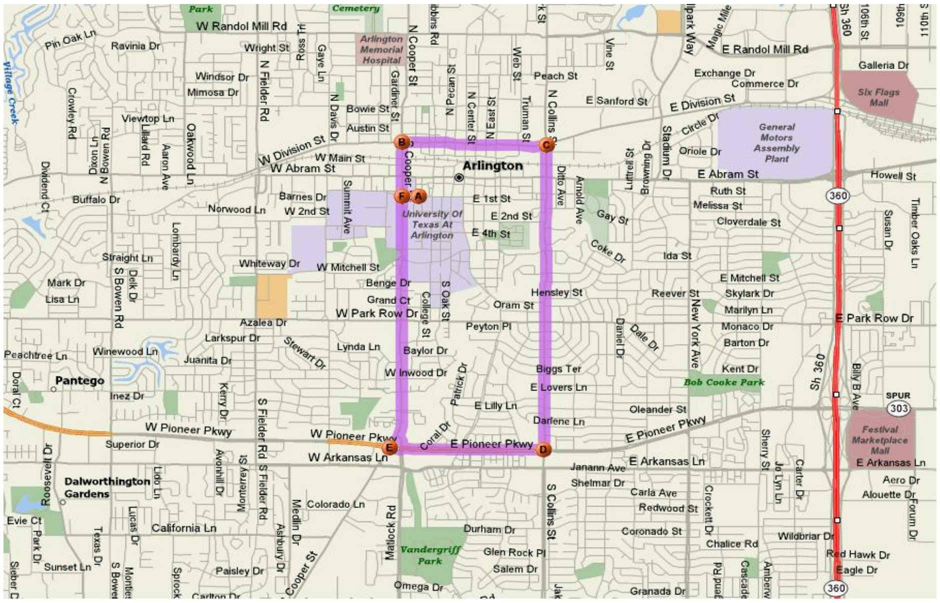


Figure 3.2 Arterial test track

- **Highway Test Track:** From Cooper, travel west I-30 to I-820. South on I-820 to I-20. East on I-20 to Spur-408. North on Spur-408 to Loop 12. North on Loop 12 to I-30. West on I-30 to Cooper.

Figure 3.3 shows the path of the highway test track.

Figure 3.3 Highway test track

3.1.3 Baseline and post removal testing

40 hours of baseline data was collected prior to the application of Ethos®, as defined in the Standard Test Procedure. The baseline testing was carried out in order to compare the before and the after data, which subsequently gives the effect of Ethos® on the emission trends.

A post removal testing was carried out after the Ethos® FR was completely drained from the fuel tank for 10 hours on both the test tracks. The post removal data was collected to ensure that emissions corresponded to that of the baseline data.

3.2 Data Collection Equipment

3.2.1 Study vehicle

The light duty gasoline vehicle on which the research was conducted was a Chevrolet Astro Van, 2000 model, set up at University of Texas at Arlington. The overall specifications of the study vehicle are listed in Table 3.1. The van housed OBS-1300 to collect second by second data; the details of OBS-1300 are given in 3.2.2 Section. Figure 3.4 shows the Chevrolet Astro Van.

Table 3.1 Overall specifications for study vehicle

Parameter	**Value**
Model Year	2000
Engine	4.3L V6
Power	142 kW, 190 HP @ 4400 rpm
Fuel tank capacity	25 gallons
Injection system	Multi-point

(Source: Chevrolet Astro Vehicle Manual)

Figure 3.4 Chevrolet astro van

3.2.2 Installation of OBS 1300

The On-Board emission System (OBS-1300) is manufactured by Horiba Instrument, Inc. This system measures CO, CO_2, HC and NO_X emissions, Air to Fuel ratio (AFR), and exhaust flow rate at every second; mass emissions and fuel consumption can be calculated. The analyzers in this setup are Heated Non-Dispersive Infrared (HNDIR) type, which analyzes CO, CO_2 and HC emissions, and a non-sampling zirconia type, which analyzes NO_X. The sensors and the analyzers capture vehicle velocity and engine revolution along with the data. The sample tube is routed through the window and fastened to the tailpipe attachment using hose clamps. Figure 3.5 shows the general set up of the OBS-1300. The various components of the OBS-1300 include:

1. MEXA-1170 HNDIR Unit
2. Data Integration Unit (DIU)
3. Data logger PC
4. Power supply Unit (PSU)
5. Other Accessories

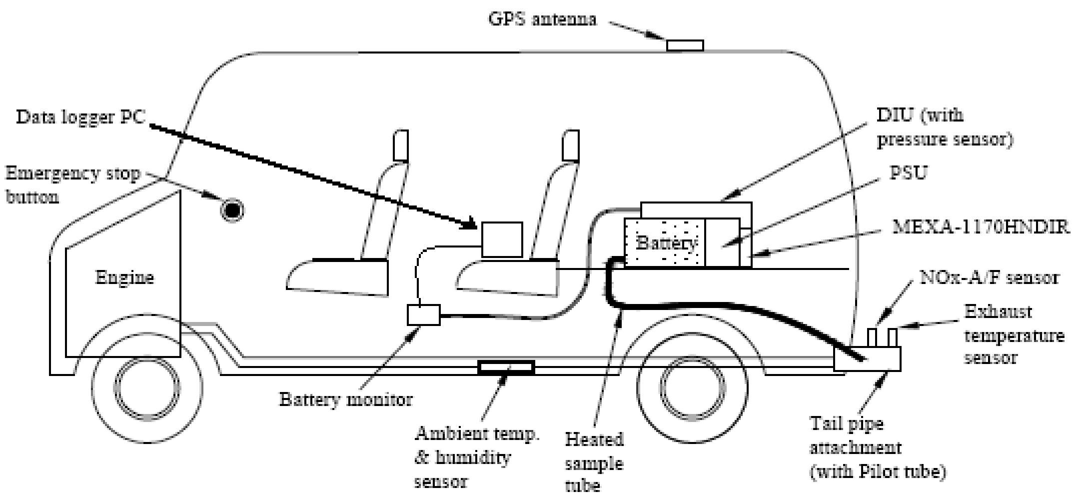


Figure 3.5 Setup of OBS 1300 on the study vehicle

(Source: Horiba's OBS instruction manual)

3.2.2.1 MEXA-1170 HNDIR unit

MEXA-1170 uses a Heated Non-Dispersive Infrared (HNDIR) detection technique to measure HC, CO and CO_2 emissions. This unit does not require an additional large dehumidifier for sampling the exhaust gasses since the water vapor is compensated in the analyzer.

This unit includes a power switch and a screen that acts as an interface between the analyzer and the data logger PC. At the rear end, there is an exhaust gas outlet, sample gas inlet, and various inlets for all of the calibration gasses like the zero gas, span gas and purge gas. There is a provision for connecting the remote control, heated sampling tube and connectors for leak checks. It should be ensured that no water stays in the tube as the exhaust port of the analyzer discharges it. Figure 3.6 shows the MEXA-1170 HNDIR Unit.

"The HNDIR technique is based on the principle of selective absorption. The gas taken in absorbs the infrared radiation in an amount directly proportional to its molecular concentration. It means that a particular wavelength of infrared energy peculiar to that particular gas will be absorbed by it while the other wavelengths will be transmitted." *(Work et al, 1998;, Kanukolanu, 2006)*

3.2.2.2 Data Integration Unit (DIU)

This unit houses MEXA-720 NO_X analyzer (non-sampling zirconia sensor), which measures the NO_x concentrations and Air to Fuel Ratio (AFR). The DIU acts as an interface for the analyzer and data logger PC. The rear end includes different ports for exhaust pressure, ambient pressure, and differential pressure and connectors for GPS, temperature and humidity. Figure 3.6 shows the Data Integration Unit and Figure 3.7 shows MEXA -720.

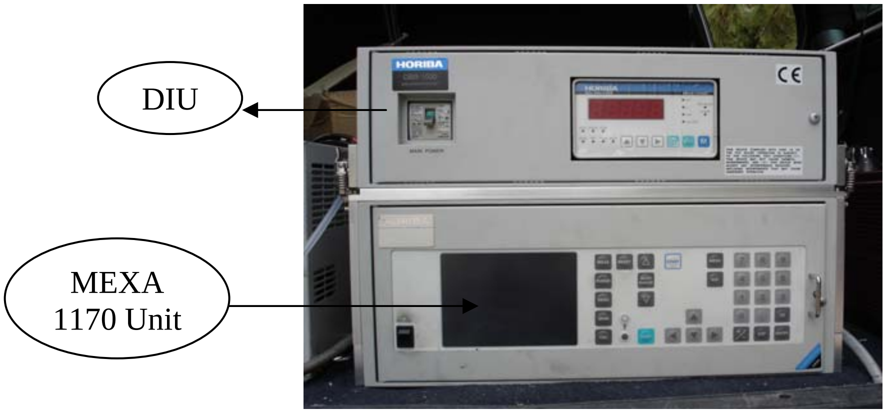


Figure 3.6 MEXA-1170 unit and DIU.

Figure 3.7 MEXA-720 unit and NO_X sensor

(Source: Horiba, Inc.)

3.2.2.3 Data logger PC

The data logger PC (DELL laptop) is connected to OBS-1300. It contains a PCMCIA card that converts analog to digital. The laptop is equipped with suitable software for data collection. Figure 3.8 shows the data logger PC.

Figure 3.8 Data logger PC

3.2.2.4 Power Supply Unit (PSU)

This unit converts 24 V DC to AC current. This power is then supplied to the whole OBS setup. The PSU also converts the AC to DC power, which can be used to charge the batteries. Figure 3.9 shows the Power Supply Unit.

Figure 3.9 Power Supply Unit

3.2.2.5 Other accessories

Other accessories include batteries, Geographic Positioning System (GPS), remote controller, humidity sensor and tailpipe attachment. **Batteries,** as shown in Figure 3.10, are the source of electrical energy to the OBS. There are two sets of deep cycle batteries, with 12V each. The batteries last till they reach 19V, which is about four hours. These batteries are connected to the PSU, which is in turn connected to the PC, which monitors the voltage of the batteries.

Figure 3.10 12- Volt deep cycle batteries

The **GPS unit** is provided to obtain the velocity, latitude and altitude of the vehicle along with the data collected. The GPS antenna is connected to the data logger PC. Figure 3.11 shows the GPS antenna.

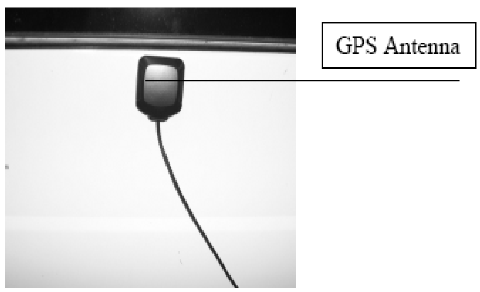


Figure 3.11 **GPS antenna**

A remote controller which is connected to the DIU makes it accessible to the person taking the reading. It holds basic functions like ZERO, SPAN, CAL, PURGE, MEASURE and RESET. Figure 3.12 shows the remote controller.

Figure 3.12 Remote controller

A **humidity sensor** is provided to measure the humidity and the ambient temperature of the outside air. There is an **attachment to the exhaust system** for measuring the levels of pollutant. Figure 3.13 shows the sensors attached to the tailpipe. The NO_X sensor measures NO_X concentration at the tailpipe. The sampling tube attachment collects a sample, which is pumped up to the HNDIR unit for measurement of CO, CO_2 and HC.

Figure 3.13 Tailpipe attachment

3.2.3 Factors affecting data collection

- **Calibration:** Calibration of the analyzers and sensors was very essential for the accuracy of the data.
- **Cold starts:** Cold starts were avoided by warming up the whole system prior to data collection.
- **Weather:** The data was not collected during rainy days due to the risk of the damage caused by splashing water onto the sensor.
- **Time of the day:** The data collection was carried out at both peak and off-peak hours and was classified accordingly during data analysis.
- **Vehicle speed:** The speed of the vehicle was maintained similar to other vehicles to ensure that emissions were representative to the maximum possible extent.
- **Battery power:** A voltage drop below 21V resulted in unreliable data; hence, it was ensured that batteries had enough power during data collection.
- **Data logging software:** Various parameters on the analog to digital converter (ADC) setup in the software are required to be configured to correct values. Table 3.2 lists the various parameters that need to be configured.

Table 3.2 Parameters configured in ADC setup

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 of 1.5-2.0 seconds as estimated by Horiba Instruments, Inc. for converting the sensor measured concentration from analog to digital output and logging the results in the data logging software.

- **Inspection:** Regular inspections were carried on the whole system to make sure that the emissions measured or exhausted did not vary with time.
- **Driver's Behavior:** The driver's behavior, like tendency to accelerate, break and approach signals and intersections, also may affect the consistency of data.

3.3 Calibration

3.3.1 OBS warm-up and general calibration

Calibration is very essential to maintain the accuracy of data. Figure 3.14 gives the OBS warm-up and general calibration which is done before collecting data. The whole calibration takes about 1 hour. The following steps are required to complete the warm-up calibration.

- Ensure two sets of 12 Volt deep cycled batteries are completely charged before the data collection.
- Turn on the DIU using AC power and start the HNDIR unit after 1 minute.
- Warm up the DIU and HNDIR units for 45 minutes and switch their source to DC power.
- Warm up the DIU and HNDIR units for 45 minutes and switch their source to DC power.
- Turn on the DIU and after a minute the HNDIR unit.
- ***PURGE*** the HINDIR unit using Zero gas for 5 minutes.
- Press ***RESET***
- Press ***ZERO*** button and wait for 90 seconds
- Press ***RESET***
- Connect the span gas from the cylinder, press ***SPAN*** button and wait for 90 seconds
- Press ***RESET***

- Press ***CAL*** button. The machine will do both ***ZERO*** and ***SPAN*** calibration and will ***RESET*** itself.
- This ends the warm-up and calibration of OBS -1300.

Note: The Zero gas is pure nitrogen gas and has no oxygen in it.

The following gasses constitute span gas:

1. 0.5% of CO
2. 6.0% of CO_2
3. 301 ppm of NO_X, and
4. 201 ppm of C_3H_8

3.3.2 Calibration during runs

Once the OBS warm-up and calibration is completed, a step wise procedure is followed for the data collection. The following are some of the key points prior to data collection to ensure quality of results.

1. At the starting point, turn the vehicle ignition OFF and ensure zero calibration of the instrument.
2. Press CAL for pitot tube calibration.
3. Press RESET followed by PURGE to start the purging of the instrument.
4. While purging, turn on the vehicle ignition and the PC.
5. Press MEASURE button after 90 seconds of purging and start logging.

To make sure not to get any negative flow rate values, calibration of pitot tube is very necessary. This above calibration is done for every other run on the arterial test track and every run on the highway test track.

3.3.3 Calibration of NO_X sensor

To ensure the accuracy of the data, calibration of the NO_X sensor was required. The NO_X sensor calibration procedure is as follows:

1. The calibration unit consists of a flow meter, sensor adapter, bubbler, and water inlet and the NO_X sensor is fixed in the sensor adapter of the calibration unit.
2. Distilled water is filled through water inlet into the calibration unit.
3. The regulator valve connects the gas cylinder to the calibration unit.
4. Scott Speciality Gases provides the calibration gasses (O_2 and N_2) used for this process.
5. The exhaust outlet is connected to Teflon tube, through which discharges calibration gas outside.
6. The calibration gas is allowed to flow at a rate of 1.5L/min to 2.5 L/min. Ensure that the ball in the flow meter is between the two levels.
7. NO_X sensor is switched on and calibrated after the gas is allowed to flow.
8. CAL/SET is pressed and held for approximately three seconds and the mode of the analyzer switches to setting mode. Channel number (ch000) appears on the display.

9. The calibration is finished when the value of concentration on the calibration gas label is input.

Figure 3.14 shows the NO_x sensor calibration setup.

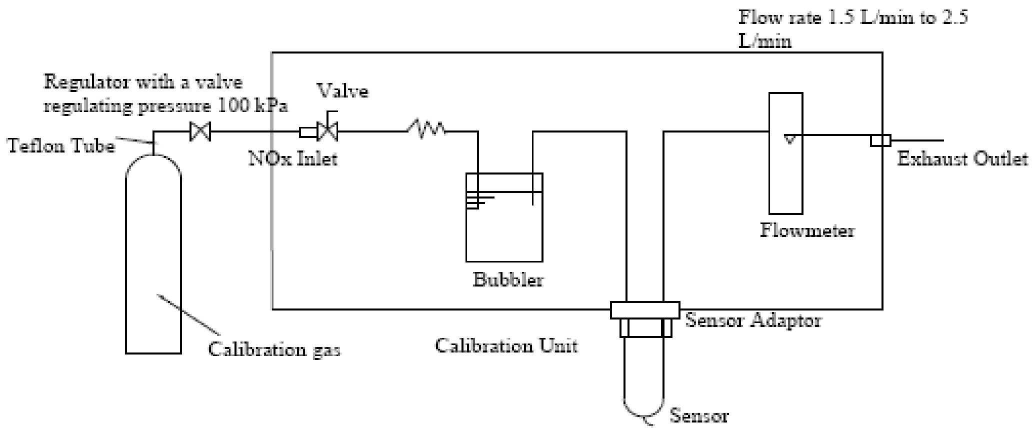


Figure 3.14 NO_X sensor calibration setup

(Source: Horiba's OBS instruction manual)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The data collected using OBS-1300 was analyzed to determine the results. Various parameters logged onto the PC were required for data analysis. The second by second data collected was saved as a txt file in Note Pad and then exported to Microsoft Excel sheets. Table 4.1 lists all the parameters measured while data was collected.

Table 4.1 Parameters measured during data collection.

PARAMETERS	UNITS
Date and Time	mm/dd/yr
CO Concentration	% Volume
CO_2 Concentration	% Volume
HC Concentration	ppm
NO_X Concentration	ppm
Exhaust flowrate	L/min
Exhaust temperature	Deg C
Exhaust pressure	KPa
GPS Velocity	Km/hr
AFR	-

Table 4.1 - continued

Humidity	%
Latitude and Longitude	Degree
Altitude	m

Although various parameters were measured, only a few of the above parameters like date and time, CO, CO_2, HC and NO_X concentrations were required for this particular data analysis.

<u>4.2 Data Classification</u>

To analyze the emission trends, a number of classifications of the data were carried out. The steps below were followed to conduct data analysis.

Note: The arterial and highway data were analyzed separately. The same procedure was followed for both before and after data.

1. As mentioned earlier, data collected was saved as a txt file in Note Pad and then exported to the Microsoft Excel sheets.
2. Initially, a distinction was made between peak and off-peak data. The time schedule to differentiate the peak from the off-peak hours was discussed in Chapter 3.
3. Although data was collected at different times during peak hours, AM & PM were combined into a single peak time interval.
4. Both peak and off-peak time interval data sets were then classified on a modal basis into the four standard driving modes as follows:

- **Acceleration mode** as portions having positive incremental speed changes greater than 0.1 m/sec/sec,
- **Cruising mode** as portions having absolute incremental speed changes of less than 0.1 m/sec/sec,
- **Deceleration mode** as portions having negative incremental speed changes less than 0.1 m/sec/sec, and
- **Idling mode** as zero speed and instantaneous acceleration.

Note: Highway data does not include idling mode classification for obvious reasons.

7. Each driving mode was then categorized into different clusters based on GPS velocity intervals of 5 mile/hr. Averages and standard deviation were calculated for each velocity interval.
8. The values of the average velocity and their corresponding average emission concentrations were transferred to new spreadsheets.
9. Finally, graphs were plotted for each mode with average velocity (x-axis) vs. average emission concentration (y-axis).
10. Once the data was classified and graphical analysis was done, percent emission reductions for each mode, before and after application of Ethos® FR, were determined for the 4 pollutants. T-tests were conducted to determine whether emission trends were statistically significant.

Prior to plotting graphs, certain changes were made without compromising the quality of data. The changes made include:

- For the highway data, velocity clusters below 45 mile/hr were omitted, due to insufficient data points. These velocities were being considered with the arterial data set. The data velocity clusters > 85 mile/hr with very few data points were also omitted as outliers.
- In addition, the velocity clusters below 45 mile/hr with single data points were not considered for the highway data.
- For the arterial data, velocity clusters > 46 to 50 mile/hr were omitted, due to insufficient data and these were being considered by highway data set.

4.3 Results

The results were presented in three ways: graphical analysis gave a comparison between before and after data by means of graphs, overall percentage reduction was calculated to get a better knowledge of before and after data by means of numbers, and t-tests were conducted to statistically determine if the difference between before and after data was significant. Each one of them is described in detail in the subsequent sections.

4.3.1 Graphical analysis

As discussed in section 4.2, the data was classified and graphs of average velocity and average emissions were plotted for each mode. A total of 96 graphs were plotted, which included both base-line and Ethos® data set for arterial and highway test tracks. Table 4.2 shows the number of individual graphs plotted for each data set.

__Table 4.2 Number of individual graphs plotted for each test track__

	Baseline-data			**Ethos-data**		
	Acceleration	Deceleration	Cruising	Acceleration	Deceleration	Cruising
Peak	4*	4*	4*	4*	4*	4*
Off-peak	4*	4*	4*	4*	4*	4*

* Four graphs because one graph for each pollutant namely CO, CO_2, HC and NO_X

Initially, the graphs for baseline data and for Ethos® data were plotted separately. Later both the data set were combined and graphs were plotted to observe the change in emission trends.

Since it is not possible to incorporate all the 96 graphs in this chapter, only 16 graphs with the discussion of their trends are included. The rest of the graphs are available in Appendix A for review. The 16 graphs include test tracks, peak and off-peak time interval and all the driving modes for all the pollutants.

The following cases exemplify the emission trends:

Case I: Emission trends of arterial test track, peak time interval for Deceleration mode.

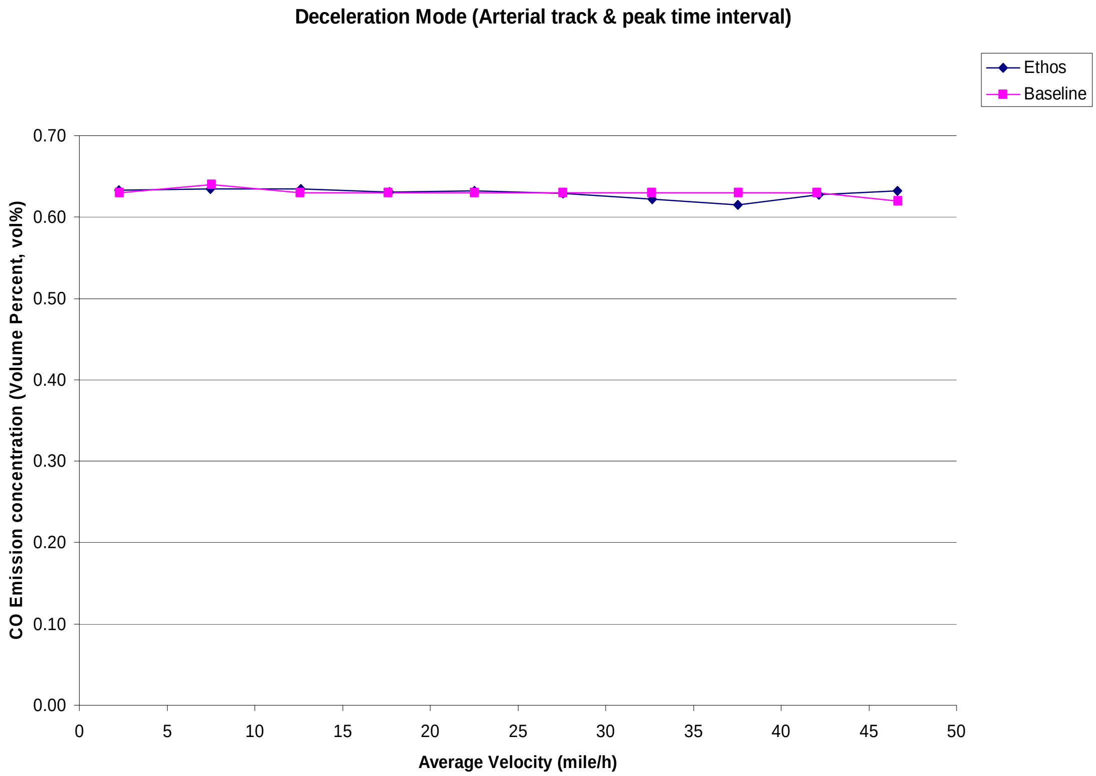


Figure 4.1 CO emission trends of arterial test track and peak time interval for deceleration mode

Observations: Figure 4.1 shows the CO emission trends for arterial test track and peak time interval in deceleration mode. It can be observed from the figure that there is no significant reduction in CO emission concentration after the application of Ethos®. A similar trend was observed for acceleration and cruise modes for peak time interval on the arterial test track; however, for the Idling mode, there is a slight increase in the CO emissions after using Ethos®.

Figure 4.2 shows CO_2 emissions for arterial test track and peak time interval in deceleration mode.

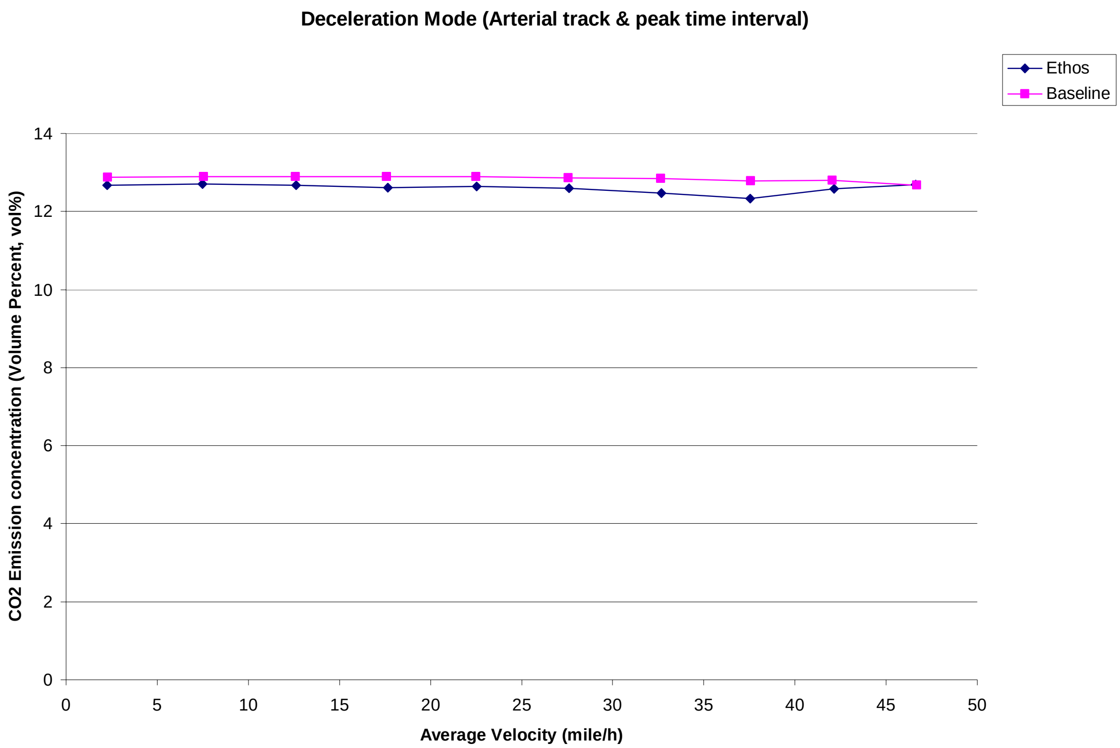


Figure 4.2 CO_2 emission trends of arterial test track and peak time interval for deceleration mode

<u>Observations</u>: It can be observed that there is a slight reduction in the CO_2 emission concentration with the application of Ethos®. A similar trend was observed in other modes for the arterial test track during the peak time interval.

Figure 4.3 shows HC emission concentration for arterial test track and peak time interval in deceleration mode.

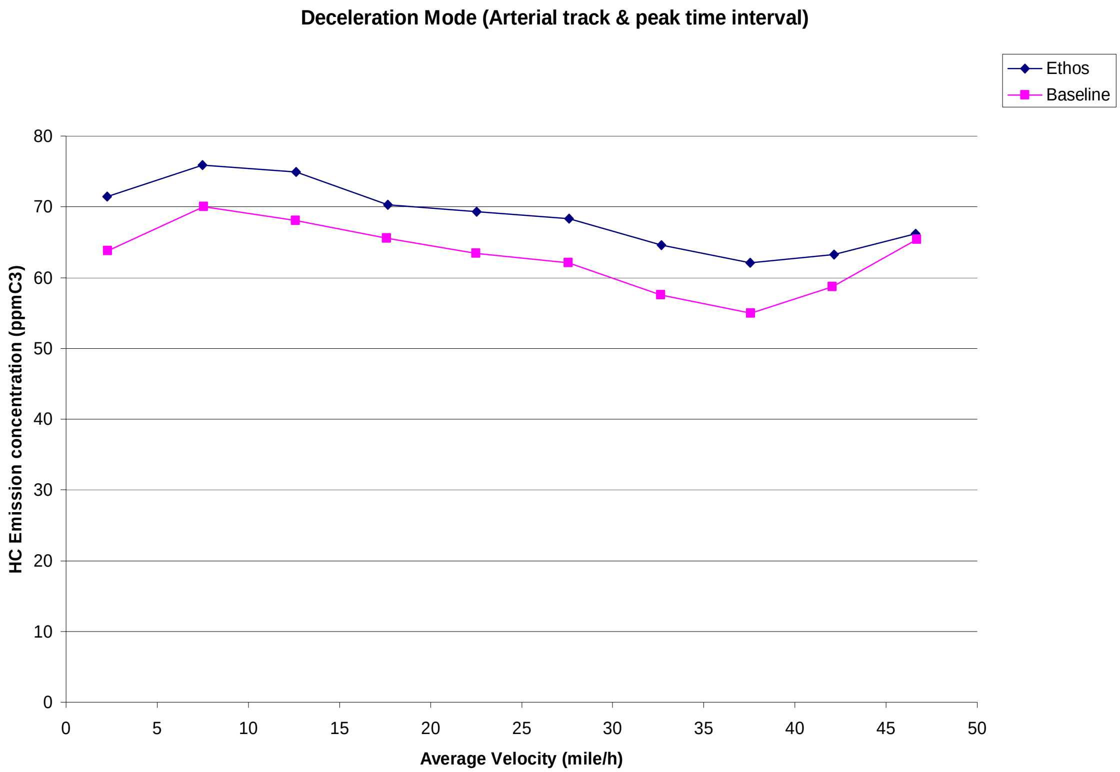


Figure 4.3 HC emission trends of arterial test track and peak time interval for deceleration mode

Observations: From Figure 4.3 it can be observed that there is a significant increase in HC emission concentration with application of Ethos®. Similar trends were observed in all the cases of arterial track and peak time interval for HC emissions. HC emissions may have increased because Ethos® itself consists of hydrocarbons.

Figure 4.4 shows NO_X emission concentrations for arterial test track and peak time interval in deceleration mode.

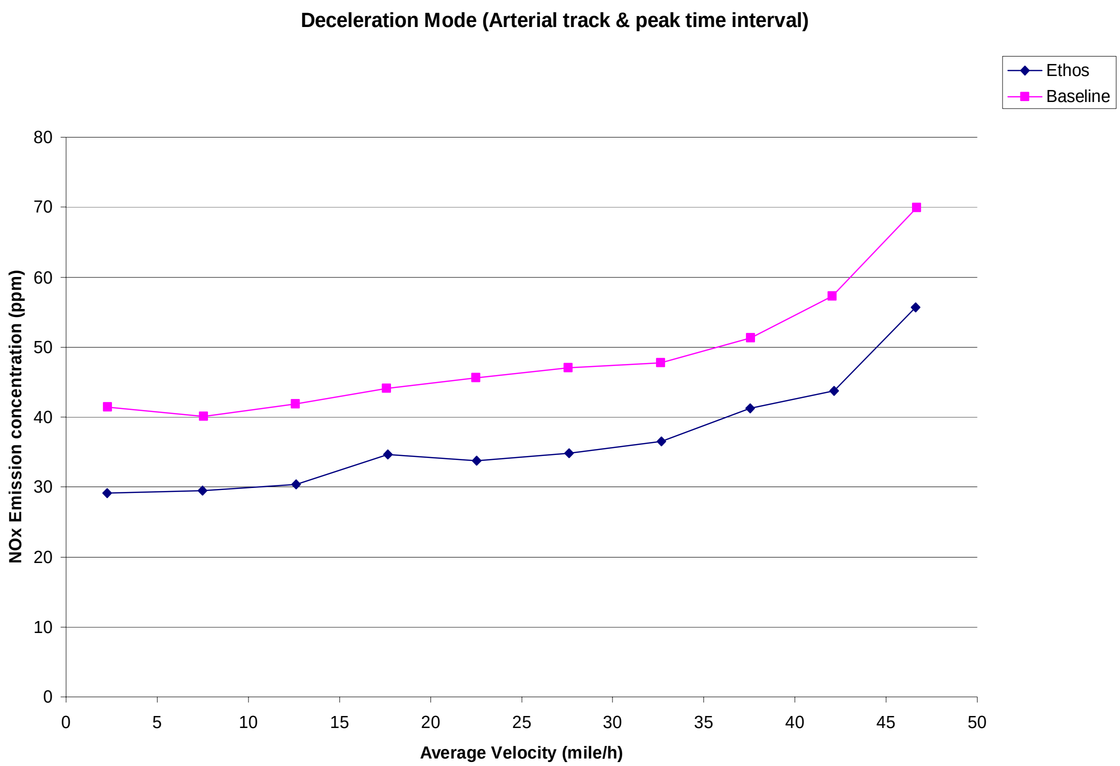


Figure 4.4 NO_X emission trends of arterial test track and peak time interval for deceleration mode

<u>Observations</u>: Figure 4.4 clearly shows that there is a significant reduction in emissions of NO_X concentrations due to the application of Ethos®. Similar trends were observed in all other cases for arterial test track and peak time interval. Ethos® may have reduced NO_X concentrations by lowering the temperature in the engine (the higher the engine temperature, the more NO_X is formed).

Case II: Emission trends of arterial test track, off-peak time interval for Acceleration mode

Figure 4.5 shows CO emissions for arterial test track and off-peak time interval in acceleration mode.

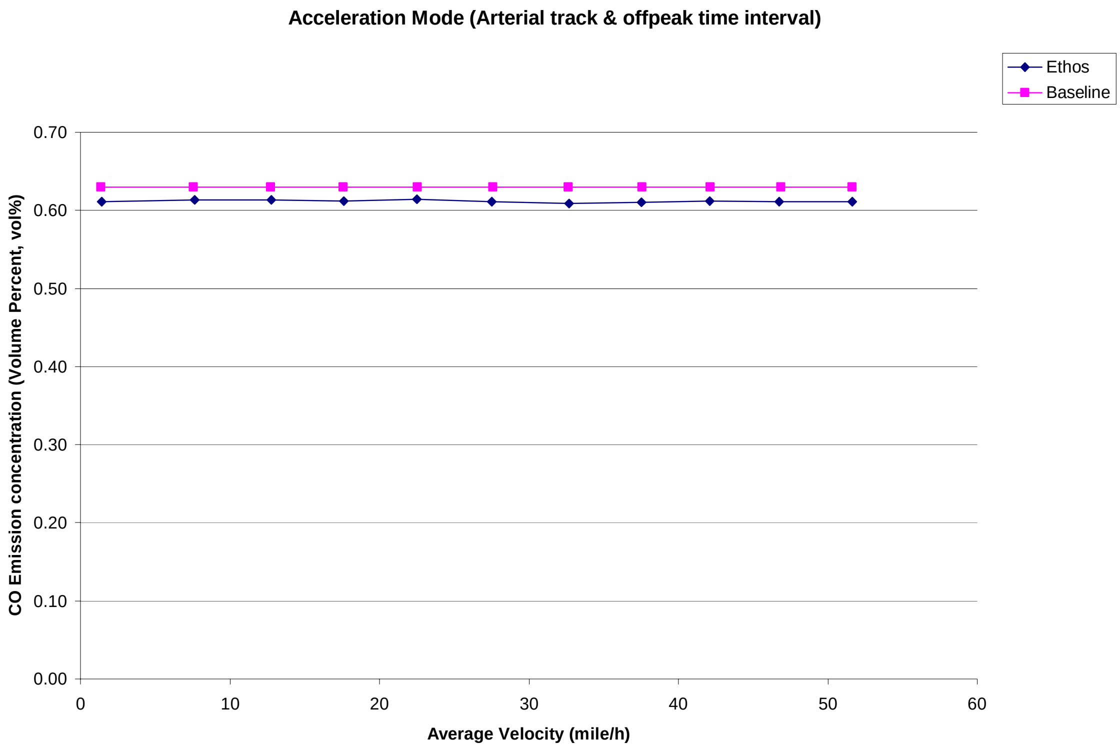


Figure 4.5 CO emission trends of arterial test track and off- peak time interval for acceleration mode

Observations: One can observe that there is as a slight reduction in CO emission concentrations after using Ethos®. Similarly in all other cases the same emission trends were observed for arterial test track and off-peak time interval.

Figure 4.6 shows CO_2 emissions for arterial test track and off-peak time interval in acceleration mode.

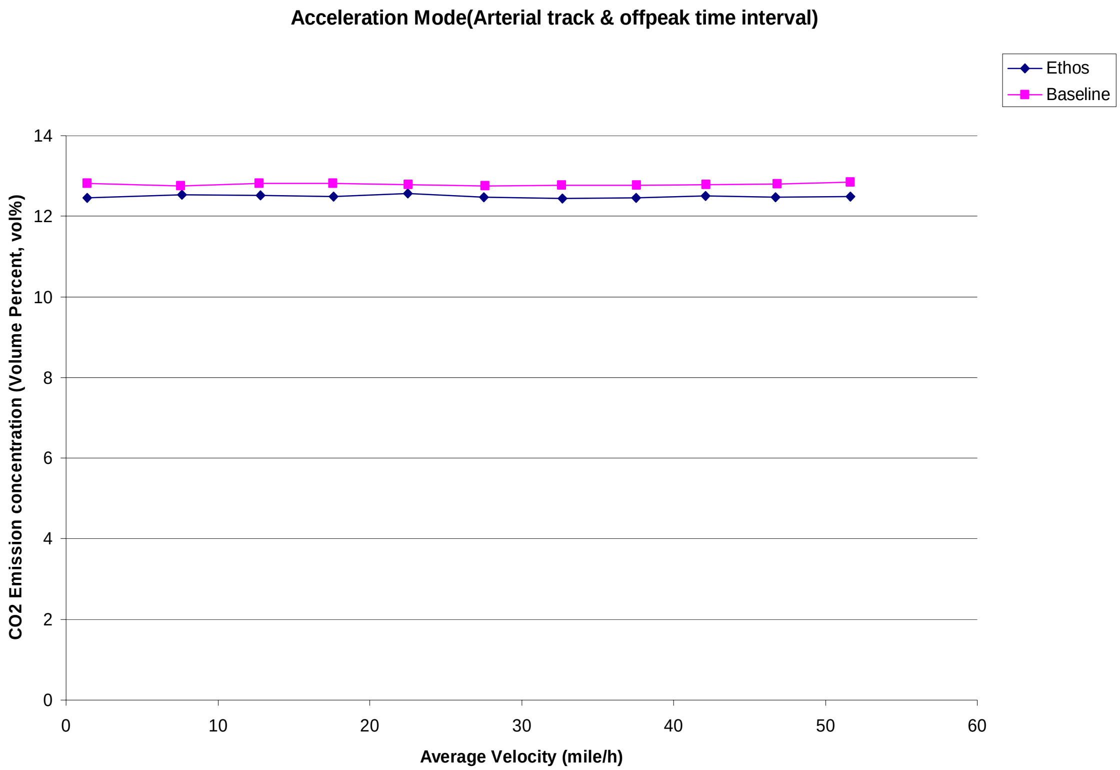


Figure 4.6 CO_2 emission trends of arterial test track and off- peak time interval for acceleration mode

<u>Observations</u>: From Figure 4.6 a small drop can be observed after application of Ethos®. A similar trend was observed in all cases of the arterial test track and off-peak time interval.

Figure 4.7 shows HC emissions for arterial test track and off-peak time interval in acceleration mode.

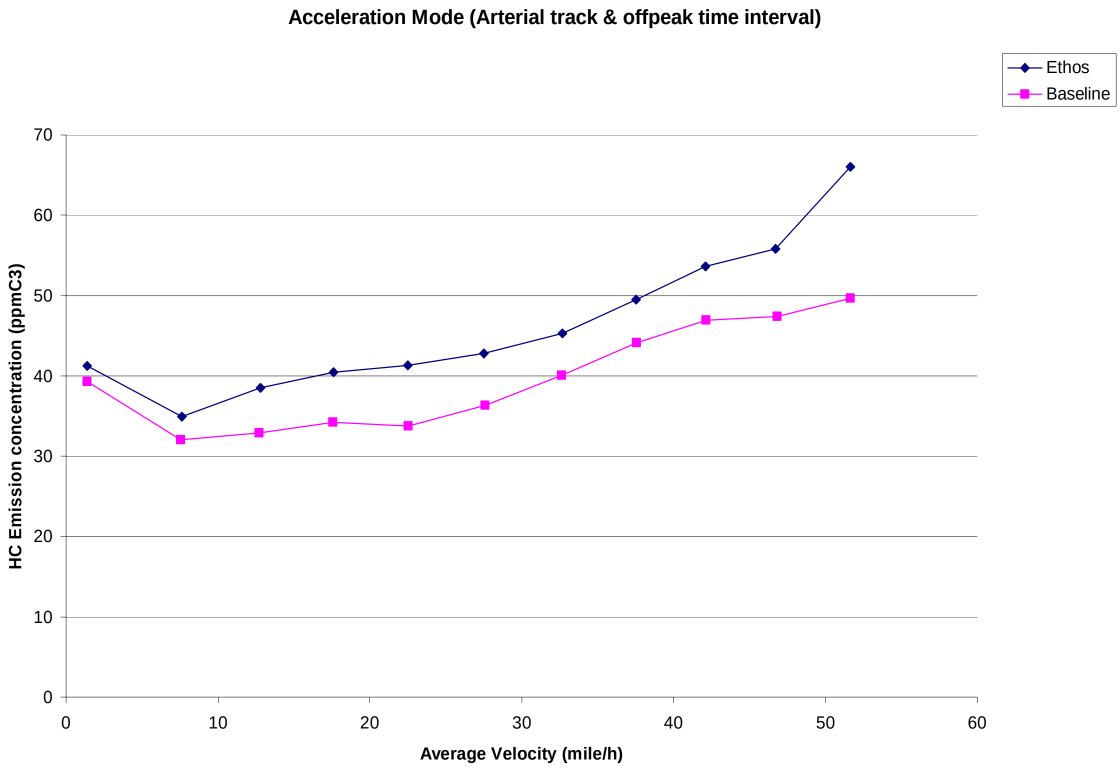


Figure 4.7 HC emission trends of arterial test track and off- peak time interval for acceleration mode

<u>Observations</u>: It can be observed that HC emission concentrations significantly increase with application of Ethos®. A similar trend was observed for all cases in the arterial track and off-peak time interval except idling mode.

Figure 4.8 shows NO_X emission concentrations for arterial test track and off-peak time interval in acceleration mode.

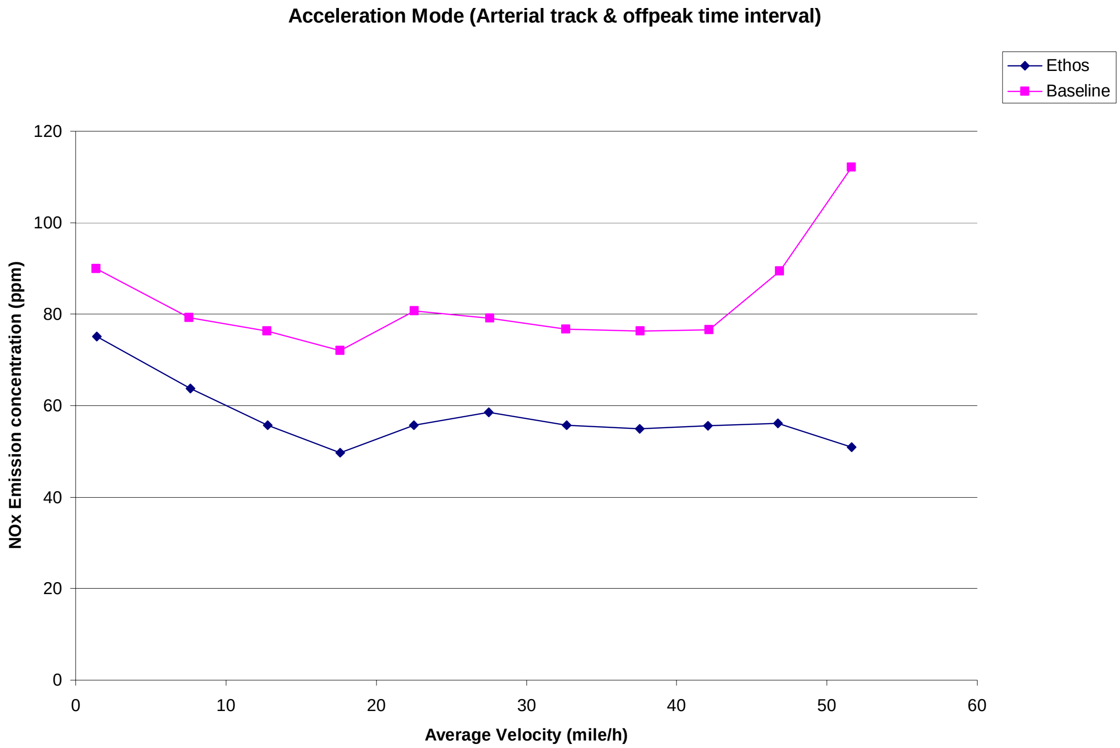


Figure 4.8 NO_X emission trends of arterial test track and off- peak time interval for acceleration mode

<u>Observations</u>: It can be observed that application of Ethos® has made a significant impact by reducing the emissions of NO_X concentrations. A similar trend was observed in all the modes of arterial test track and off-peak time interval.

Case III: Emission trends of highway test track, peak time interval for Cruising mode

Figure 4.9 shows CO emission concentrations for highway test track and peak time interval in cruising mode.

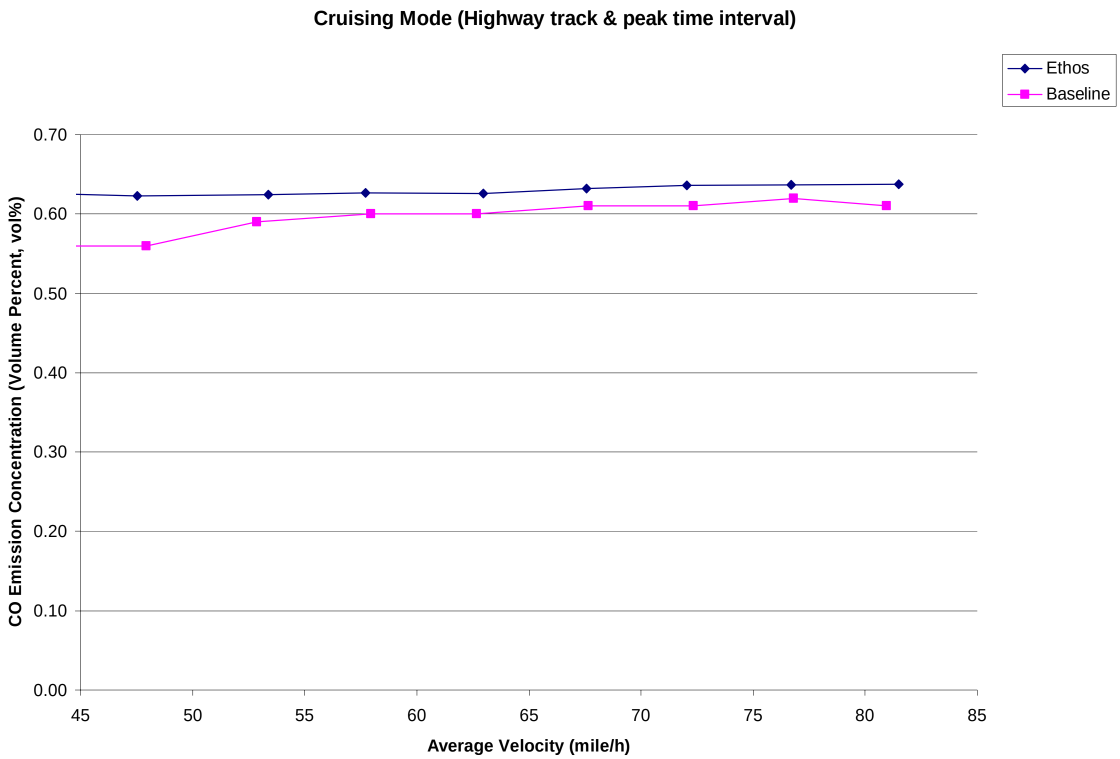


Figure 4.9 CO emission trends of highway test track and peak time interval for cruising mode

Observations: From Figure 4.9 it can be observed a slight increase in CO emission concentrations due to the application of Ethos®. A similar trend is observed for all the modes in the highway track and peak time interval.

Figure 4.10 shows CO_2 emission concentration for highway test track and peak time interval in cruising mode.

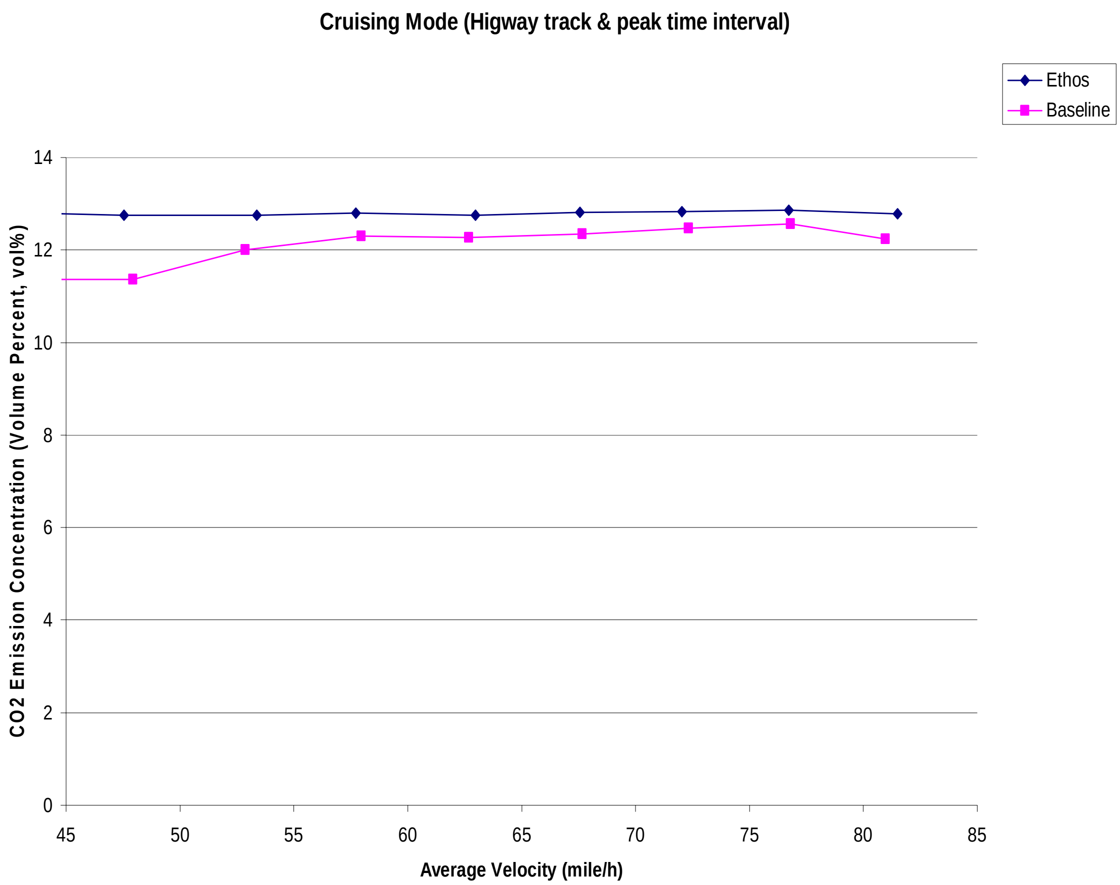


Figure 4.10 CO_2 emission trends of highway test track and peak time interval for cruising mode

Observations: A slight increase in emissions of CO_2 concentration can be observed in Figure 4.10. Similar trends were observed for all the cases in highway test track and peak time interval.

Figure 4.11 shows HC emission concentration for highway test track and peak time interval in cruising mode.

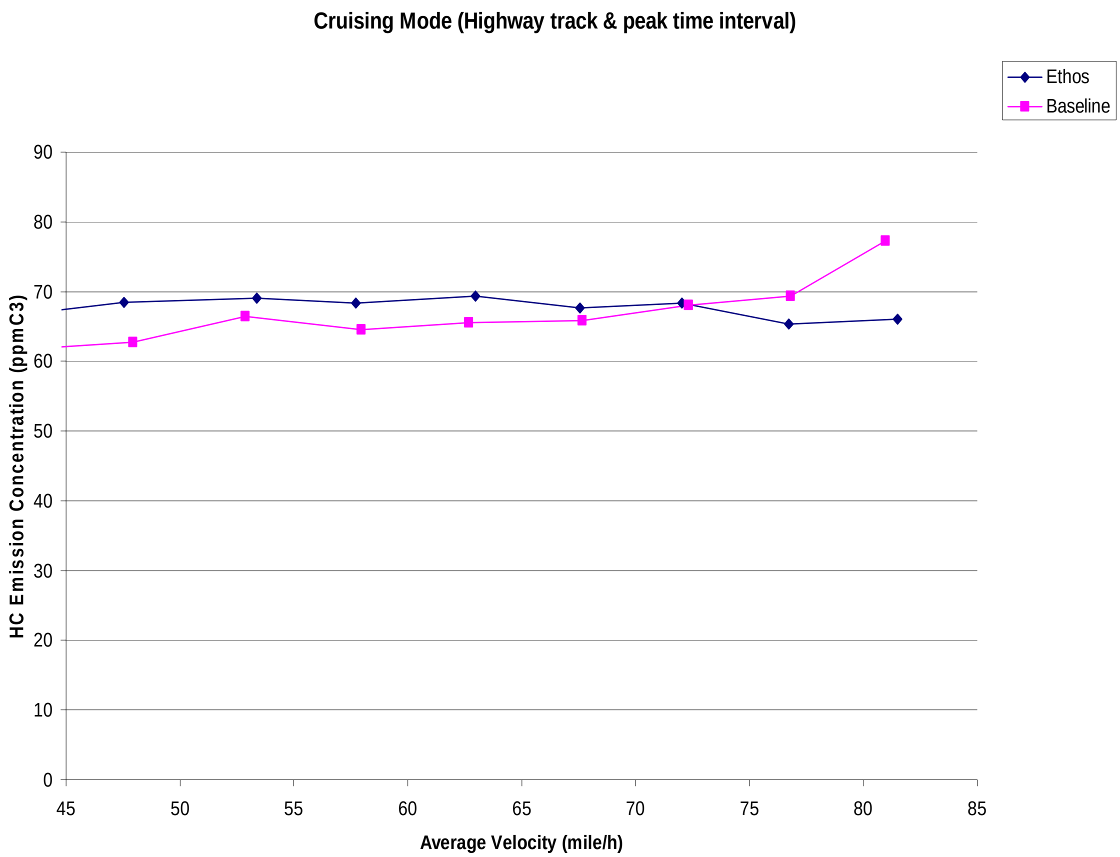


Figure 4.11 HC emission trends of highway test track and peak time interval for cruising mode

<u>Observations</u>: A slight increase in the HC emission concentration can be seen due to application of Ethos®, however above 70 miles/hr there is a drastic decrease in emissions. Unlike the Cruising mode, in other modes there is always a slight decrease in HC emissions unlike the Cruising mode for highway test track and peak time interval.

Figure 4.12 shows NO_X emission concentrations for highway test track and peak time interval in cruising mode.

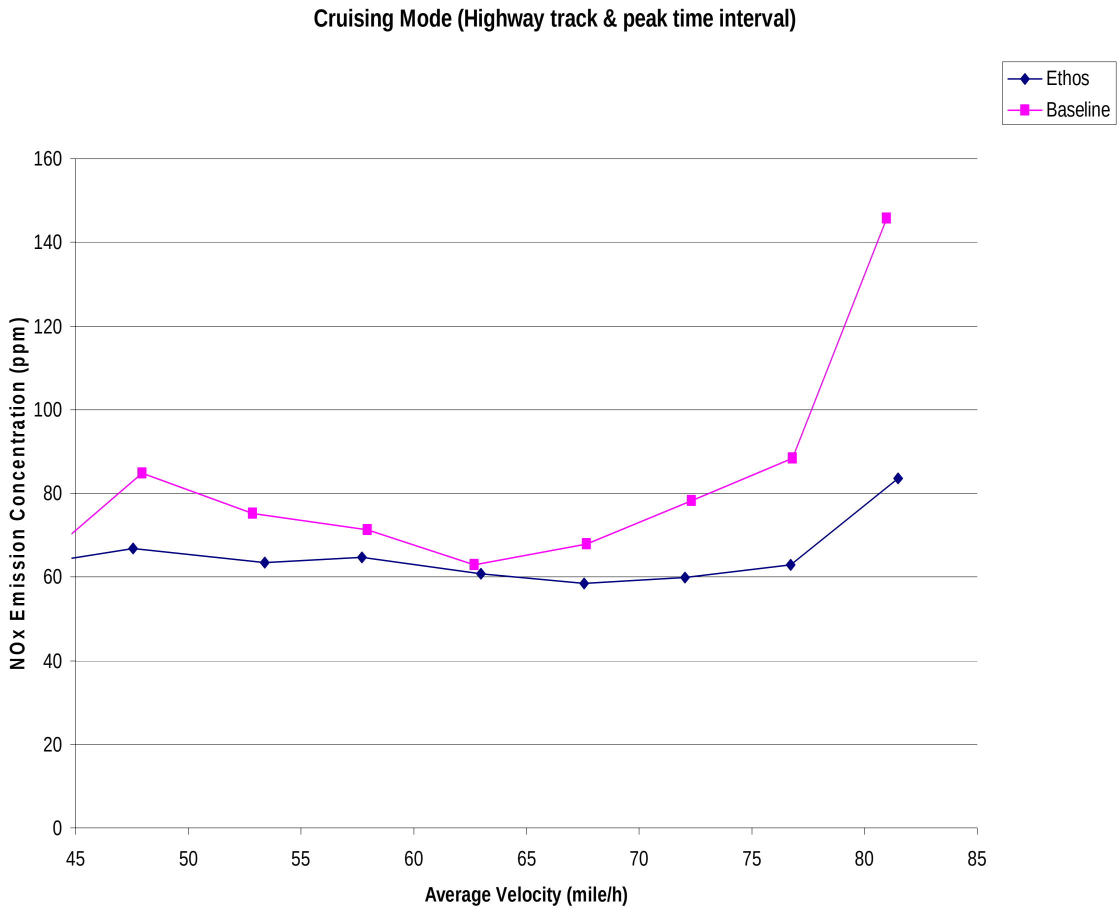


Figure4.12 NO_X emission trends of highway test track and peak time interval for cruising mode

<u>Observations</u>: A decrease in the emissions of NO_X concentrations can be observed from Figure 4.12, at a velocity between 60 mile/hr and 65mile/hr, some data points seem to have overlapped. There is a reduction of NO_X concentration in all the modes of highway test track and peak time interval.

Case IV: Emission trends of highway test track, off-peak time interval for Acceleration mode

Figure 4.13 shows CO emission concentrations for highway test track and off-peak time interval in acceleration mode.

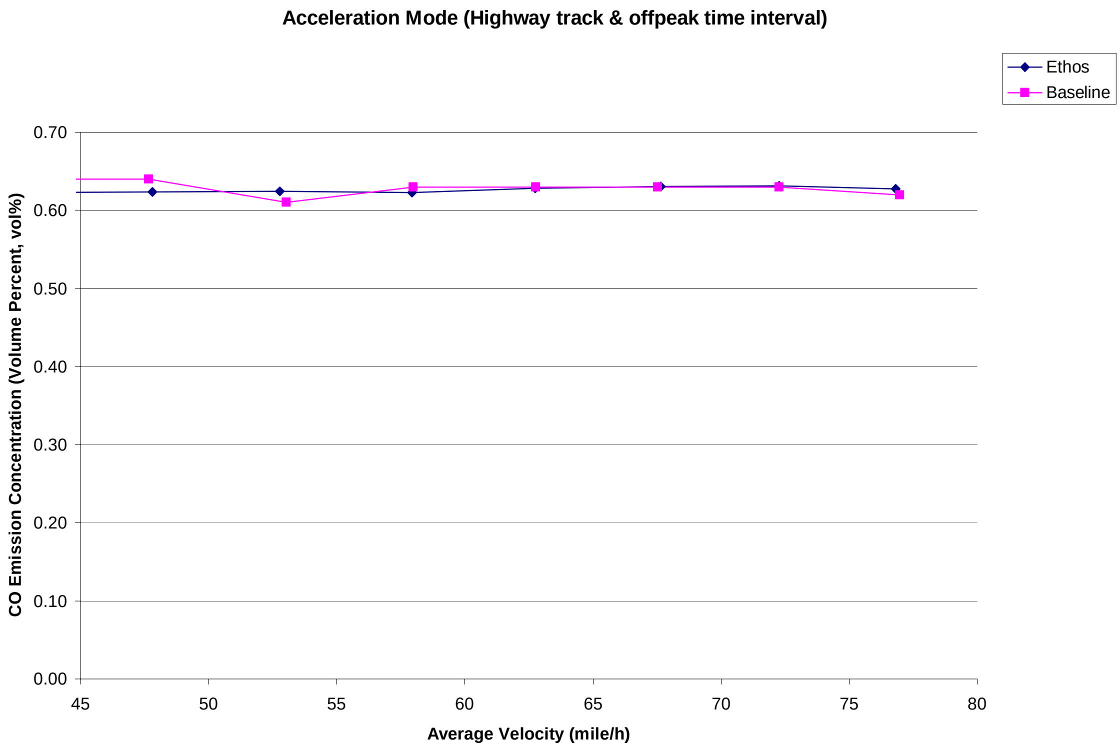


Figure 4.13 CO emission trends of highway test track and off-peak time interval for acceleration mode

Observations: From Figure 4.13, no clear distinction can be made between the lines: at some points it shows slight decrease or increase, and at a few other points it seems to have overlapped. In fact there is a very negligible increase in CO emission concentrations after the application of Ethos®. A similar trend is observed in all the modes of highway test track and off-peak time interval.

Figure 4.14 shows CO_2 emission concentrations for highway test track and off-peak time interval in acceleration mode.

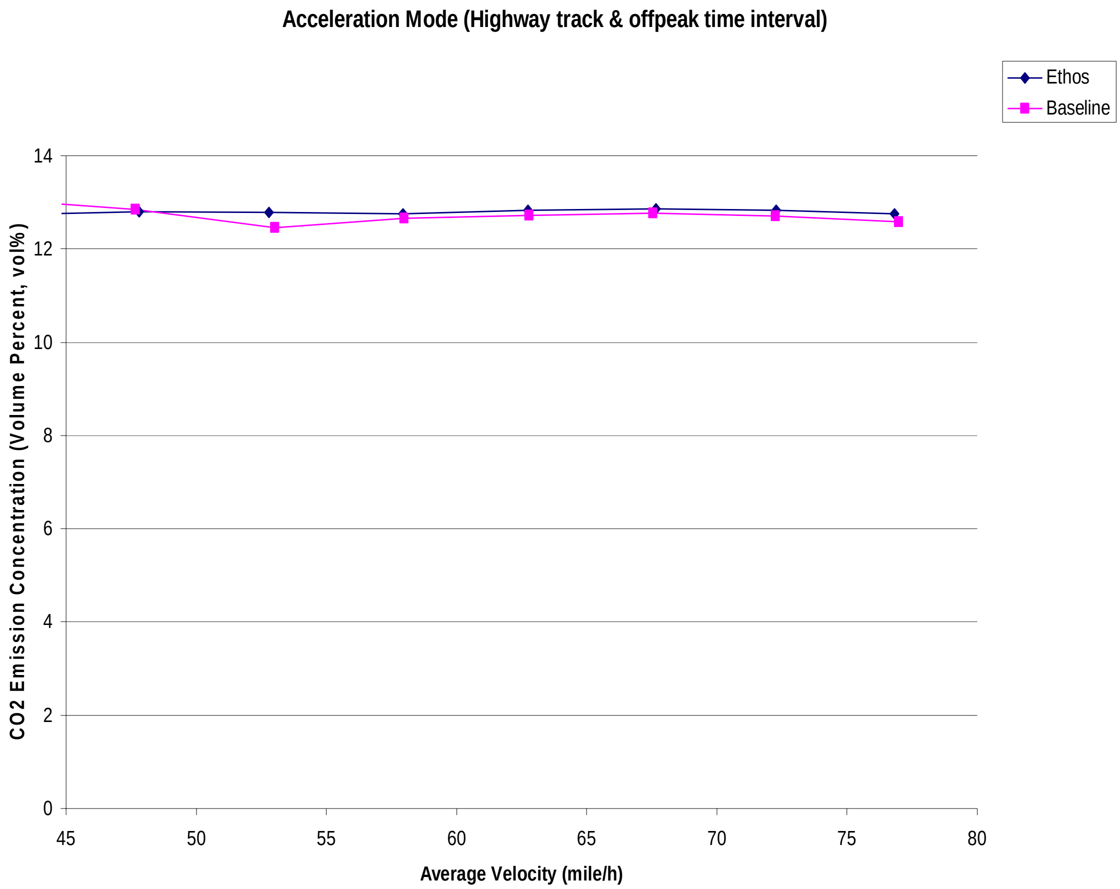


Figure 4.14 CO_2 emission trends of highway test track and off-peak time interval for acceleration mode

Observations: From observing Figure 4.14, it can be said that there is a very slight increase in the CO_2 emission concentrations due to the application of Ethos®. A similar trend is observed for all the cases in highway test track and off-peak time interval.

Figure 4.14 shows HC emission concentrations for highway test track and off-peak time interval in acceleration mode.

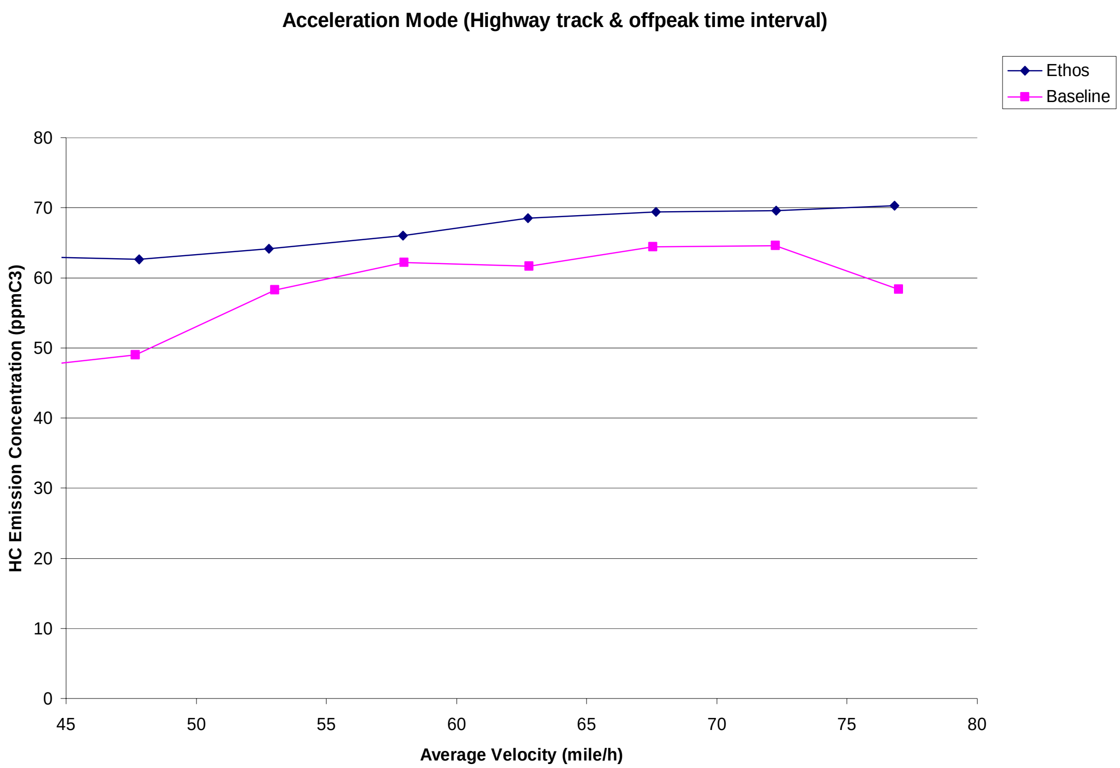


Figure 4.15 HC emission trends of highway test track and off-peak time interval for acceleration mode

Observations: An increase in HC emission concentrations is observed from Figure 4.15. Similar trends are observed in all other modes on highway test track and off-peak time interval.

Figure 4.16 shows NO_X emission concentrations for highway test track and off-peak time interval in acceleration mode.

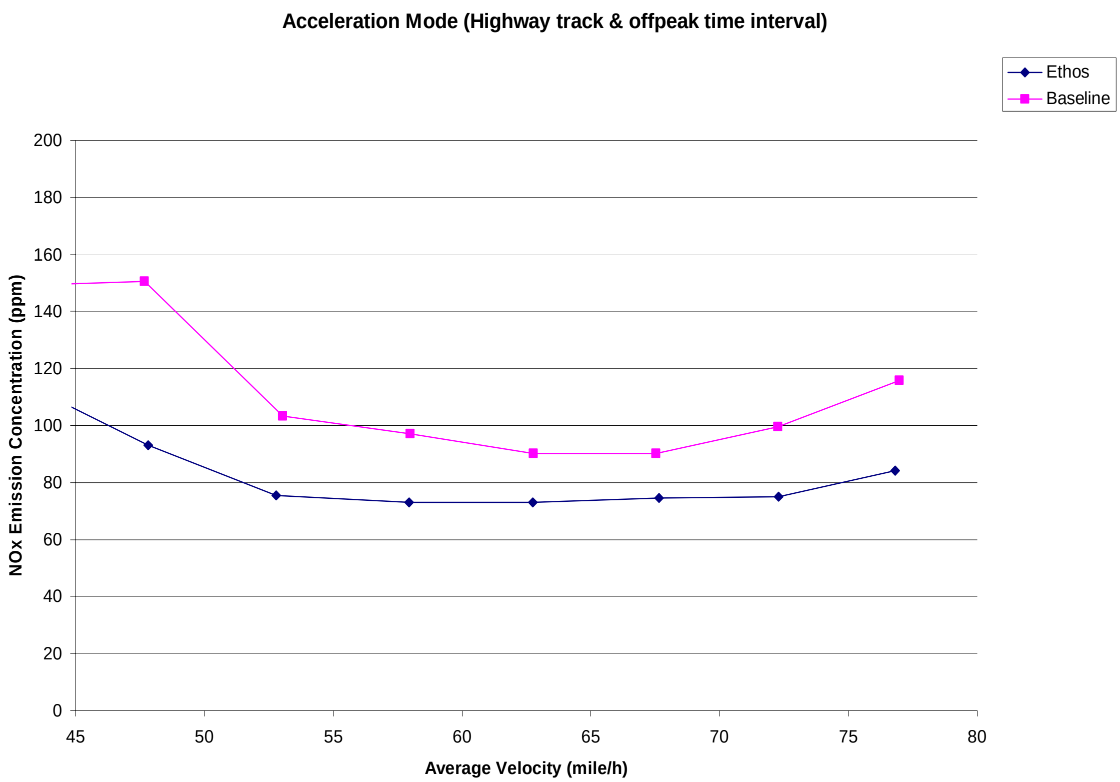


Figure 4.16 NO_X emission trends of highway test track and off-peak time interval for acceleration mode

Observations: A significant reduction in NO_X emission concentrations can be observed from Figure 4.16. Similar trends were observed in all the cases in highway test track and off-peak time interval, with a maximum reduction of 25.4% in this particular mode (acceleration mode).

Note: The above graphs are comparisons between baseline and Ethos® data sets. No clear conclusions can be drawn by observing how the lines are varying. Statistical analysis is very required to validate the results.

4.3.2 Percent reduction

Although graphical analysis gives an indication of emission concentration trends, percentage reduction quantifies it through numbers. For each mode, percentage reduction is carried out by comparing the overall concentration of the base-line and the Ethos® data. Tables 4.3, 4.4, 4.5 and 4.6 present average percent emission concentration reductions. These reductions are measured in ppm for NO_X and HC emissions, and percent volume for CO and CO_2 emissions. The percent emission reductions are presented for the 4 pollutants and all the four driving modes, categorized by highway vs. arterial and peak vs. off-peak. A negative value indicates an '***increase'*** in emissions.

Table 4.3 Overall percentage reduction for acceleration mode

OVERALL PERCENTAGE REDUCTION				
	Arterial test track		**Highway test track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	0.15	2.47	-6.49	-0.59
CO_2	2.03	2.38	-6.62	-1.03
HC	-14.91	-13.60	2.17	-10.27
NO_X	12.69	27.87	17.63	25.36

Table 4.4 Overall percentage reduction for cruising mode

OVERALL PERCENTAGE REDUCTION				
	Arterial test track		**Highway test track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	0.02	2.58	-3.98	-0.09
CO_2	1.83	2.57	-4.03	-0.45
HC	-12.28	-9.02	-0.17	-6.65
NO_X	20.26	36.65	14.84	16.14

Table 4.5 Overall percentage reduction for deceleration mode

OVERALL PERCENTAGE REDUCTION				
	Arterial test track		**Highway test track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	0.58	2.95	-6.46	-0.09
CO_2	2.23	2.80	-6.68	-0.52
HC	-10.04	-10.94	1.80	-7.29
NO_X	23.65	32.79	15.19	19.78

Table 4.6 Overall percentage reduction for idling mode

OVERALL PERCENTAGE REDUCTION				
	Arterial test track		**Highway test track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	-2.09	1.29	---	---
CO_2	0.93	1.18	---	---
HC	-21.05	-1.93	---	---
NO_X	45.58	45.14	---	---

Note: Here the "---" indicate that data was not available for that particular case.

Observations: The above results indicated a close match with the emission concentration trends in graphical analysis. The maximum reduction shown in percentage reduction was 45.6 % and 45.2 % in the idling mode. For the arterial test track which has lower speeds (50 mph), Ethos® reduced CO, CO_2 and NO_X emission concentrations for all modes, but increased HC. For the highway test track, which has higher speeds (>45 mph), Ethos® increased CO and CO_2 emission concentrations, and in most cases increased HC emissions; however, it decreased NO_X emission concentrations.

4.3.3 T-tests

4.3.3.1 General

T-tests were conducted to determine whether the percent reductions were statistically significant. T-tests were carried for all the four pollutants on the baseline and the Ethos® data sets to ascertain the significant difference.

T-tests were carried out for the following two specific cases:

I. Overall modal data sets

II. Velocity category data sets

4.3.3.2 T-test calculation procedure

"Two-sample t-test assuming equal variances" analysis tool under Data Analysis function of MS EXCEL was used to conduct t-test. A one tail t-test was used for analyzing the data sets with the subsequent inputs and outputs.

Inputs:

1. Variable 1 Range: Ethos® data
2. Variable 2 Range: Baseline data
3. Hypothesized Mean Difference: Zero (0)
4. Alpha: 0.05 (95% confidence level)

Outputs:

1. Mean
2. Variance
3. Observations
4. Pooled variance
5. Degrees of freedom (df)
6. t stat (or t calculated)
7. P (T<=t) one-tail
8. t Critical one-tail
9. P (T<=t) two-tail
10. t Critical two-tail

The hypothesized mean difference is **zero,** meaning that the null hypothesis for this t-test calculation is "**NO Significant difference between Baseline and Ethos® data"** and the alternate hypothesis is **"there is a significant difference between the two data sets".**

$| t_{stat} | < t_{critical}$ shows that there is no significant difference between the data sets.

$| t_{stat} | > t_{critical}$ shows that there is significant difference between the data sets.

The following is the hypothesis testing criteria used for this research:

$\mathbf{H_0: \mu_1 \geq \mu_2}$

$\mathbf{H_1: \mu_1 < \mu_2}$

μ_1 = Ethos® data mean,

μ_2 = Baseline data mean,

H_0 = null hypothesis

H_1 = alternate hypothesis

4.3.3.3 Overall results

Results of the t-tests have been summarized in tables. Tables 4.7, 4.8, 4.9 and 4.10 represent the overall modal t-test results for one of the pollutants from each of test track and time interval and for all the modes. The rest of the tables are provided in Appendix B for review.

Table 4.7 Overall t-tests for CO emission concentrations for highway test track and peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	-6.49
Cruising Mode	YES	-3.98
Deceleration Mode	YES	-6.46

Table 4.8 Overall t-tests for CO_2 emission concentrations for highway test track and off-peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	-1.03
Cruising Mode	YES	-0.45
Deceleration Mode	NO	-0.52

Table 4.9 Overall t-tests for HC emission concentrations for arterial test track and peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	-14.91
Cruising Mode	YES	-12.28
Deceleration Mode	YES	-10.04
Idling Mode	YES	-21.05

Table 4.10 Overall t-tests for NO_X emission concentrations for arterial test track and off-peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	27.87
Cruising Mode	YES	36.65
Deceleration Mode	YES	32.79
Idling Mode	YES	45.14

The following four tables are examples of t-test results for velocity category data sets. The tables shows whether the emissions with and without Ethos® are statistically different for 5 mile/hour velocity clusters for each mode. The rest of the tables are provided in Appendix C for review.

Table 4.11 Velocity category t-tests for CO emissions in all the modes for highway test track and peak data set

Acceleration Mode		Cruising Mode		Deceleration Mode	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	YES	45-49.99	YES
50-54.99	YES	50-54.99	YES	50-54.99	YES
55-59.99	YES	55-59.99	YES	55-59.99	YES
60-64.99	YES	60-64.99	YES	60-64.99	YES
65-69.99	YES	65-69.99	YES	65-69.99	YES
70-74.99	YES	70-74.99	YES	70-74.99	YES
75-79.99	YES	75-79.99	YES	75-79.99	YES
80-84.99	YES	80-84.99	YES	80-84.99	YES
85-89.99	YES	85-89.99	YES	85-89.99	YES

Table 4.12 Velocity category t-tests for CO_2 emissions in all the modes for highway test track and off-peak data set

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
35-39.99	NO	35-39.99	NO	35-39.99	NO
40-44.99	NO	40-44.99	YES	40-44.99	NO
45-49.99	NO	45-49.99	NO	45-49.99	YES
50-54.99	YES	50-54.99	NO	50-54.99	NO
55-59.99	YES	55-59.99	NO	55-59.99	YES
60-64.99	YES	60-64.99	NO	60-64.99	NO
65-69.99	YES	65-69.99	YES	65-69.99	YES
70-74.99	YES	70-74.99	NO	70-74.99	YES
75-79.99	YES	75-79.99	YES	75-79.99	YES
80-84.99	YES	80-84.99	YES	80-84.99	YES
85-89.99	YES	85-89.99	YES	85-89.99	YES

Table 4.13 Velocity category t-tests for HC emissions in all the modes for arterial test track and peak data set

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
0-4.99	YES	0-4.99	YES	0-4.99	YES
5-9.99	YES	5-9.99	YES	5-9.99	YES
10-14.99	YES	10-14.99	NO	10-14.99	YES
15-19.99	YES	15-19.99	YES	15-19.99	YES
20-24.99	YES	20-24.99	YES	20-24.99	YES
25-29.99	YES	25-29.99	YES	25-29.99	YES
30-34.99	YES	30-34.99	YES	30-34.99	YES
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	NO	45-49.99	NO
50-54.99	NO	50-54.99	NO	50-54.99	YES

Table 4.14 Velocity category t-tests for NO_X emissions in all the modes for arterial test track and off-peak data set

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
0-4.99	YES	0-4.99	YES	0-4.99	YES
5-9.99	YES	5-9.99	YES	5-9.99	YES
10-14.99	YES	10-14.99	YES	10-14.99	YES
15-19.99	YES	15-19.99	YES	15-19.99	YES
20-24.99	YES	20-24.99	YES	20-24.99	YES
25-29.99	YES	25-29.99	YES	25-29.99	YES
30-34.99	YES	30-34.99	YES	30-34.99	YES
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	YES	45-49.99	YES
50-54.99	YES	50-54.99	YES	50-54.99	NO

Observations: The results obtained graphically and through percentage reductions are validated by the t-test results.

4.3.4 Fuel economy

An estimate of the fuel economy of the van was obtained with and without the application of Ethos® FR as fuel additive. For this purpose, data was collected for 2 hours on the highway test track and 1 hour on the arterial test track. These tracks were traversed as set by NCTCOG. On highway track test track, it took two trips to complete two hours of driving, and on the arterial test track it took five trips to complete one hour of driving. Fuel consumed was noted down for every round on both the test tracks. Data collected was summarized in the following tables.

Table 4.15 Mileage of the van at different points on the freeway test track with the application of Ethos® FR

Location	Mileage (miles)	Time
Starting point at garage	35040	12:56 AM
Initial point of highway (I-30 W)	35042	01:06PM
End of trip one (back to initial point of highway)	35092	2:00PM
End of trip 2	35092	2:10 PM
Final point -gas station	35142	2:56 PM

Fuel economy is calculated as follows:

Fuel consumed for this entire trip was **6.6 gallons**

Fuel economy = (35142mil - 35040mil)/ 6.6 gallons = **15.45 mil/gallon**
Total time of travel is 2hrs

Fuel economy for time taken to travel = 6.6 gallons/2 hr = **3.3 gallons/hr**

Fuel economy per hour of travel time is 3.3 gallons/hr

Table 4.16 Mileage of the van at different points on the arterial test track with the application of Ethos® FR

Location	Mileage (miles)	Time
Gas station	34970	12:31 PM
Starting point at UTA Blvd.	34971	12:48PM
End of 1st trip, back to UTA Blvd (beginning of 2nd trip)	34977	1:04 PM
End point for 2nd trip (beginning of 3rd trip)	34983	1:18 PM
End of 3rd trip (beginning of 4th trip)	34989	1:33 PM
End of 4th trip (beginning of fifth trip)	34995	1:46 PM
End of fifth trip	35002	2:03 PM
Garage (final point of arrival)	35003	---

Fuel economy is calculated as follows:

Fuel consumed for the entire journey here was **2.8 gallons**

Fuel economy = (35003 mil – 34970 mil)/2.8 gallons = **11.8 mile/gallon**

Total time of travel is 1hr 32min

Fuel economy for time taken to travel = 2.8 gallons/1.53 hr = **1.83 gallons/hr**

Fuel economy per hour of travel time is 1.83 gallons/hr

Table 4.17 Mileage of the van at different points on the freeway test track without the application of Ethos® FR- Baseline data

Location	Mileage (miles)	Time
Starting point at Garage	34808	10:00 AM
Initial point of highway	34811	---
End of trip one (back to initial point of highway)	34861	10:52 AM
End of trip 2	34911	11:49 AM
Final point -gas station	34915	12:03 AM

Fuel economy is calculated as follows:

Fuel consumed from starting point to Final point was **6.05 gallons**

Fuel economy = (34915 mil – 34808 mil)/6.05 gallons = **17.7 mile/gallon**

Total time of travel is 2hr 3min

Fuel economy for time of travel = 6.05 gallons/2.05 hr = **2.95 gallons/hr**

Fuel economy per hr of travel is 2.95 gallons

Table 4.18 Mileage of the van at different points on the arterial test track without the application of Ethos® FR - Baseline data

Location	Mileage (miles)	Time
Gas station	34934	3:41 PM
Starting point at UTA Blvd.	34936	3:44 PM
End of 1st trip, back to UTA Blvd (beginning of 2nd trip)	34942	4:03 PM
End point for 2nd trip (beginning of 3rd trip)	34948	4:18 PM
End of 3rd trip (beginning of 4th trip)	34954	4:32 PM
End of 4th trip (beginning of fifth trip)	34961	4:47 PM
End of fifth trip	34967	5:02 PM
Garage (final point of arrival)	34968	---

Fuel economy is calculated as follows:

Fuel consumed from starting point till final point (garage) was **2.2 gallons**.

Fuel economy = (34968 mil – 34934 mil)/2.2 gallons = **15.5 mile/gallon**

Total time of travel is 1hr 25min

Fuel economy for time of travel = 2.2 gallons/1.42 hr = **1.55 gallons/hr**

Fuel economy per hr of travel = 1.55 gallons

Conclusion: On highway there is **12.7%** reduction and on the arterial test track there is **23.9%** reduction in fuel economy with usage of Ethos® as fuel additive.

Note: No statistical conclusions can be drawn on the limited amount of data collected.

4.3.5 Dynamometer testing results

As part of the on-going NCTCOG Aftermarket Technology and Fuel Additive Research Program, the Air Quality Research group also conducted a dynamometer test to investigate the effectiveness of the Ethos® FR in reducing emissions and to confirm the results achieved with the on-board emission measurement system (OBS1300). With the dynamometer test, the study vehicle (Chevy 2000 Astro van) was placed on a dynamometer and subjected to a simulated urban driving trip intended to represent a typical driving pattern in urban areas. The dynamometer test was conducted by the Department of Public Safety in Irving.

The dynamometer test was first conducted without the application of Ethos®. The procedure was then repeated with the application of the fuel additive. Comparison was then made with results from the field data (arterial data) collected using OBS1300 unit in the cruising mode and at 15mph and 25mph speed levels and the dynamometer results obtained from Figure 4.17 and Figure 4.18.

From Dynamometer results, at 15 mph, a decrease in the emissions of CO, CO_2, HC and NO_X concentrations is observed. At 25 mph, the following changes were observed:

- there is no change in CO emission concentrations,

- a slight increase in CO_2 emission concentrations,
- a significant increase in HC emission concentrations and
- significant increase in NO_X emission concentrations was observed

However, for both dynamometer testing and OBS testing showed a decrease in emissions of NOx concentration for both speed levels with application of Ethos® FR. The percentage change in pollutant emissions is represented in Table 4.17 below. These differences will be further examined in phase II testing.

The conclusions presented in this addendum are anecdotal in nature because the researchers lack the necessary sample sizes to draw any statistical conclusions.

Table 4.19 Comparison of percentage reduction of dynamometer and OBS

PERCENTAGE REDUCTION						
	Dynamometer		**OBS-1300 (Peak)**		**OBS-1300 (Off-peak)**	
	15 mph	**25 mph**	**15 mph**	**25 mph**	**15 mph**	**25 mph**
CO	50	0.00	0.79	-1.59	3.17	3.17
CO_2	2.00	-1.33	2.41	1.9	1.71	2.11
HC	26.66	-100	-6.41	-11.07	-30.21	-30.24
NO_x	91.3	94.2	17.98	18.64	25.42	25.84

Note: A negative change indicates emission increase.

Vehicle Identification		Station Identification	
Test Date/Time:	09/19/2006, 02:14 PM	Station Name:	TEXAS DEPARTMENT OF PUBLI
Test Type:	INITIAL	Station Number:	1G25792
Test:	ASM Test	Station Address:	1613 W IRVING BLVD
Version Number:	0509	Station City:	IRVING
License Number:	111	Station Zip Code:	750610000
Vehicle ID Number:	11111111111111111	Inspector First Name:	
Vehicle Make:	CHEV	Inspector Last Name:	
Vehicle Model:	ASTRO	Analyzer Number:	WW510015
Vehicle Year:	1995		
Vehicle Type:	TRUCK	Safety Inspection Fee:	$ 0.00
Engine Size:	4300	Safety Repair Costs:	$ 0.00
Cylinders/Ignition:	6/D	Emission Test Fee:	$ 0.00
Transmission/GVW:	AUTOMATIC / 5950	Emission Repair Costs:	$ 0.00
Odometer/Fuel Type:	GASOLINE / 34607	Total Inspection Cost:	$ 0.00

Pollutant	High Speed Emission Results (25mph) RPM: 0			Low Speed Emission Results (15 mph) RPM: 0		
	Standard	Current Reading	Result	Standard	Current Reading	Result
HC(ppm):	151	4	PASS	155	15	PASS
CO(%):	1.68	0.00	PASS	1.31	0.04	PASS
CO2(%):		15.0			15.0	
O2(%):		0.0			0.0	
Nox(ppm):	956	103	PASS	1046	115	PASS
DILUTION:	>6.0	15	PASS	>6.0	15.04	PASS

Gas Cap Missing: No. Gas Cap Testable: Yes. Gas Cap Integrity Result: PASS.

OVERALL RESULT: PASS

CONGRATULATIONS, your vehicle has passed the emissions (I/M) test portion of your annual safety inspection! By maintanining your vehicle in good working condition, you are doing your share for clean air. You are also saving money on gas and extending the life of your vehicle bacause your emissions control equipment is working as it should.

I certify that I have properly performed the emissions test according to state regulations and procedures manuals.

Certified Inspector's Signature

VIN: 11111111111111111

Plate Type: 1, Plate Number: 111 , TxDot:

Figure 4.17 Texas vehicle inspection report for baseline

Vehicle Identification			Station Identification
Test Date/Time:	10/19/2006,11:01	Station Name:	TEXAS DEPARTMENT OF PUBLI
Test Type:	Initial	Station Number:	1G25792
Test:	ASM	Station Address:	1613 W IRVING BLVD
Version Number:		Station City:	IRVING
License Number:	111111	Station Zip Code:	750610000
Vehicle ID Number:	1GNDM19W0YB152497	Inspector First Name:	CHARLES
Vehicle Make:	CHEV	Inspector Last Name:	SAMUELS
Vehicle Model:	ASTRO	Analyzer Number:	ES213839
Vehicle Year:	1995		
Vehicle Type:	Truck/Van	Safety Inspection Fee:	----.--
Engine Size:	4300	Safety Repair Costs	--.--
Cylinders/Ignition:	6 D	Emissions Test Fee:	--.--
Transmission/GVW:	Automatic/5950	Emissions Repair Costs:	--.--
Odometer/Fuel Type:	35021/Gasoline		-----------
		Total Inspection Cost:	--.--

Emissions Test Results

Pollutant	High Speed Emission Results (25 mph) RPM: 0			Low Speed Emission Results (15 mph) RPM: 0		
	Standard	Current Reading	Result	Standard	Current Reading	Result
HC(PPM)	143	8	PASS	147	11	PASS
CO (%)	1.60	0.00	PASS	1.24	0.02	PASS
CO2 (%)		15.2			15.3	
O2 (%)		6.2			6.3	
NOx(ppm)	905	6	PASS	990	10	PASS
DILUTION(%)	>6	15.2		>6	15.3	

Gas Cap Integrity: PASS

Overall Result: PASS

CONGRATULATIONS, your vehicle has passed the emissions (I/M) test portion of your safety inspection! By maintaining your vehicle in good working condition, you are doing your share for clean air. You are also saving money on gas and extending the life of your vehicle because your emissions control equipment is working as it should.

I certify that I have properly performed the emissions test according to state regulations and procedure manuals.

Certified Inspector's Signature

111111

1GNDM19W0YB152497

Figure 4.18 Texas vehicle inspection report for Ethos®

4.3.6 Post removal data analysis

A post removal testing was carried out for 10 hours after the Ethos® FR was completely drained from the fuel tank for on both arterial and highway test tracks. The post removal data was collected to ensure that emissions corresponded to that of the baseline data. The following section gives the results of comparison of Post removal data with baseline data through graphical analysis and percent reduction. T-tests were not carried out on post removal data due to insufficient data set.

The post removal data was classified like the Baseline and the Ethos® data and graphs of corresponding average velocity and average emissions were plotted for each mode. A total of 48 individual graphs were potted for the post removal data and later combined with the baseline graphs to observe any change.

Since it is not possible to incorporate 48 graphs in this section, only 8 graphs are included. The rest of the graphs are available in Appendix C for review. The 8 graphs include both test tracks, peak and off-peak time interval for acceleration and deceleration driving modes for all four pollutants.

<u>Case I Graphical comparison of post removal data with Baseline data for arterial test track and peak time interval for Acceleration mode.</u>

Figure 4.9 shows CO emission concentrations of post removal data for arterial test track and peak time interval for acceleration mode.

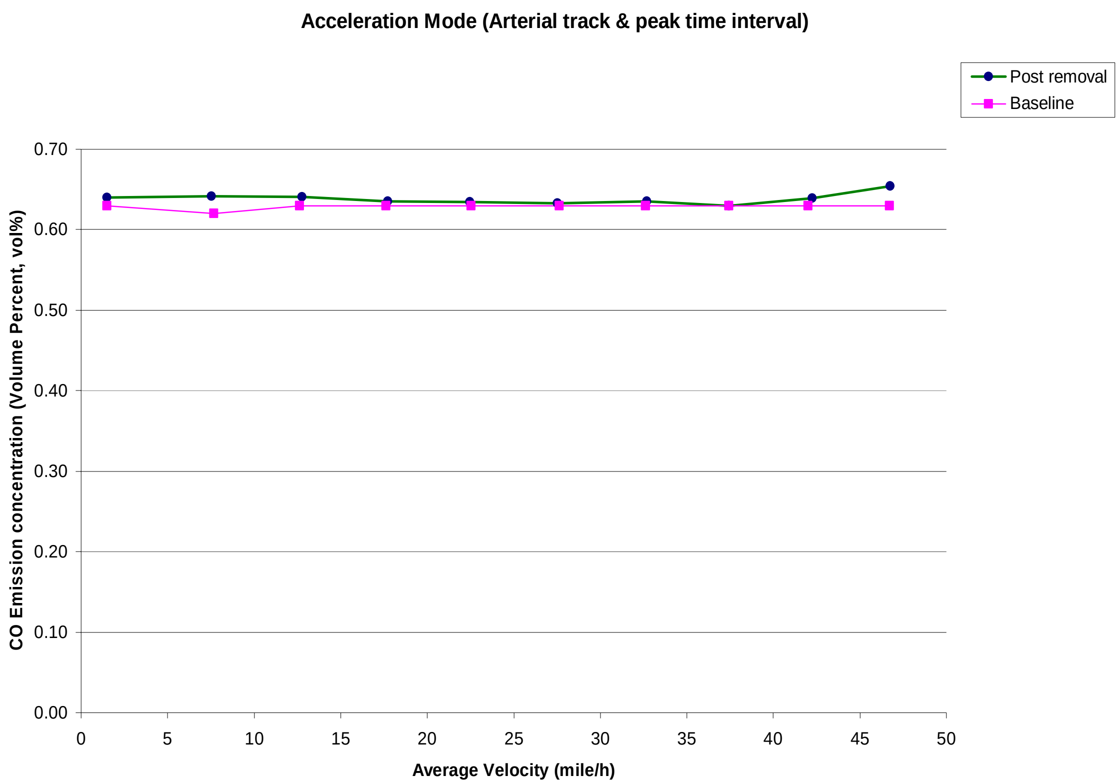


Figure 4.19 CO emission of arterial test track, peak time interval for acceleration mode

Figure 4.10 shows CO_2 emission concentrations of post removal data for arterial test track and peak time interval for acceleration mode.

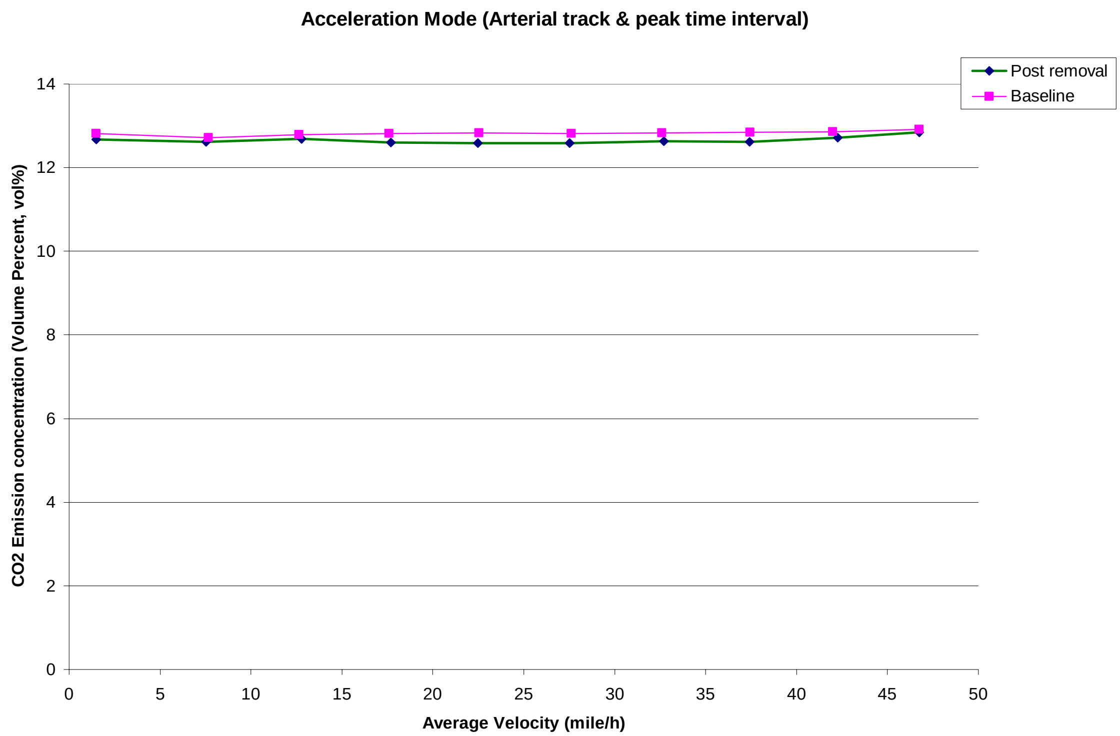


Figure 4.20 CO_2 emission of arterial test track, peak time interval for acceleration mode

Figure 4.11 shows HC emission concentrations of post removal data for arterial test track and peak time interval for acceleration mode.

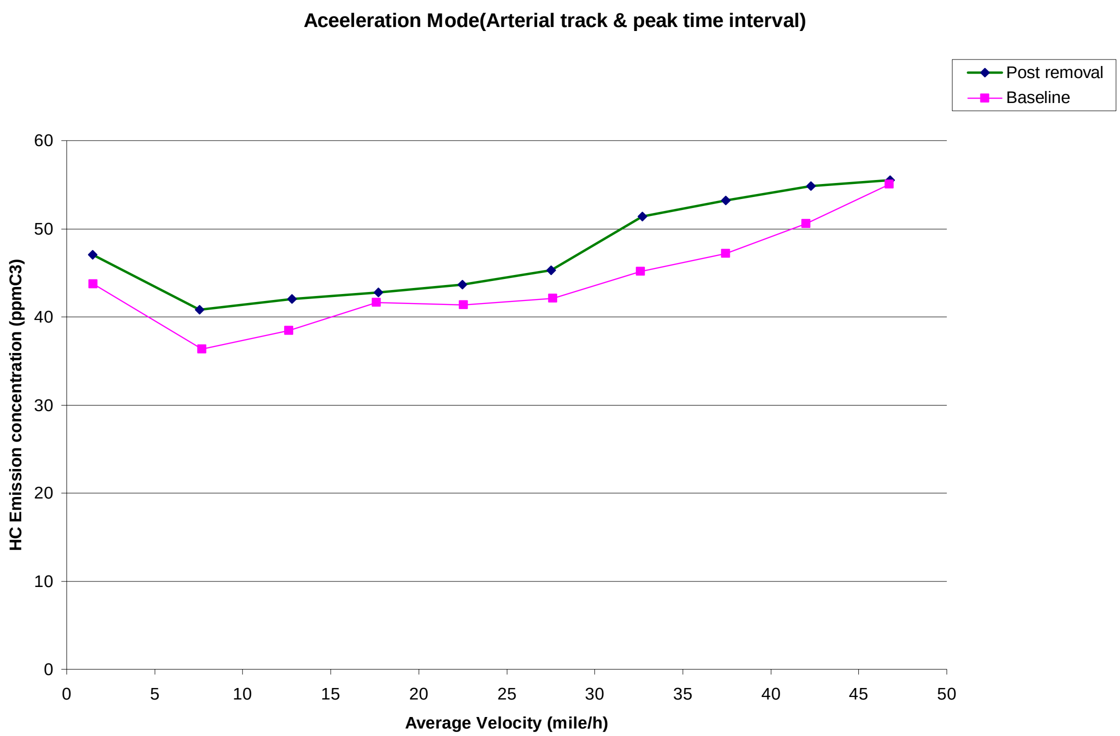


Figure 4.21 HC emission of arterial test track, peak time interval for acceleration mode

Figure 4.12 shows NO_X emission concentrations of post removal data for arterial test track and peak time interval for acceleration mode.

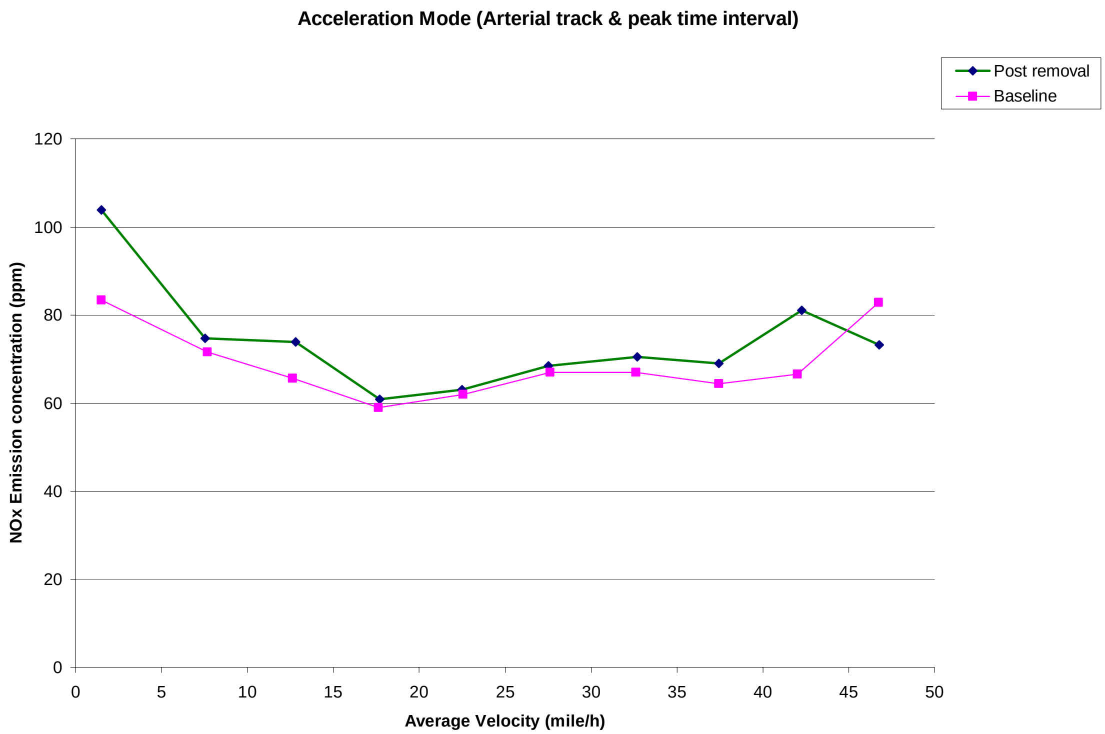


Figure 4.22 NO_X emission of arterial test track, peak time interval for acceleration mode

Case II Graphical comparison of post removal data with Baseline data for highway test track and off-peak time interval for Deceleration mode.

Figure 4.23 shows CO emission concentrations of post removal data for highway test track and off-peak time interval for deceleration mode.

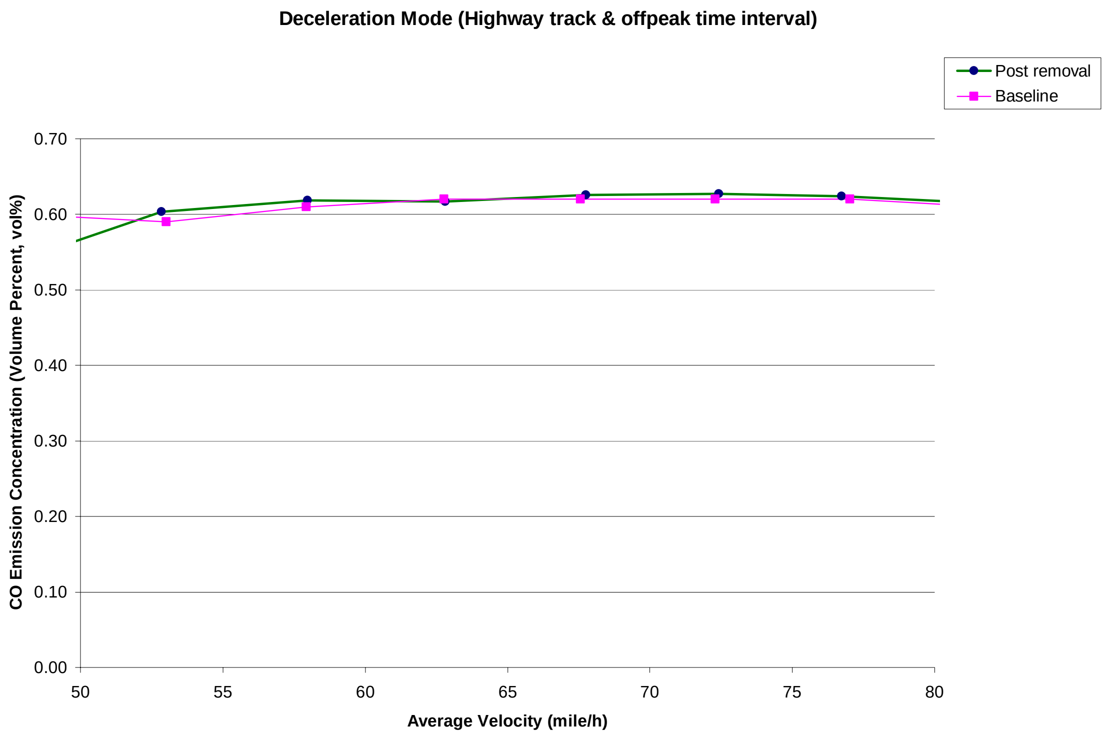


Figure 4.23 CO emission of highway test track, off- peak time interval for deceleration mode

Figure 4.24 shows CO_2 emission concentrations of post removal data for highway test track and off-peak time interval for deceleration mode.

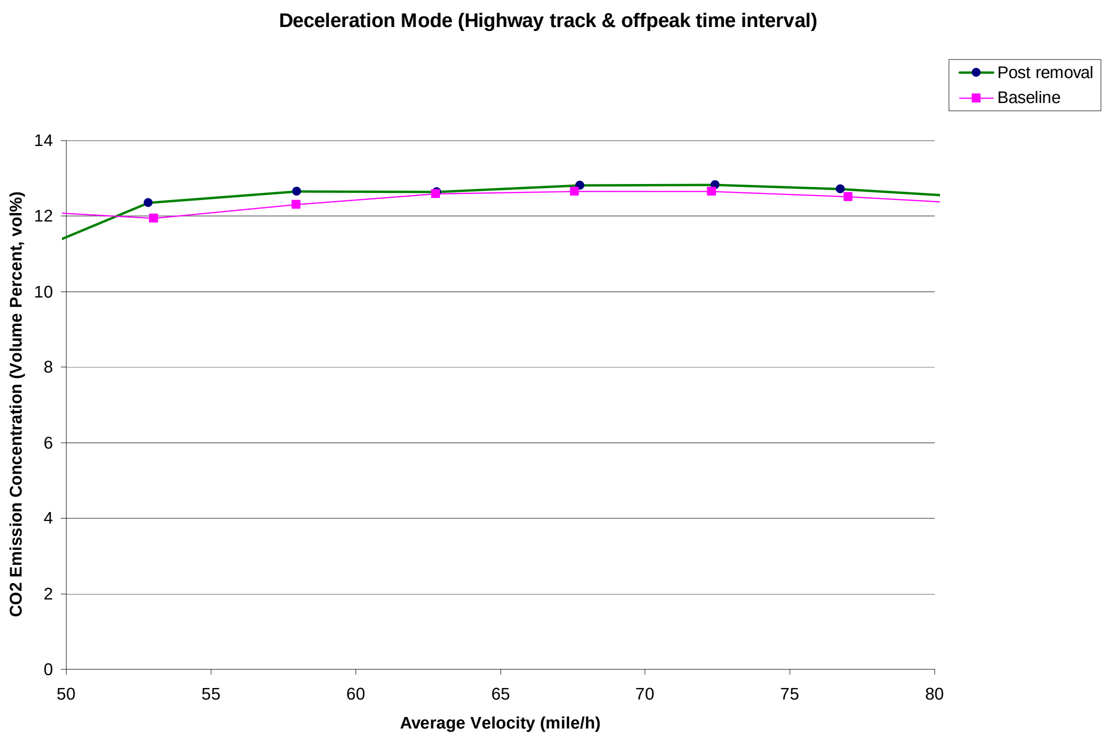


Figure 4.24 CO_2 emission of highway test track, off- peak time interval for deceleration mode

Figure 4.25 shows HC emission concentrations of post removal data for highway test track and off-peak time interval for deceleration mode.

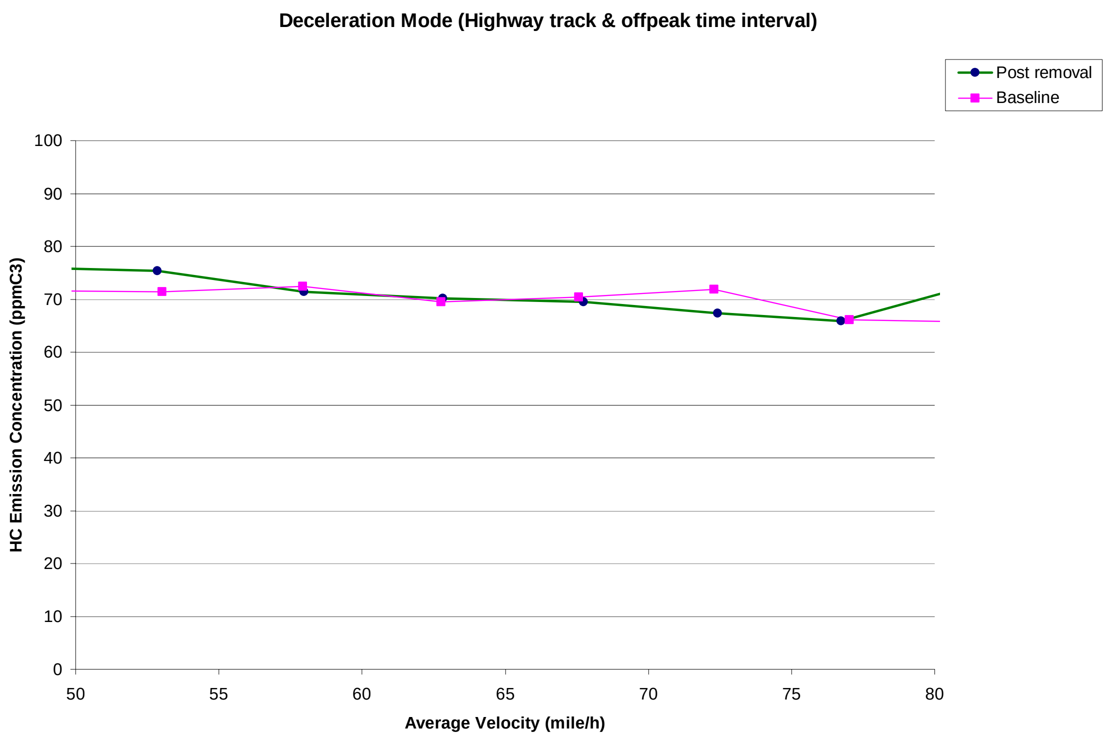


Figure 4.25 HC emission of highway test track, off-peak time interval for deceleration mode

Figure 4.26 shows NO_X emission concentrations of post removal data for highway test track and off-peak time interval for deceleration mode.

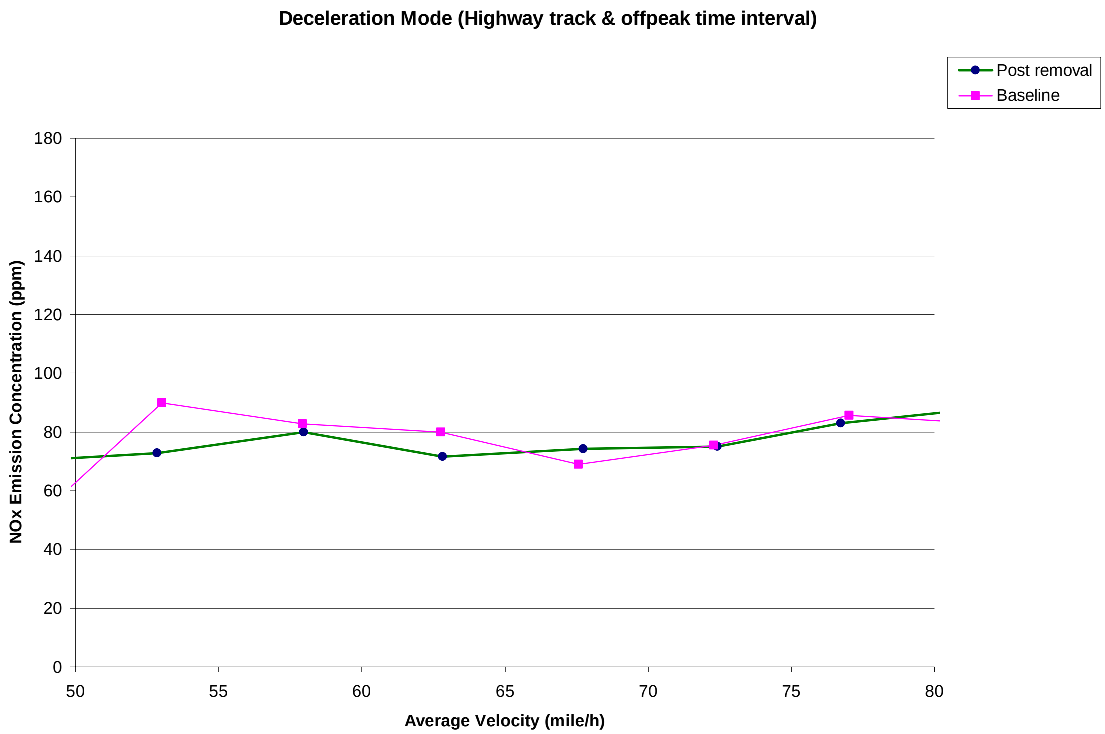


Figure 4.26 NO_X emission of highway test track, off-peak time interval for deceleration mode

For each mode, percentage reduction was carried out by comparing the overall concentration of post removal data and the Baseline data. Tables 4.20, 4.21, 4.22 and 4.23 present average percent emission concentrations reductions. These reductions are measured in ppm for NO_X and HC emissions, and percent volume for CO and CO_2 emissions. The percent emission reductions are presented for the four pollutants and all the four driving modes, categorized by highway vs. arterial and peak vs. off-peak. A negative value indicates an ‘***increase’*** in emissions.

Table 4.20 Overall percentage reduction of post removal data set for acceleration mode

OVERALL PERCENTAGE REDUCTION				
	Arterial test track		Highway test track	
	Peak	Off-peak	Peak	Off-peak
CO	-1.13	1.11	-5.14	-0.33
CO_2	1.41	1.40	-5.90	-1.18
HC	-9.45	-17.62	4.96	-0.75
NO_X	-8.24	8.53	-4.30	5.55

Table 4.21 Overall percentage reduction of post removal data set for cruising mode

OVERALL PERCENTAGE REDUCTION				
	Arterial test track		Highway test track	
	Peak	Off-peak	Peak	Off-peak
CO	-1.73	0.84	-3.09	0.08
CO_2	1.13	1.44	-3.84	0.62
HC	-7.85	-13.90	3.81	0.94
NO_X	-17.24	-16.6	-8.28	-2.01

Table 4.22 Overall percentage reduction of post removal data set for deceleration mode

OVERALL PERCENTAGE REDUCTION				
	Arterial test track		**Highway test track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	-1.03	1.25	-5.57	-0.58
CO_2	1.45	1.55	-6.4	-1.30
HC	-13.74	-12.55	4.47	1.62
NO_X	-3.07	-4.94	-4.86	2.48

Table 4.23 Overall percentage reduction of post removal data set for idling mode

OVERALL PERCENTAGE REDUCTION				
	Arterial test track		**Highway test track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	-1.81	1.46	---	---
CO_2	1.16	1.74	---	---
HC	-9.88	-11.43	---	---
NO_X	-14.25	-7.39	---	---

Observations: In some cases there is no significant change between the post removal and the baseline data; however, for other cases, a significant difference can be observed potentially due to the following reasons.

1. There could be remains of Ethos® in the fuel tank.
2. Post removal data was collected for 10 hours, which could be inadequate to compare with the baseline data.
3. Humidity, temperature and the time of the data collection differed for post removal and baseline cases and could have affected emissions.
4. Calibration may not be accurate for all the cases.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main research objective was to determine the effect of Ethos® FR on CO, CO, CO_2, HC and NO_X emission concentrations from gasoline vehicles. The following conclusions can be drawn from this research:

1. Graphical analysis gives a general idea about the emission concentrations trends: whether they have decreased or increased due to the effect of Ethos® FR used as fuel additive.

2. The Overall percentage reductions were calculated for each mode, traffic conditions and time interval. Table 5.1 and 5.2 present the range of percentage reductions observed in highway test track and arterial test track.

Table 5.1 Summary of overall percentage reduction in arterial test track

Pollutant	Arterial test track	
	Percentage reduction ranges, %	**Significant**
CO	-2.09 % to 2.95 %	YES
CO_2	0.93 % to 2.80 %	YES
HC	-21.05 % to -1.93 %	YES
NO_X	12.69 % to 45.58 %	YES

Table 5.2 Summary of overall percentage reduction in highway test track

Pollutant	Highway test track	
	Percentage reduction ranges, %	**Significant**
CO	-6.49 % to -0.09 %	YES
CO_2	-6.68 % to -0.52 %	YES
HC	-10.27 % to 2.17%	YES
NO_X	14.84 % to 25.36 %	YES

3. A significant decrease in emissions of NO_X concentration is seen in all the results, with maximum of 45.48 % in idling mode by the application of Ethos® FR.

4. It can be concluded that in CO emissions and CO_2 emission concentrations slightly decreased.

5. However HC emissions increased significantly by using the fuel additive.

6. The t-test results validated that the difference between baseline and Ethos® data is statistically significant, although it is not clearly seen in graphical analysis.

7. The velocity category t-tests results provided a better picture of emission concentration changes statistically.

8. The fuel economy of the van is estimated. There is a 12.7% reduction on the highway test track and 23.9 % reduction on the arterial test track with the application of Ethos® FR as fuel additive. However no statistical conclusions can be drawn on the limited amount of data.

9. From dynamometer results, at 15 mph, a decrease in the emission concentrations of CO, CO_2, HC and NO_X concentrations is observed. At 25 mph, the following conclusions can be drawn:

    a. There is no change in CO emissions,

    b. A slight increase in CO_2 emissions,

c. A significant increase in HC emissions and

d. Significant increase in NO_X emissions was observed.

5.2 Recommendations

- Ethos® FR appears to have a considerable impact on the emissions of NO_x concentrations in most of the cases. The fuel additive is recommended for Phase- II testing for further assessment.
- Data analysis based on emission concentrations in terms of gram per mile (g/mile) and gram per second (g/sec) with accurate flow rate is required for any definitive conclusions.
- Data collection on different routes other than the pathway mentioned in Chapter 3 is recommended, for comparison of emissions under different traffic conditions.
- Adequate data should be collected to get accurate results for the fuel economy since statistically significant conclusions cannot be drawn with insufficient data.
- Ethos® FR can be administered with different dosages to the fuel tank for evaluating emission comparison.
- A regulatory framework is suggested to address the special problems like other gasses escaping from the exhaust of the tailpipe.

- More post-removal data collection is required for comparing with the baseline data.

- Data analysis of cold starts is recommended since emissions are higher during cold start.

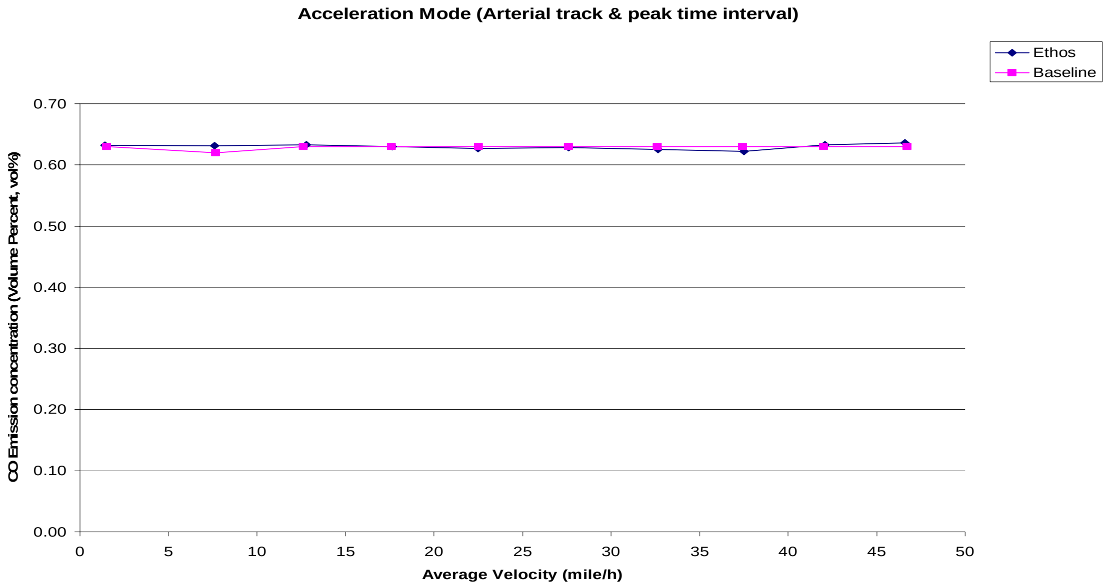
- Efforts should be made to ensure calibration is done accurately at all the times for quality of results.

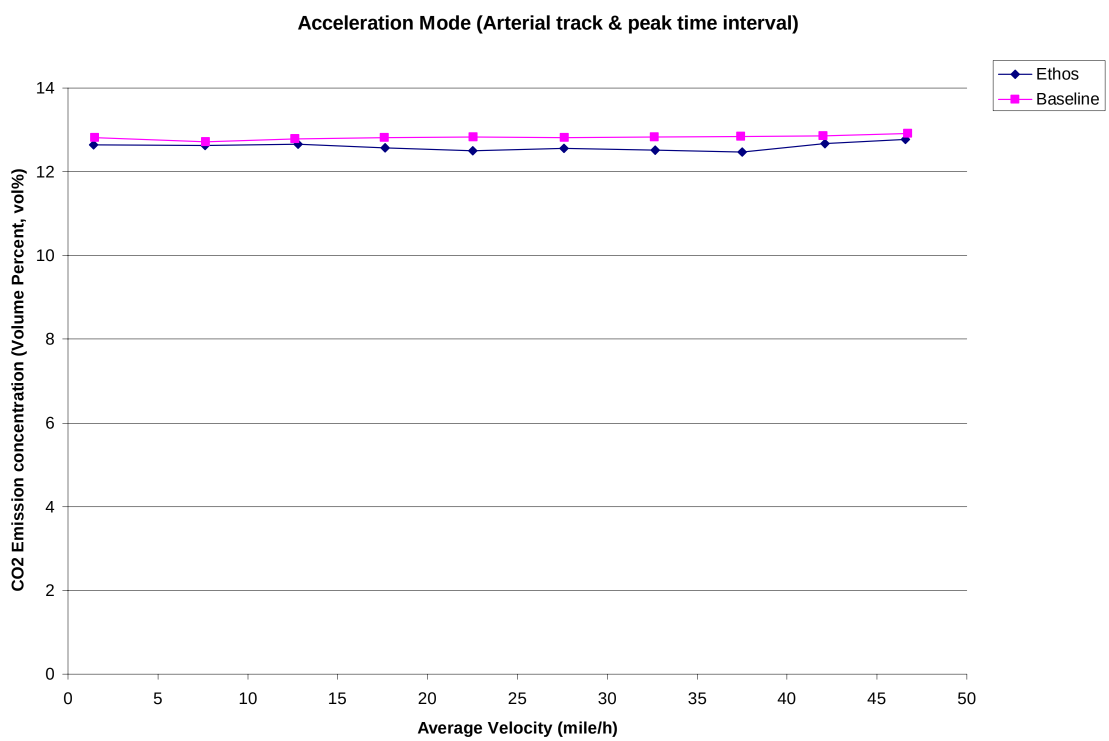
- An analysis should be conducted to observe tons of CO, CO_2, HC and NO_X emissions added or reduced per month and fuel saved per month with the application of Ethos® in DFW metroplex.

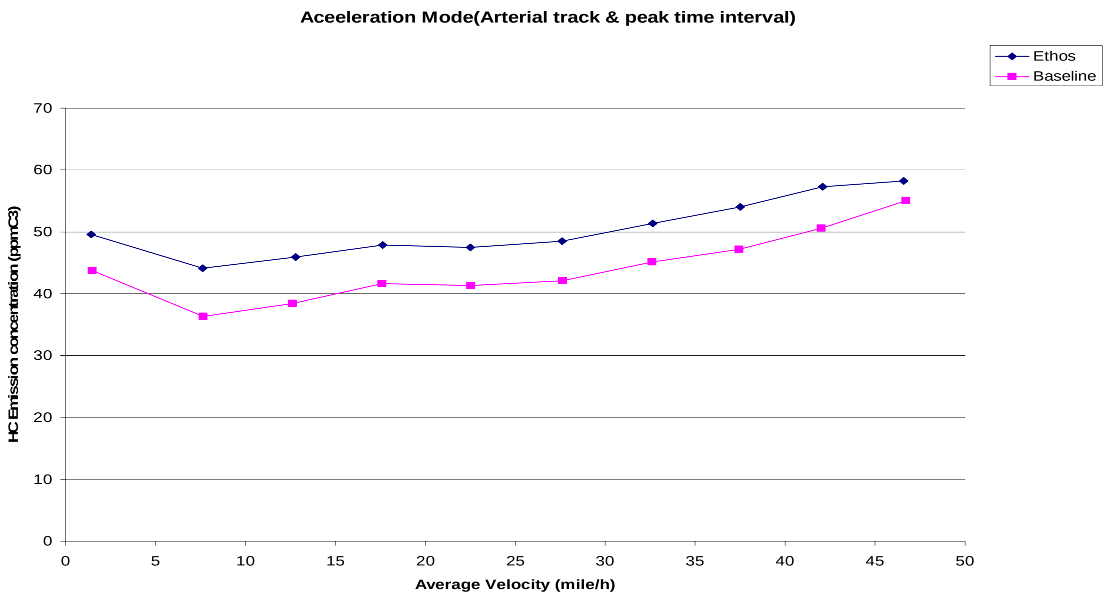
APPENDIX A

EMISSION TRENDS: GRAPHICAL COMPARISON OF BASELINE AND ETHOS® DATA

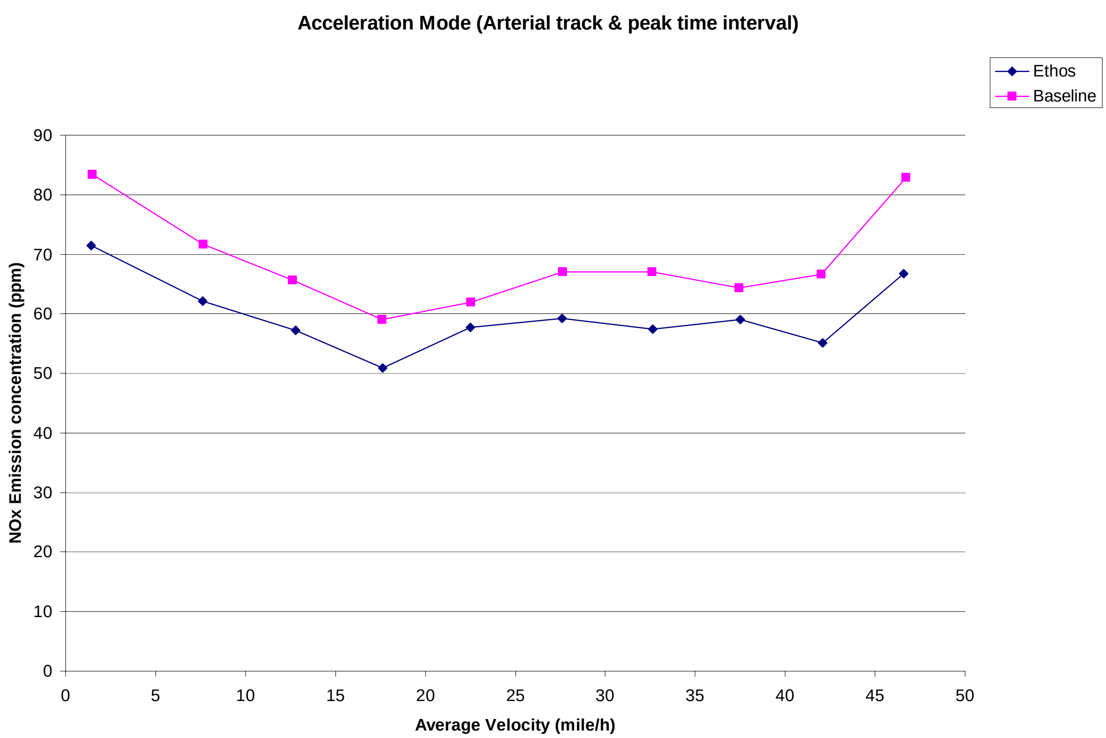
Case A: Emission trends of arterial test track and peak time interval for Acceleration mode





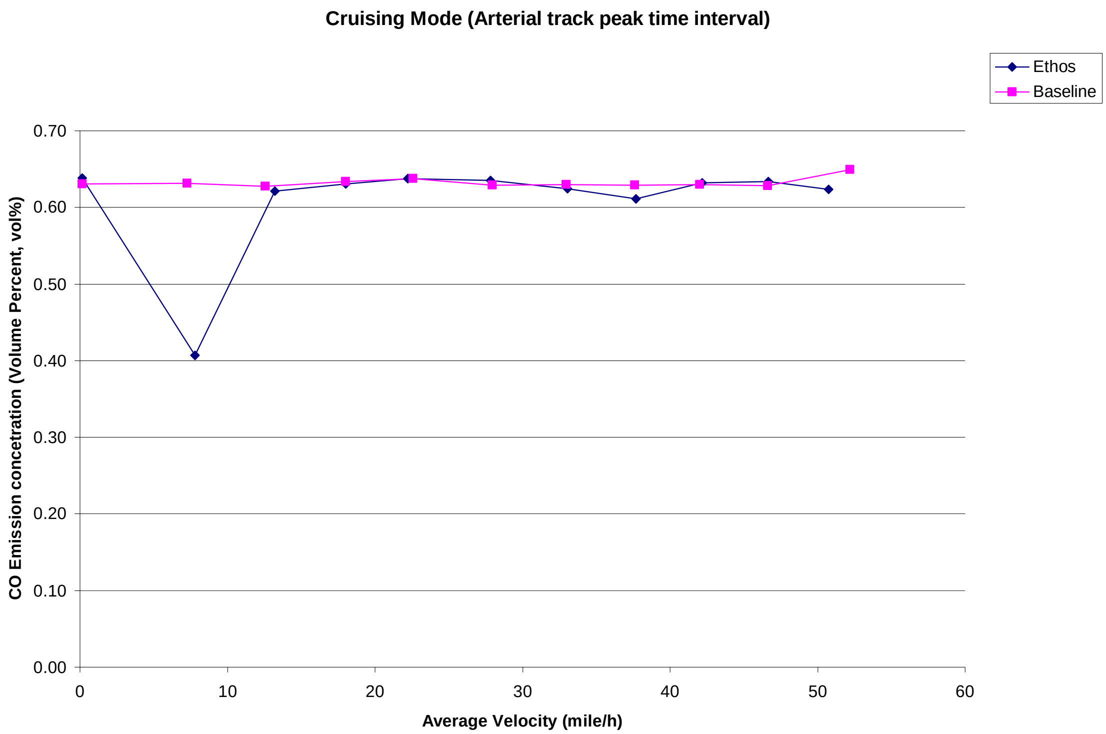


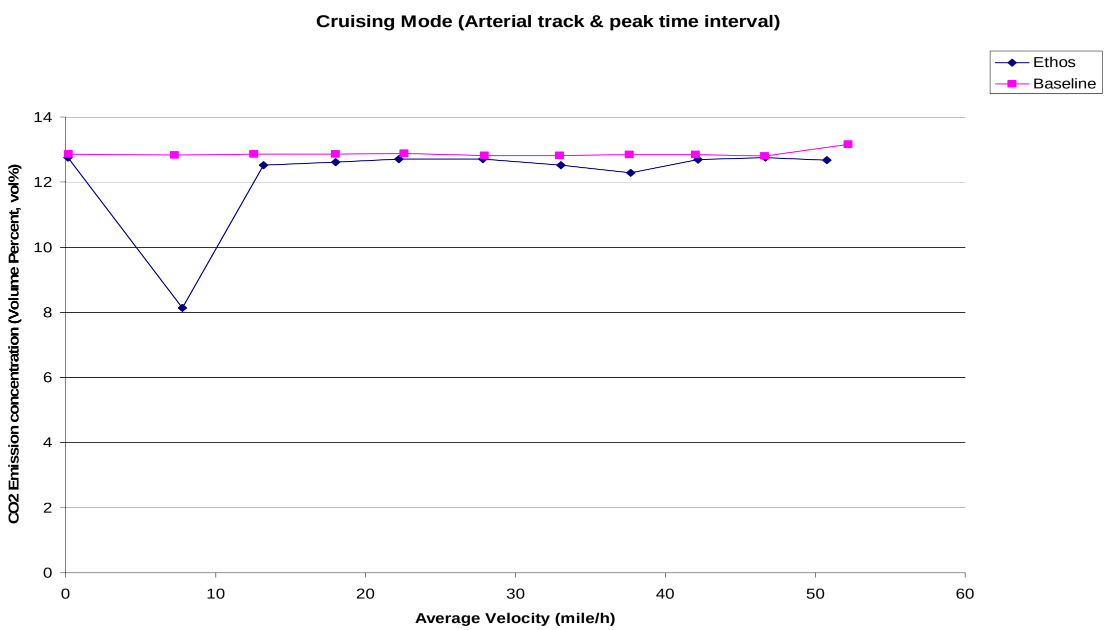
Aceeleration Mode(Arterial track & peak time interval)
Ethos
Baseline
HC Emission concentration (ppmC3)
Average Velocity (mile/h)



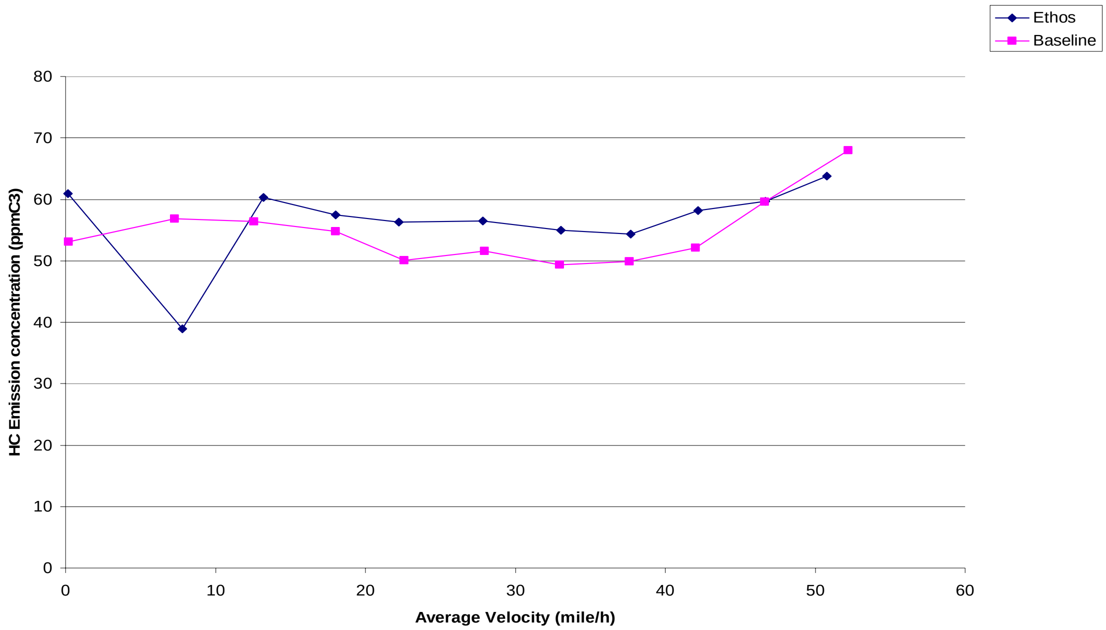
Acceleration Mode (Arterial track & peak time interval)
Ethos
Baseline
NOx Emission concentration (ppm)
Average Velocity (mile/h)

Case B: Emission trends of arterial test track and peak time interval for Cruising mode

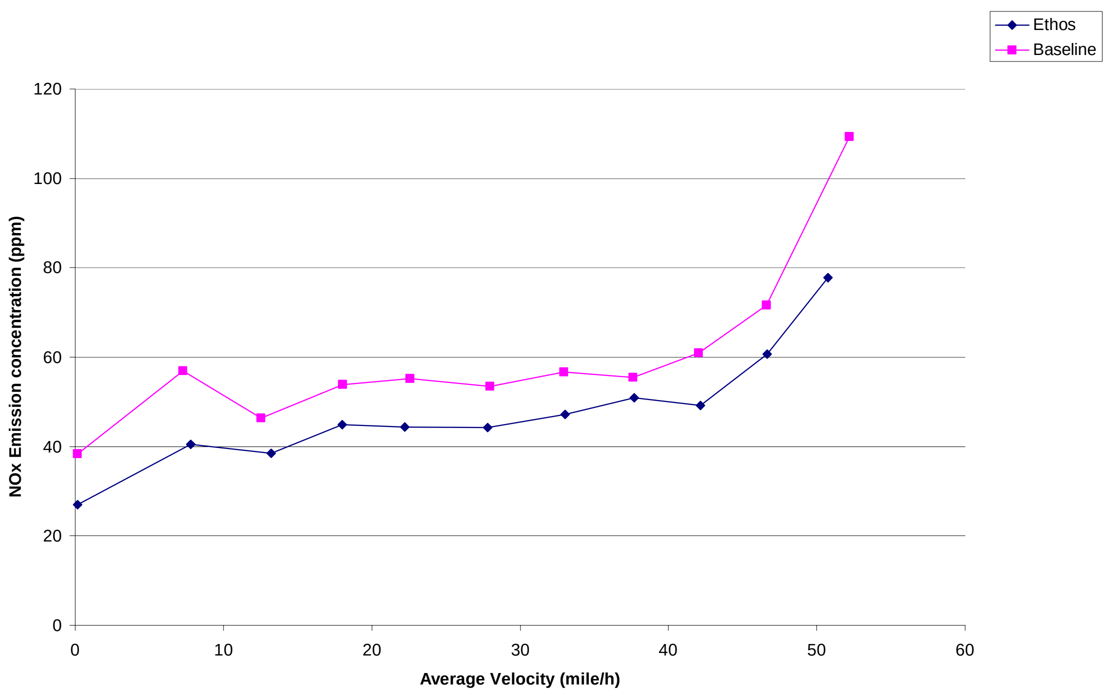




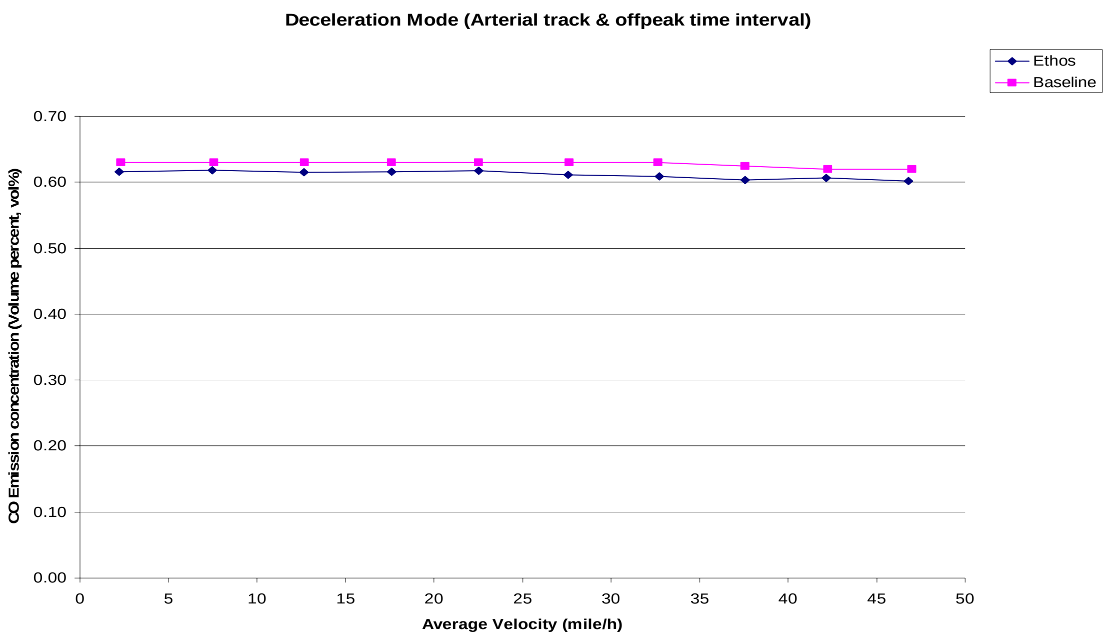
Cruising Mode (Arterial track & peak time interval)

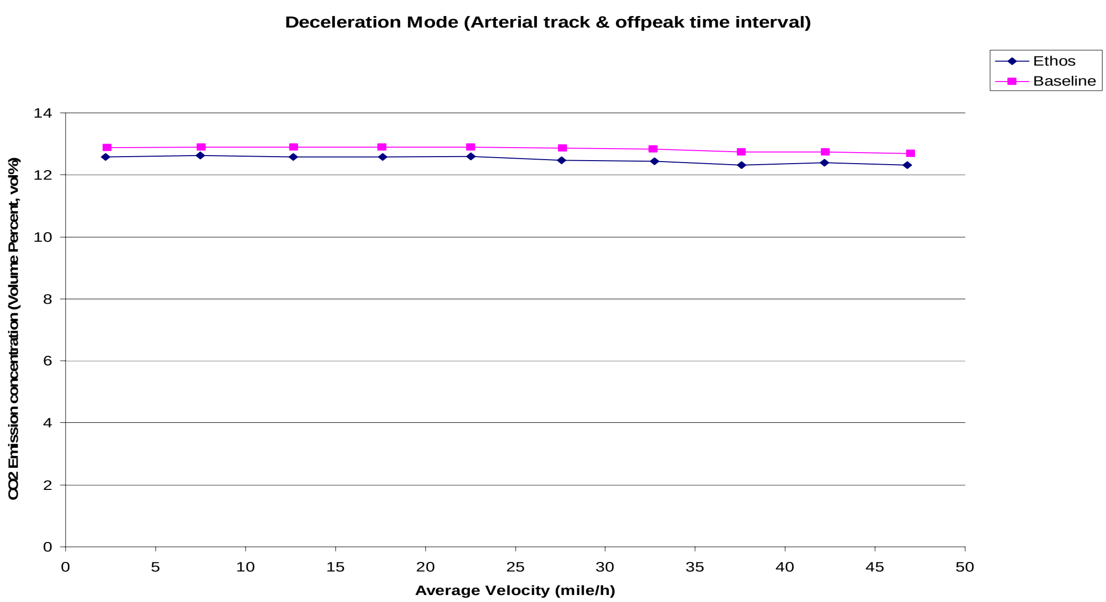


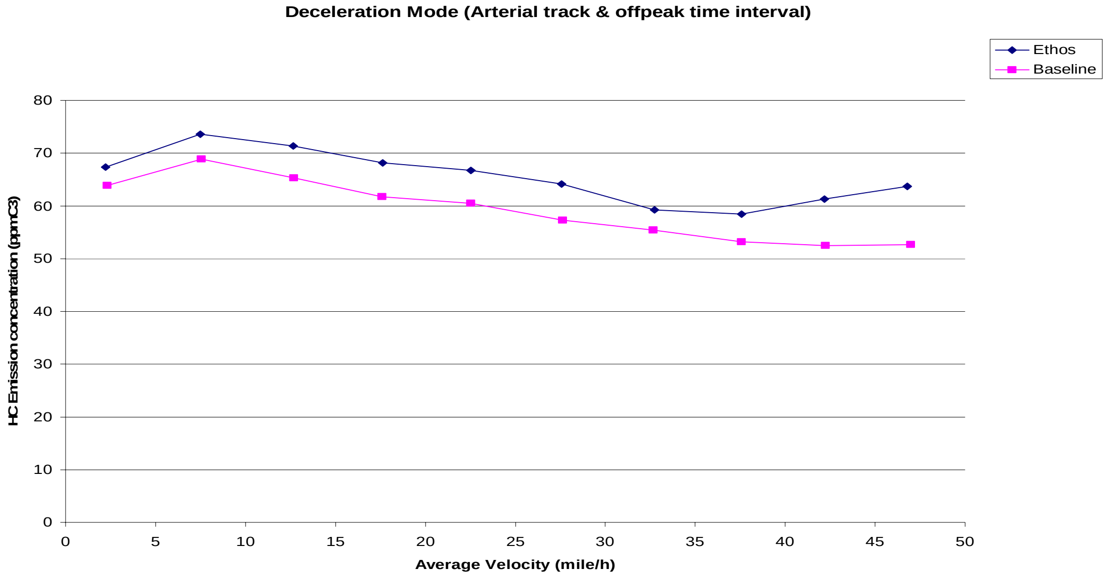
Cruising Mode (Arterial track & peak time interval)

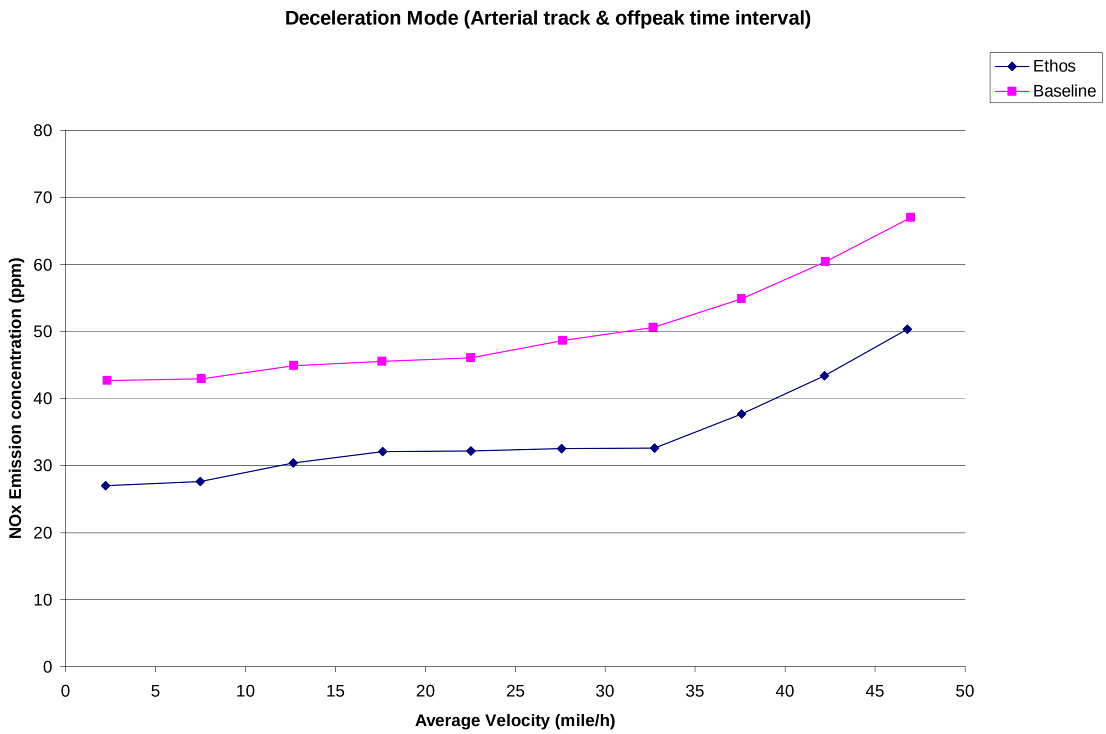


Case C: Emission trends of arterial test track and off- peak time interval for Deceleration mode

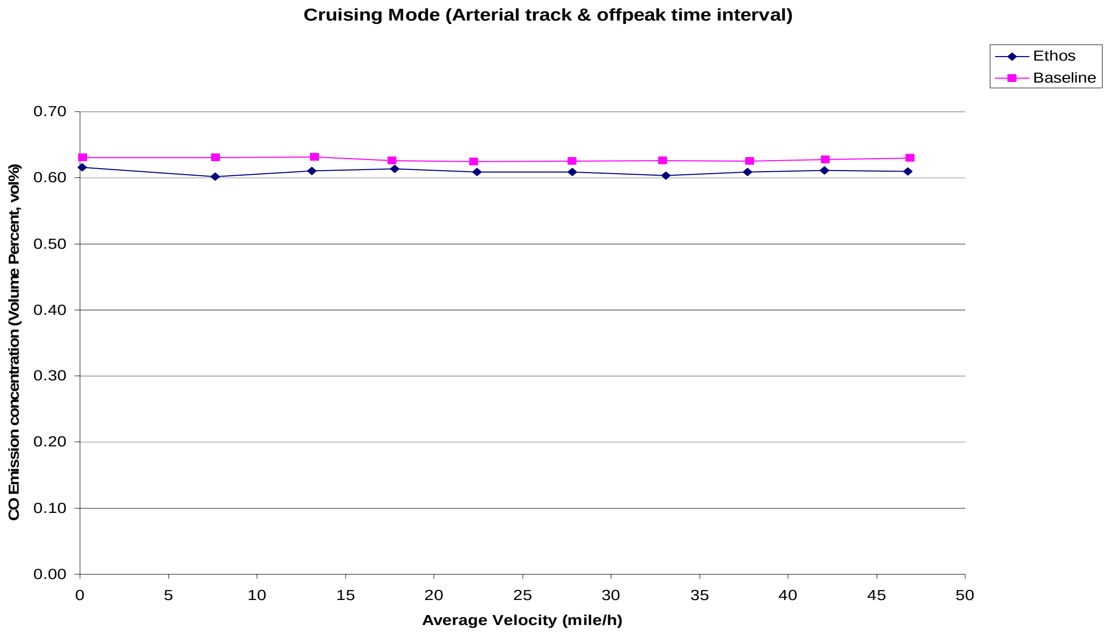


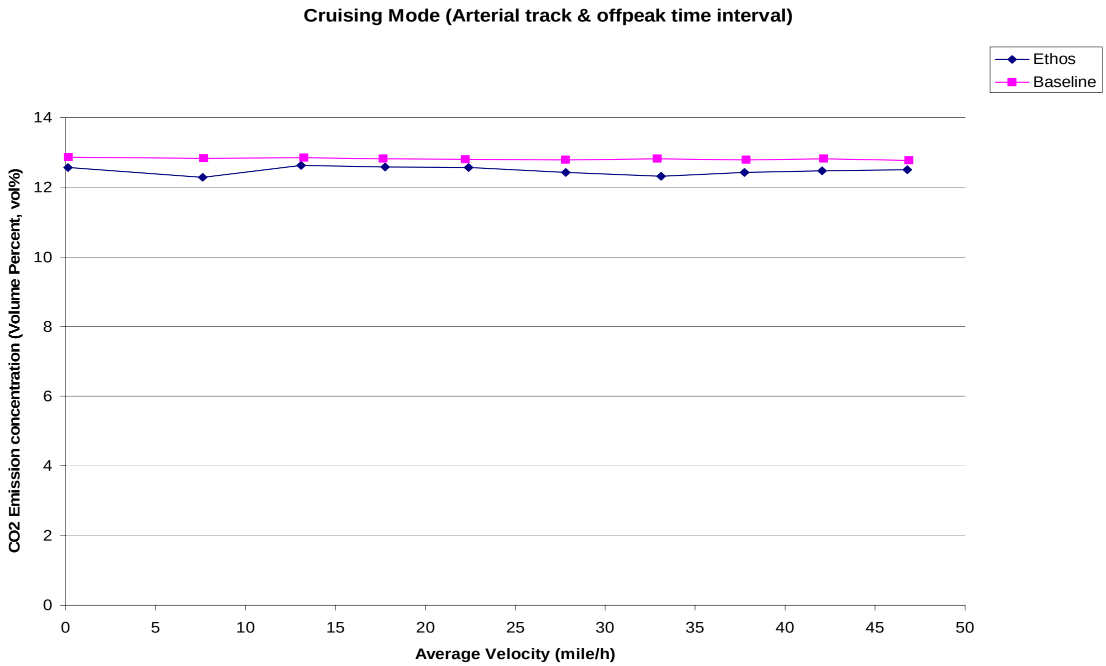


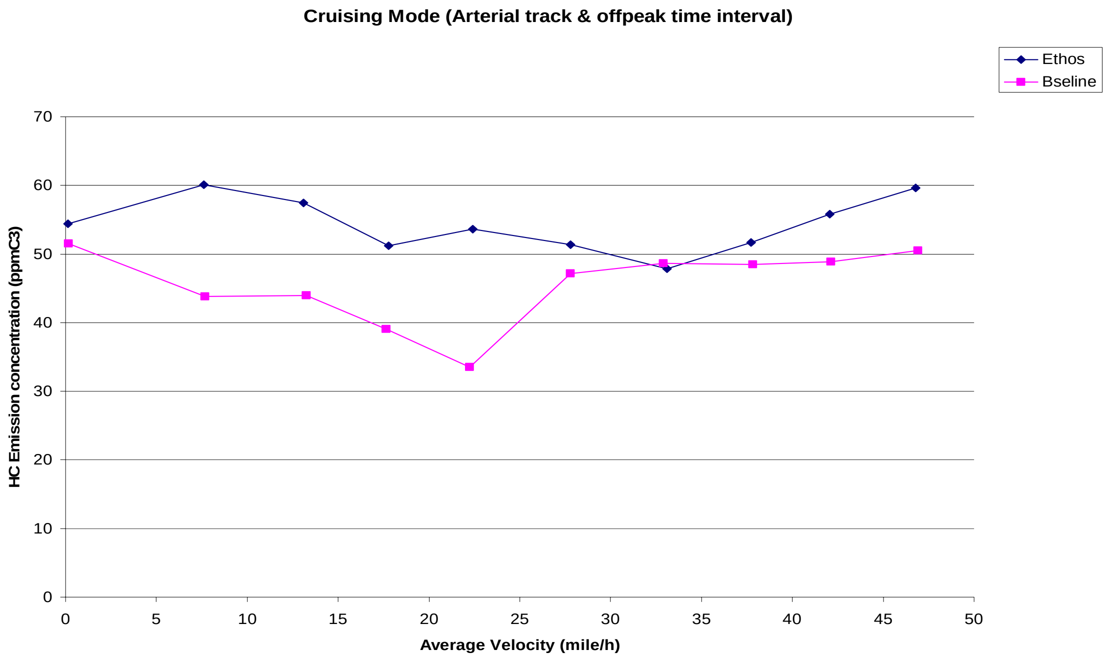

Deceleration Mode (Arterial track & offpeak time interval)
Ethos
Baseline
HC Emission concentration (ppmC3)
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40
45
50
Average Velocity (mile/h)

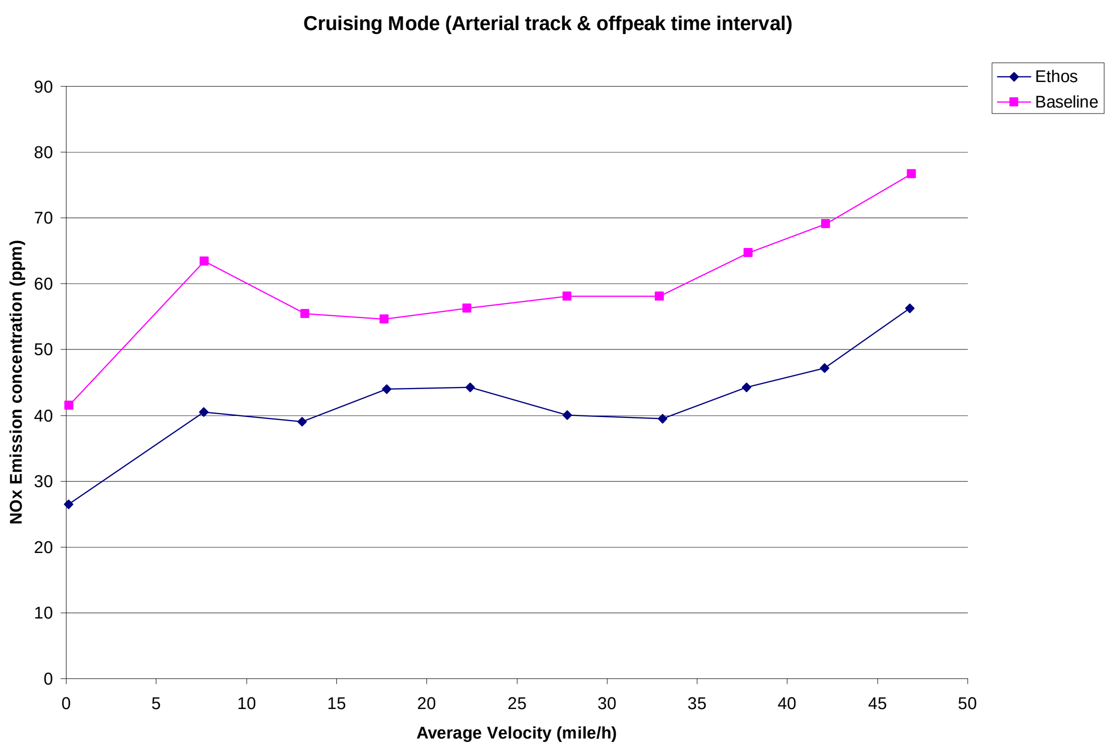

Deceleration Mode (Arterial track & offpeak time interval)
Ethos
Baseline
NOx Emission concentration (ppm)
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40
45
50
Average Velocity (mile/h)

Case D: Emission trends of arterial test track and off- peak time interval for Cruising mode

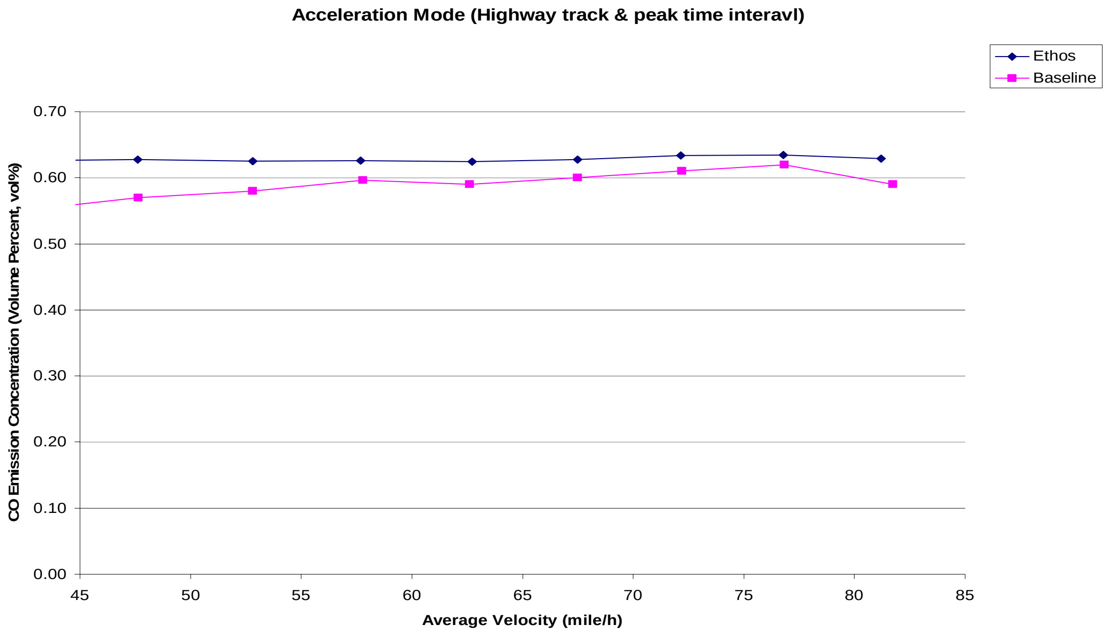


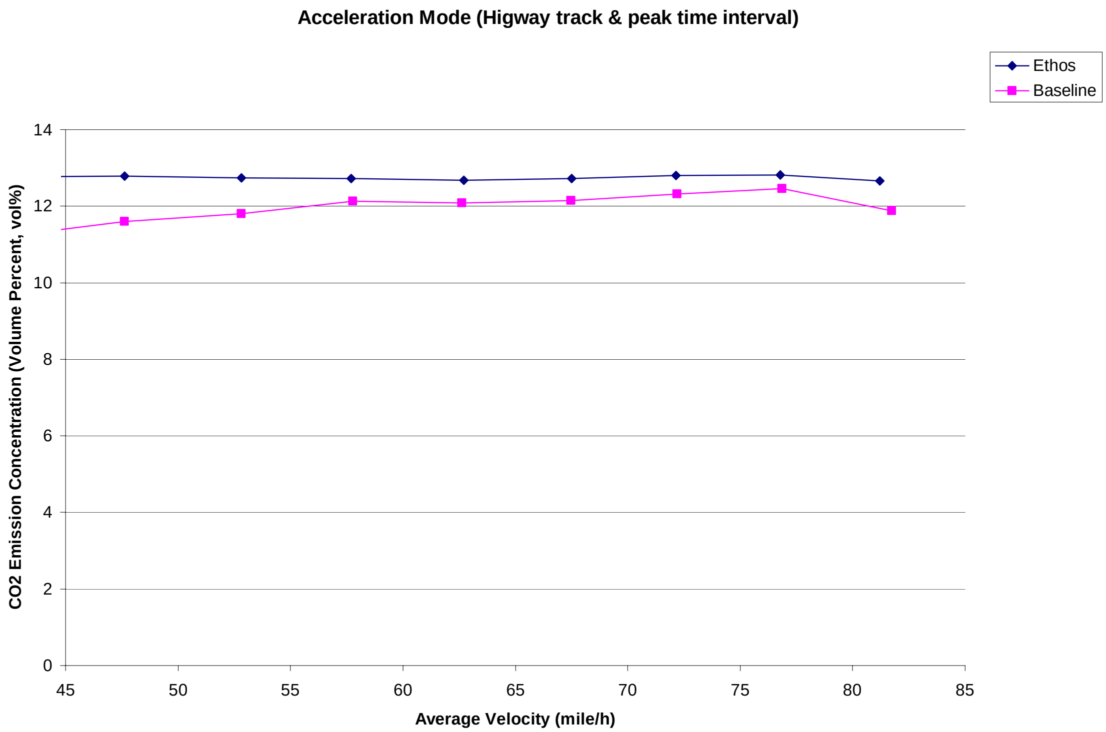



Cruising Mode (Arterial track & offpeak time interval)
Ethos
Bseline
HC Emission concentration (ppmC3)
Average Velocity (mile/h)
0
10
20
30
40
50
60
70
0
5
10
15
20
25
30
35
40
45
50

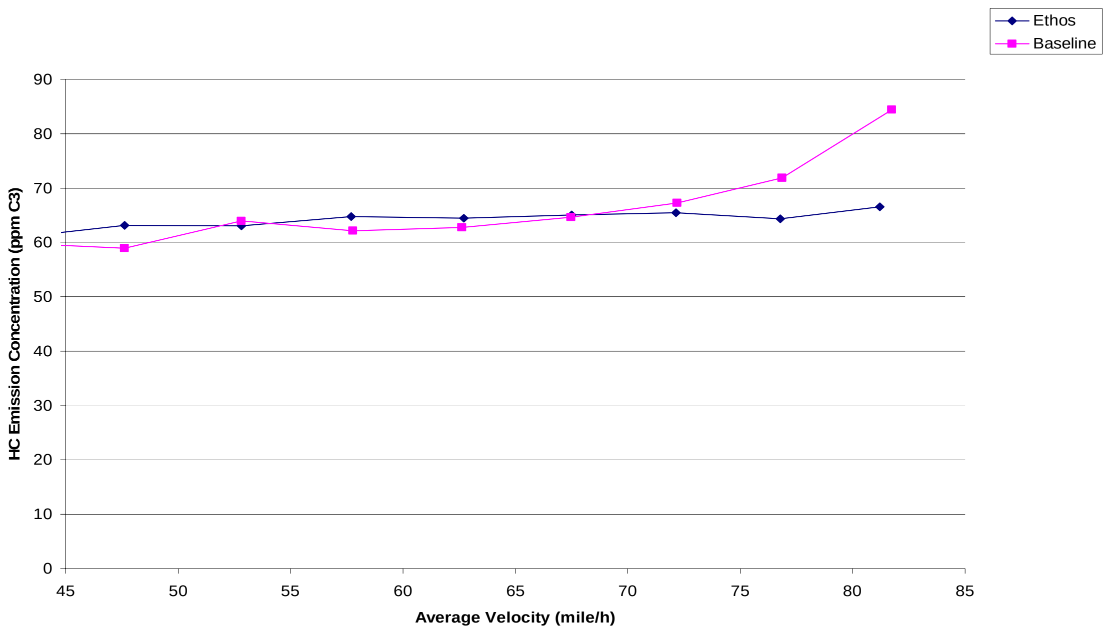

Cruising Mode (Arterial track & offpeak time interval)
Ethos
Baseline
NOx Emission concentration (ppm)
Average Velocity (mile/h)
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
35
40
45
50

Case E: Emission trends of highway test track and peak time interval for Acceleration mode

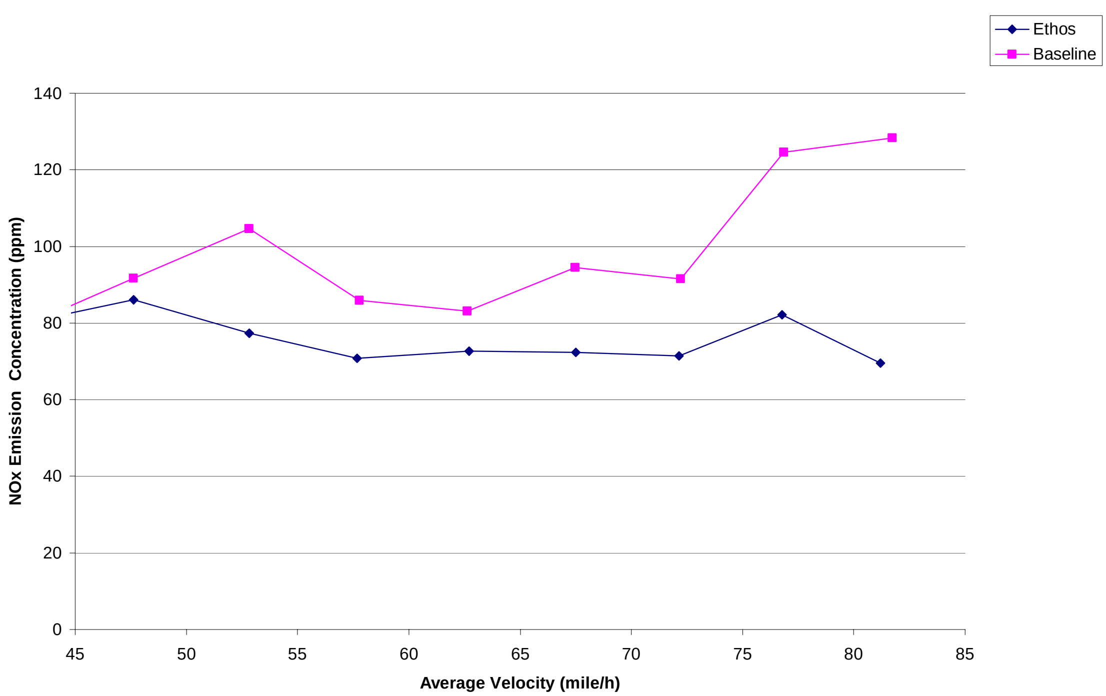




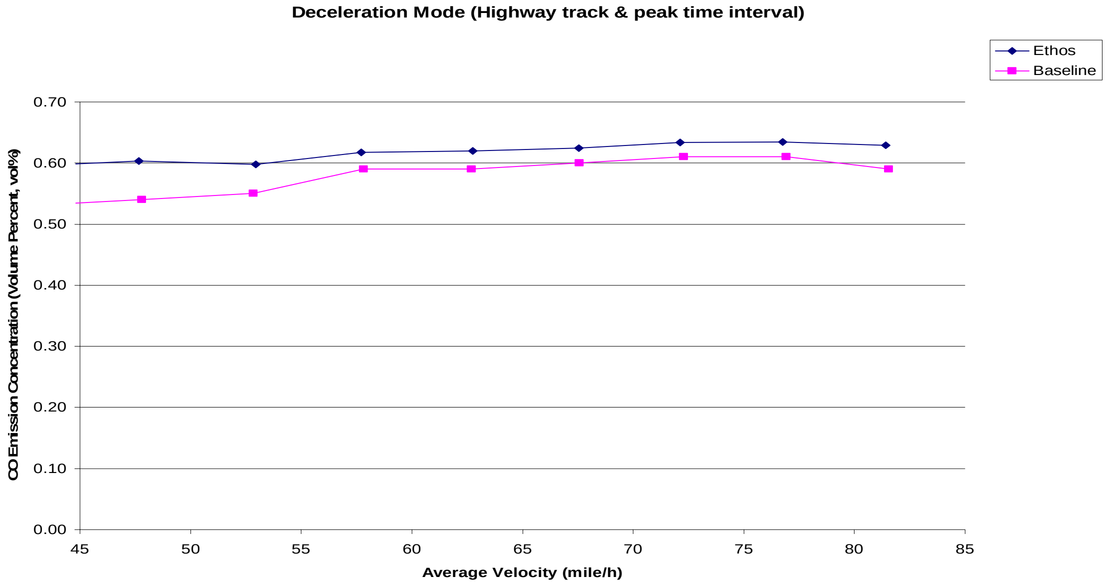
Acceleration Mode (Highway track & peak time interval)

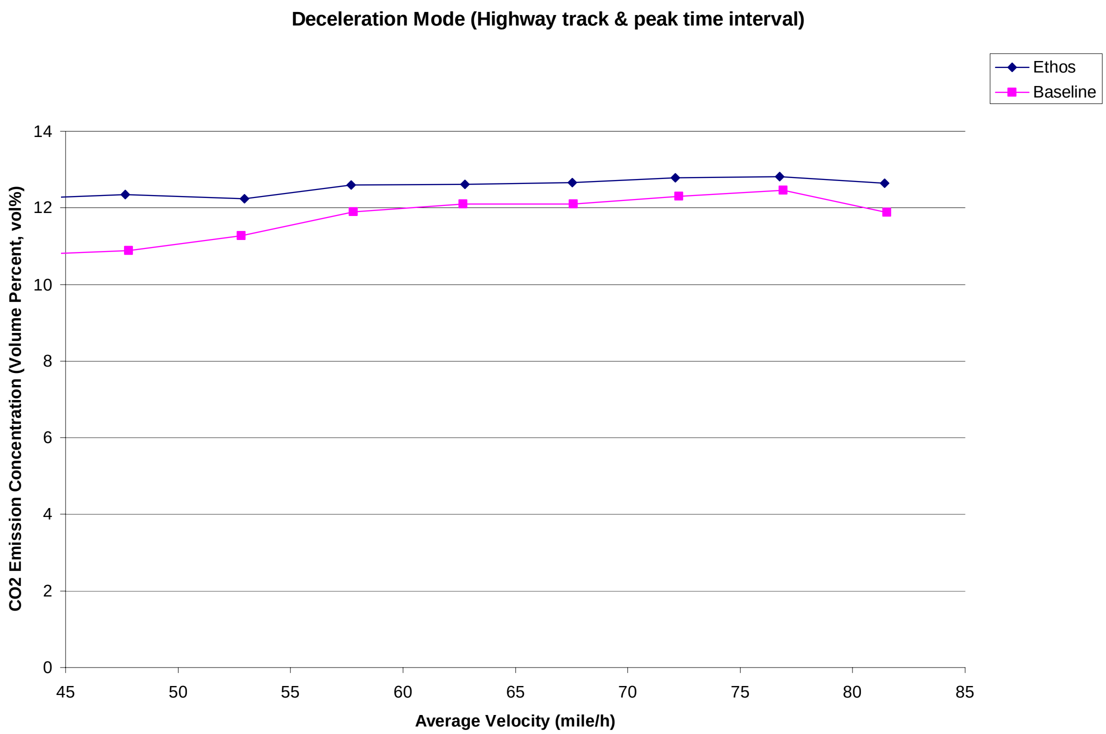


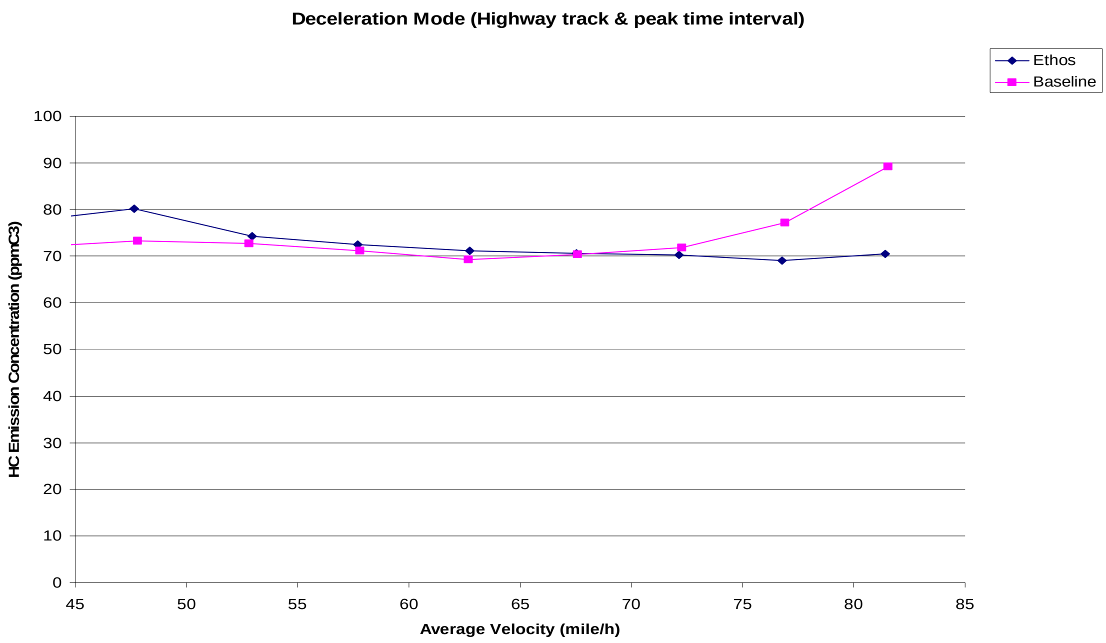
Acceleration Mode (Highway track & peak time interval)

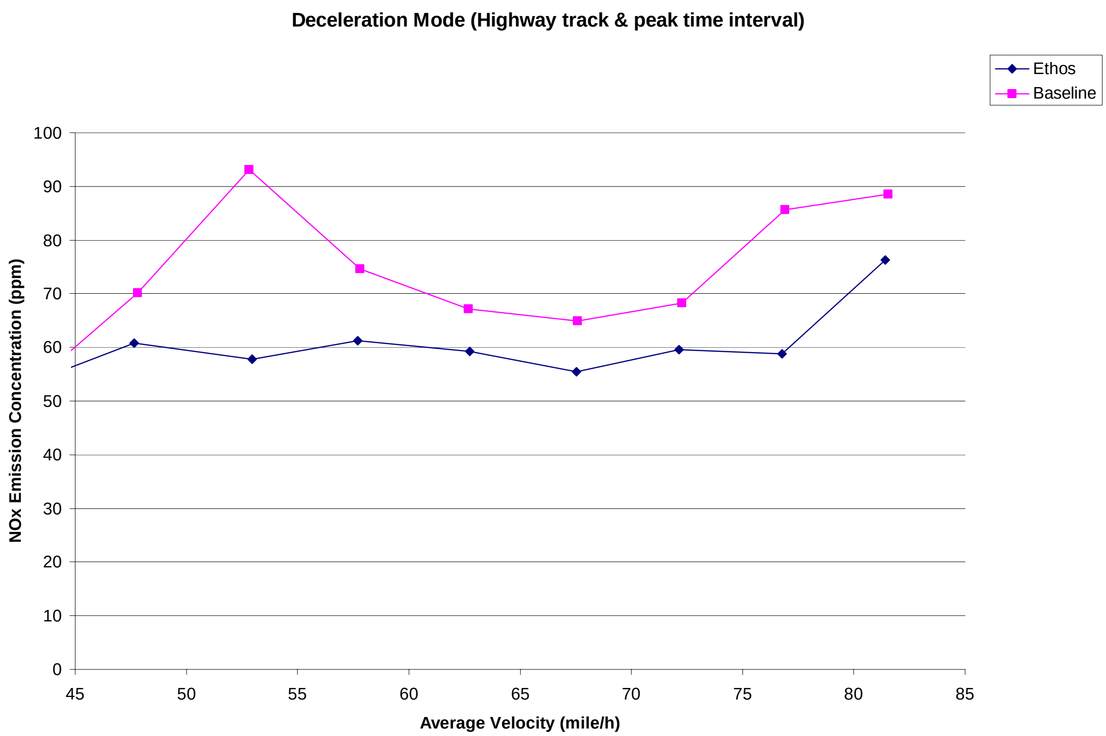


Case F: Emission trends of highway test track and peak time interval for Deceleration mode

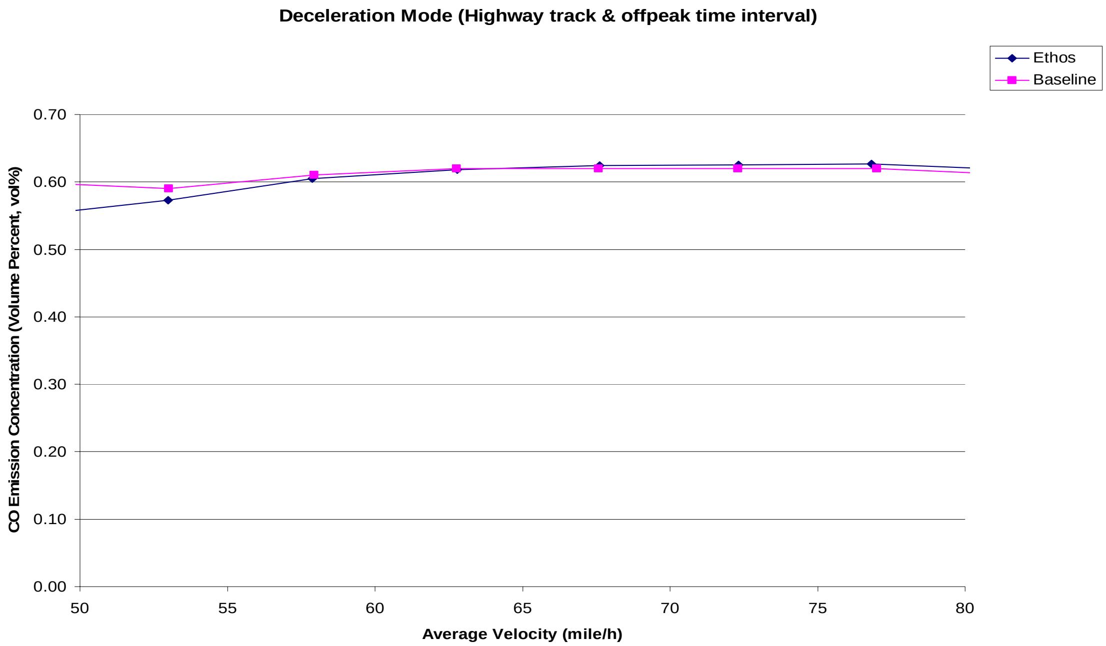


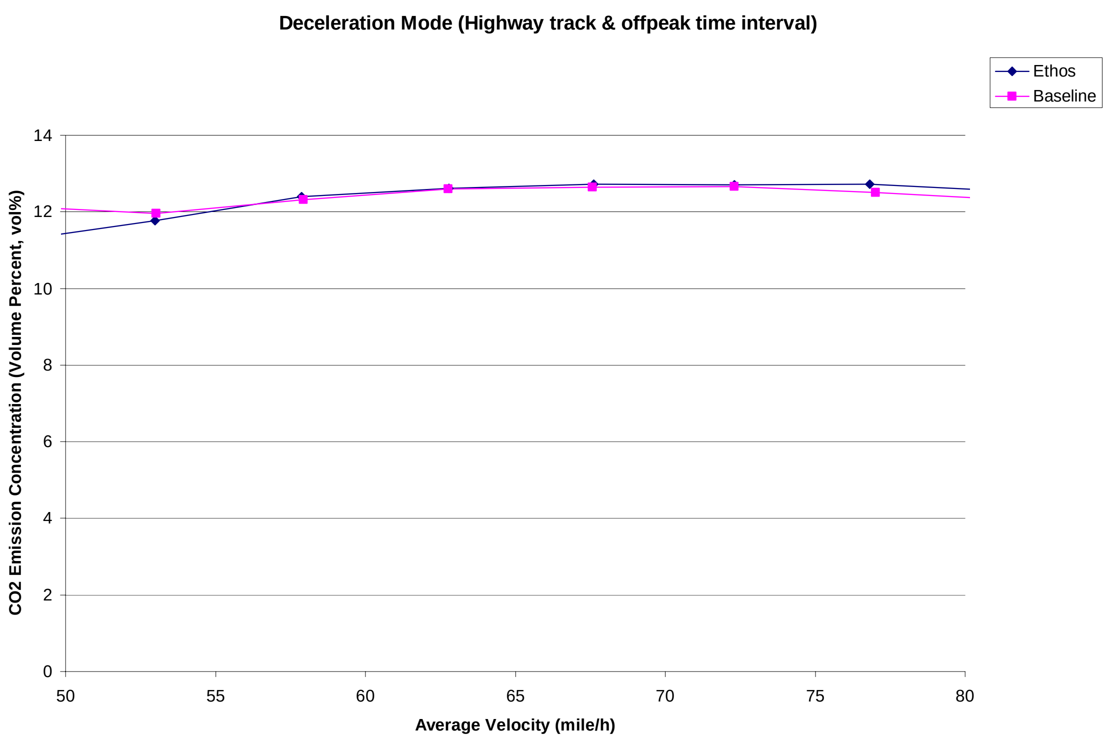


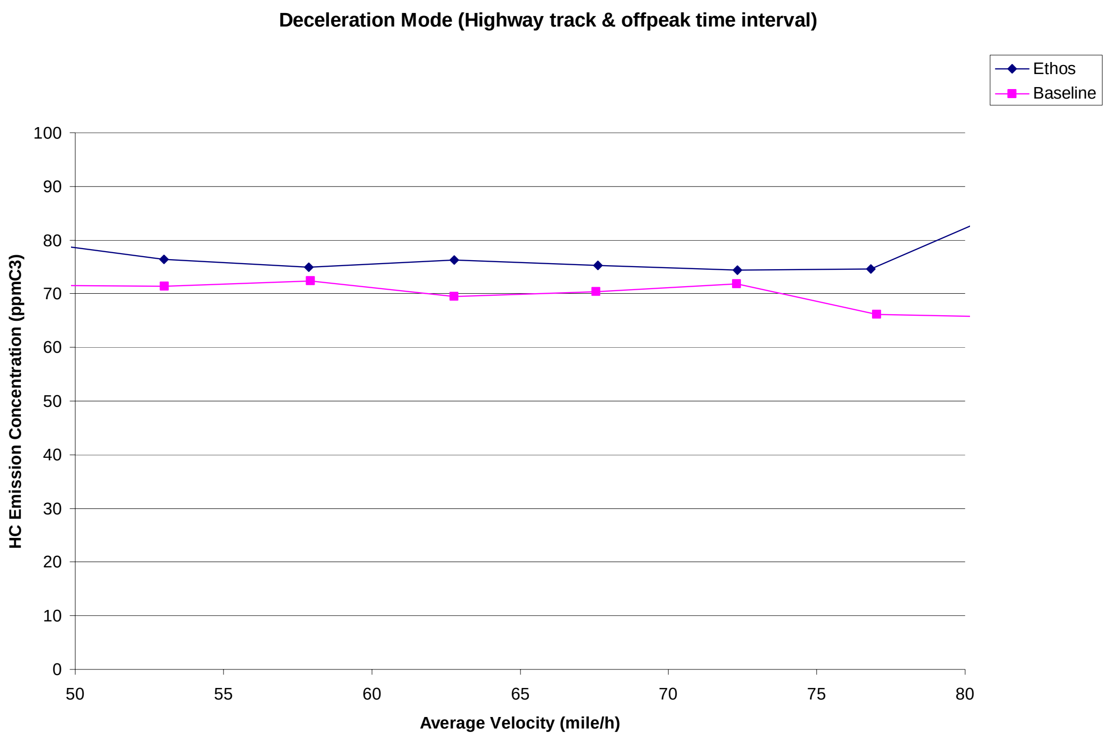

Deceleration Mode (Highway track & peak time interval)
Ethos
Baseline
HC Emission Concentration (ppmC3)
Average Velocity (mile/h)
0
10
20
30
40
50
60
70
80
90
100
45
50
55
60
65
70
75
80
85

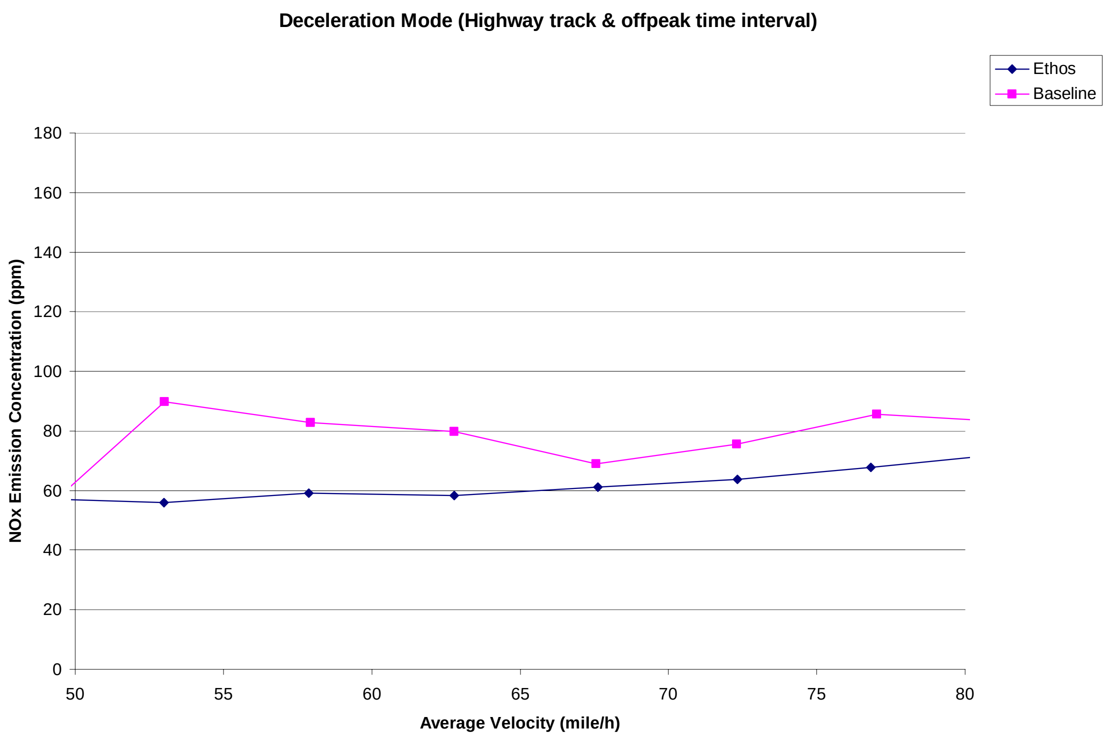

Deceleration Mode (Highway track & peak time interval)
Ethos
Baseline
NOx Emission Concentration (ppm)
Average Velocity (mile/h)
0
10
20
30
40
50
60
70
80
90
100
45
50
55
60
65
70
75
80
85

Case G: Emission trends of highway test track and off-peak time interval for Deceleration mode

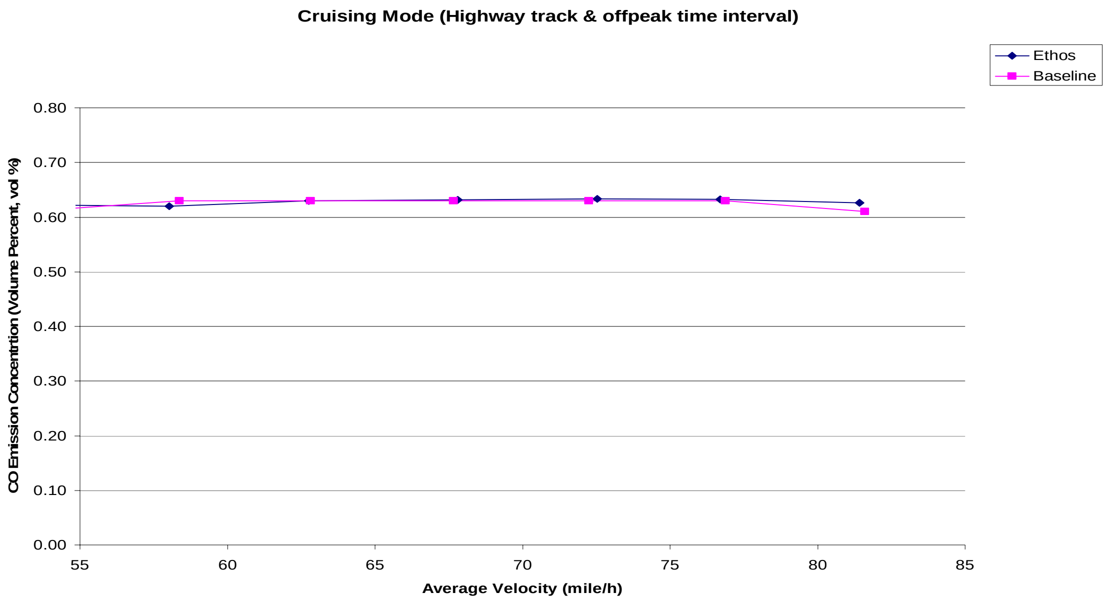


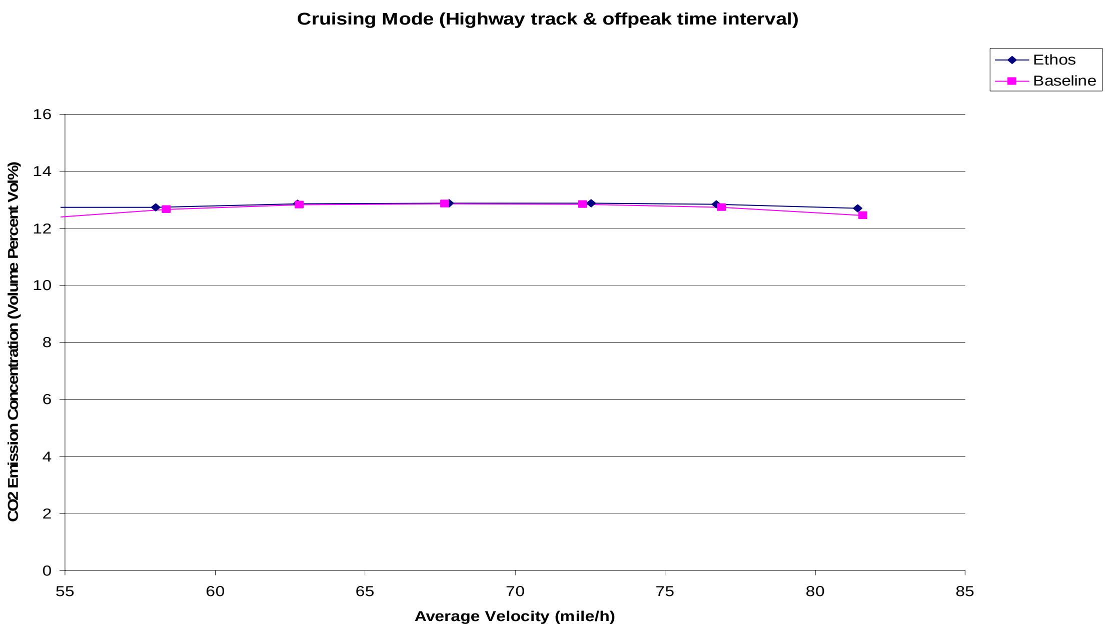



Deceleration Mode (Highway track & offpeak time interval)
Ethos
Baseline
HC Emission Concentration (ppmC3)
100
90
80
70
60
50
40
30
20
10
0
50
55
60
65
70
75
80
Average Velocity (mile/h)

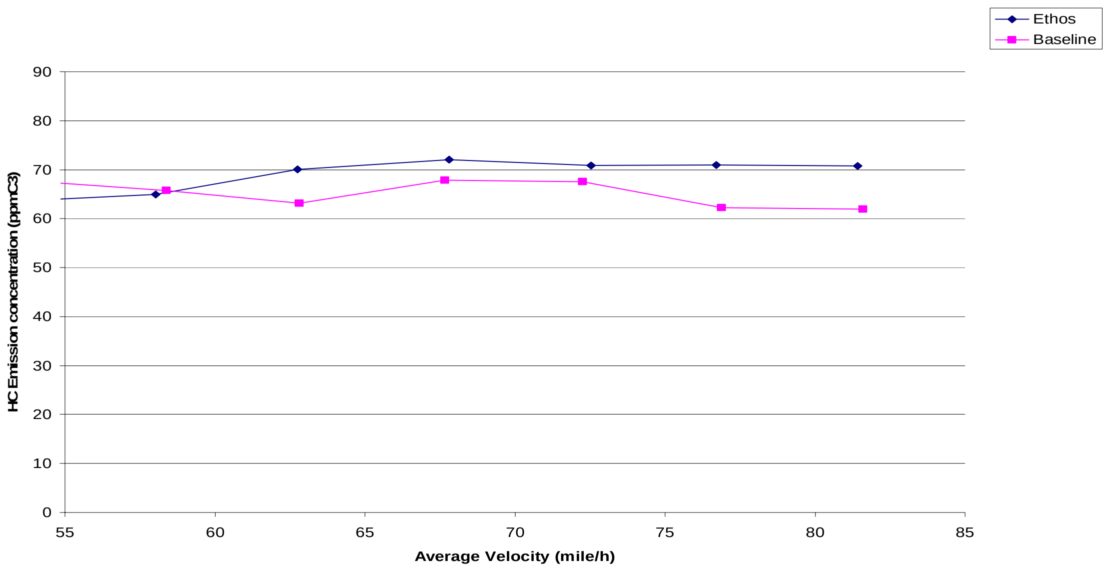

Deceleration Mode (Highway track & offpeak time interval)
Ethos
Baseline
NOx Emission Concentration (ppm)
180
160
140
120
100
80
60
40
20
0
50
55
60
65
70
75
80
Average Velocity (mile/h)

Case H: Emission trends of highway test track and off-peak time interval for Cruising mode

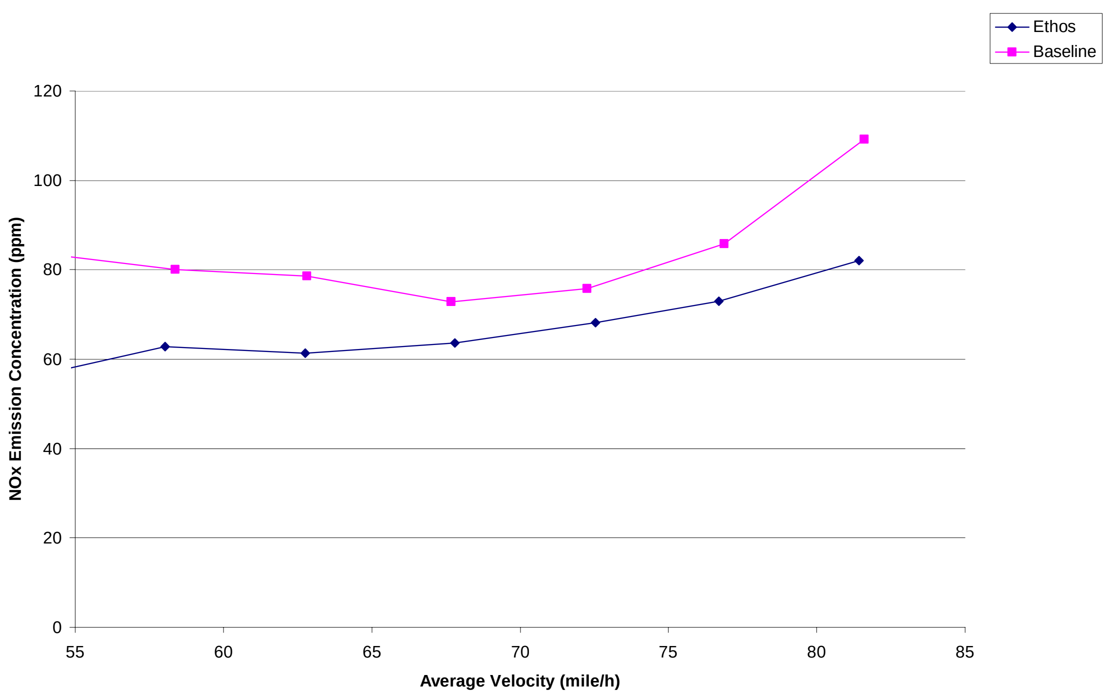




Cruising Mode (Highway track & offpeak time interval)



Cruising Mode (Highway track & offpeak time interval)



APPENDIX B

T-TESTS FOR OVERALL MODAL DATA SETS

Case I: CO emission concentrations

Table B-1 Overall t-tests for arterial test track and peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	NO	0.15
Cruising Mode	NO	0.02
Deceleration Mode	YES	0.58
Idling Mode	YES	-2.09

Table B-2 Overall t-tests for arterial test track and off-peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	2.47
Cruising Mode	YES	2.58
Deceleration Mode	YES	2.95
Idling Mode	YES	1.29

Table B-3 Overall t-tests for highway test track and off- peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	-0.59
Cruising Mode	NO	-0.09
Deceleration Mode	NO	-0.09

Case II: CO_2 emission concentrations

Table B-4 Overall t-tests for arterial test track and peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	2.03
Cruising Mode	YES	1.83
Deceleration Mode	YES	2.23
Idling Mode	YES	0.93

Table B-5 Overall t-tests for arterial test track and off-peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	2.38
Cruising Mode	YES	2.57
Deceleration Mode	YES	2.80
Idling Mode	YES	1.18

Table B-6 Overall t-tests for highway test track and peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	-6.62
Cruising Mode	YES	-4.03
Deceleration Mode	YES	-6.68

Case III: HC emission concentrations

Table B-7 Overall t-tests for arterial test track and off- peak time interval

Modes	**Significant difference (%)**	**Overall Percent reduction (%)**
Acceleration Mode	YES	-13.6
Cruising Mode	YES	-9.02
Deceleration Mode	YES	-10.94
Idling Mode	NO	-1.93

Table B-8 Overall t-tests for highway test track and peak time interval

Modes	**Significant difference (%)**	**Overall Percent reduction (%)**
Acceleration Mode	YES	2.17
Cruising Mode	NO	-0.17
Deceleration Mode	YES	1.80

Table B-9 Overall t-tests for highway test track and off- peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	-10.27
Cruising Mode	YES	-6.65
Deceleration Mode	YES	-7.29

Case IV: NO_X emission concentrations

Table B-10 Overall t-tests for arterial test track and peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	12.69
Cruising Mode	YES	20.26
Deceleration Mode	YES	23.65
Idling Mode	YES	45.58

Table B-11 Overall t-tests for highway test track and peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	17.63
Cruising Mode	YES	14.84
Deceleration Mode	YES	15.19

Table B-12 Overall t-tests for highway test track and off-peak time interval

Modes	Significant difference (%)	Overall Percent reduction (%)
Acceleration Mode	YES	25.36
Cruising Mode	YES	16.14
Deceleration Mode	YES	19.78

APPENDIX C

T-TESTS FOR VELOCITY CATEGORY DATA SETS

Case I: CO emission concentrations

Table C-1 Velocity Category t-tests for arterial test track and peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
0-4.99	NO	0-4.99	YES	0-4.99	NO
5-9.99	YES	5-9.99	YES	5-9.99	NO
10-14.99	YES	10-14.99	NO	10-14.99	NO
15-19.99	NO	15-19.99	NO	15-19.99	NO
20-24.99	NO	20-24.99	NO	20-24.99	NO
25-29.99	NO	25-29.99	NO	25-29.99	NO
30-34.99	NO	30-34.99	NO	30-34.99	YES
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	NO	40-44.99	NO	40-44.99	NO
45-49.99	NO	45-49.99	YES	45-49.99	YES
50-54.99	YES	50-54.99	YES	50-54.99	YES

Table C-2 Velocity Category t-tests for arterial test track and off-peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
0-4.99	YES	0-4.99	YES	0-4.99	YES
5-9.99	YES	5-9.99	NO	5-9.99	YES
10-14.99	YES	10-14.99	YES	10-14.99	YES
15-19.99	YES	15-19.99	NO	15-19.99	YES
20-24.99	YES	20-24.99	YES	20-24.99	YES
25-29.99	YES	25-29.99	YES	25-29.99	YES
30-34.99	YES	30-34.99	YES	30-34.99	YES
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	YES	45-49.99	YES
50-54.99	NO	50-54.99	YES	50-54.99	YES

Table C-3 Velocity Category t-tests for highway test track and off-peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
35-39.99	YES	35-39.99	NO	35-39.99	NO
40-44.99	YES	40-44.99	NO	40-44.99	NO
45-49.99	YES	45-49.99	NO	45-49.99	NO
50-54.99	YES	50-54.99	YES	50-54.99	NO
55-59.99	NO	55-59.99	NO	55-59.99	NO
60-64.99	NO	60-64.99	YES	60-64.99	NO
65-69.99	NO	65-69.99	NO	65-69.99	NO
70-74.99	YES	70-74.99	YES	70-74.99	YES
75-79.99	YES	75-79.99	YES	75-79.99	YES
80-84.99	YES	80-84.99	YES	80-84.99	YES
85-89.99	YES	85-89.99	YES	85-89.99	NO

Case II: CO_2 emission concentrations

Table C-4 Velocity Category t-tests for arterial test track and peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
0-4.99	YES	0-4.99	YES	0-4.99	YES
5-9.99	NO	5-9.99	NO	5-9.99	YES
10-14.99	YES	10-14.99	NO	10-14.99	YES
15-19.99	YES	15-19.99	YES	15-19.99	YES
20-24.99	YES	20-24.99	YES	20-24.99	YES
25-29.99	YES	25-29.99	YES	25-29.99	YES
30-34.99	YES	30-34.99	YES	30-34.99	YES
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	NO	45-49.99	NO
50-54.99	YES	50-54.99	YES	50-54.99	YES

Table C-5 Velocity Category t-tests for arterial test track and off-peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
0-4.99	YES	0-4.99	YES	0-4.99	YES
5-9.99	YES	5-9.99	NO	5-9.99	YES
10-14.99	YES	10-14.99	NO	10-14.99	YES
15-19.99	YES	15-19.99	NO	15-19.99	YES
20-24.99	YES	20-24.99	NO	20-24.99	YES
25-29.99	YES	25-29.99	YES	25-29.99	YES
30-34.99	YES	30-34.99	YES	30-34.99	YES
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	YES	45-49.99	YES
50-54.99	YES	50-54.99	YES	50-54.99	YES

Table C-6 Velocity Category t-tests for highway test track and peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
35-39.99	YES	35-39.99	NO	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	YES	45-49.99	YES
50-54.99	YES	50-54.99	YES	50-54.99	YES
55-59.99	YES	55-59.99	YES	55-59.99	YES
60-64.99	YES	60-64.99	YES	60-64.99	YES
65-69.99	YES	65-69.99	YES	65-69.99	YES
70-74.99	YES	70-74.99	YES	70-74.99	YES
75-79.99	YES	75-79.99	YES	75-79.99	YES
80-84.99	YES	80-84.99	YES	80-84.99	YES
85-89.99	YES	85-89.99	YES	85-89.99	YES

Case III: HC emission concentrations

Table C-7 Velocity Category t-tests for arterial test track and off- peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
0-4.99	YES	0-4.99	YES	0-4.99	YES
5-9.99	YES	5-9.99	YES	5-9.99	YES
10-14.99	YES	10-14.99	YES	10-14.99	YES
15-19.99	YES	15-19.99	YES	15-19.99	YES
20-24.99	YES	20-24.99	YES	20-24.99	YES
25-29.99	YES	25-29.99	YES	25-29.99	YES
30-34.99	YES	30-34.99	NO	30-34.99	YES
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	YES	45-49.99	YES
50-54.99	NO	50-54.99	YES	50-54.99	NO

Table C-8 Velocity Category t-tests for highway test track and peak time interval

Acceleration Mode		Cruising Mode		Deceleration Mode	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	YES	45-49.99	YES
50-54.99	YES	50-54.99	NO	50-54.99	NO
55-59.99	YES	55-59.99	NO	55-59.99	NO
60-64.99	YES	60-64.99	NO	60-64.99	NO
65-69.99	YES	65-69.99	YES	65-69.99	YES
70-74.99	YES	70-74.99	YES	70-74.99	YES
75-79.99	YES	75-79.99	YES	75-79.99	YES
80-84.99	YES	80-84.99	YES	80-84.99	YES
85-89.99	YES	85-89.99	YES	85-89.99	YES

Table C-9 Velocity Category t-tests for highway test track and off-peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
35-39.99	YES	35-39.99	NO	35-39.99	YES
40-44.99	YES	40-44.99	NO	40-44.99	NO
45-49.99	YES	45-49.99	NO	45-49.99	YES
50-54.99	YES	50-54.99	YES	50-54.99	YES
55-59.99	YES	55-59.99	NO	55-59.99	NO
60-64.99	YES	60-64.99	YES	60-64.99	YES
65-69.99	YES	65-69.99	YES	65-69.99	YES
70-74.99	YES	70-74.99	YES	70-74.99	YES
75-79.99	YES	75-79.99	YES	75-79.99	YES
80-84.99	YES	80-84.99	YES	80-84.99	YES
85-89.99	YES	85-89.99	NO	85-89.99	NO

Case IV: NO_X emission concentrations

Table C-10 Velocity Category t-tests for arterial test track and peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
0-4.99	YES	0-4.99	YES	0-4.99	YES
5-9.99	YES	5-9.99	YES	5-9.99	YES
10-14.99	YES	10-14.99	NO	10-14.99	YES
15-19.99	YES	15-19.99	YES	15-19.99	YES
20-24.99	YES	20-24.99	YES	20-24.99	YES
25-29.99	YES	25-29.99	YES	25-29.99	YES
30-34.99	YES	30-34.99	YES	30-34.99	YES
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	YES	40-44.99	YES	40-44.99	YES
45-49.99	YES	45-49.99	YES	45-49.99	YES
50-54.99	NO	50-54.99	NO	50-54.99	NO

Table C-11 Velocity Category t-tests for highway test track and peak time interval

Acceleration Mode		**Cruising Mode**		**Deceleration Mode**	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
35-39.99	YES	35-39.99	YES	35-39.99	YES
40-44.99	NO	40-44.99	YES	40-44.99	NO
45-49.99	NO	45-49.99	YES	45-49.99	NO
50-54.99	YES	50-54.99	NO	50-54.99	YES
55-59.99	YES	55-59.99	NO	55-59.99	YES
60-64.99	YES	60-64.99	NO	60-64.99	YES
65-69.99	YES	65-69.99	NO	65-69.99	YES
70-74.99	YES	70-74.99	YES	70-74.99	YES
75-79.99	YES	75-79.99	NO	75-79.99	YES
80-84.99	YES	80-84.99	NO	80-84.99	NO
85-89.99	YES	85-89.99	YES	85-89.99	YES

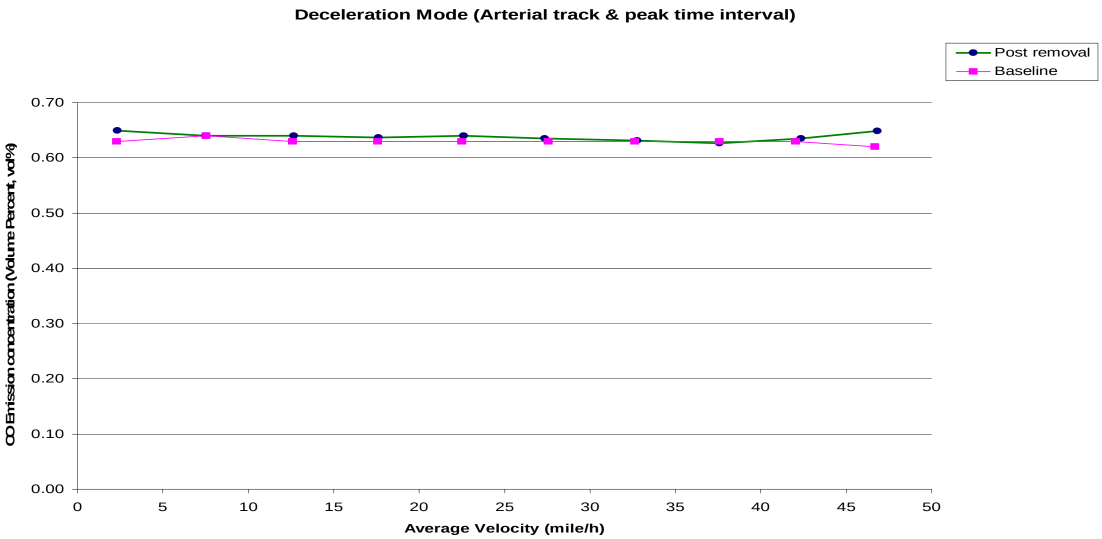
Table C-12 Velocity Category t-tests for highway test track and off-peak time interval

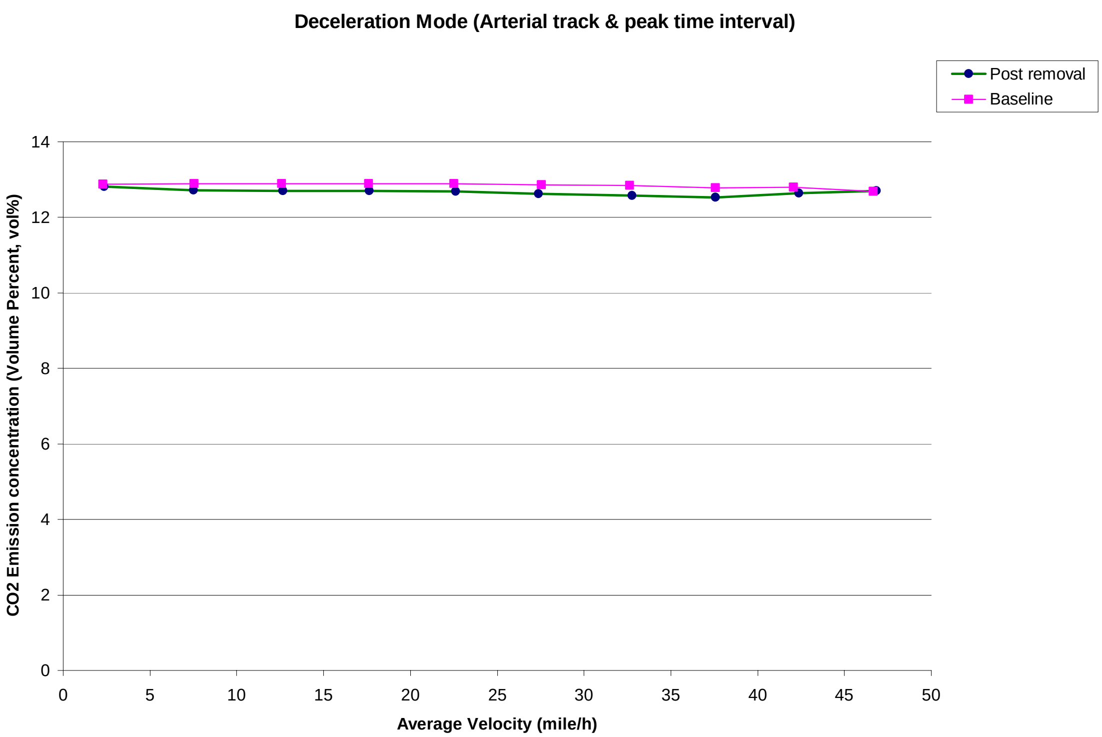
Acceleration Mode		Cruising Mode		Deceleration Mode	
Velocity Clusters	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**	**Velocity Clusters**	**Significant difference (%)**
35-39.99	YES	35-39.99	YES	35-39.99	NO
40-44.99	YES	40-44.99	NO	40-44.99	NO
45-49.99	NO	45-49.99	NO	45-49.99	NO
50-54.99	YES	50-54.99	YES	50-54.99	YES
55-59.99	YES	55-59.99	YES	55-59.99	YES
60-64.99	YES	60-64.99	YES	60-64.99	YES
65-69.99	YES	65-69.99	YES	65-69.99	YES
70-74.99	YES	70-74.99	YES	70-74.99	YES
75-79.99	YES	75-79.99	YES	75-79.99	YES
80-84.99	YES	80-84.99	YES	80-84.99	NO
85-89.99	YES	85-89.99	YES	85-89.99	NO

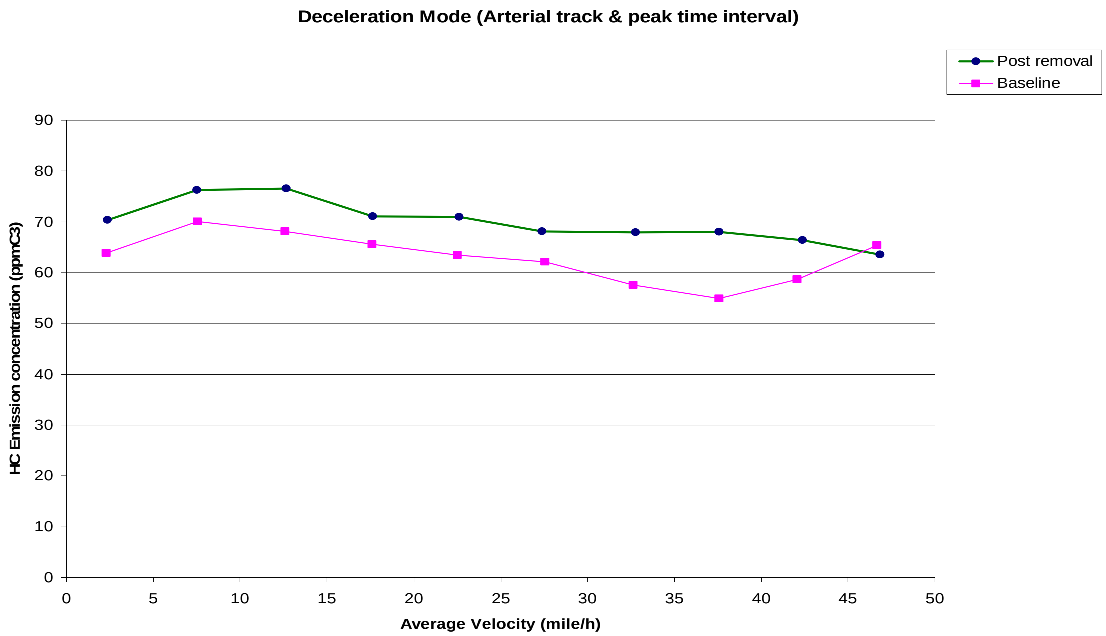
APPENDIX D

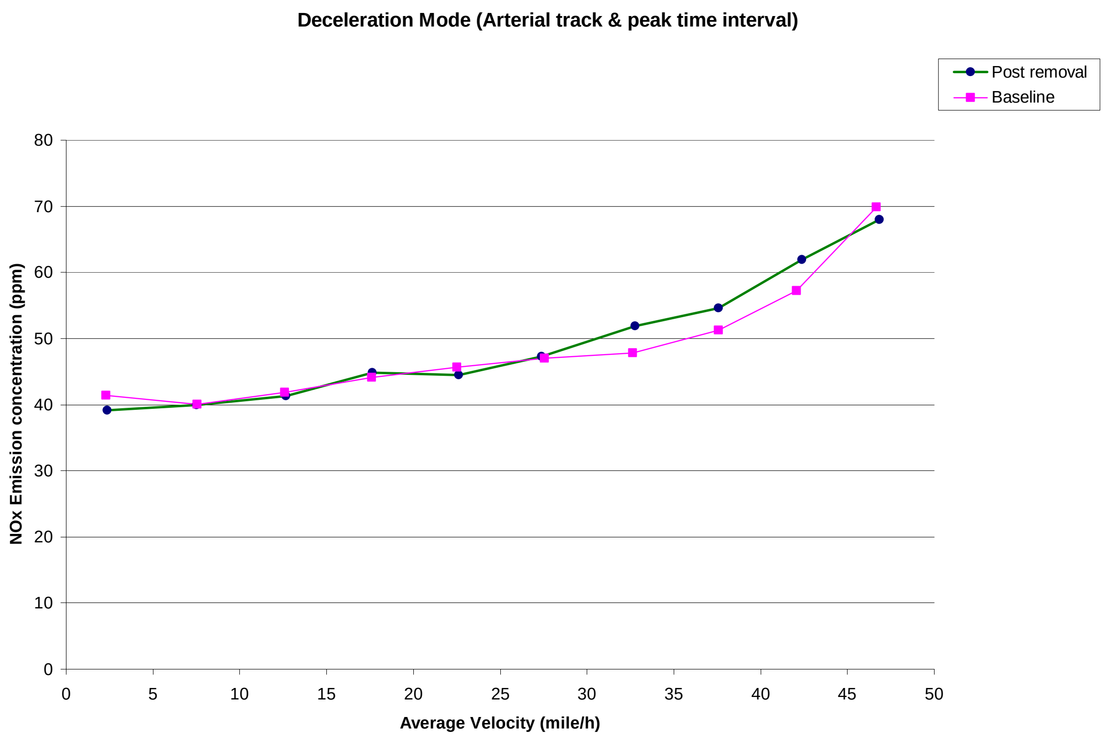
GRAPHICAL COMPARISON OF BASELINE AND POST-REMOVAL DATA

Case A: Graphical comparison of post removal data of arterial test track and peak time interval for Deceleration mode

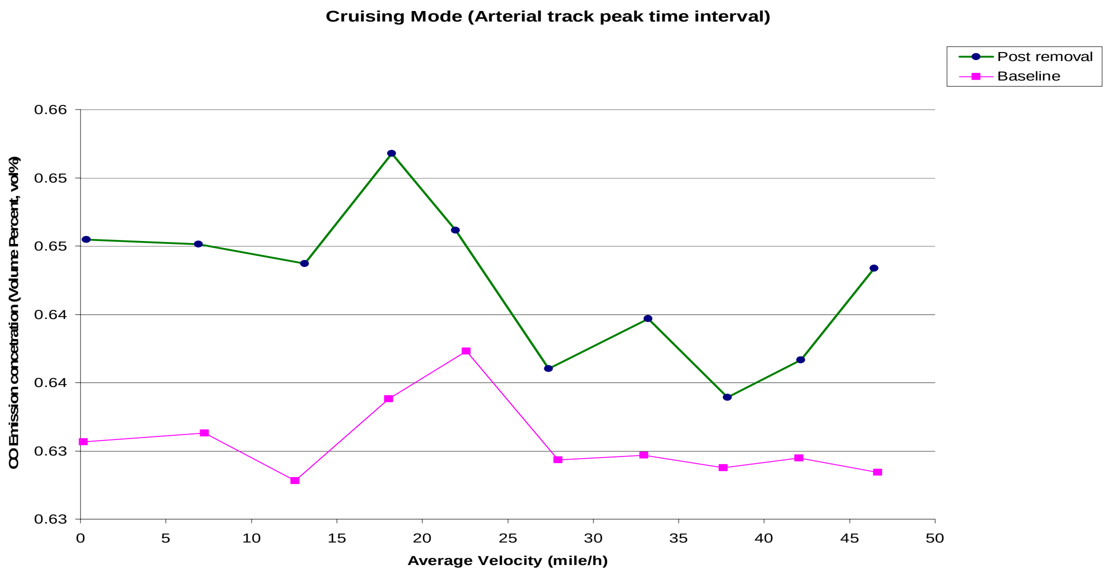


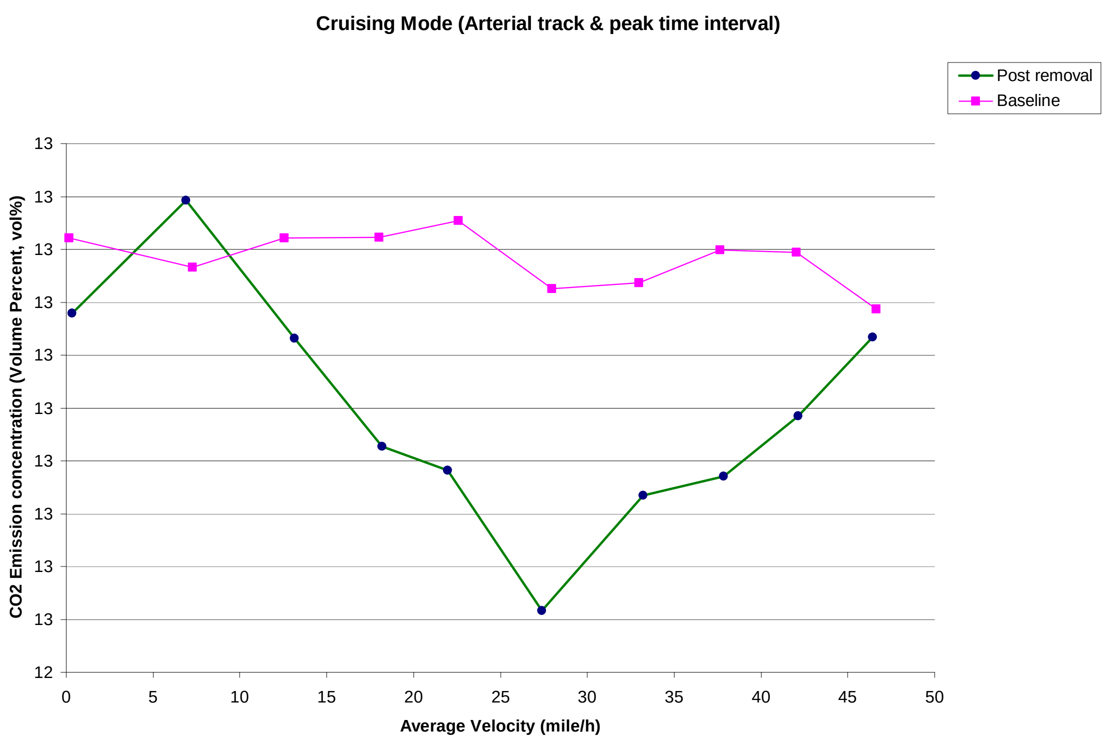



Deceleration Mode (Arterial track & peak time interval)
Post removal
Baseline
HC Emission concentration (ppmC3)
Average Velocity (mile/h)
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
35
40
45
50

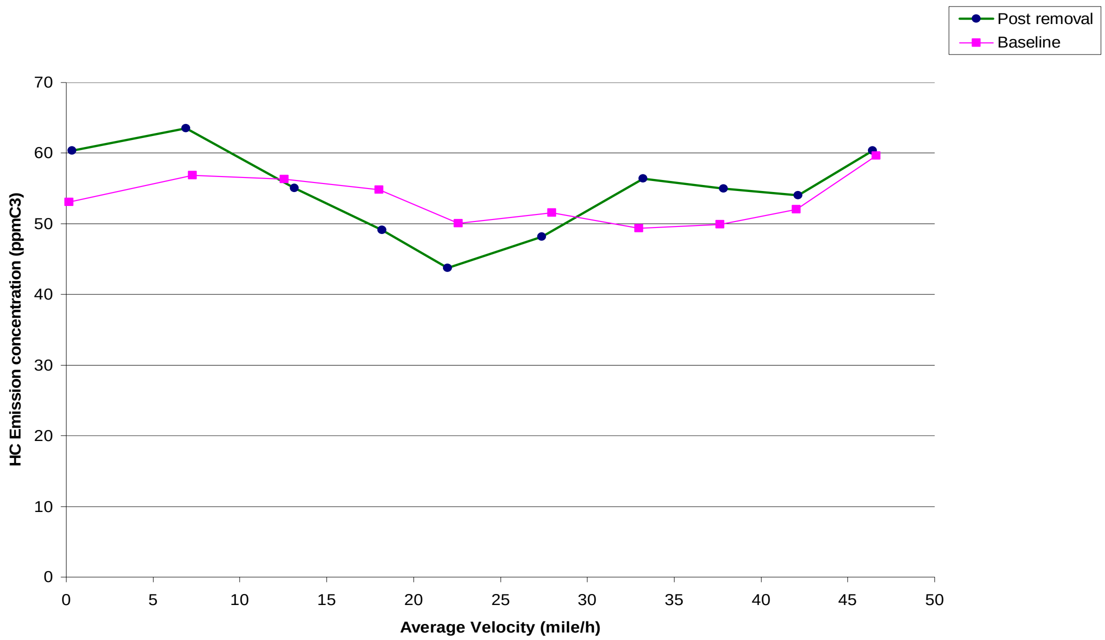

Deceleration Mode (Arterial track & peak time interval)
Post removal
Baseline
NOx Emission concentration (ppm)
Average Velocity (mile/h)
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40
45
50

Case B: Graphical comparison of post removal data of arterial test track and peak time interval for Cruising mode

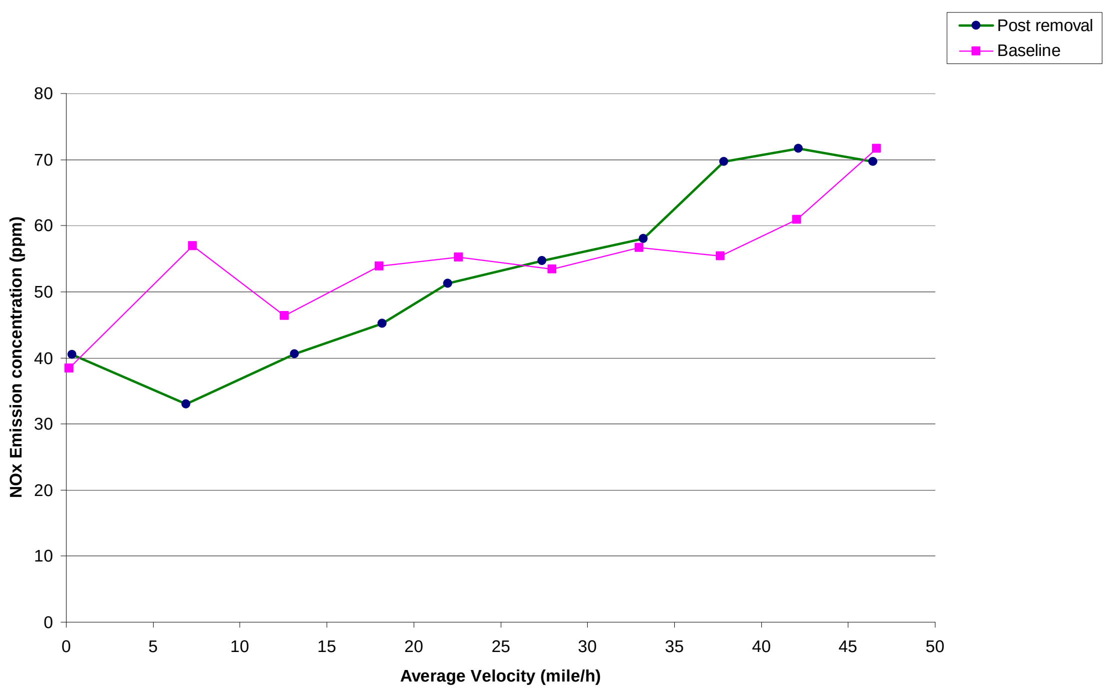




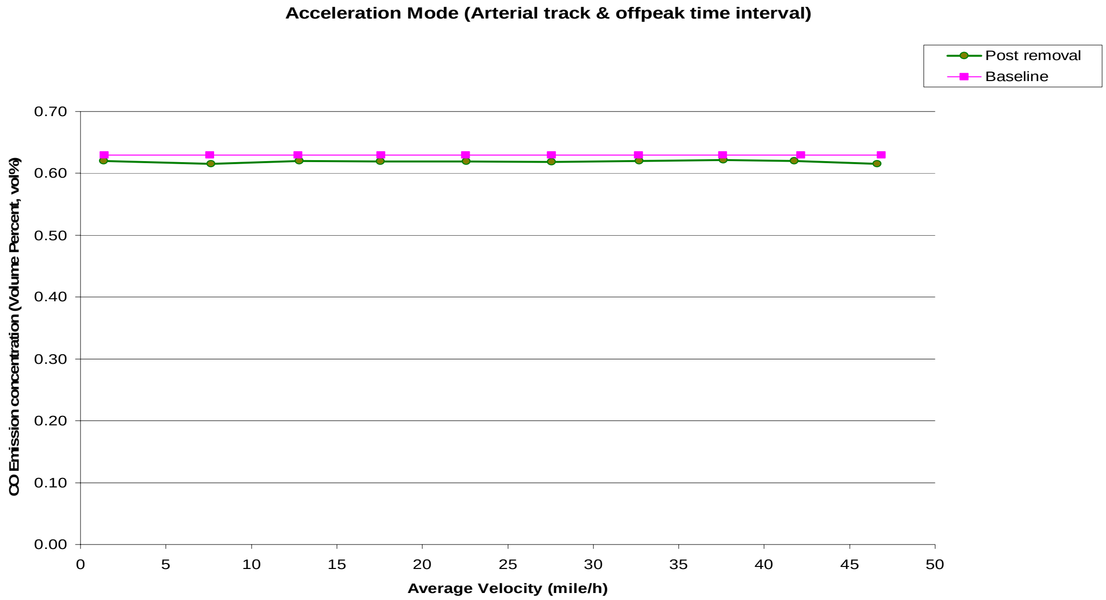
Cruising Mode (Arterial track & peak time interval)

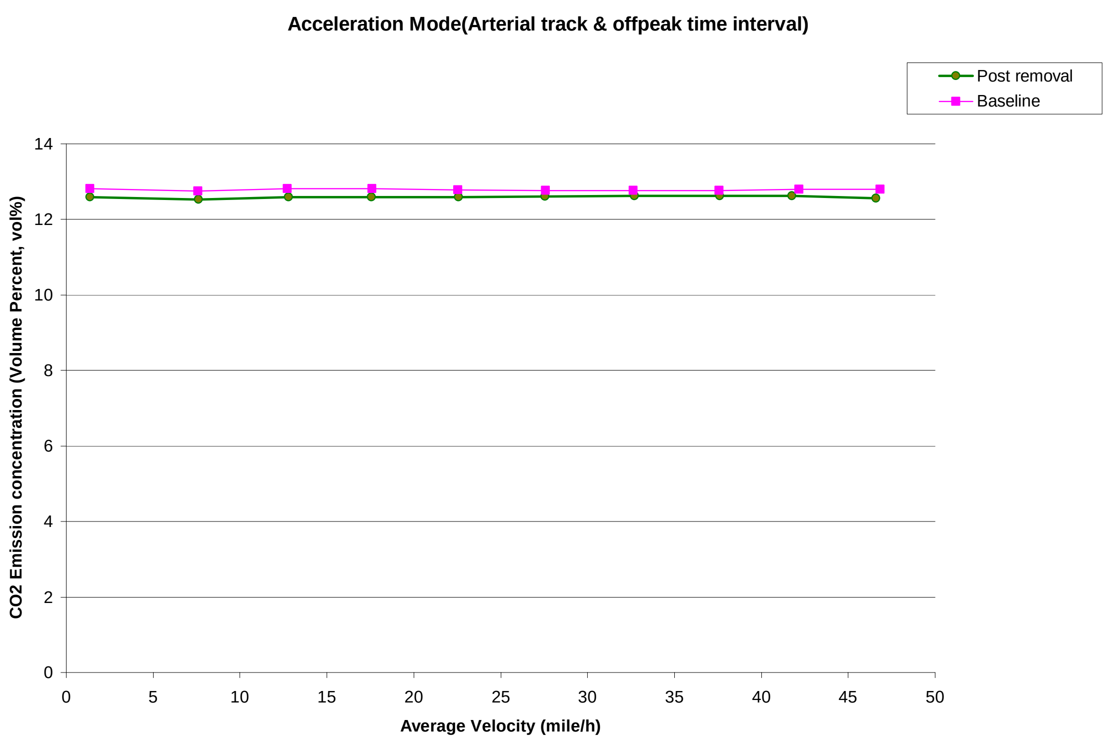


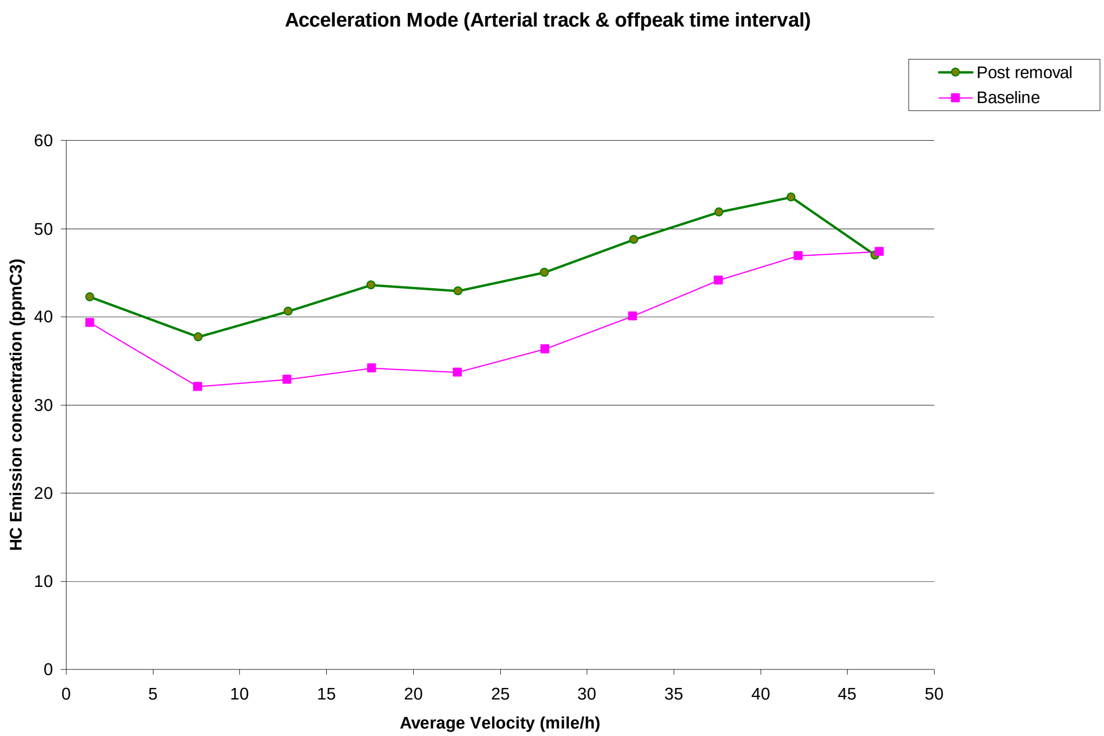
Cruising Mode (Arterial track & peak time interval)

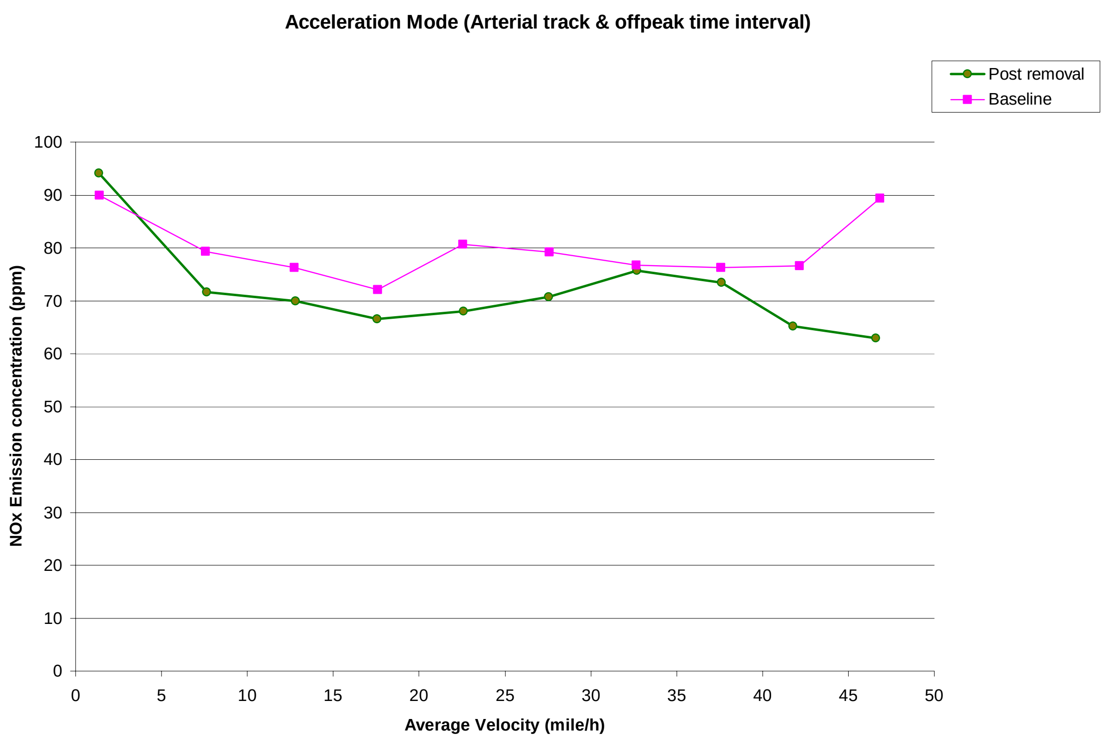


Case C: Graphical comparison of post removal data of arterial test track and off-peak time interval for Acceleration mode

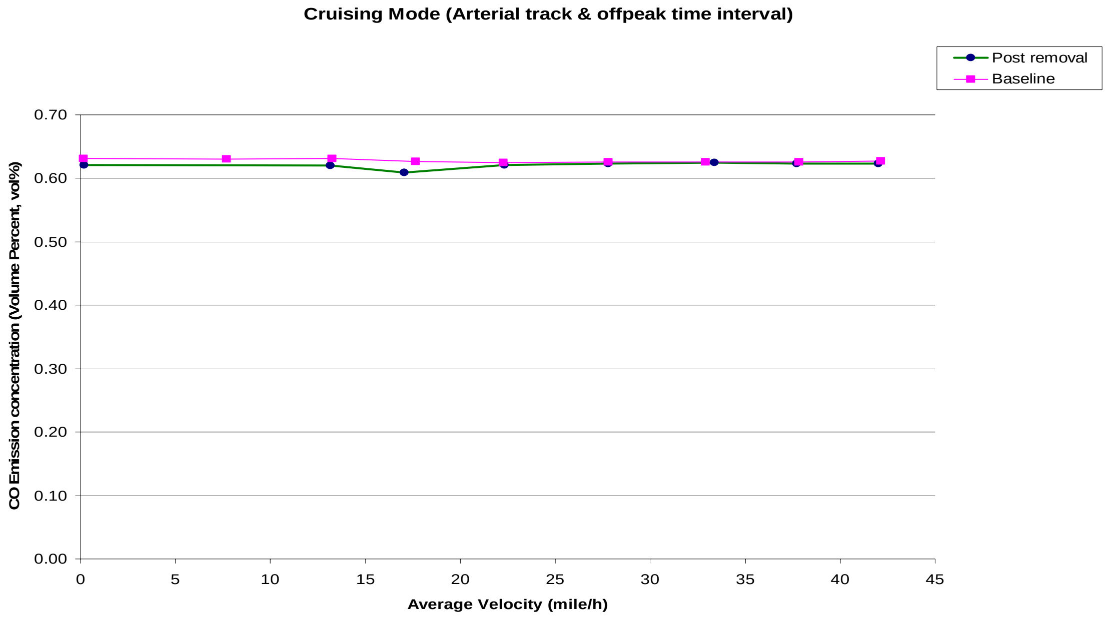


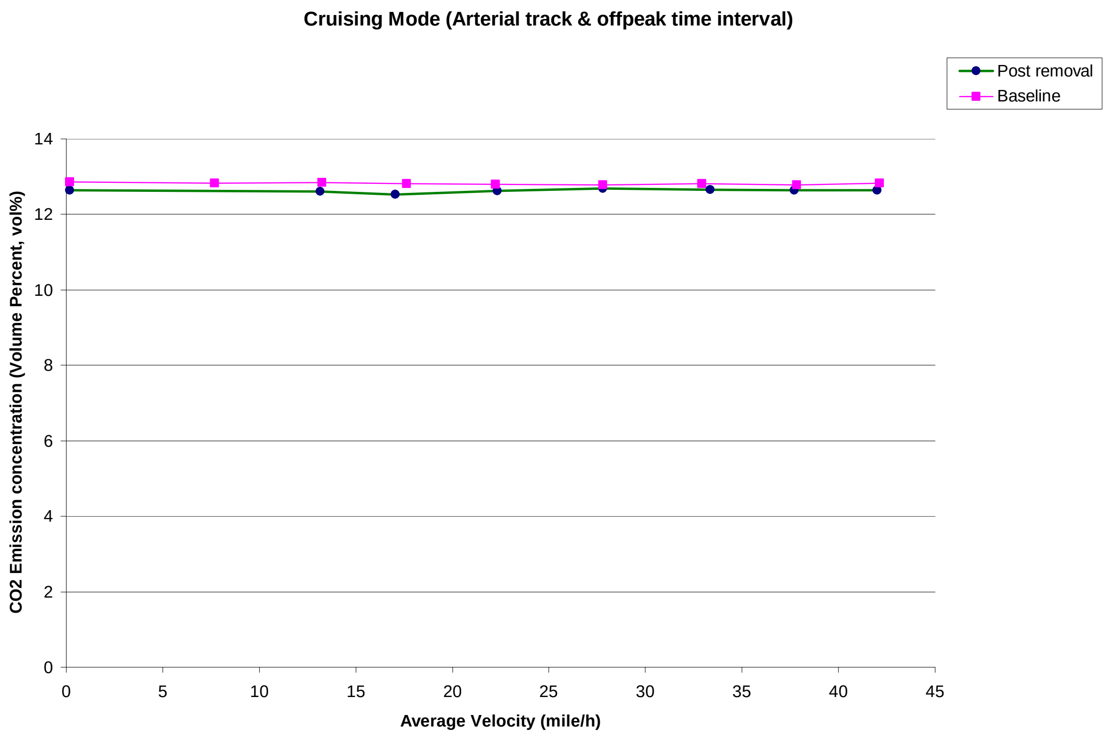



Acceleration Mode (Arterial track & offpeak time interval)
Post removal
Baseline
HC Emission concentration (ppmC3)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45
50
Average Velocity (mile/h)

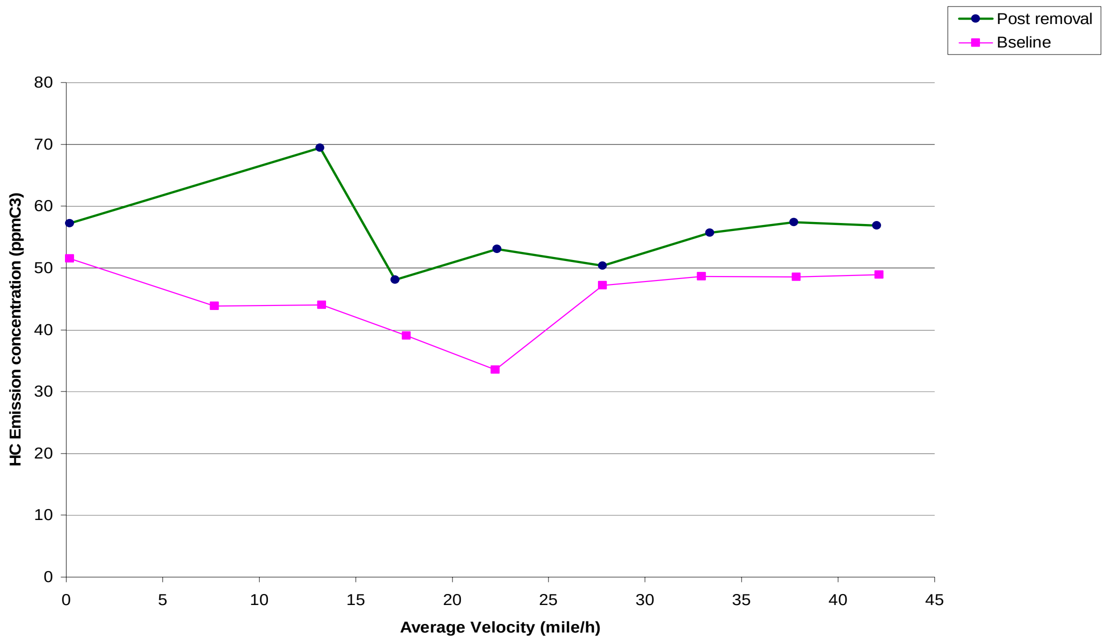

Acceleration Mode (Arterial track & offpeak time interval)
Post removal
Baseline
NOx Emission concentration (ppm)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40
45
50
Average Velocity (mile/h)

Case D: Graphical comparison of post removal data of arterial test track and off-peak time interval for Cruising mode

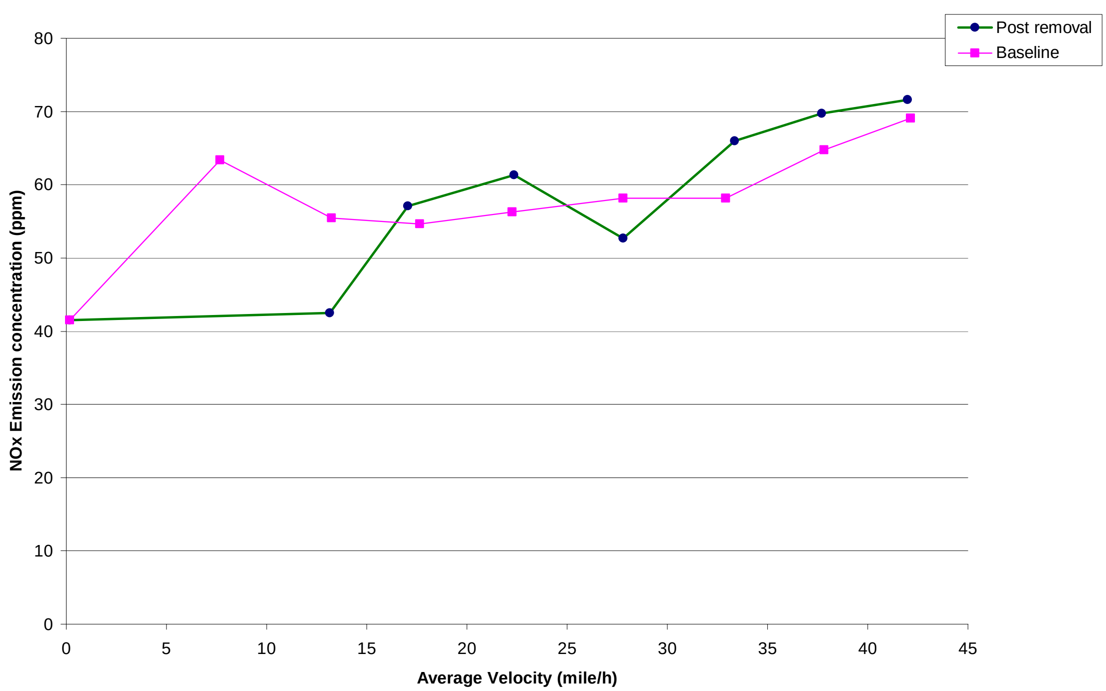




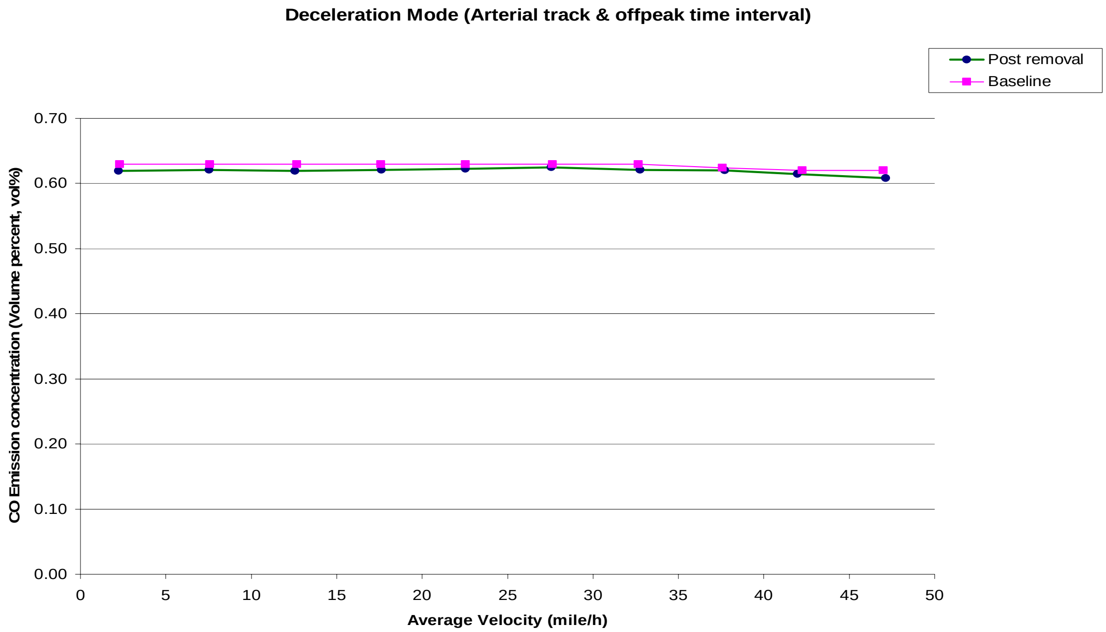
Cruising Mode (Arterial track & offpeak time interval)

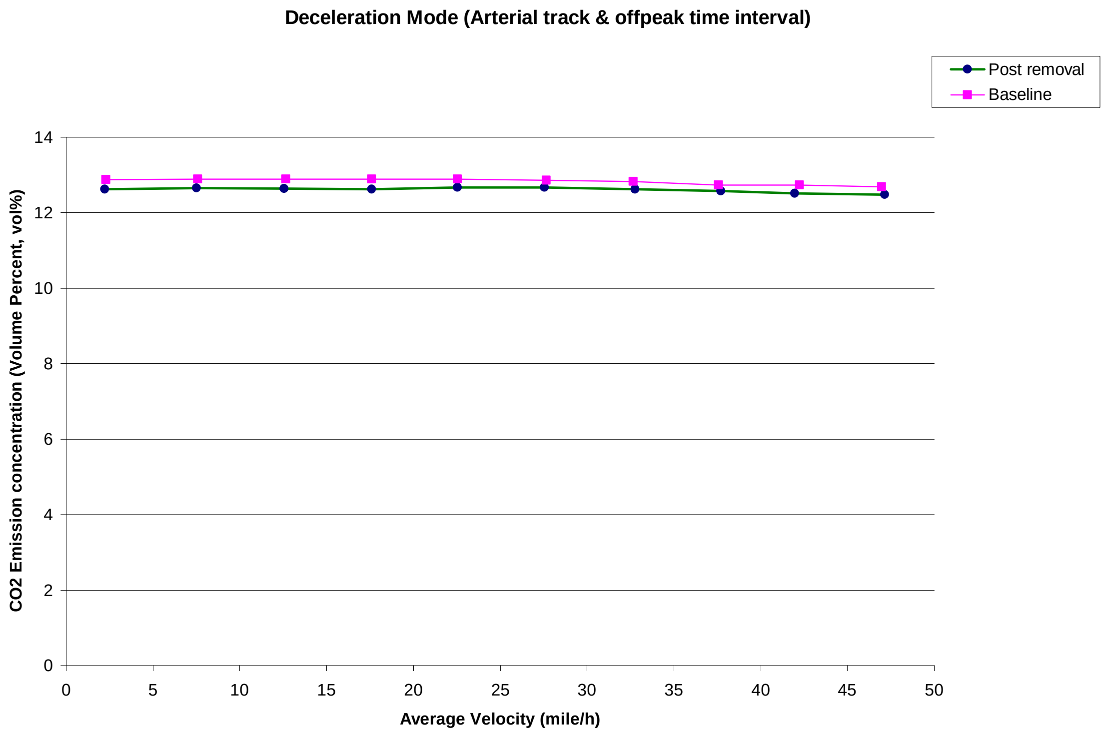


Cruising Mode (Arterial track & offpeak time interval)

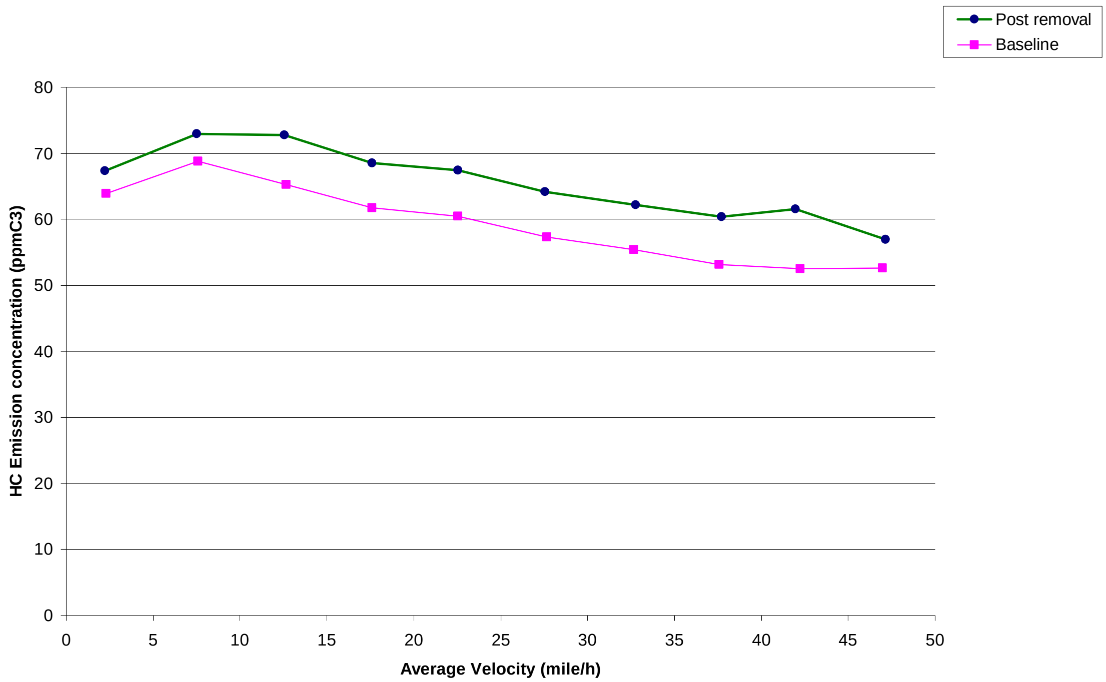


Case E: Graphical comparison of post removal data of arterial test track and off-peak time interval for Deceleration mode

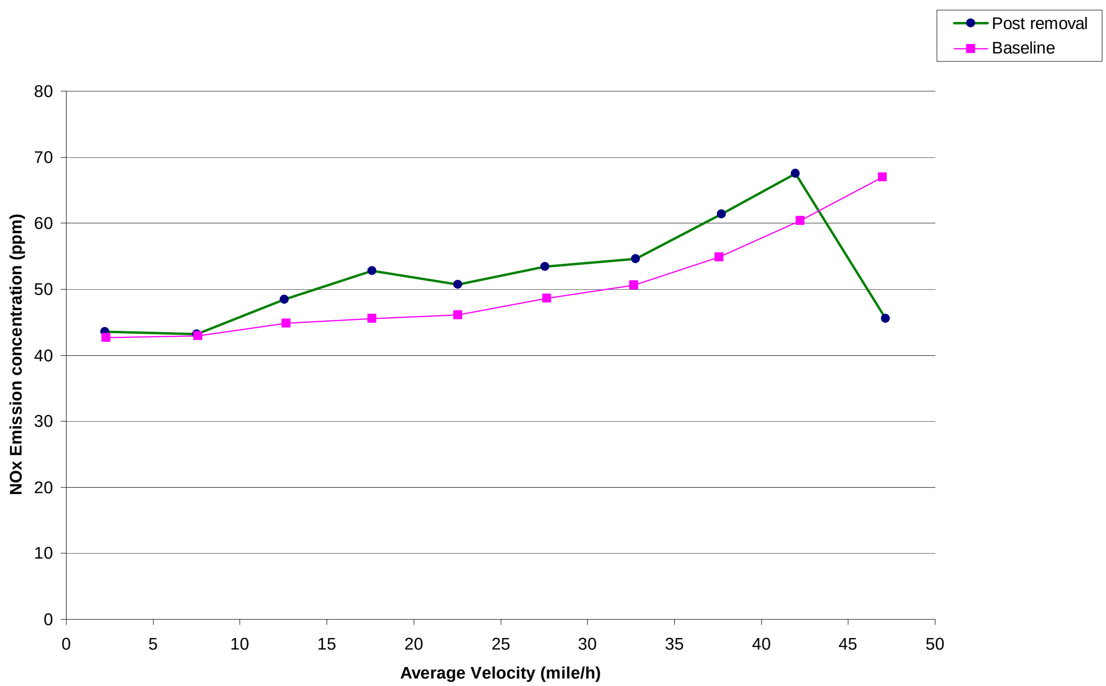




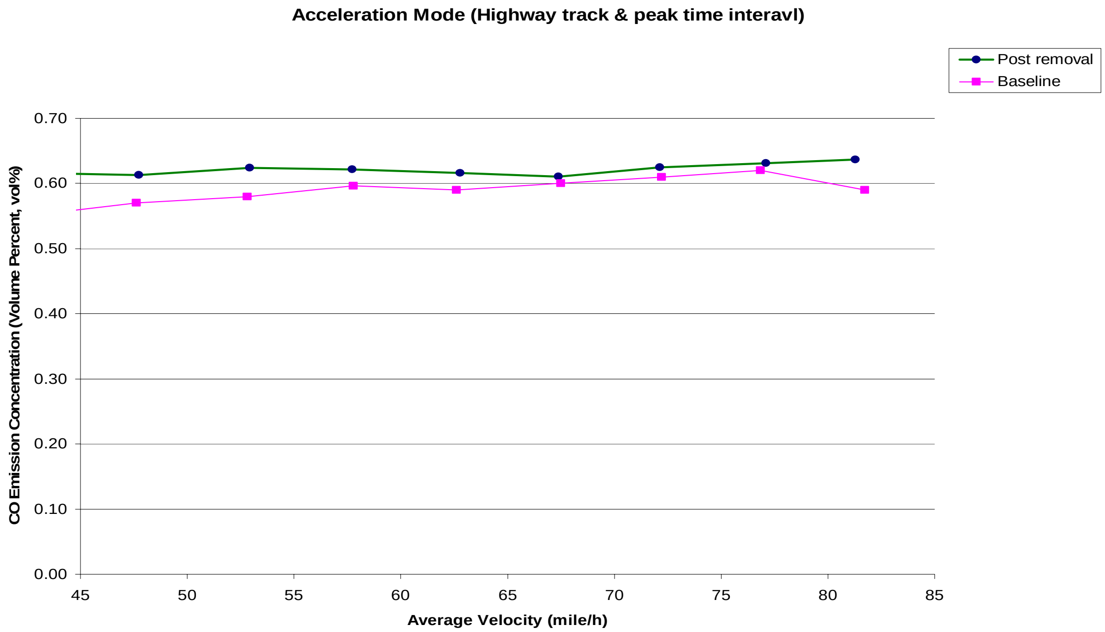
Deceleration Mode (Arterial track & offpeak time interval)

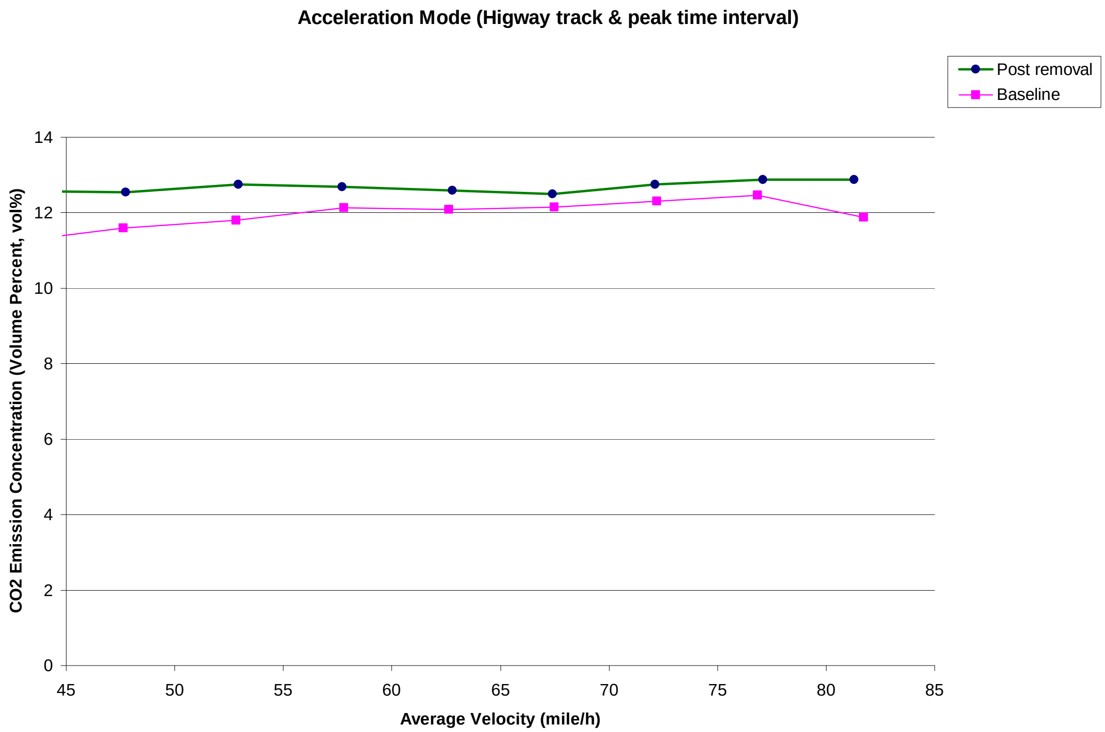


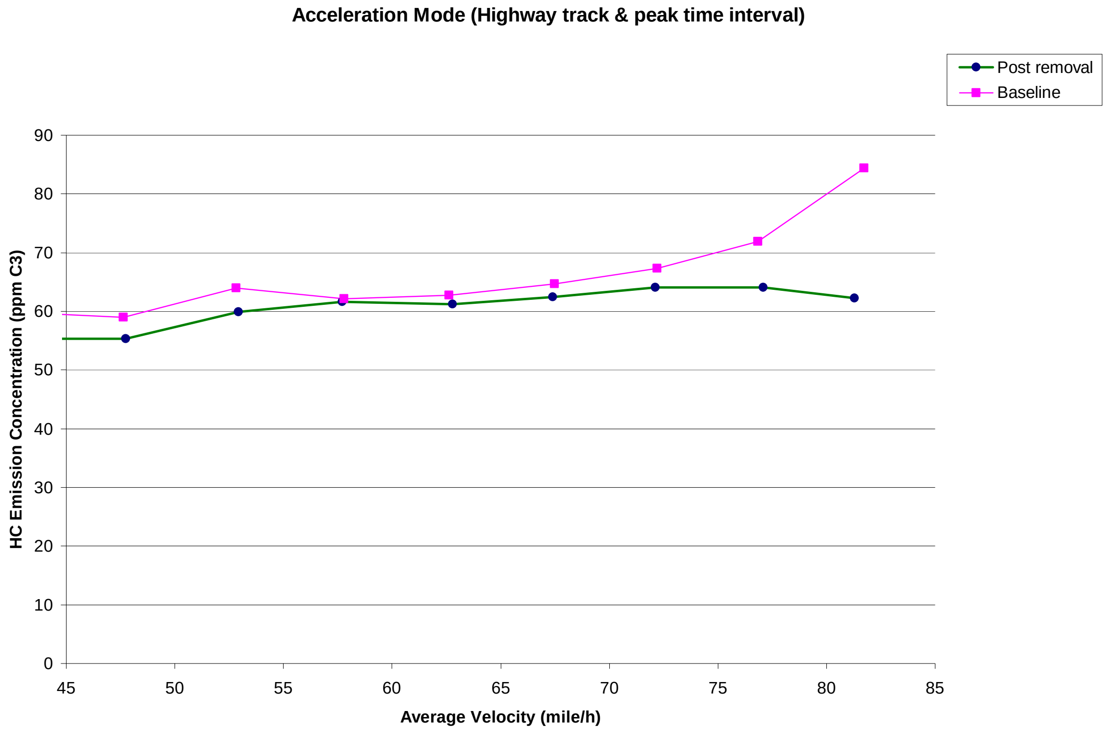
Deceleration Mode (Arterial track & offpeak time interval)

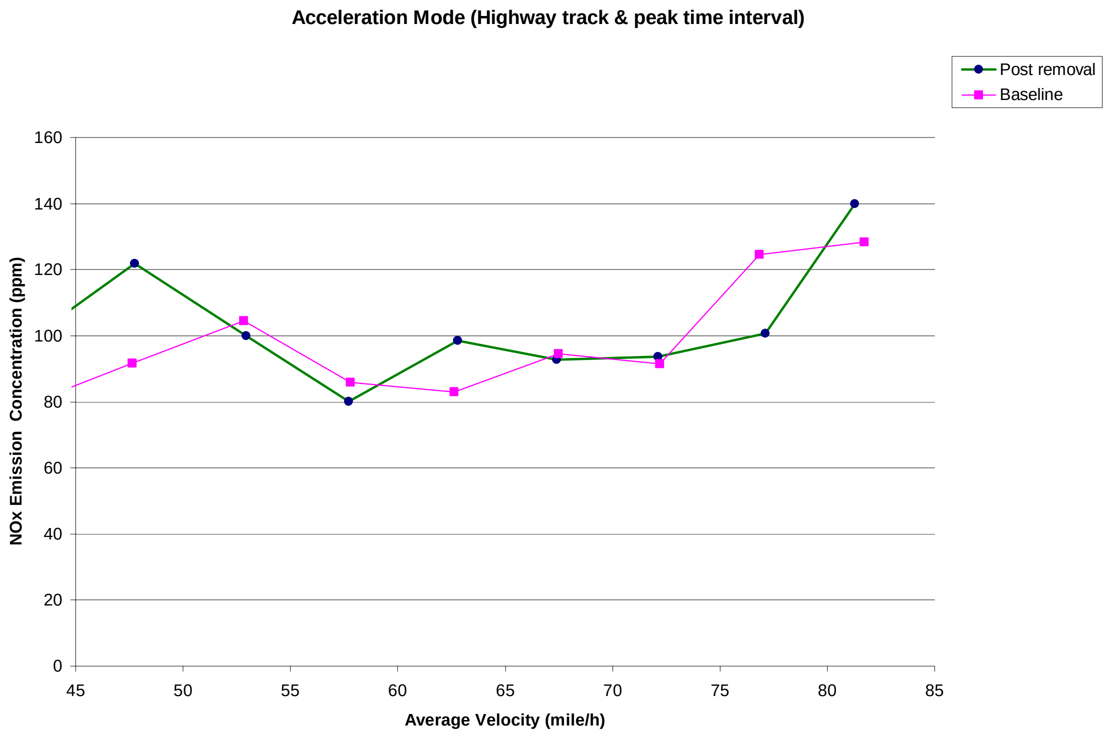


Case F: Graphical comparison of post removal data of highway test track and peak time interval for Acceleration mode

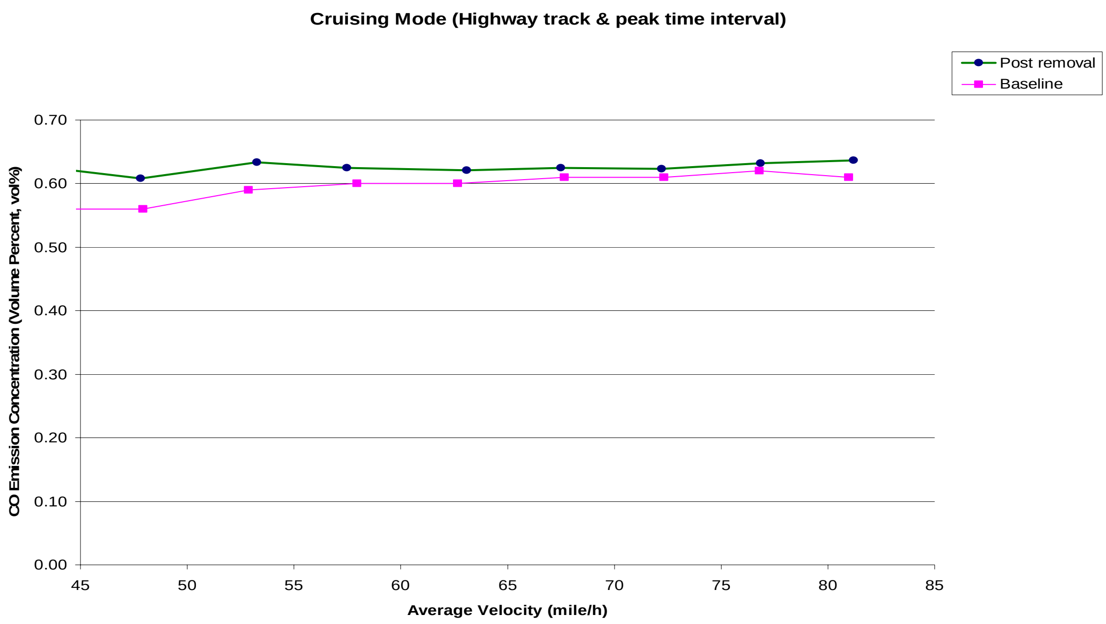


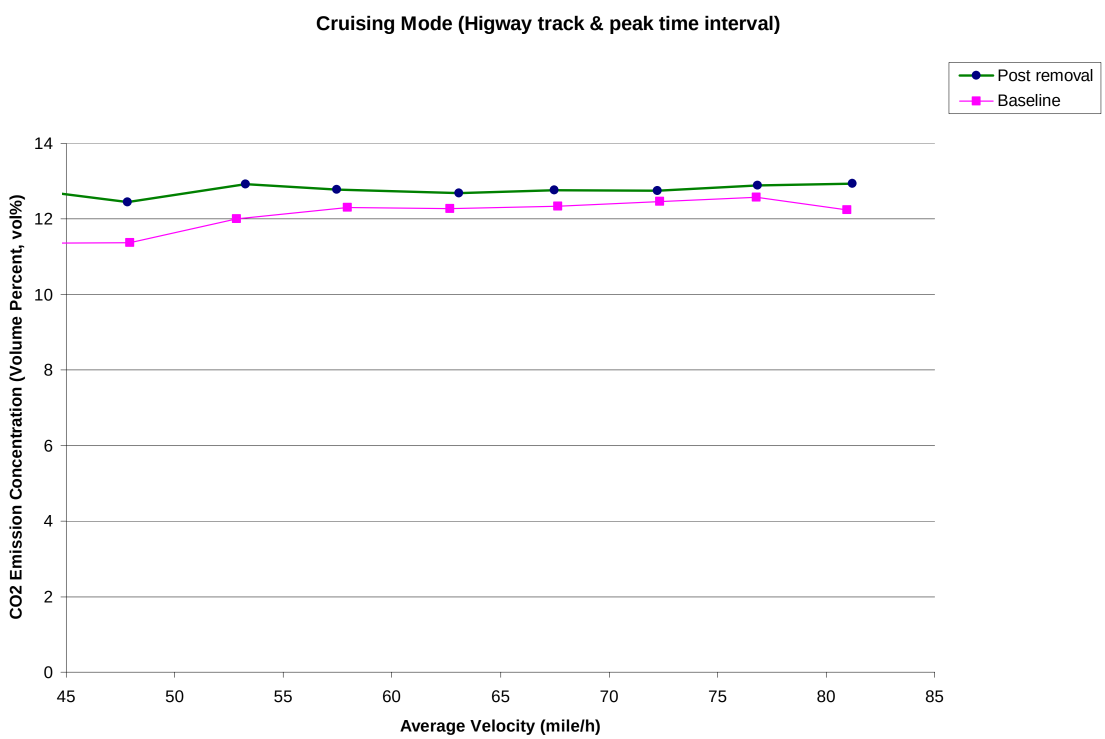


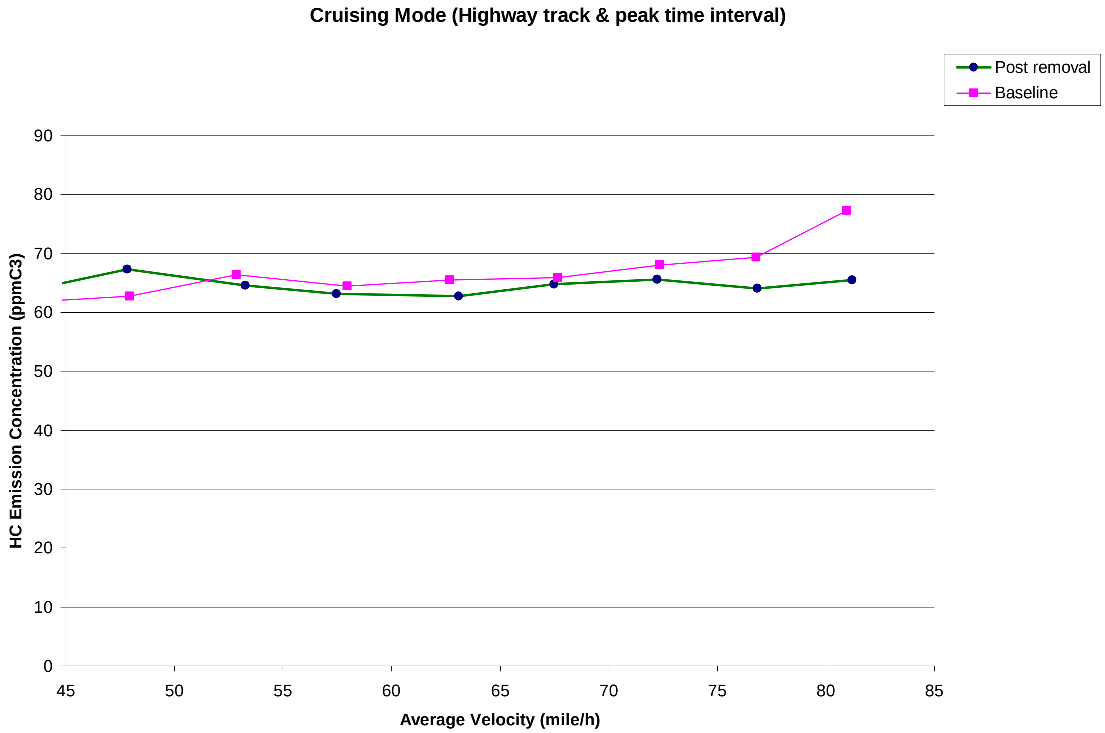

Acceleration Mode (Highway track & peak time interval)
Post removal
Baseline
HC Emission Concentration (ppm C3)
Average Velocity (mile/h)
0
10
20
30
40
50
60
70
80
90
45
50
55
60
65
70
75
80
85

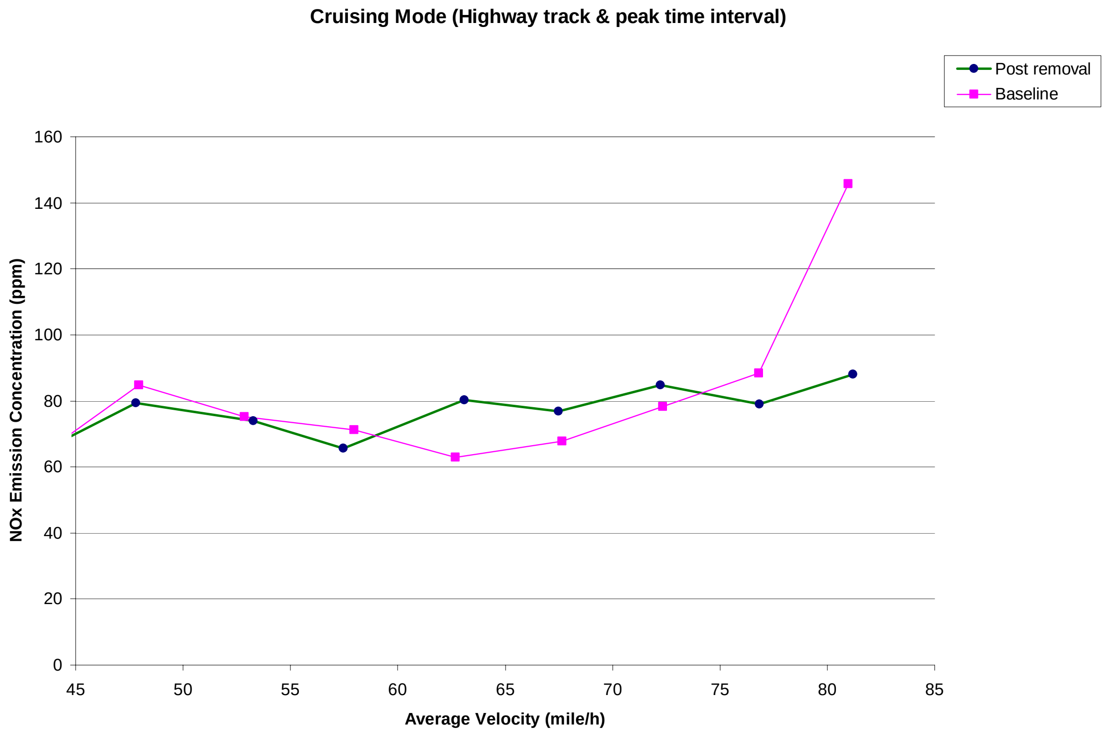

Acceleration Mode (Highway track & peak time interval)
Post removal
Baseline
NOx Emission Concentration (ppm)
Average Velocity (mile/h)
0
20
40
60
80
100
120
140
160
45
50
55
60
65
70
75
80
85

Case G: Graphical comparison of post removal data of highway test track and peak time interval for Cruising mode

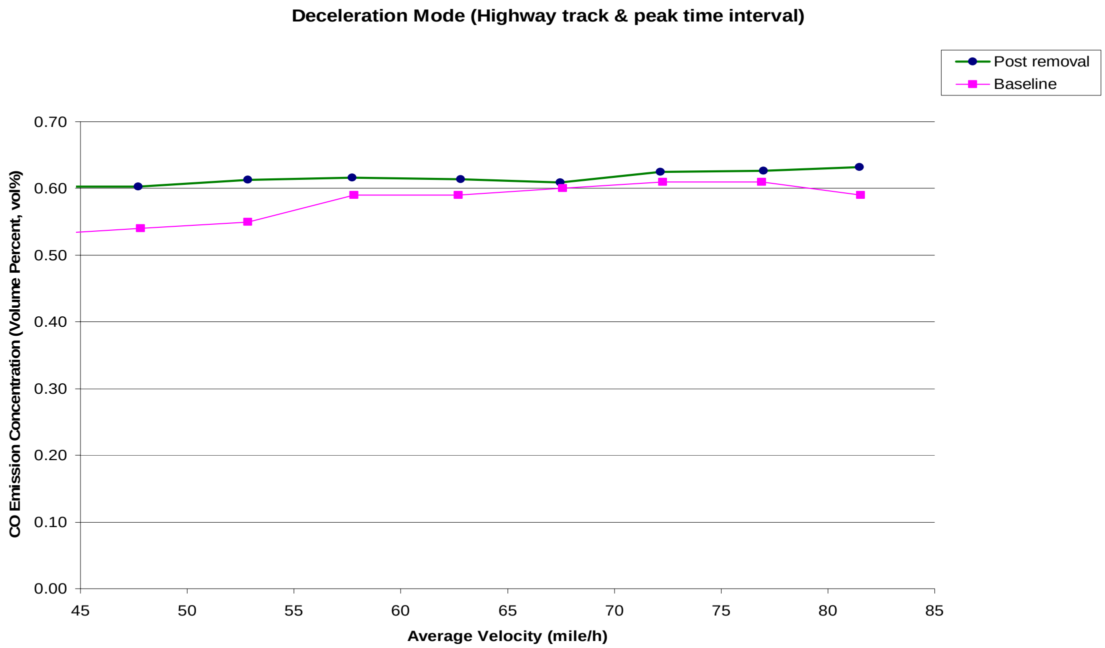


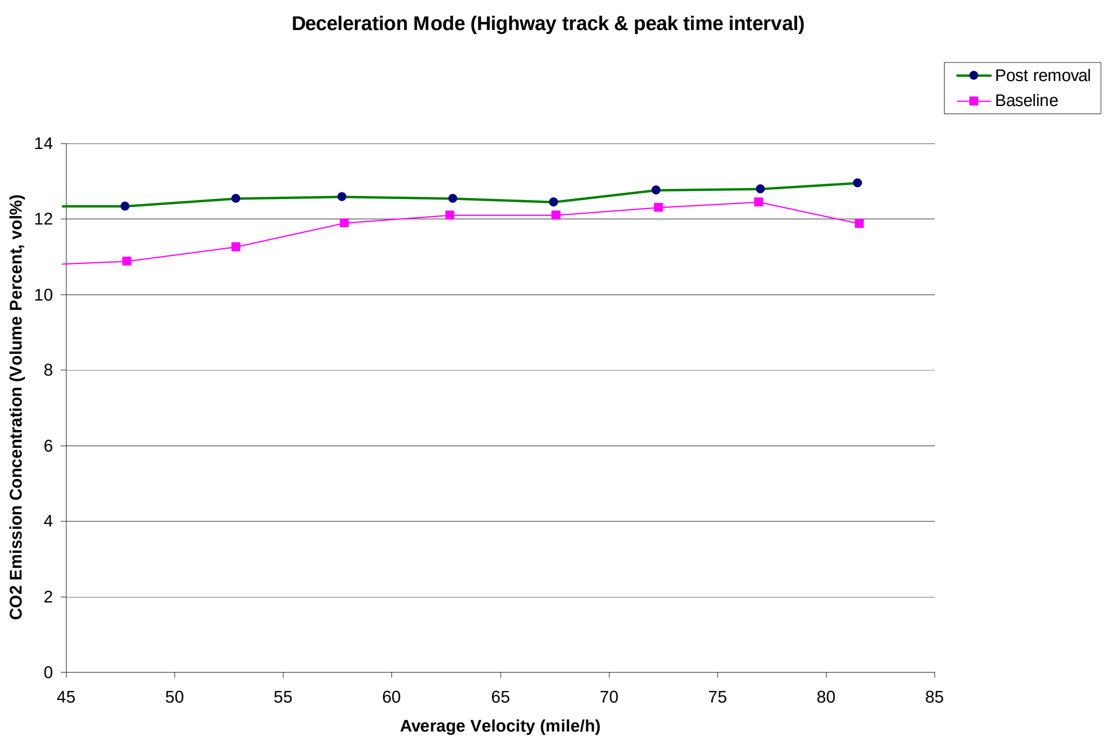


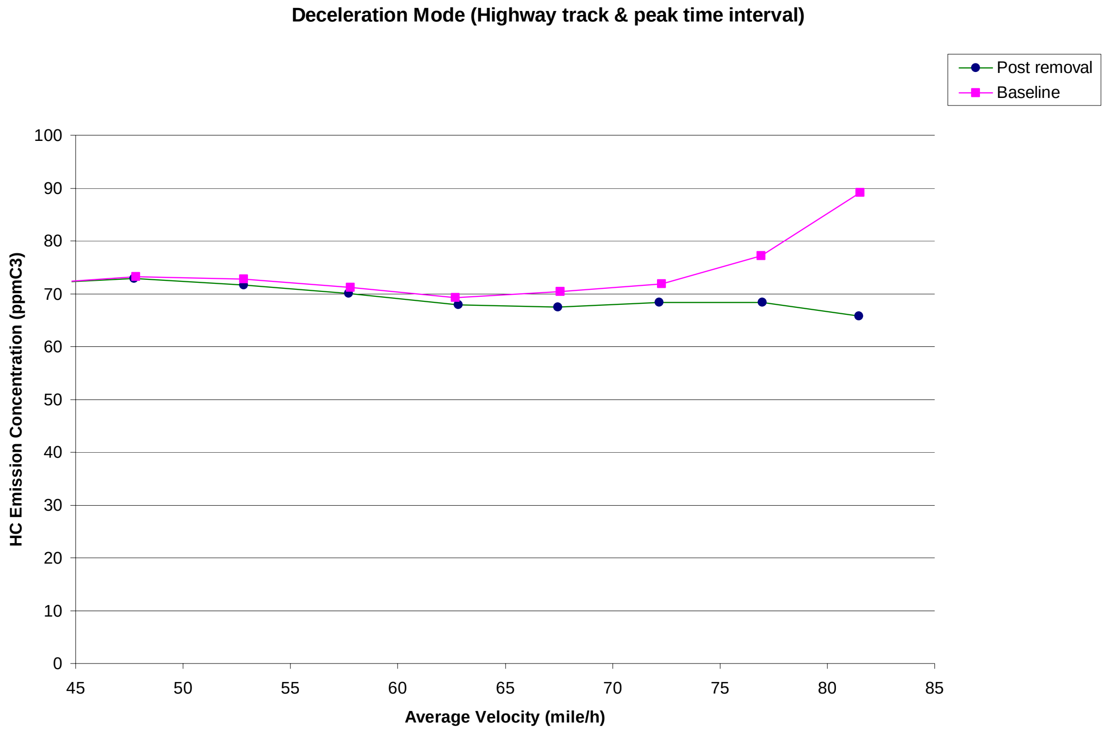

Cruising Mode (Highway track & peak time interval)
Post removal
Baseline
HC Emission Concentration (ppmC3)
90
80
70
60
50
40
30
20
10
0
45
50
55
60
65
70
75
80
85
Average Velocity (mile/h)


Cruising Mode (Highway track & peak time interval)
Post removal
Baseline
NOx Emission Concentration (ppm)
160
140
120
100
80
60
40
20
0
45
50
55
60
65
70
75
80
85
Average Velocity (mile/h)

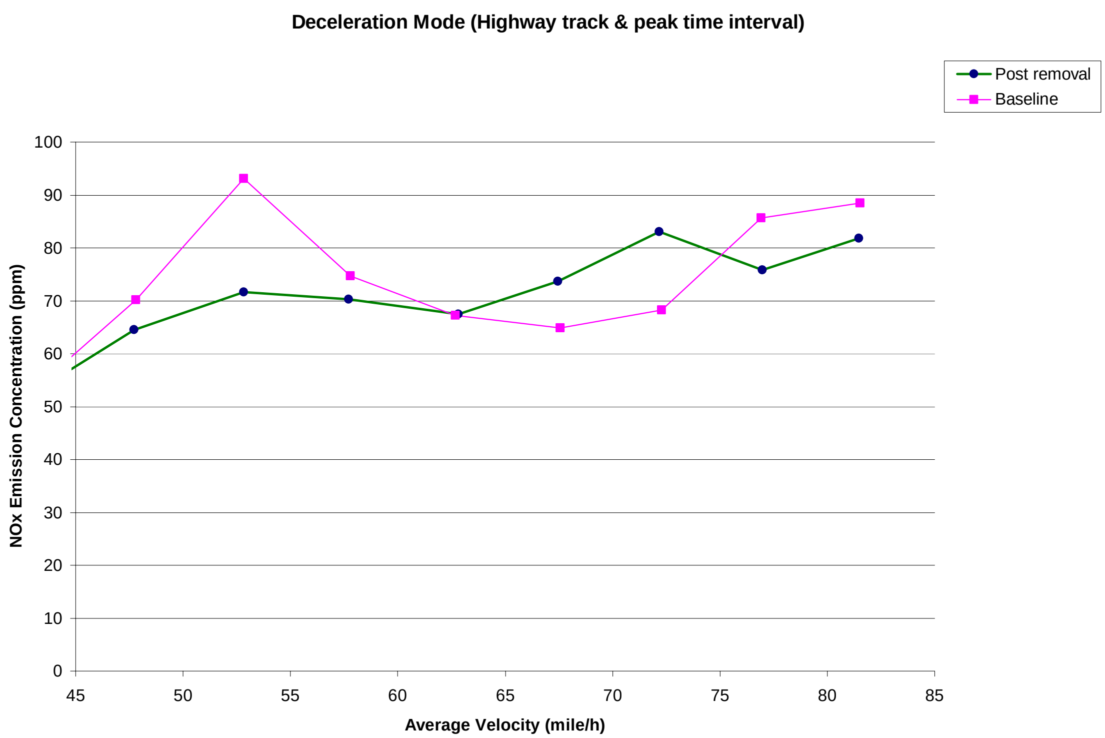
Case H: Graphical comparison of post removal data of highway test track and peak time interval for Deceleration mode





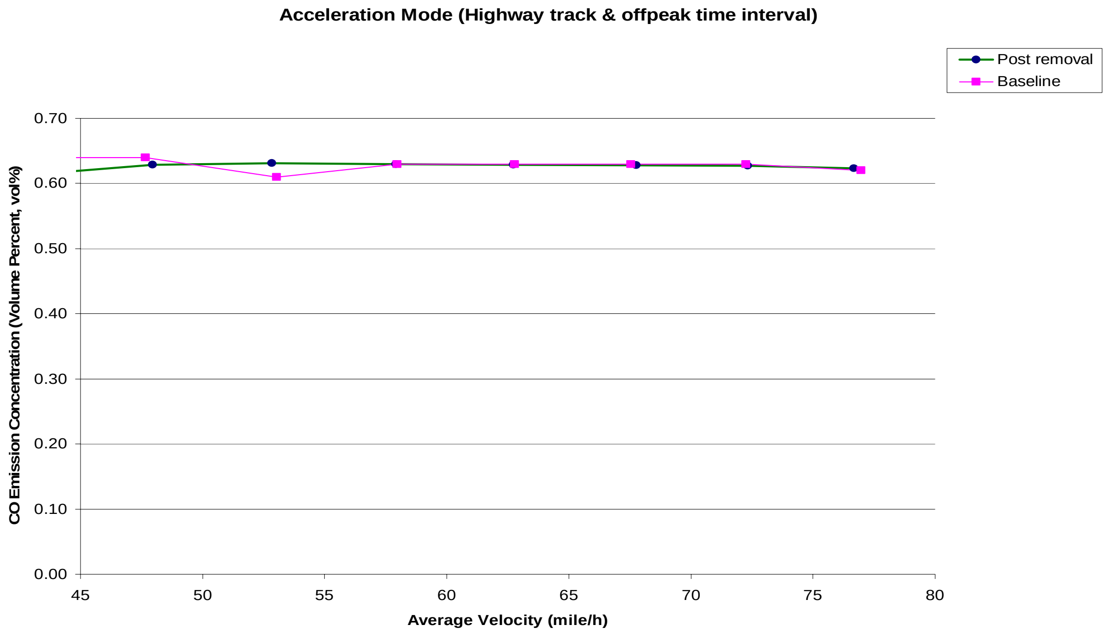


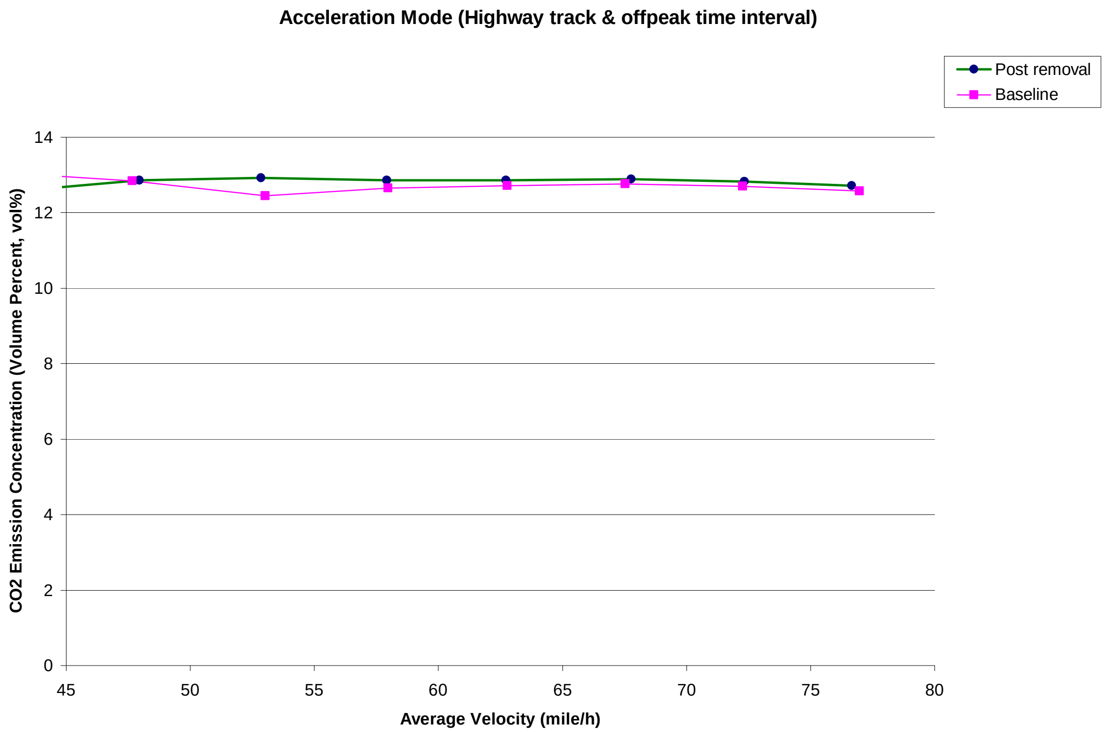
Deceleration Mode (Highway track & peak time interval)
Post removal
Baseline
HC Emission Concentration (ppmC3)
100
90
80
70
60
50
40
30
20
10
0
45
50
55
60
65
70
75
80
85
Average Velocity (mile/h)

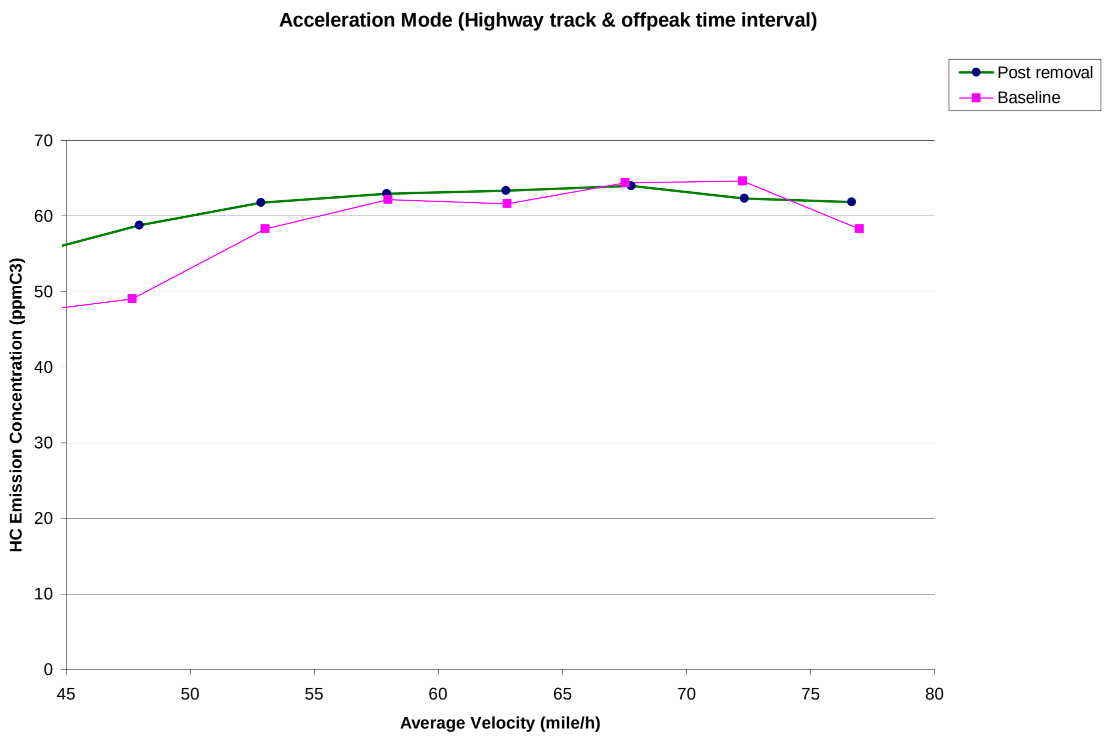


Deceleration Mode (Highway track & peak time interval)
Post removal
Baseline
NOx Emission Concentration (ppm)
100
90
80
70
60
50
40
30
20
10
0
45
50
55
60
65
70
75
80
85
Average Velocity (mile/h)

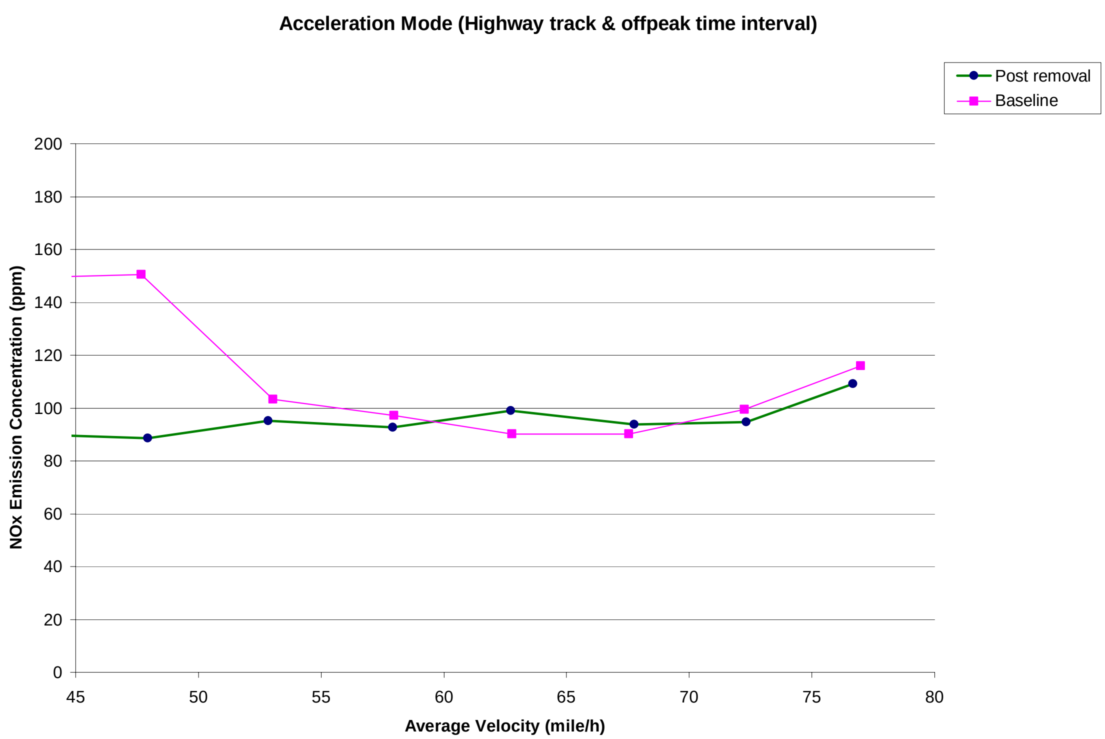
Case I: Graphical comparison of post removal data of highway test track and off-peak time interval for Acceleration mode





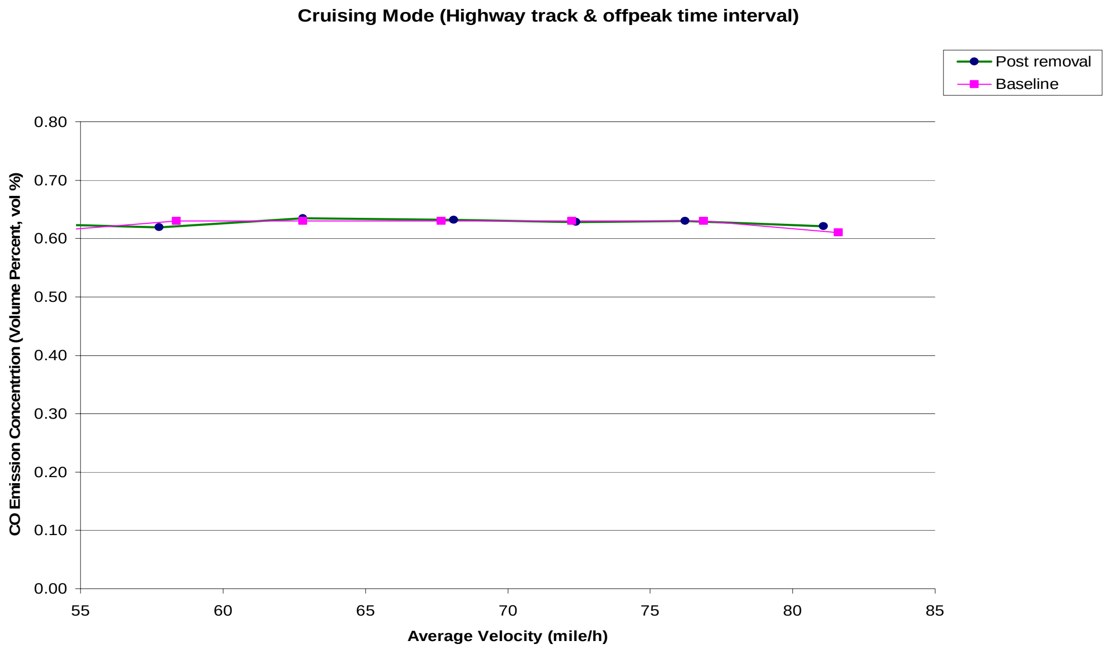


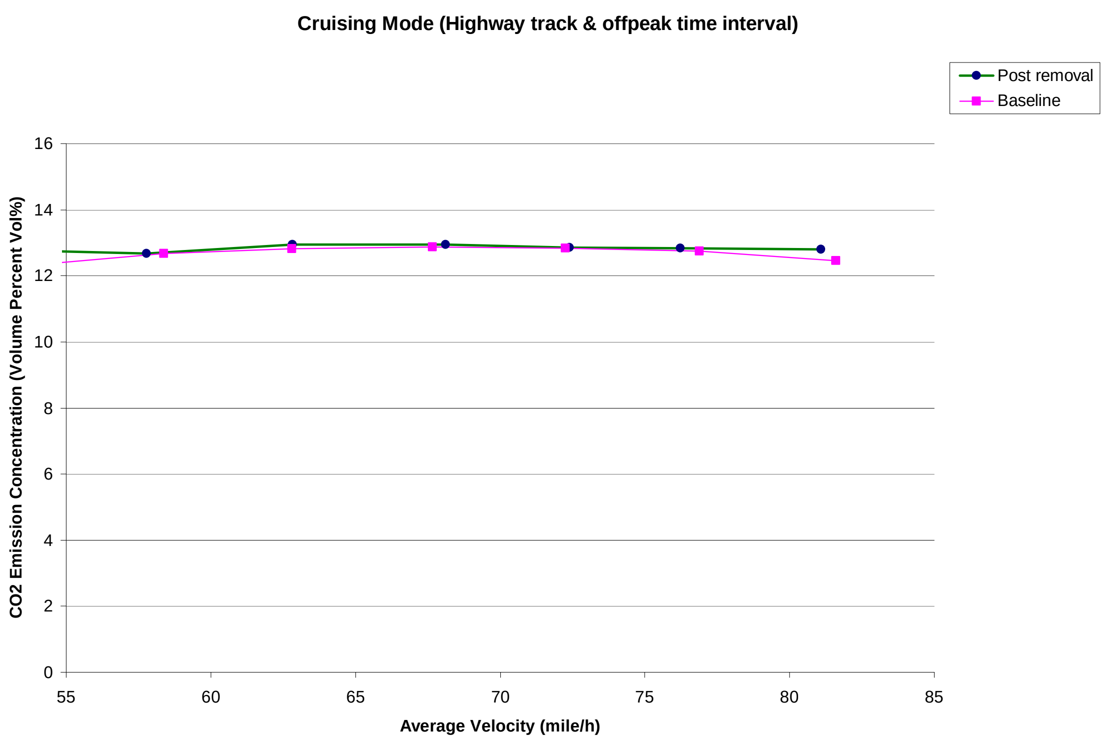
Acceleration Mode (Highway track & offpeak time interval)
Post removal
Baseline
HC Emission Concentration (ppmC3)
Average Velocity (mile/h)
0
10
20
30
40
50
60
70
45
50
55
60
65
70
75
80

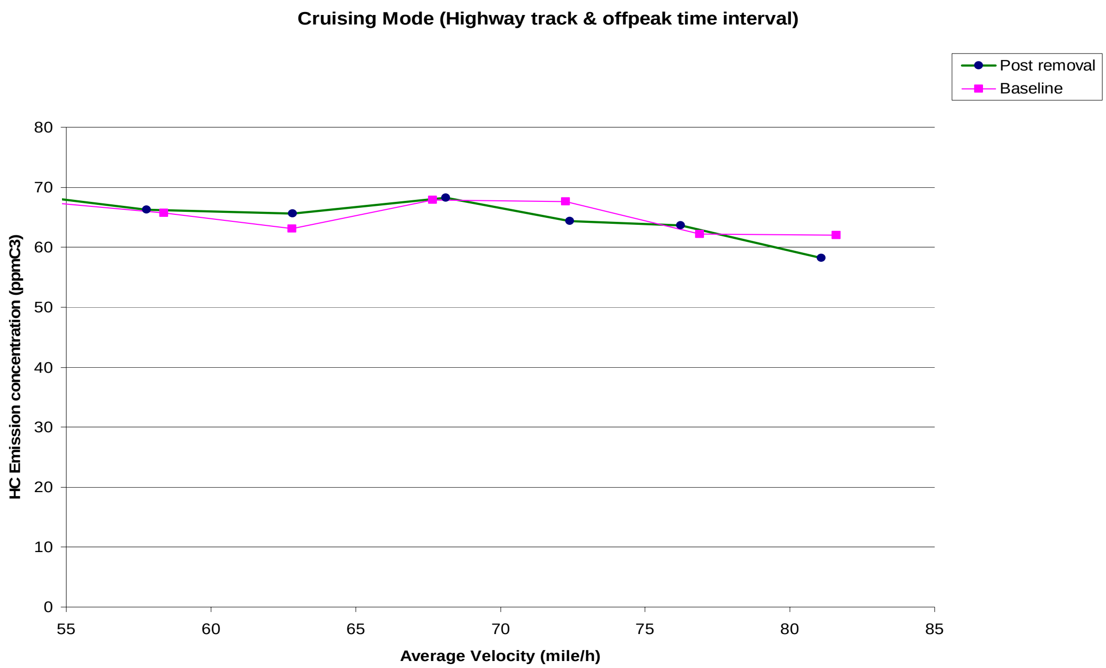


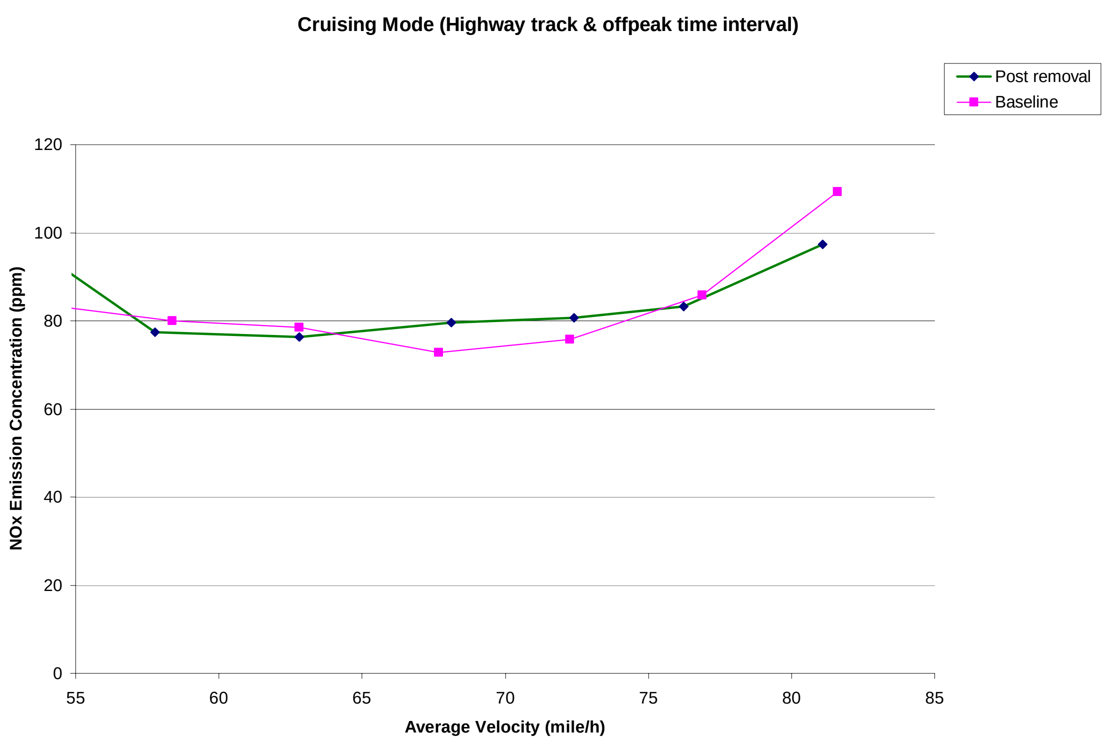
Acceleration Mode (Highway track & offpeak time interval)
Post removal
Baseline
NOx Emission Concentration (ppm)
Average Velocity (mile/h)
0
20
40
60
80
100
120
140
160
180
200
45
50
55
60
65
70
75
80

Case J: Graphical comparison of post removal data of highway test track and off-peak time interval for Cruising mode






Cruising Mode (Highway track & offpeak time interval)
Post removal
Baseline
HC Emission concentration (ppmC3)
80
70
60
50
40
30
20
10
0
55
60
65
70
75
80
85
Average Velocity (mile/h)


Cruising Mode (Highway track & offpeak time interval)
Post removal
Baseline
NOx Emission Concentration (ppm)
120
100
80
60
40
20
0
55
60
65
70
75
80
85
Average Velocity (mile/h)

REFERENCES

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

Kanukolanu, Sriharsha., (2006). *Impact of a pre-combustion retrofit device on Vehicular Emissions: A case study.* M.S thesis, University of Texas at Arlington.

Parikh, Rajashi., (2006). *Effect of Signal Coordination as Emission Reduction measure for Vehicles.* M.S thesis, University of Texas at Arlington.

Bhatt, Hetal H., (2005). *Determination of safe buffer width of roadway to protect human health from harmful* NO_X *exposure.* M.S thesis, University of Texas at Arlington.

Sattler, Melanie L., University of Texas at Arlington, "Transportation and Air Quality" class notes, Fall 2005.

Horiba Instruments Inc., Horiba Ltd. *On-board Emission Measurement System OBS-1000 Instructional Manual*, 2003.

North Central Texas Council of Governments., http://www.nctcog.org/. Accessed in September – October 2006.

U.S Environmental Protection Agency., http://www.epa.gov/, Accessed in September 2006.

Texas Commission of Environmental Quality., http://www.tceq.com, Accessed in September 2006.

Environmental NW fuel reformulator in Vancouver, Washington – Ester Technology, Accessed in October 2006.

http://www.ethosfrglobal.com/, Accessed in October 2006.

http://www.ethosfr.com/OurProduct/ProductsOverview.html - Ethos® Emissions.

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.

Tong, Hing Yan., (2001). *Vehicular Emissions and Fuel Consumption At Urban Traffic,Vehicular Nitrogen Oxide Emissions.* M.S. thesis, University of Texas at Arlington.

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

BIOGRAPHICAL INFORMATION

Shruthi Satyanarayan was born on February 18th, 1982. She earned her Bachelor degree in Civil Engineering from B.M.S College of Engineering, Bangalore, India. Later she worked as a teaching assistant in the same university and helped the students with Environmental theory as well as lab which motivated her to pursue her higher studies.

She completed her M.S in Environmental Engineering in December 2006, with Air Quality as her major at University of Texas at Arlington. During her tenure she was appointed as Graduate Research Assistant by Dr. Melanie Sattler. Her Master's thesis was based on "Trends of vehicular emissions due to the effect of Ethos® FR as fuel additive". The main objective of the research was to verify any significant difference in the emissions trends of CO, CO_2, HC and NO_X with application of the fuel additive in DFW metroplex. She has also been an active member and treasurer of Air & waste Management Association student chapter at University of Texas at Arlington.