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IMPACT OF A PRE-COMBUSTION RETROFIT DEVICE ON VEHICULAR EMISSIONS: A CASE STUDY

by

SRI HARSHA KANUKOLANU

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

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DEDICATED TO MY PARENTS AND MY BROTHER

“*pillars of my strength*”

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ABSTRACT

IMPACT OF A PRE-COMBUSTION RETROFIT DEVICE ON VEHICULAR EMISSIONS: A CASE STUDY

Publication No. ______

Sri Harsha Kanukolanu, M.S.

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Vehicular emissions are a major cause of air pollution in the cities worldwide. Increased numbers of vehicles and the vehicle miles traveled by them every year means that the emissions are going to have a detrimental effect on the life and environment of this planet. Various control strategies are employed by the transportation and air quality managers at the state and regional levels to improve the ambient air quality.

This research was conducted as part of the North Central Texas Council of Governments‟ Aftermarket Technology and Fuel Additive Research Program, its effort to make the DFW region‟s air cleaner. The DFW Metroplex is designated as a “non-attainment” area for ozone. 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 carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and nitrogen oxides (NOx), under on-road traffic conditions. Emission measurements were carried out for 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 has a major impact on NOx emissions, with a maximum decrease of 26.2% occurring at highway track‟s off-peak acceleration mode. A significant decrease in emissions of CO_2 could also be seen in case of all the modes and both the time intervals on an arterial test track.

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CHAPTER 1

INTRODUCTION

1.1 Air Pollution and Mobile Sources

One of the main problems that the world is facing today is the menace of air pollution. Mobile, industrial and natural sources form the core of the air pollution sources. Most of the main cities of the world like Los Angeles, Beijing, Delhi, and Tokyo are today battling severe air pollution caused by mobile sources, i.e. vehicular emissions. According to the U.S. Environmental Protection Agency (EPA), in 2003, all the mobile sources in the U.S. contributed:

79% of all carbon monoxide (CO) emissions,

53% of all nitrogen oxides (NOx) emissions,

43% of all volatile organic compounds (VOC) emissions,

21% of all particulate matter ($PM_{2.5}$) emissions,

30% of all carbon dioxide (CO_2) emissions.

1.1.1 Why is air pollution from vehicles a problem?

The National Ambient Air Quality Standards (NAAQS) set by the EPA consider VOCs, NOx, CO, lead (Pb), sulfur dioxide (SO_2), and ozone (O_3) as the six principal air pollutants that are known to cause damage to the environment and public health. These pollutants in one way or another contribute to effects like acid rain deposition, formation of ozone and particulates, and various health hazards to living life, depending upon the level and period of exposure to a particular pollutant. Air pollution from mobile source is also known to be a major cause for visibility reductions in cities worldwide.

1.2 Various Control Measures in Use to Reduce Vehicular Emissions

Since the amendments to the Clear Air Act in 1970 and the subsequent formation of the EPA in that same year, various measures where initiated by the state and regional transportation and air quality managers to meet the NAAQS. Some of the main control measures that are in use now are:

Changes in the vehicle to reduce emissions

- a) Engine changes
- b) Use of alternative fuels
- c) Use of retrofit devices to control tailpipe emissions

Reducing emissions via changes in vehicle operating conditions

- a) Speed limit reductions
- b) Intersection improvements
- c) Signalization improvements
- d) Intelligent transportation systems
- e) Driver behavior education

Reducing the number of vehicles on the road

- a) Encouraging carpooling
- b) Promoting the use of mass transit systems
- c) HOV lines

Reducing the number of miles traveled per vehicle

a) Trip chaining

b) Land use planning

(Adapted from Sattler, Transportation & Air Quality Course, UTA, Fall 2004)

Among the various available measures/technologies mentioned above, my scope of research focuses on the performance of a new retrofit device, a pre-combustion catalytic converter, fitted to a Chevy 2000 Van. The data is collected under real world conditions using an on-board system to measure the tail pipe emissions.

1.3 Why is Emission Measurement Important?

For the Dallas-Fort Worth (DFW) region, Figure 1.1 shows the various source percentage contributions for NOx and VOC emissions in 2005.

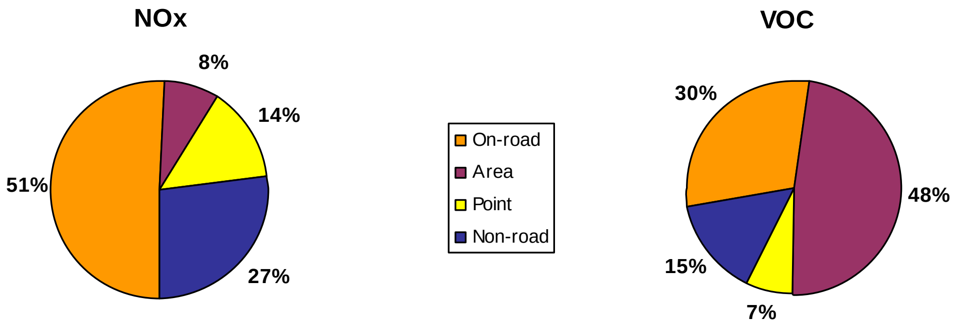

Figure 1.1 DFW Region, 2005 Emissions (Source: NCTCOG's Transportation Department)

We can see here that the on-road sources contribute to significant percentages of NOx and VOCs. These two pollutants are significant in the fact that they are precursors to ozone formation; the DFW region is a “non-attainment” region under the 8-hour ozone standard.

CO and CO_2 emission measurement is also very important. Carbon dioxide is the most prevalent of all the greenhouse gases. It falls under the category of greenhouse gases that are produced by various industrial and vehicular activities, as well as which occur in nature. CO_2 in nature is produced from plant decay and events like forest fires and volcanic explosions. Greenhouse gases have the ability to trap excessive heat in the atmosphere, resulting in heating up of the earth‟s surface and thus contributing to global warming.

In the case of CO, which is one of the criteria pollutants, exposure to high levels is known to be lethal to humans and animals. It quickly enters the bloodstream through the lungs and reduces oxygen delivery to vital organs by poisoning the hemoglobin in the blood, leading to death if unattended to immediately. In cities, 85 to 95 percent of all CO emissions may come from on-road vehicles (EPA). Though the present levels of CO in ambient air in the U.S. do not pose any threat to humans, it is a problem in places with highly congested traffic. Ten counties in the U.S. fall under “non-attainment” regions as off March 2006 (EPA). Wood-burning stoves, incinerators and industrial sources are other major sources of CO.

Moreover, emission inventories that make up an important component of the State Implementation Plan (SIP), a compliance blueprint that a “non-attainment” region needs to develop, need to have accurate and real world emission data inputs for their effective use. These emission inventories are inputted into a regional photochemical model to predict ozone concentrations. Hence, emission measurement of NOx and VOCs are also important for the success of the SIP.

Thus, this research focuses on measuring on-road NOx, VOC, CO and CO_2 emissions from the tailpipe.

1.4 North Central Texas Council of Governments (NCTCOG) Aftermarket Technology and Fuel Additive Research Program

As part of their initiative to make the North Texas air cleaner, one of the programs that NCTCOG administers is the Aftermarket Technology and Fuels Research program to evaluate retrofit devices and fuel additives that claim to reduce vehicle exhaust emissions. The University of Texas at Arlington‟s Department of Civil & Environmental Engineering conducts the required emission testing as a research partner to NCTCOG.

This research involves the testing of the Clean Air Associates‟ pre-combustion retrofit device as part of the Aftermarket Technology Research program.

1.5 Research Objectives

The main objective of this research project was to determine whether the pre-combustion device provided by the Clean Air Associates Inc. significantly reduces NOx, VOC, CO and CO_2 emissions.

1.6 Overview of Thesis Report

Table 1.1 lists the overall organization of the thesis.

Table 1.1 Overall Thesis Report Organization

Chapters	Contents
2	This chapter consists of literature review of similar studies carried out using pre-combustion devices.
3	This chapter discusses the methodology of the emission data collection.
4	This chapter reviews results and analysis of the collected emission data.
5	This chapter discusses the conclusions deduced from the analysis of the data. It also contains recommendations and the future scope of research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

2.1.1 Background

Vehicular transportation is a major form of transportation for the movement of people, goods and supplies, from one place to another, worldwide. Economies around the world thrive mainly because of vehicular traffic. As explained earlier, vehicles contribute a major percentage of emissions every year in the United States. Though cars today are 90% cleaner than they used to be in the early 70‟s (EPA), the problem is with the increased number of vehicles on the road and the Vehicle Miles Traveled (VMT) by them. Figure 1.1 illustrates this increase in the VMT over a span of 35 years.

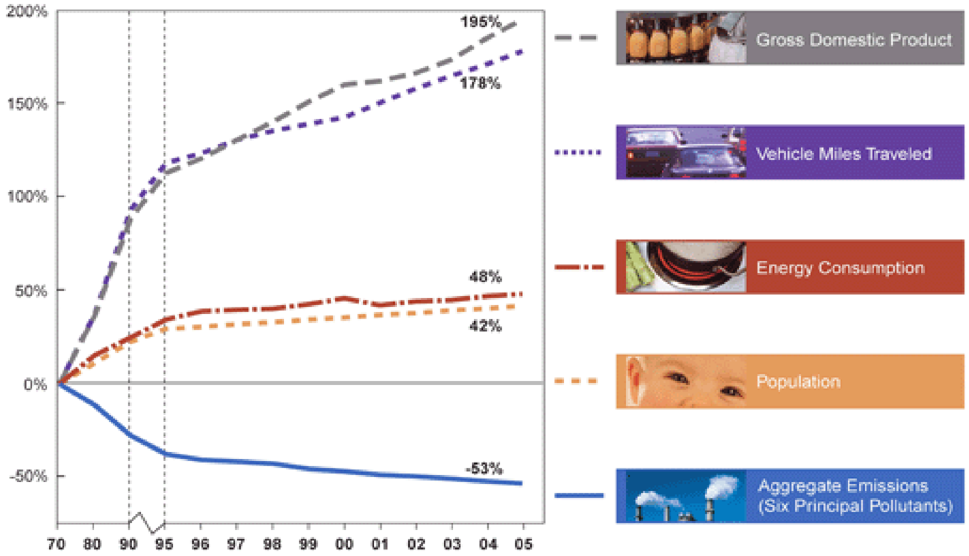

Figure 2.1 Increase in VMT from 1970-2005 (EPA, Air Emissions Trends - Continued Progress through 2005)

In Figure 2.1, one can also see that there has been a significant drop in the overall emissions since the 70‟s, mainly due to stringent EPA standards and limits. Eventually it is expected that the drop in emissions is going to even out and would start increasing due to a greater number of vehicles on roads. Figure 2.1 also shows us the increase in energy consumption that puts great pressure on an already scarce fuel energy sources. In fact, the transportation sector was the second largest consumer of energy in the U.S. in 2004, according to the United States‟ Energy Information Administration (EIA). *(Source: http://www.eia.doe.gov/emeu/aer/pdf/pages/sec2_2.pdf)*

2.1.2 Air Quality Standards

As mentioned earlier, the U.S. EPA has set the NAAQS for the six “criteria” pollutants that are known to be detrimental to public health and environment. These national standards are of two types:

a) **Primary standards** to protect public health, including the health of the “highly vulnerable” populations like the elderly, children and the diseased.

b) **Secondary standards** to protect public welfare, including protection against decreased visibility, damage to animals, vegetation, crops and buildings.

The limits for these standards are listed below in Table 2.1.

Table 2.1 National Ambient Air Quality Standards (EPA, 2006)

Pollutant	Primary NAAQS	Averaging Time	Secondary NAAQS
Carbon Monoxide	35 ppm	1-hour[1]	---
	9 ppm	8-hour[1]	---

Table 2.1 Continued

Pollutant	Primary NAAQS	Averaging Time	Secondary NAAQS
Lead	1.5 µg/m^3	Quarterly Average	Same as Primary
Nitrogen Dioxide	0.053 ppm (53 ppb)	Annual (Arithmetic Mean)	Same as Primary
Particulate Matter (PM_{10})	150 µg/m^3	24-hour[1]	Same as Primary
	50 µg/m^3	Annual[2] (Arithmetic Mean)	
Particulate Matter ($PM_{2.5}$)	65 µg/m^3	24-hour[4]	Same as Primary
	15 µg/m^3	Annual[3] (Arithmetic Mean)	
Ozone	0.085 ppm (85 ppb)	8-hour[5]	Same as Primary
Sulfur Oxides	---	3-hour[1]	0.55 ppm (550 ppb)
	0.145 ppm (145 ppb)	24-hour[1]	---
	.035 ppm (35 ppb)	Annual (Arithmetic Mean)	---

Notes:

[1] Not to be exceeded more than once per year.

[2] To attain this standard, the 3-year average of the weighted annual mean PM_{10} concentration at each monitor within an area must not exceed 50 µg/m^3.

[3] To attain this standard, the 3-year average of the weighted annual mean $PM_{2.5}$ concentrations from single or multiple community-oriented monitors must not exceed 15 µg/m^3.

[4] To attain this standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 65 µg/m^3.

[5] To attain this standard, the 3-year average of the fourth-highest daily maximum 8-hour average ozone concentrations measured at each monitor within an area over each year must not exceed 0.085 ppm.

Based on the Table 2.1 limits for the NAAQS, the Clear Air Act Amendments of 1990 classified the country into two basic zones or areas:

1. **Attainment area**: An area that complies with a NAAQS standard for a criteria pollutant is known to be in "attainment" for that particular pollutant.
2. **Non-attainment area**: An area where air pollution levels persistently exceed NAAQS or that contribute to poor air quality standards in surrounding areas is called as a "non-attainment" area.

2.1.3 Air Quality in Dallas/Forth Worth (DFW) Metroplex

The U.S. EPA in 1990 classified the DFW Metroplex as a moderate non-attainment area for ozone as per the 1990 Clean Air Act Amendments (CAAA). This classification was based on the 1-hour ozone standard in use at that time. In 2004, the 1-hour ozone was replaced by the more stringent 8-hour ozone standard. This resulted in the designation of nine counties in North Central Texas as non-attainment for the new 8-hour ozone standard.

The 8-hour ozone standard is said to be violated when the annual fourth-highest daily maximum 8-hour average ozone concentration, averaged over three consecutive years, at any monitor within an area exceeds 0.085 ppm or 85 ppb.

The Clean Air Act requires that non-attainment areas develop a State Implementation Plan (SIP) that demonstrates how the state will reduce and maintain air pollution emissions in order to comply with the federal standards within a time limit.

The DFW Metroplex must comply with the NAAQS by June 15, 2010.

2.2 On- Board Emission Measurement Study

A research that involves measuring the impact of using a retrofit device on vehicular emissions needs an accurate measuring system. A system that measures the impacts at „micro‟ level rather than „macro‟ level is needed to quantify the real world emissions. Hence, an on-board emission measurement system was chosen for this research.

The on-board system used in this research measures the real world tailpipe emissions under actual conditions rather than simulated conditions in modeling. The tailpipe emissions are measured for the four known modes of driving operation (idling, cruising, acceleration, and deceleration) rather than under simulated conditions in a laboratory using a dynamometer.

The main advantage of an on-board system is that it can measure the second by second emissions from the tailpipe continuously along the path or route the vehicle travels. This also results in the measuring of many parameters like velocity, instantaneous acceleration, exhaust flow rate, and exhaust temperature that not only increases the accuracy of the research but also provides the opportunity to study how these parameters affect the emission measurements from the vehicles.

Horiba Instruments‟ OBS-1300 system was used as the on-board emission measuring system in this particular research.

2.3 Combustion and Emissions

2.3.1 Introduction

To better understand the type of emissions coming out of the exhaust of gasoline vehicles, it is important to know what happens in their engines during the burning of the fuel. This section deals with the process of combustion in gasoline engine vehicles and the emissions occurring as a result of that.

2.3.2 What is Combustion?

Crude oil is nothing but a mixture of complex hydrocarbons (HCs), primarily alkanes and aromatics. Hydrocarbons are molecules containing only hydrogen (H) and carbon (C). The gasoline that we use in the vehicles today is the lightest liquid part resulting from the distillation of crude oil in a refinery. Therefore, gasoline is also a mixture of hydrocarbons.

Combustion is a process in which the fuel burns in the presence of air at relatively high temperatures. It is an exothermic process. The engine takes in the air from the atmosphere. The overall reaction can be represented in the basic shorthand form as:

$$HC + O_2 \xrightarrow[\Delta]{} H_2O + CO_2 + \text{Heat}$$

The above reaction represents ideal or complete combustion with enough oxygen present to completely burn the fuel and resulting in the formation of water (H_2O) and carbon dioxide (CO_2).

However, real combustion is not ideal. Incomplete combustion takes place in the 4-stroke engine gasoline vehicles in use today due to:

Lack of sufficient oxygen for the complete burning of the fuel,

Quenching by cylinder walls resulting in lower temperatures,

Poor engine performance.

This results in the formation of volatile organic compounds (VOCs) and carbon monoxide (CO) as products.

The nitrogen oxides (NOx) emissions in the exhaust of the gasoline vehicles occur due to very high engine temperatures resulting in:

Reaction between the nitrogen (N_2) and oxygen (O_2) present in the taken in atmospheric air (major source of NOx).

Oxidation of nitrogen-containing compounds in the fuel (minor source of NOx).

90% of NOx is released in the form of nitric oxide (NO). Later the NO is converted in the atmosphere to the more toxic nitrogen dioxide (NO_2).

In addition, the emissions of particulate matter (PM) and sulfur dioxide (SO_2) form a very small percentage of the emissions from a gasoline vehicle.

(Adapted from Sattler, Transportation & Air Quality Course, UTA, Fall 2004)

Figure 2.2 illustrates the relationships between the emissions and the combustion temperatures in engines. It summarizes most of the above discussed points.

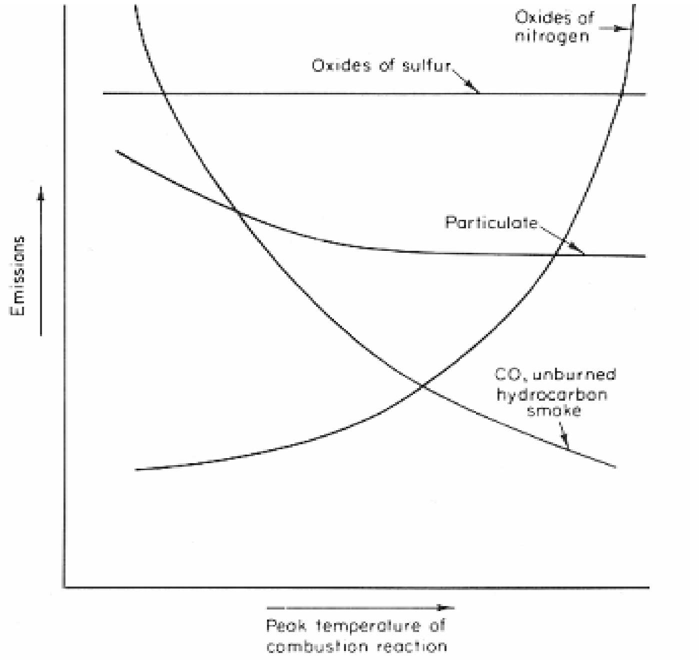

Figure 2.2 Emissions as a function of peak combustion temperatures (Source: Boubel et al., 1994)

As observed in Figure 2.2, as the combustion temperature increases the emissions of CO, HC and particulates decrease as a result of more complete combustion taking place in the engine.

2.4 Catalytic Converter

2.4.1 Relevance of the topic to this research

Though no mention of a catalytic converter was made in this research until now, there is a certain relevance of this particular term in this research. The manufacturers, Clean Air Associates Inc., of the device that was tested in this research call the device by a slightly different terminology than the research team at UTA. They call this device a “Pre-combustion Catalytic Converter”. The research team at UTA believes that this is a misnomer and is more appropriate for it to be called a "Pre-combustion Retrofit Device". The reason for this is discussed below.

2.4.2 What is a Catalytic Converter?

A catalytic converter is a device used on vehicles to reduce the toxicity of the emissions coming out of it. It was first introduced in vehicle models of the mid 70"s to comply with the tightening EPA laws on emissions from vehicles. In fact, they are still widely used in motor vehicles of today.

The ideal location of a catalytic converter in a vehicle is generally between the exhaust outlet of the engine and the acoustic muffler.

2.4.3 What does it do?

Gasoline vehicles of today have 3-way catalytic converters that perform the following three simultaneous tasks:

1. Oxidize CO to CO_2

   $$CO + O_2 \xrightarrow{\qquad\qquad} CO_2$$

2. Oxidize VOCs, or HCs, to H_2O and CO_2

   $$HC + O_2 \xrightarrow{\qquad\qquad} H_2O + CO2$$

3. Reduce NOx to N_2 and O_2

   $$NOx \xrightarrow{\qquad\qquad} N_2 + O_2$$

(Adapted from Sattler, Transportation & Air Quality Course, UTA, Fall 2004)

So the name a three-way catalytic converter is used because it reduces all the three substances in the same catalyst bed. For diesel engines, a two-way catalytic converter is used to lower the emissions of CO and HC.

2.4.4 Composition of a Catalytic Converter

A catalytic converter is mainly made up of three components:

a) **Core or substrate** is a honeycomb-type monolithic structure that supports the catalyst. It is often made of ceramic and in recent times metal (like stainless steel foil) is being widely used.

b) **Catalyst** is generally a combination of Platinum (Pt) and Rhodium (Rh) in 5:1 ratio. They are the precious metals in the converter. In the converter, Pt enhances the rate of oxidation of the HC and CO, and Rh accelerates the NOx reduction.

c) **Washcoat** is generally a mixture of Alumina (Al_2O_3), Cerium Oxide (CeO_2) and small percentages of Pt and Rh that is added to the core to make it more efficient. When added the washcoat forms a rough and porous surface over the core, thus providing a far greater surface area than monolith cores without a washcoat. Greater surface area means that more active sites for the catalyst. The catalyst is added to the washcoat (in suspension) before applied to the core.

(Adapted from Sattler, Transportation & Air Quality Course, UTA, Fall 2004)

The whole honeycomb-type monolith structure is then placed in a metal housing, made mostly of steel, to protect it from shocks and vibrations.

2.4.5 Why is it a misnomer?

The device literature provided by the Clean Air Associates Inc., calls the device a “Pre-combustion Catalytic Converter”. However, the U.S. EPA defines catalytic converters as completely different devices.

According to the EPA, "The presence of the catalytic converter ***in the engine exhaust system*** breaks down the chemicals in the exhaust and reduces harmful pollutant emissions." (*http://www.epa.gov/OMS/retrofit/glossary.htm*) Therefore, it is a device that is placed after the combustion zone and away from the fuel line of the vehicle.

In contrast, the Clean Air Associates" device used in the research was installed along the fuel line of the vehicle and between the fuel tank and the engine. Therefore, it is more of a pre-combustion retrofit device rather than a catalytic converter as defined by the EPA.

2.5 EPA's Retrofit Technology Program

The U.S. EPA has a very active retrofit technology program as part of its efforts to curb emissions from vehicles. However, most of its efforts have been limited to the emissions resulting from diesel vehicles. As part of its National Clean Diesel Campaign (NCDC) to make diesel engines and fuels much cleaner, it formulated various control strategies and programs that aid the research in this particular area. (*Source: http://www.epa.gov/cleandiesel/*) Since it takes much longer time for new engines and fuels to breakthrough and replace the older units, part of its efforts where also concentrated towards short term solutions for the immediate future.

The Voluntary Diesel Retrofit Program is one such program of EPA. Under this program, the EPA has verified around 25 retrofit devices (EPA) and approved for use in various heavy-duty, medium-heavy duty, light-heavy duty and non-road diesel vehicles. In addition, the U.S. EPA has also set a verification processes for retrofit devices to be approved and used in the various diesel vehicles mentioned earlier. In fact, the

Aftermarket Technology and Fuel Additive Research Program of NCTCOG, under which this research was carried out, was modeled on the EPA‟s program.

As of now, EPA has not sanctioned any retrofit device for use in light duty gasoline vehicles.

2.6 Previous Research on Pre-combustion Retrofit Devices

This particular research is unique in the sense that it is the first time that any university research team is carrying out the testing of a pre-combustion retrofit device. Use of retrofit devices and the related research is quite widespread, but it is the first that time that a pre-combustion retrofit device is being tested for light duty gasoline vehicles. As mentioned earlier, even EPA has not approved any pre-combustion retrofit device for light duty gasoline vehicles to data.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter discusses about the standard test procedure, equipment and its installation, data collection procedure, maintenance and calibration procedures.

3.1 General

3.1.1 Standard Test Procedure

Modeled after EPA‟s Aftermarket Retrofit Device Evaluation Program, NCTCOG has set a standard test procedure to be followed for the testing of the retrofit devices. The test procedure involves multi-phase testing of the product to determine its range and potential, with necessity of each phase depending upon the former‟s success. This research was limited only to the Phase 1 testing. All the technical specifications required for the test like hours and fuel specifics were set by NCTCOG at the time of the drafting of the test procedure.

3.1.1.1 Product Procurement and Installation

The product tested here was a pre-combustion retrofit device manufactured by the Clear Air Associates Inc., Texas, USA. The product was installed along the fuel line of the study vehicle with the help of additional special tubing connecting the line. The fuel line in a vehicle facilitates the movement of the fuel from the fuel tank to the engine, where combustion occurs. The personnel of the Physical Plant at the university carried out the installation. Officials from NCTCOG as well as the representatives from the manufacturer were present at the time of installation.

3.1.1.2 Test Procedure

As mentioned earlier, the testing in Phase 1 was carried out using a light duty gasoline 2000 Chevrolet Van. Real-world emissions of CO_2, CO, HC and NOx were measured and collected using an on-board system (OBS) in the van, installed by the Horiba Instruments Inc., Michigan, US. The van and the OBS are described in more detail in section 3.2.

The Standard Test Procedure consists of 40 hours of on-road testing in real world traffic conditions with the device installed. This includes 20 hours on the arterial test track and 20 hours on the highway test track, which are described below. The 20 hours on each track are divided into 10 hours of peak data and 10 hours of off-peak data.

<u>Arterial Test Track</u>

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.

<u>Highway Test Track</u>

From Cooper, travel west on I-30 to 820. South on 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.

Testing was conducted from Monday afternoon through Friday morning. Through out the duration of the test, the fuel used was of the same octane rating and from the same refiner.

Prior to the product testing, additional 40 hours of baseline testing, as defined in the Standard Test Procedure, was also conducted on the van. This baseline testing is important because it gives us the opportunity to compare it with the product test data, which gives the before and after emission trends resulting from the installation of the retrofit device.

3.1.1.3 Device Removal and Post-Removal Emissions Testing

After the completion of the product test data collection, the physical plant personnel removed the installed retrofit device. This was then followed by up to 10 hours of post-removal testing of the van to bring the emission levels to baseline levels. These 10 hours included equal proportion of arterial and highway track hours.

3.2 Data Collection Equipment

3.2.1 Study Vehicle

This research was carried out by installing the pre-combustion retrofit device on a light duty gasoline vehicle. UTA‟s transportation research van, a 2000 Chevrolet Astro Van, was used as the study vehicle for this research. The van is shown in Figure 3.1.

Figure 3.1 Chevrolet Astro Van

The specifications of this vehicle are listed in Table 3.1.

Table 3.1: Specifications of 2000 Chevrolet Astro Van

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

(Source: 2000 Chevrolet Astro Vehicle Manual)

Extensive on-board measurement study was conducted by installing a data sampling kit consisting of an OBS-1300 emissions measurement system from Horiba Instruments Inc., Michigan, US, described in the next section.

3.2.2 OBS-1300

Horiba Instruments‟ OBS-1300 is a vehicle-mounted on-board emissions measurement system that performs analysis of exhaust gases from an on-road study vehicle. It is mainly composed of two on-board gas analyzers, a power supply unit, a laptop computer equipped with data logging software and other accessories. This whole setup could be used to measure emissions of NO_x CO, CO_2, and HC; the air to fuel ratio (A/F); and exhaust gas flow rate at 1-second intervals. Mass emissions and fuel consumption can also be calculated. Figure 3.2 shows the setup of the OBS-1300 system in the study vehicle.

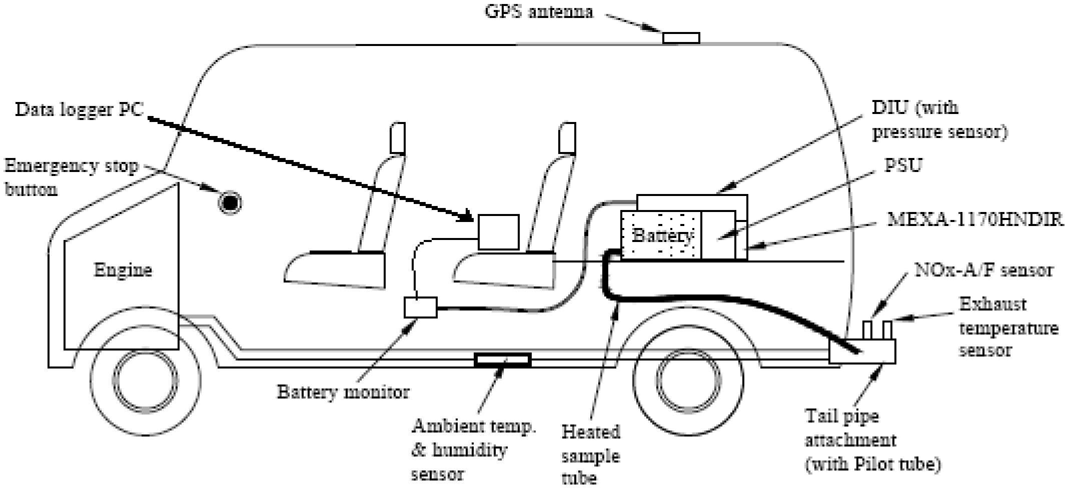

Figure 3.2 OBS-1300 setup in the study vehicle (Adapted from Horiba’s OBS Instruction Manual)

The various components of the OBS-1300 system are described in more detail in the following pages.

1. **Battery:**

Batteries, shown in Fig. 3.3, are the source of electrical energy on which the whole OBS runs.

Figure 3.3 Two 12 V each deep cycle batteries

The whole OBS setup runs on two deep cycle batteries of 12 V each, acquired from Trojan batteries. Figure 3.3 shows the batteries used in this research. These two batteries connected to the PSU should last for around four hours after fully charged. A battery monitor is also provided to monitor the voltage of the batteries.

2. **Power Supply Unit (PSU):** Figure 3.4 shows the PSU unit.

Figure 3.4 Power Supply Unit (PSU)

The PSU converts the battery output power (24 V in this case) to AC current and supplies it to all the units of the OBS-1300 setup. It also serves as a battery charger by converting AC input power to DC current. The PSU is connected to battery, data integration unit and for charging the battery, to the external power supply.

3. **Data Integration Unit (DIU) and NOx Analyzer (MEXA-720 unit):**

A DIU acts as an interface unit for each sensor, analyzer and data logger PC (a laptop in this case) of the whole OBS-1300 setup. This unit also houses pressure sensors and the MEXA-720 NOx analyzer. Figure 3.5 shows the DIU unit and the MEXA-1170 HNDIR unit.

Figure 3.5 DIU and MEXA-1170 HNDIR unit

The individual MEXA-720 analyzer unit and the NOx sensor are shown in the Figure 3.6.

Figure 3.6 MEXA-720 unit and NOx sensor (Source: Horiba, Inc.)

The MEXA-720 NOx analyzer is a non-sampling type zirconia sensor that measures NOx concentrations and A/F ratios. It comes pre-installed in the DIU unit as discussed earlier. Figure 3.7 shows the sensor probe being attached to the tail pipe attachment.

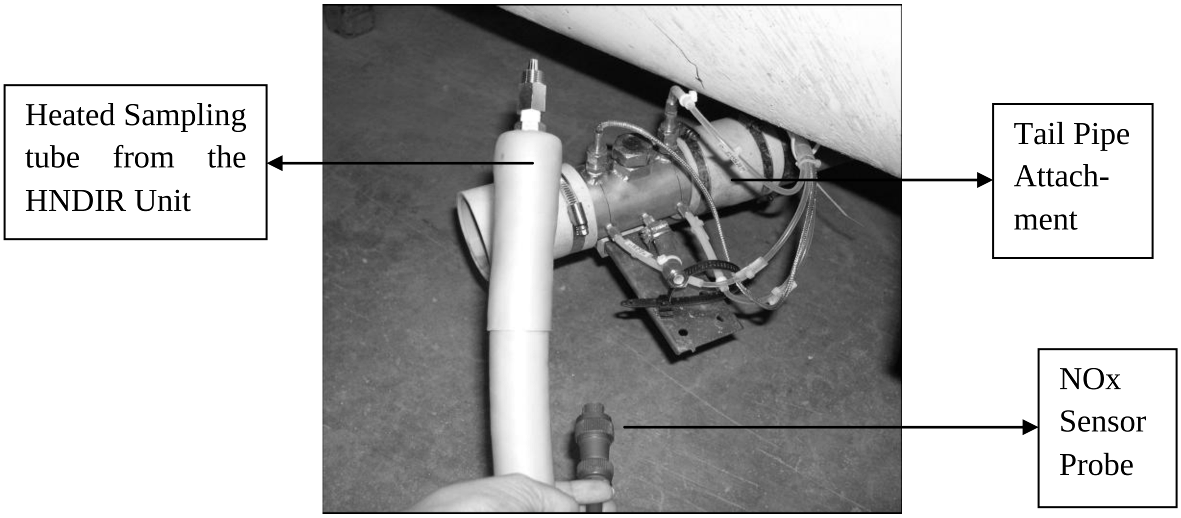

Figure 3.7 Sampling and NOx sensor tube attached to the tail pipe attachment

4. **MEXA-1170 HNDIR Unit:**

This unit uses the Heated Non-Dispersive Infrared (HNDIR) detection technique to measure CO, HC and CO_2 emissions. Being a heated analyzer means that sampling of the exhaust gases from the tailpipe can be done without providing an additional large dehumidifier.

The NDIR technique is based on the principle of selective absorption. Here the gas species 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 other wavelengths will be transmitted For example, the absorption band for CO is between 4.5 and 5 µm (*Wark et al., 1998*).

The HNDIR unit has a heated tube attached to the tail pipe attachment, as shown in Figure 3.7, which takes in the sample for analysis. This unit also connects the analog output to DIU.

5. **Data Logger PC:**

A DELL laptop loaded with an OBS-1000 series data logging software is provided. A PCMCIA card is included with it for data import. This unit logs the earlier indicated pollutant concentrations, A/F ratio, exhaust pipe temperature, ambient temperature and ambient humidity data.

6. **Remote Controller:**

A remote controller is provided for the rider (or data logger), who takes care of the data logging procedures on the laptop during the run, to operate the MEXA-1170

HNDIR unit from the back seat of the study vehicle. Figure 3.8 shows the remote controller.

Figure 3.8 Remote controller

It holds calibration buttons like “CAL”, “ZERO”, and “SPAN” and other buttons like “PURGE”,“RESET” and “MEASURE”. The remote facilitates the tasks of HNDIR unit calibration and initiation of data sampling functions for the rider at the back with the earlier mentioned buttons.

7. **Geographic Positioning System (GPS)**:

A GPS unit is provided in this setup to log the velocity, latitude and altitude of the vehicle when on a data collection run. It is placed at a convenient location on the side of the van just outside of the window so as to get accurate GPS points throughout the run.

8. Humidity sensor:

A humidity sensor is also provided in the OBS-1300 setup that measures the humidity and ambient temperature of the outside air on a second by second basis. It in a way acts as a mini weather station for the whole system.

3.3 Data Collection Procedure

3.3.1 General

The data collection procedure followed for both the baseline (before data) as well as the device data (after data) was the same and uniform. The only difference was that in the case of after data, the device was installed on the study vehicle and then the data collection was carried out. As mentioned earlier, the data collection for this research project was carried out using an OBS-1300 system, provided by the Horiba Instruments Inc., Colorado, on a 2000 Chevy Astro Van.

Runs were made for three different traffic conditions:

1. AM Peak – 6:30 to 9:00 AM
2. Off-Peak – 9:00 AM to 4:00 PM
3. PM Peak – 4:00 to 6:30 PM

These timings were selected conforming to the information given by Kimley-Horn and Associates (consultant hired by NCTCOG). The baseline testing (before data) was carried out during the months of January and May of 2006. The device testing was conducted during the months of February and March of 2006.

3.3.2 Factors Governing Data Collection

Specific factors governed the process of data collection. The main factors are listed below:

1. Warming up of the OBS-1300 system was carried out for 45 minutes to 1 hour before starting data collection. This was done so to tune the system to measure and log accurate data.

2. The required calibrations for the analyzers as well as the NOx sensor were duly carried out to maintain the accuracy of the whole setup.
3. The data collection was carried during the days when the university was in session, as traffic patterns in and around the city of Arlington were greatly impacted by this.
4. Testing was conducted from Monday afternoon through Friday morning.
5. No collection of data was carried out during rainy days.
6. The speed of the vehicle during data collection was approximately maintained with the flow speed of the traffic. This was done to enable real traffic conditions every time.
7. The two 12V batteries used for the system were fully charged before the start of data collection. Data collection was immediately suspended whenever the voltage reading showed less than 21V.
8. Regular inspections were carried out for the OBS to see to that the emissions coming from the exhaust and those measured by the device were not varying with time and usage.

3.3.3 Configuration of Data Logging Software

For the data logging software to log the correct values of the measured emissions and other required parameters, it was ensured that the software was configured to a set of values provided by the Horiba Instruments, Inc. Table 3.2 lists the configured set of values.

Table 3.2 Configured Value Ranges in the Analog Digital Conversion Setup

Parameters	Range of Values	Units
NO_x	0-4989	ppm
Air to Fuel Ratio (AFR)	0-100	
Exhaust Temperature	0-1000	Deg. C
Exhaust Pressure	0-200	kPa
Ambient Temperature	0-150	Deg. C
Ambient Pressure	0-100	kPa
Ambient Humidity	0-100	%
Velocity	0-500	kmph
Revolutions	0-5000	rpm

In addition, it was estimated by that there would be a 1.5 – 2 second delay in the logging of the NOx data. Horiba Instruments Inc. attributed this delay to the time it took to convert the measured concentration from analog to digital output.

3.3.4 Warm-Up and Calibration Procedures

Before the start of data collection every day, it is necessary to have two 12V batteries (DC) completely charged. The following are the steps for the warm-up and calibration procedure that were followed during the duration of the research:

Using AC Power, turn on the DIU and then after 5 to 10 seconds, turn on the HNDIR unit.

Let the system warm up for around 45 minutes to 1 hr. Then switch off both units and change the power source from AC to DC.

Turn on the DIU and after 5 to 10 seconds the HNDIR unit.

Open the valve of the zero gas cylinder.

Purge for 5 minutes by pressing the "PURGE" button on the HNDIR unit.

Press "RESET".

Press "ZERO" button on the HNDIR unit. Wait for around 2 minutes.

Connect the span gas cylinder to the HNDIR unit and open its valve.

Press "RESET".

Press "SPAN" button. Wait for around 2 minutes.

Press "RESET".

Press "CAL" and the OBS-1300 will do both the zero and span calibrations. It will reset by itself at the end of the process.

3.3.5 Procedures and Steps during the Runs

The „runs‟ for the data collection were started every day only after the earlier mentioned warm-up and calibration procedures were completed. The OBS-1300 setup runs on the DC power of the two batteries throughout the length of the session in which the data is collected. The steps for data collection are listed below:

a) Start the engine by turning on the ignition.

b) Log onto the PC and start the OBS-1300 data logging software.

c) Activate the GPS by selecting the appropriate port in which a satellite‟s signal is available (Save the GPS option).

d) Perform the pitot tube calibration to stabilize the exhaust flow rate value.

e) Start data logging by saving data in the file when the desired starting point is reached.

f) Stop the data logging after crossing the last point of the run and turn off the OBS system.

g) Perform ZERO ⟶ RESET ⟶ PURGE ⟶ MEASURE functions after every two runs in a session for arterial test track and after each run on highway track. Buttons on the remote controller can be used to perform these functions, and a time interval of 1 minute is allowed between each of these functions.

h) Repeat the steps (e), (f) and (g) until the assigned hours of data collection are completed in each session.

3.3.6 Calibration of NOx Sensor

The calibration of the NOx sensor was carried out every week throughout the data collection period. This is required to not only maintain the accuracy of NOx emission measurements but also since the NOx sensor itself is a very sensitive device, regular calibration and maintenance is required for its durability.

The setup for the NOx sensor calibration is shown in Figure 3.10. The following are the steps involved here:

A calibration unit forms the core of this whole setup. It consists of a sensor adaptor, a flow meter, bubbler, and water inlet.

The NOx sensor has to be fixed in the adaptor of the calibration unit.

The calibration gas used for this process is oxygen free N_2 and the flow of this gas from the cylinder is a regulated through a regulatory valve.

The exhaust outlet of the calibration unit is connected to a long Teflon tube, through which the calibration gas is safely discharged into the outside air.

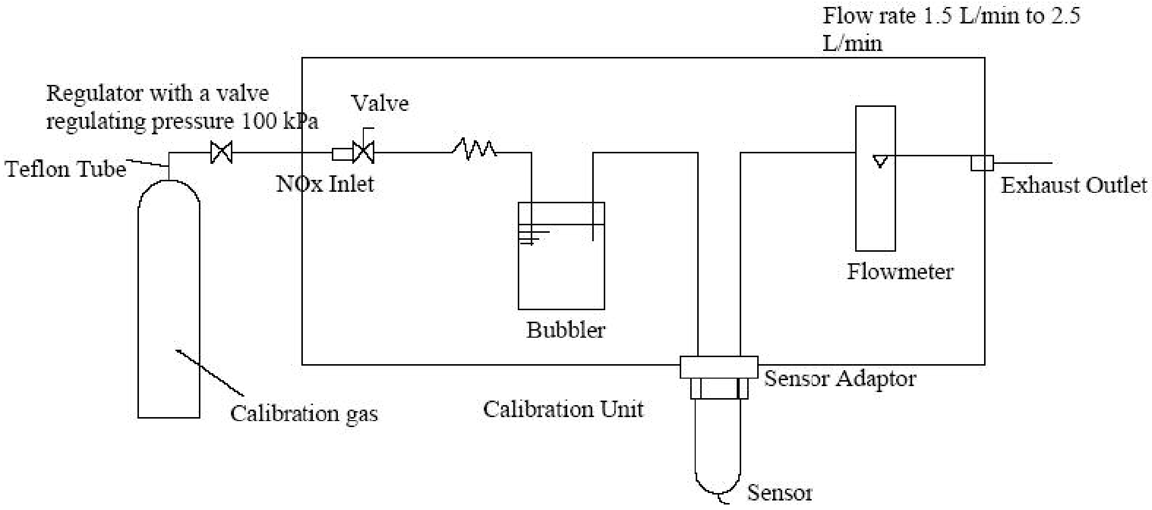

Figure 3.9 NOx Sensor Calibration Setup (Adapted from Horiba's OBS Instruction Manual)

During calibration, the calibration gas is allowed to flow at a particular rate (1.5 L/min to 2.5 L/min) so that the ball in the flow meter positions in between the two levels indicated in the flow meter.

The gas is allowed to flow for around 60 to 90 seconds.

The NOx analyzer is then switched on and steps described in the Horiba‟s OBS Instructional Manual are followed.

The CAL/SET key is pressed and held for approximately three seconds. The mode of analyzer switches to setting mode. Channel number (ch000) appears on display.

The value of concentration displayed on the label of the calibration gas cylinder is input. This finishes the calibration process.

3.3.7 Other Key Points in Calibration Procedures:

Some other points that are of interest during the calibration procedures are:

a) The span gas is made up of the following composition of gases:

0.5 % of CO,
6.0 % of CO_2,
301 ppm of NOx, and
201 ppm of C_3H_8.

b) In order to keep the pitot tube from not registering „negative‟ flow rate values, it is always seen that the pitot tube calibration was carried out pretty often during a data collection session. For this particular calibration, the option „CAL‟ tab provided on the OBS software is used, generally between the runs and with the engine of the vehicle turned off.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Data Analysis Procedure

Before presenting the results and discussion, this section the chapter deals briefly with the data analysis procedure followed for the data collected during this research.

4.1.1 Introduction

As discussed earlier in Chapter 2, the main objective of the research was to verify whether the pre-combustion device tested here significantly reduces the emissions of the HC, CO, CO_2, and NOx concentrations. The data logged in the data logger PC by using the OBS-1300 was analyzed by a modal approach here to verify this claim.

Although the OBS-1300 logs in various parameters, including engine parameters, vehicle parameters as well as emission parameters, on a second by second basis, this particular research used only some particular parameters required for the analysis. The following are the parameters of interest logged in second by second by the OBS-1300:

Date and Time

NOx Concentration (ppm)

HC Concentration (ppm)

CO Concentration (% volume)

CO_2 Concentration (% volume)

Exhaust Flow Rate (L/min)

GPS Velocity (km/hr)

Exhaust Temperature (Deg. C)

Exhaust Pressure (kPa)

4.1.2 Database Management

In order to analyze trends for the arterial and highway baseline data, a number of classifications of the data were carried out. It is to be noted that during the analysis processes, the arterial and highway baseline data were kept separate. Then the same steps of classification and analysis were carried out for both the data sets. The steps are listed below:

1. First, a clear distinction was made between peak and off-peak data sets. The previously mentioned time schedules were followed to differentiate the peak from the off-peak hours.
2. Both the AM & PM peaks were combined into a single peak hour data set.
3. The data logged in the Data Logger PC is saved as a ".txt" file ("Notepad" type files in Windows OS).
4. Then each data text file was transferred to a pre-set spreadsheet template that gives values of instantaneous acceleration (*in meter/second*^{2}), GPS velocity (*in km/hour*), and concentrations of CO (*in percent volume*), CO_2 (*in percent*

volume), HC (*in ppm*) and NOx (*in ppm)*, in separate columns. These columns were made up of second by second data points.

5. The above-mentioned columns were transferred into a separate spreadsheet and then sorted based on the ascending order of the instantaneous accelerations.
6. Next, that particular spreadsheet was sorted by modal classification (modal approach) of instantaneous accelerations, into the four known modes of vehicle operation - deceleration, acceleration, idling and cruising.
7. The four standard driving modes were defined as follows:

   idling mode as zero speed and acceleration,

   acceleration mode as portions having positive incremental speed changes > 0.1 m/sec/sec,

   cruising mode as portions having absolute incremental speed changes of less than 0.1 m/sec/sec, and

   deceleration mode as portions having negative incremental speed changes < -0.1 m/sec/sec.

7. Highway data does not have an idling mode classification for obvious reasons.
8. Then all the peak hour data sets were separated into acceleration mode, deceleration mode, cruising mode, and idling mode. The same process was repeated for off-peak hour data sets.
9. Each mode of the peak/off-peak data was then divided into different clusters of data points based on velocity intervals of 5 mile/hr.

10. Average velocity values and emission concentrations, in terms of above-mentioned units, for the classified velocity intervals were calculated for each mode.
11. Then these average velocity values and their corresponding average emission concentrations were transferred to new spreadsheets.
12. Graphs of the corresponding average velocity *vs.* average emission concentration for each mode were plotted.
13. Finally, overall percentage reductions were carried out along with the overall as well as representative velocity category t-tests to validate the obtained results.

Note:

It is important to note that we have carried out the data analysis based on the emission concentrations measured in terms of percent volume for CO and CO_2 and in parts per million for HC and NOx. We did this because the flow rate being measured by the pitot tube attached to the tailpipe attachment was found to be showing erroneous measurements. This was found to be the case after we did the analysis based on emissions in terms of „grams per mile‟ and „grams per second‟.

4.1.3 Quality Management

Before plotting the average velocity *vs.* average emission concentrations graphs, certain changes to the data were made without compromising the quality of the data. The changes made to the data are listed below:

- For the highway data, in some cases, velocity clusters below 45 mile/hr with very few or single data points were omitted, as we felt that their case was being dealt with in the arterial data set.
- For the highway data, velocity clusters > 85 mile/hr with very few or single data points were also omitted as outliers.
- For the arterial data, velocity clusters > 46 km/hr were omitted, as we felt that their case was being dealt with in the highway data set.

4.2 Results: Graphical Analysis

4.2.1 Individual Graphs in Each Data Set

After the completion of various sorting and classification procedures for the collected data, as discussed earlier, graphs for the values of average velocity and average emission concentration for each mode were plotted. The graphs were plotted for all four measured pollutants - HC, CO, CO_2, and NOx, in terms of earlier mentioned units. Plotting of graphs was carried out for both the baseline data („before‟ data) as well as the device data („after‟ data). 48 individual graphs were plotted for each data set in this research. Table 4.1 lists the number of individual graphs plotted for each data set.

Table 4.1 Number of Individual Graphs Plotted for Each Data Set

Time interval	Number of Graphs Plotted	
	Before data set	**After data set**
Peak	24	24
Off-peak	24	24

4.2.2 Comparison of the 'Before' and 'After' Plots

The completion of individual plots for each data set meant that we had two unique data set plots to compare. A total of 48 „before‟ and „after‟ combined data set plots were then plotted to observe the emission trends after the installation of the pre-combustion retrofit device on the study vehicle. Table 4.2 lists the number of combined data set graphs plotted.

Table 4.2 Number of Combined Data Set Graphs Plotted

Time interval	**Number of Graphs Plotted**
Peak time	24
Off-peak	24

Since it becomes repetitive to discuss all the 48 graphs individually, this chapter includes only 16 of the total 48 graphs that would represent the results and give us a clear idea of the trends observed in all the graphs. The rest of the graphs are attached to Appendix A for review.

To better quantify all the trends, the modes, the test tracks and the data collection hours represented here are different for the pollutants. Below are the various plots and the discussions of their trends.

Case A: Emission Trends for Arterial Test Track's Off-peak Acceleration Mode.

Figure 4.1 shows the CO emission trends for the acceleration mode of the off-peak data collected on the arterial test track.

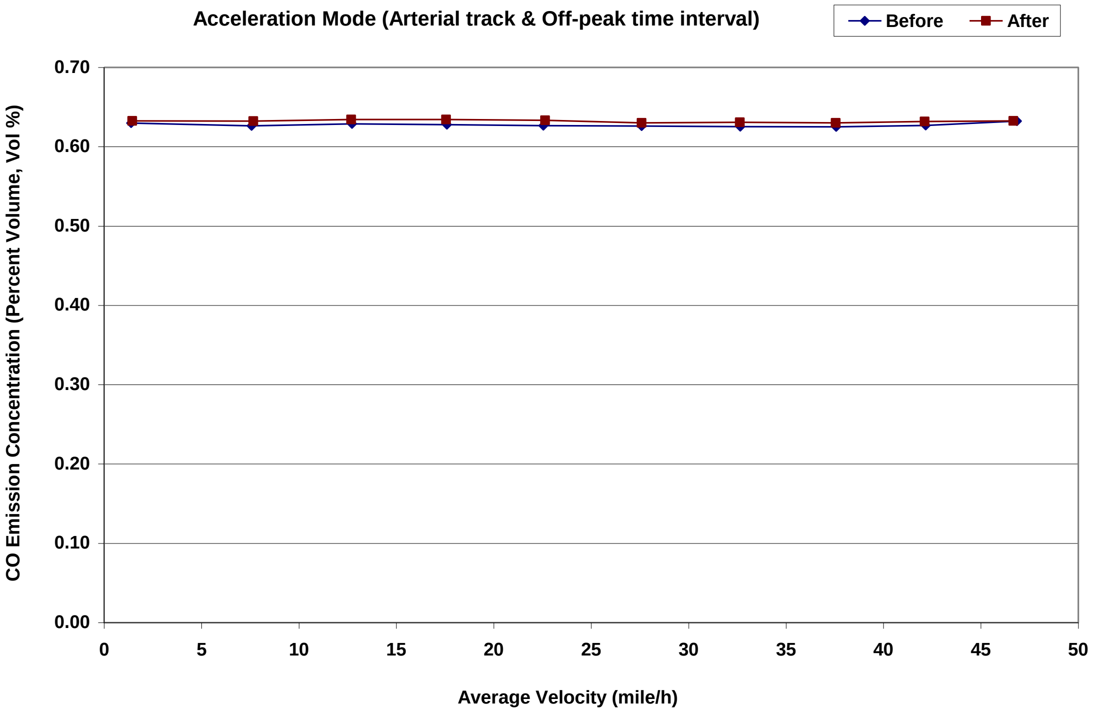

Figure 4.1 CO emission trends (Vol. %) for arterial test track's off-peak acceleration mode

Observations:

Figure 4.1 shows that there appears to be no significant change in CO emissions, after the installation of the device on the study vehicle. Similar trends were observed for the CO emissions in all other modes for arterial test track and for peak as well as off-peak data sets. However, statistical analysis is necessary to establish or validate these trends.

Figure 4.2 shows the CO_2 emission trends for the acceleration mode of the off-peak data collected on the arterial test track.

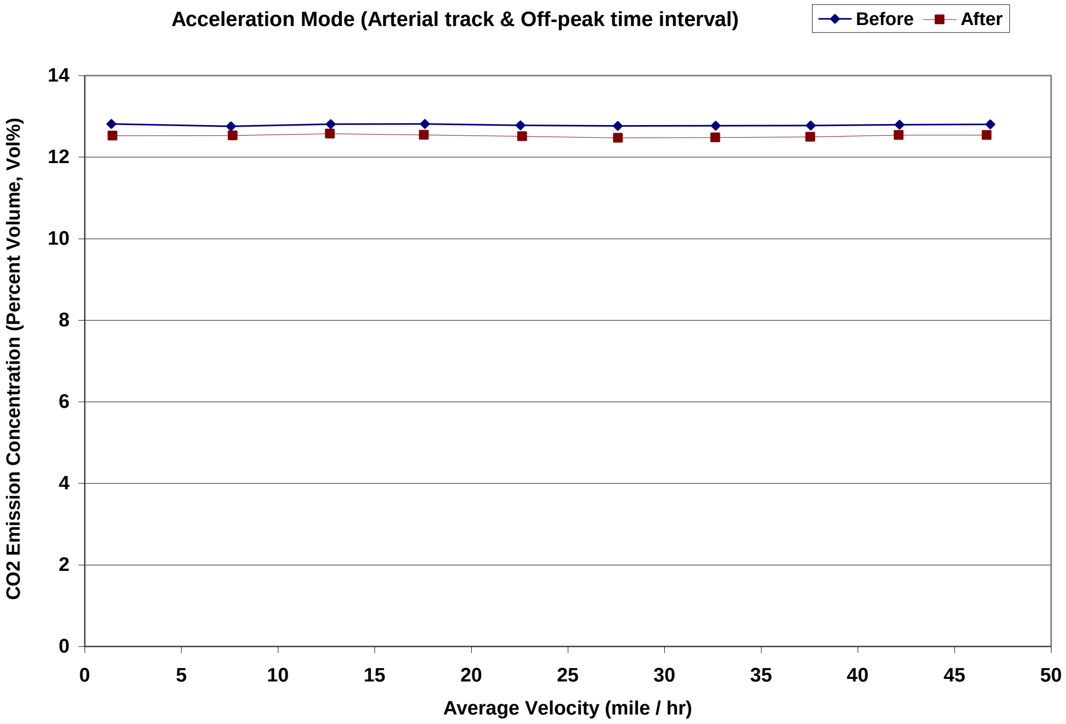

Figure 4.2 CO_2 emission trends (Vol. %) for arterial test track's off-peak acceleration mode

Observations:

Figure 4.2 shows that there appears to be a drop in the CO_2 emissions, after the installation of the device on the study vehicle. Similar trends were observed for the CO_2 emissions in all other modes for arterial test track and for peak as well as off-peak data sets. However, statistical analysis is still necessary to establish or validate these trends.

One should also keep in mind the point that since these graphs are a comparison between the „before" and „after" data sets, not much should be read into how the individual data lines are varying.

Figure 4.3 shows the HC emission trends, in parts per million, for the acceleration mode of the off-peak data collected on the arterial test track.

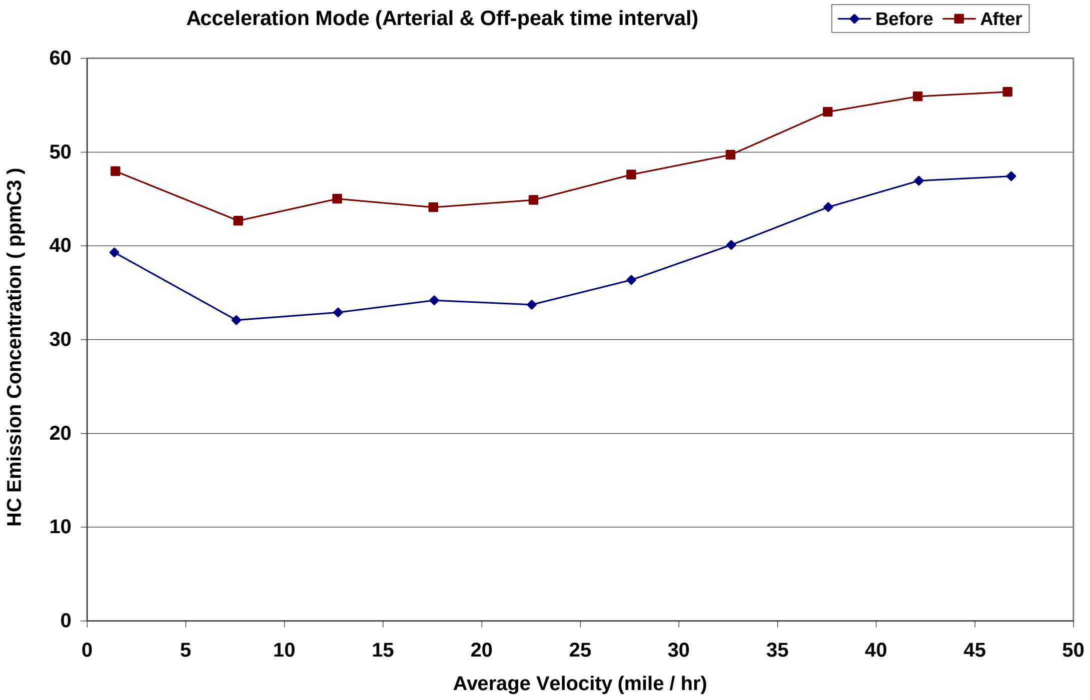

Figure 4.3 HC emission trends (ppm) for arterial test track's off-peak acceleration mode

Observations:

Figure 4.3 shows that there appears to be a significant increase in the HC emissions, measured in ppm, after the installation of the device on the study vehicle. Similar trends were observed for the HC emissions in all other modes for off-peak data sets of arterial test track.

As in case with the previous emissions, statistical analysis is needed to validate or establish the trends observed here.

Figure 4.4 shows the NOx emission trends in ppm for the acceleration mode of the off-peak data collected on the arterial test track.

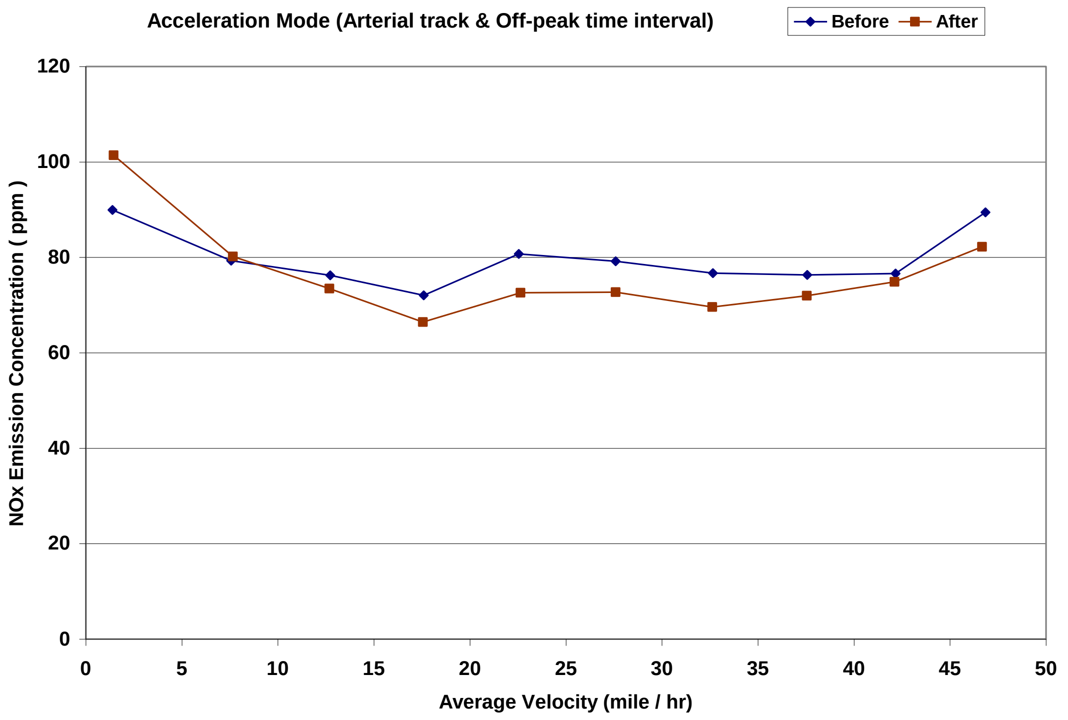

Figure 4.4 NOx emission trends (ppm) for arterial test track's off-peak acceleration mode

Observations:

Figure 4.4 shows that there appears to be a drop in the emissions of NOx, after the installation of the device on the study vehicle. However, it cannot definitely concluded whether there is a significant difference between the „before‟ data set and the „after‟ data set just by reading of the graph. Statistical analysis is required to establish the trends observed here.

Similar trends were observed for NOx emissions in all other modes, for both arterial as well as highway test tracks and for both peak and off-peak data sets, with the exception of two cases, discussed in the next section.

Case B: Emission Trends for Arterial Test Track's Peak Cruising Mode.

Figure 4.5 shows the CO emission trends in percent volume for the cruising mode of the Peak data collected on the arterial test track.

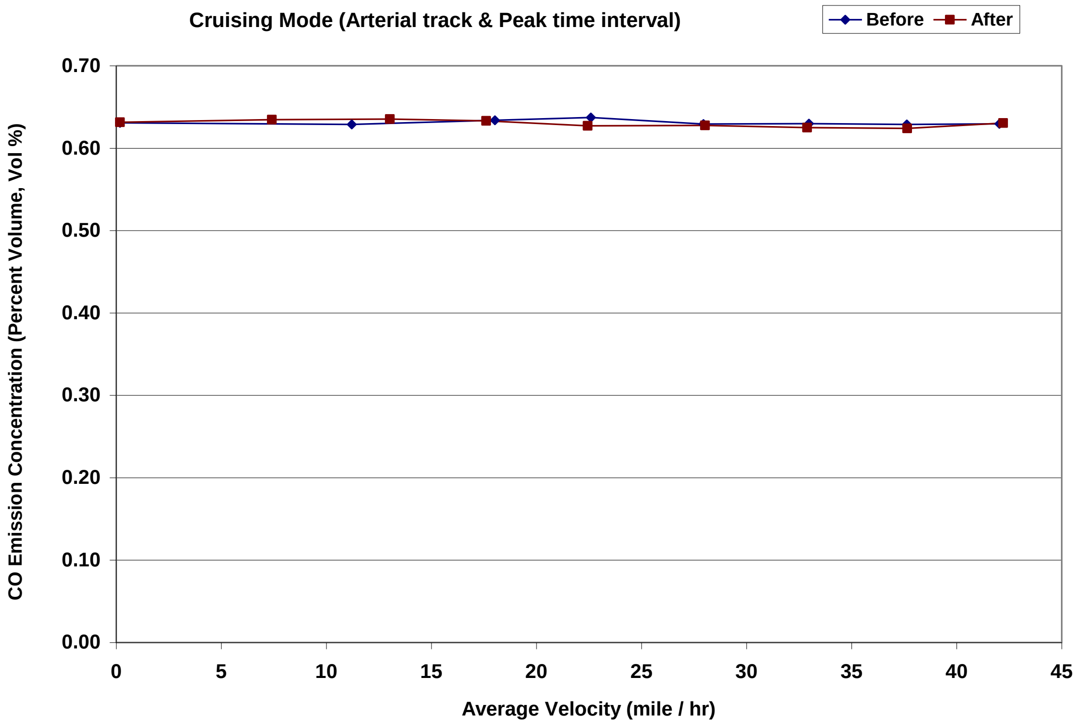

Figure 4.5 CO emission trends (Vol. %) for arterial test track's peak cruising mode

Observations:

Figure 4.5 shows that there appears to be no significant change in CO emissions, after the installation of the device on the study vehicle. Similar trends were observed for the CO emissions in all other modes for arterial test track and for peak as well as off-peak data sets. However, statistical analysis is necessary to establish or validate these trends.

Figure 4.6 shows the CO_2 emission trends in percent volume for the cruising mode of the peak data collected on the arterial test track.

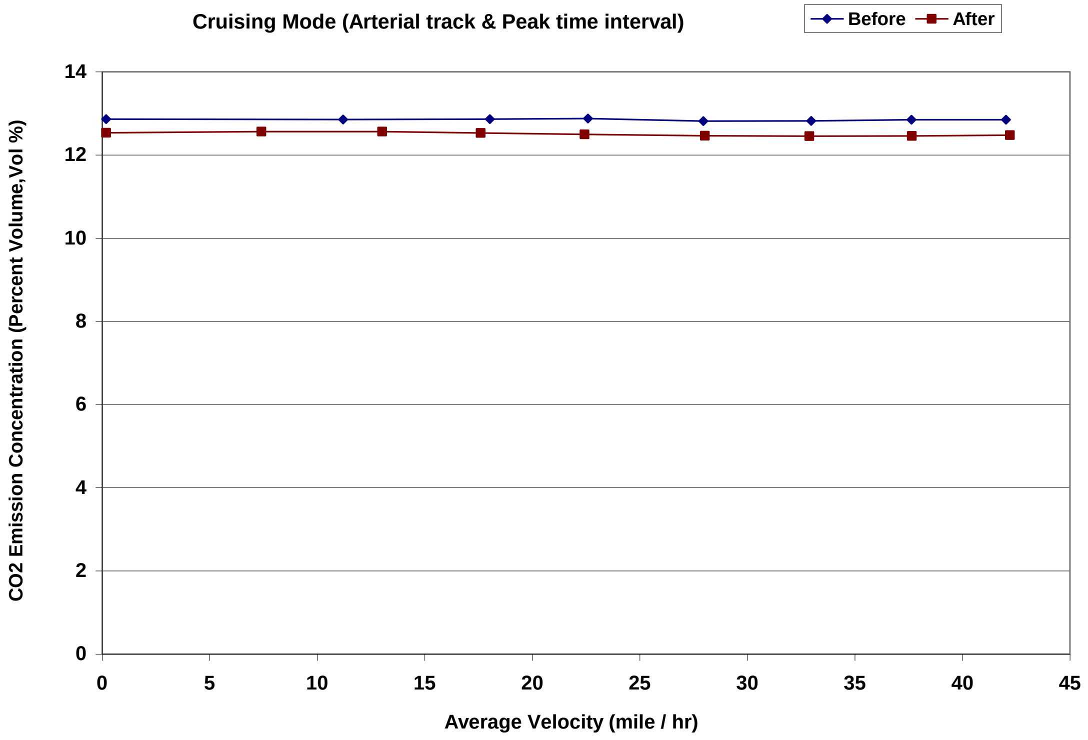

Figure 4.6 CO_2 emission trends (Vol. %) for arterial test track's peak cruising mode

Observations:

Figure 4.6 appears to shows a decrease in the CO_2 emissions relative to the „before" data set. Similar trends were observed for the CO_2 emissions in all other modes, for arterial test tracks and for peak as well as off-peak data sets. However, statistical analysis is necessary to establish or validate these trends.

Figure 4.7 shows the HC emission trends in ppm for the cruising mode of the peak data collected on the arterial test track.

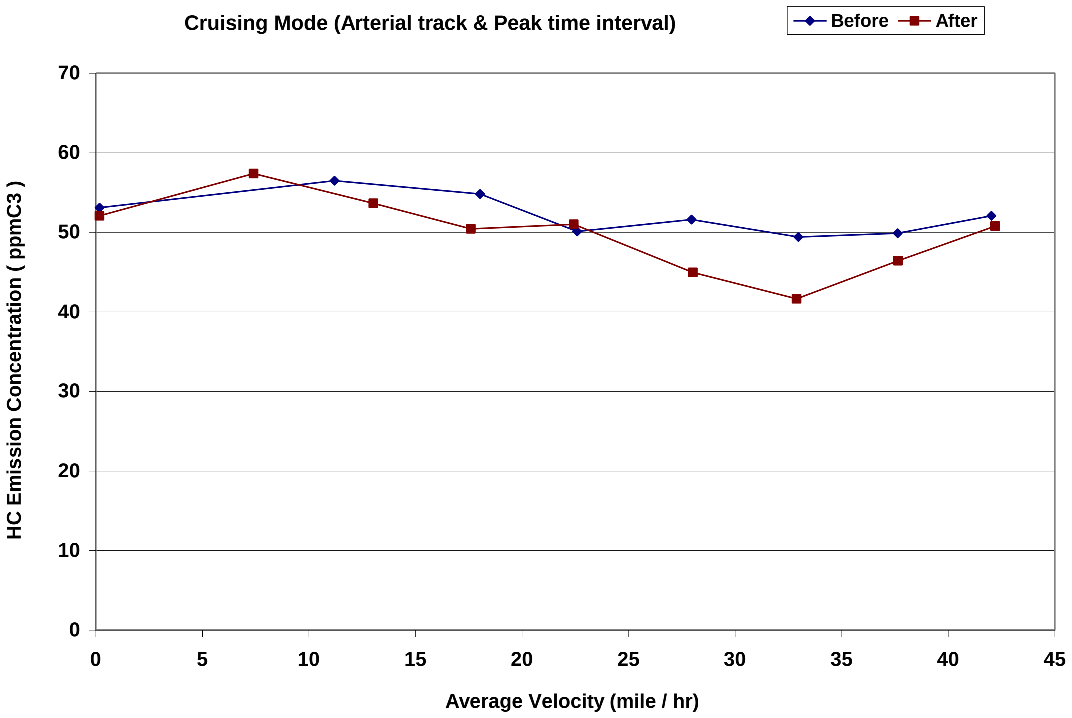

Figure 4.7 HC emission trends (ppm) for arterial test track's peak cruising mode

Observations:

Though Figure 4.7 shows an observable variation between the „before" and „after" lines across the plot, there appears to be a drop in the „after" emissions relative to the „before" data line for the major part of the plot.

Similar „decrease" trend in emissions was observed for the arterial test track"s peak data set across all the four modes.

However, statistical analysis is necessary to establish or validate these trends.

Figure 4.8 shows the NOx emission trends in ppm for the cruising mode of the peak data collected on the arterial test track.

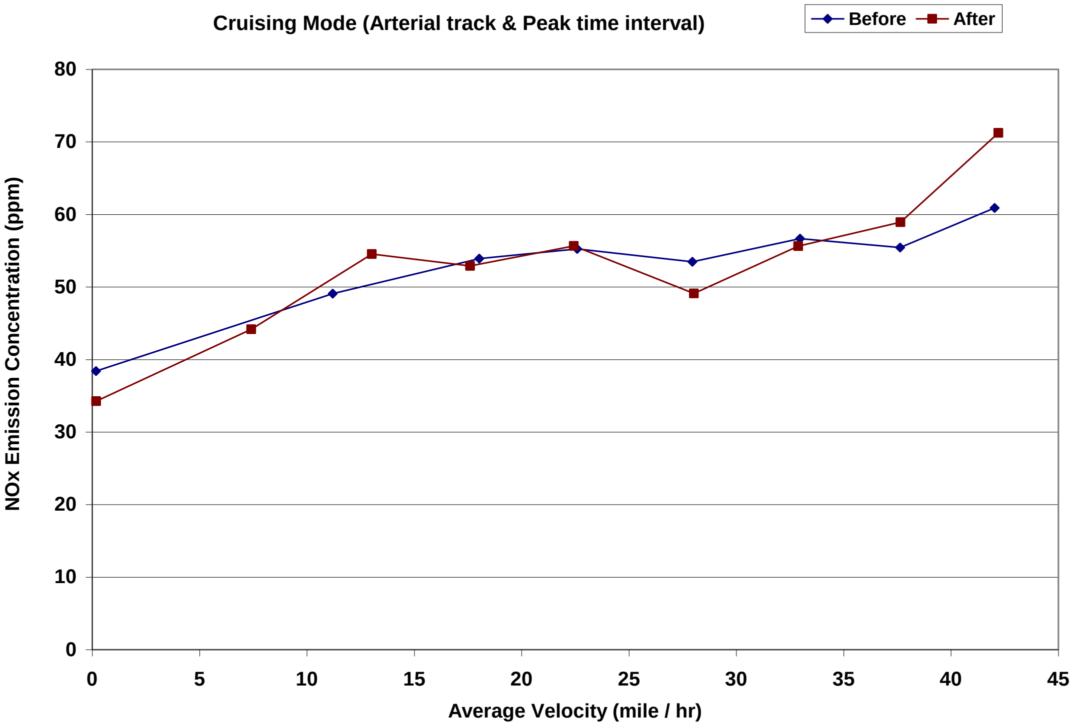

Figure 4.8 NOx emission trends (ppm) for arterial test track's peak cruising mode

Observations:

Figure 4.8 shows that there appears to be a lot of variation between the „before" and „after" data lines, and it is hard to conclude from just reading off the graph whether there is a significant difference between the „before" and „after" data sets. Statistical analysis along with the overall percentage reduction calculations are needed to establish the nature of the trend observed here.

This case is one of the two cases where NOx emissions showed a different trend compared to all the trends observed across the four modes, for both peak and off-peak data sets and for both arterial as well as highway test-tracks. The other case was the arterial test track"s peak data set, where NOx emissions showed an „increasing" trend.

Case C: Emission Trends for Highway Test Track's Peak Deceleration Mode.

Figure 4.9 shows the CO emission trends in percent volume for the deceleration mode of the Peak data collected on the Highway test track.

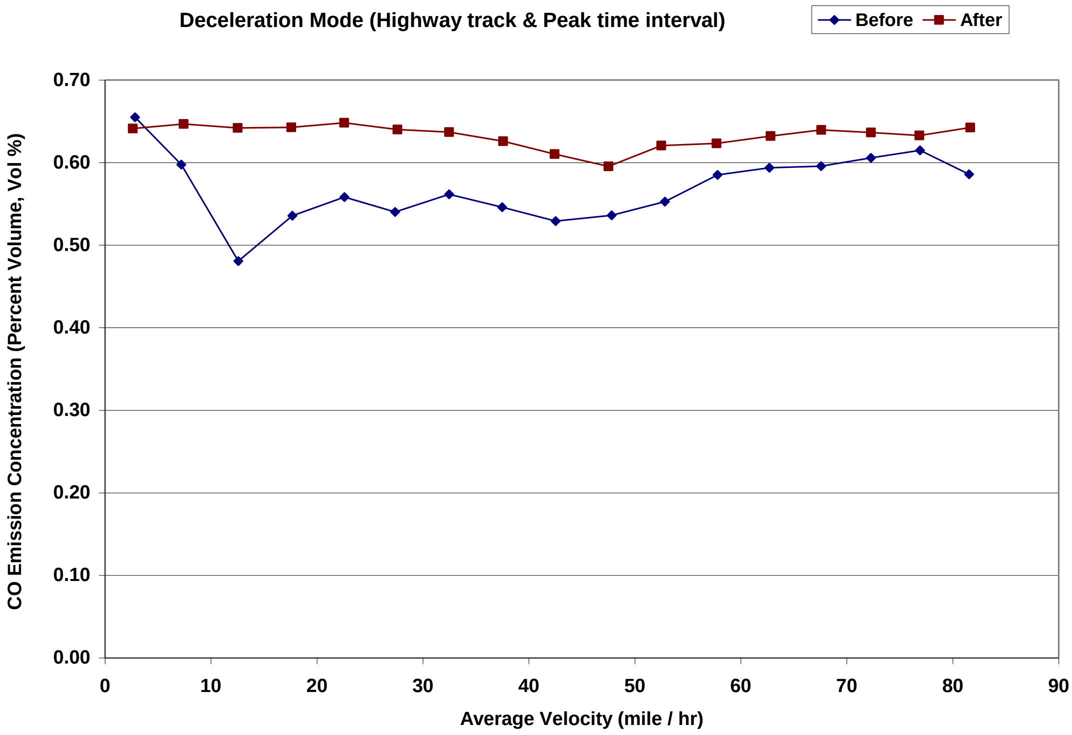

Figure 4.9 CO emission trends (Vol. %) for highway test track's peak deceleration mode

Observations:

Figure 4.9 shows that there appears to be an increase in the CO emissions after the installation of the device on the study vehicle. Similar trends were observed for the CO emissions in all other modes, for highway test track and for peak data sets.

However, statistical analysis is required to establish or validate these trends.

Figure 4.10 shows the CO_2 emission trends in percent volume for the deceleration mode of the Peak data collected on the Highway test track.

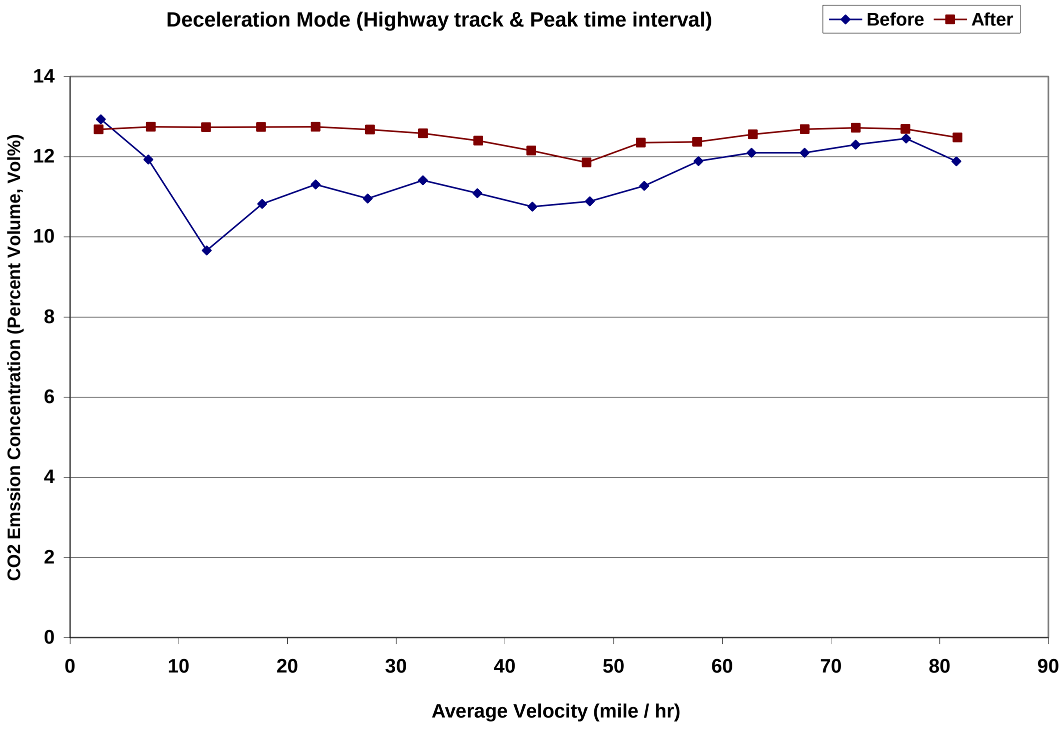

Figure 4.10 CO_2 emission trends (Vol. %) for highway test track's peak deceleration mode

Observations:

Figure 4.10 shows that there has been an increase in the CO_2 emissions after the installation of the device on the study vehicle. Similar trends were observed for the CO_2 emissions in all other modes, for highway test track and for peak data sets.

However, statistical analysis is required to establish or validate these observed trends.

Figure 4.11 shows the HC emission trends in ppm for the deceleration mode of the Peak data collected on the Highway test track.

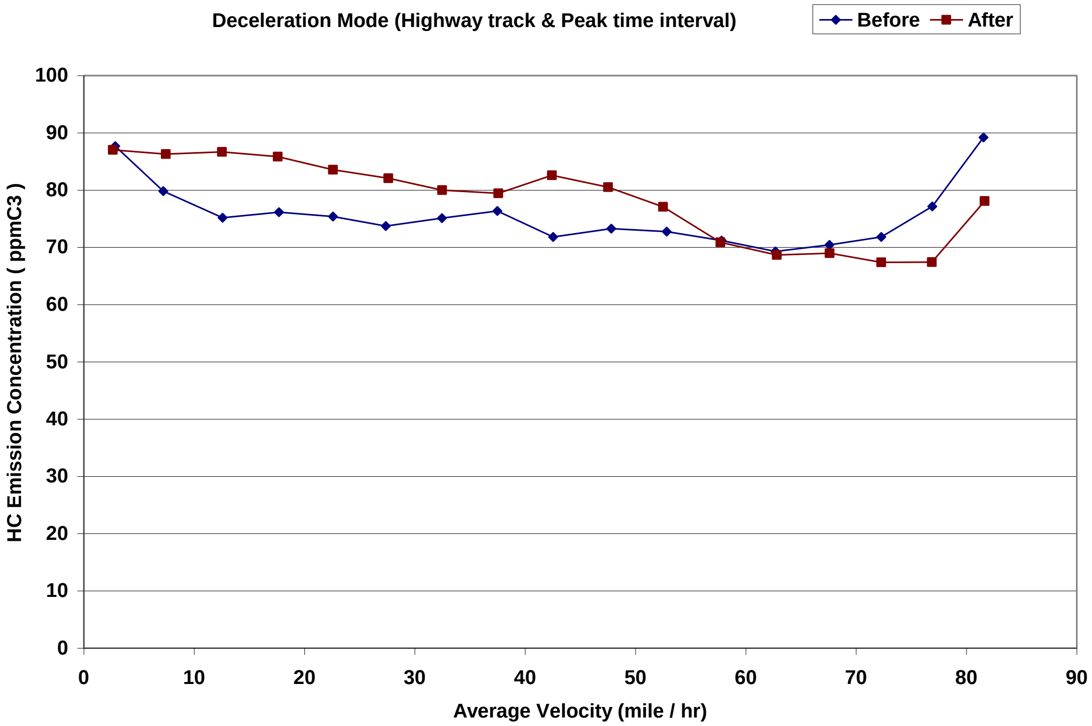

Figure 4.11 HC emission trends (ppm) for highway test track's peak deceleration mode

Observations:

Figure 4.11 shows that the trend appears to point towards an increase in emissions of HC in this case, after the installation of the device on the study vehicle. HC emissions showed both increasing as well as decreasing trends across all the modes for highway test track"s peak data sets.

As in the previous cases, statistical analysis in needed to establish definitive trends for HC emissions.

Figure 4.12 shows the NOx emission trends in ppm for the deceleration mode of the Peak data collected on the Highway test track.

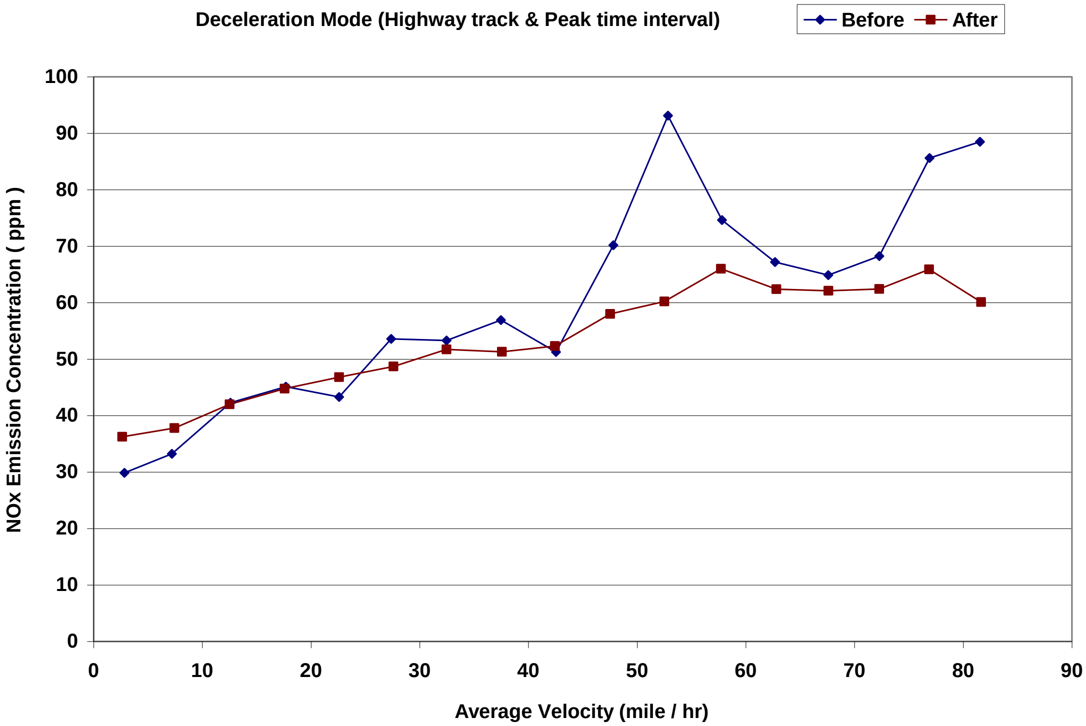

Figure 4.12 NOx emission trends (ppm) for highway test track's peak deceleration mode

Observations:

Figure 4.12 shows that though there is a lot of variation between the „before‟ and „after‟ data lines for NOx emission trends, there appears a trend pointing towards a decrease in the emissions in this case.

Similar „decreasing‟ trends were observed for NOx emissions across all the other modes, for both arterial as well as highway test tracks and in case of both peak and off-peak data sets, with the exception of the two cases discussed previously.

However, statistical analysis is required to establish or validate these observed trends.

Case D: Emission Trends for Highway Test Track's Off-peak Acceleration Mode.

Figure 4.13 shows the CO emission trends in percent volume for the acceleration mode of the off-peak data collected on the Highway test track.

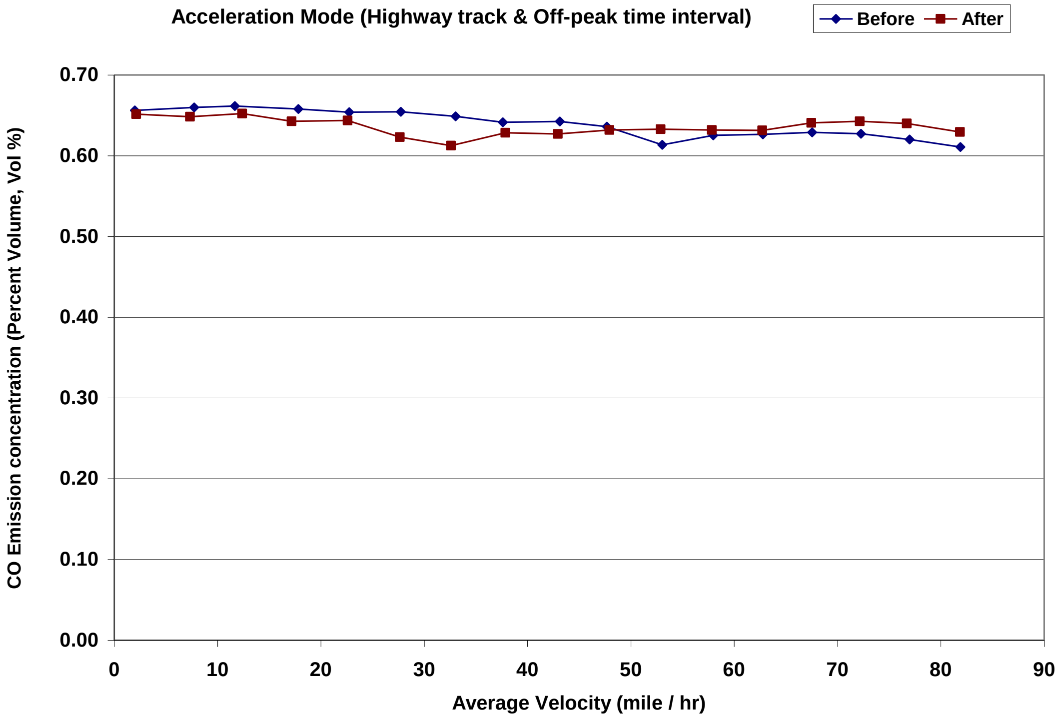

Figure 4.13 CO emission trends (Vol. %) for highway test track's off-peak acceleration mode

Observations:

Figure 4.13 appears to show no significant difference between the „before‟ data set and the „after‟ data set for CO emission concentrations, just by reading off the graph. Similar trends were observed for the CO emissions in all other modes and for highway test track‟s off-peak data sets.

However, statistical analysis is required to establish or validate these observed trends.

Figure 4.14 shows the CO_2 emission trends in percent volume for the acceleration mode of the off-peak data collected on the Highway test track.

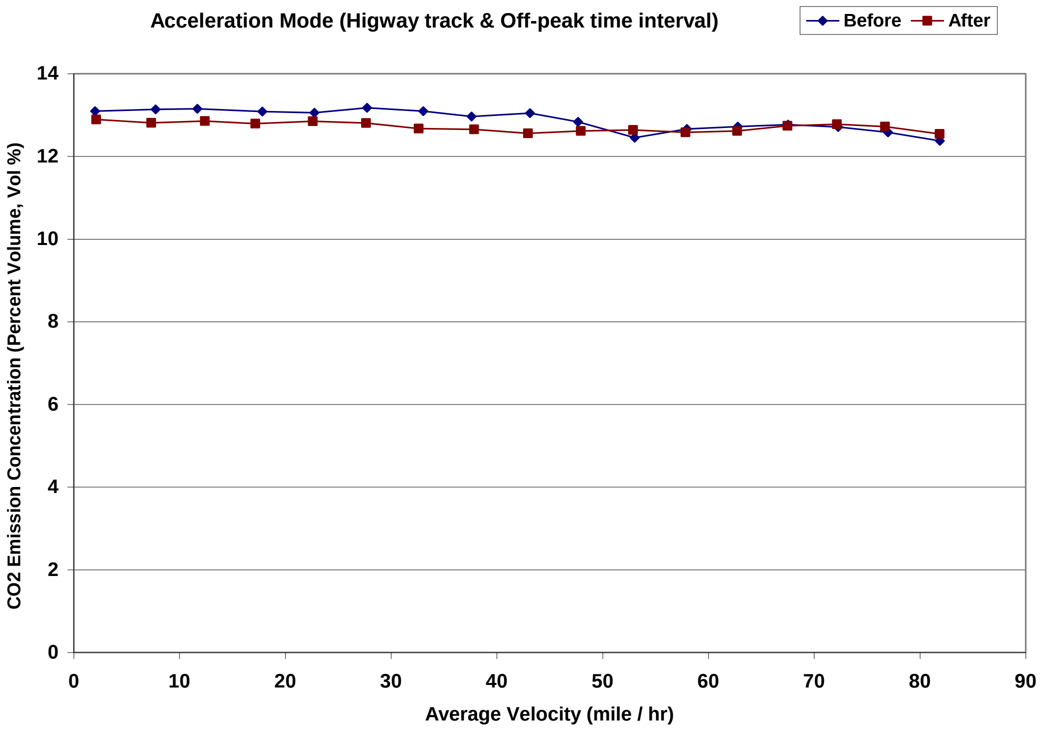

Figure 4.14 CO_2 emission trends (Vol. %) for highway test track's off-peak acceleration mode

Observations:

Figure 4.14 appears to show no significant difference between the „before" and „after" data lines for CO_2 emissions, though a slight increase or decrease could be observed between certain velocity ranges. Similar trends were observed for the CO emissions in all other modes, for highway test track"s off-peak data sets.

However, statistical analysis is required to establish or validate these observed trends.

Figure 4.15 shows the HC emission trends in parts per million for the acceleration mode of the off-peak data collected on the Highway test track.

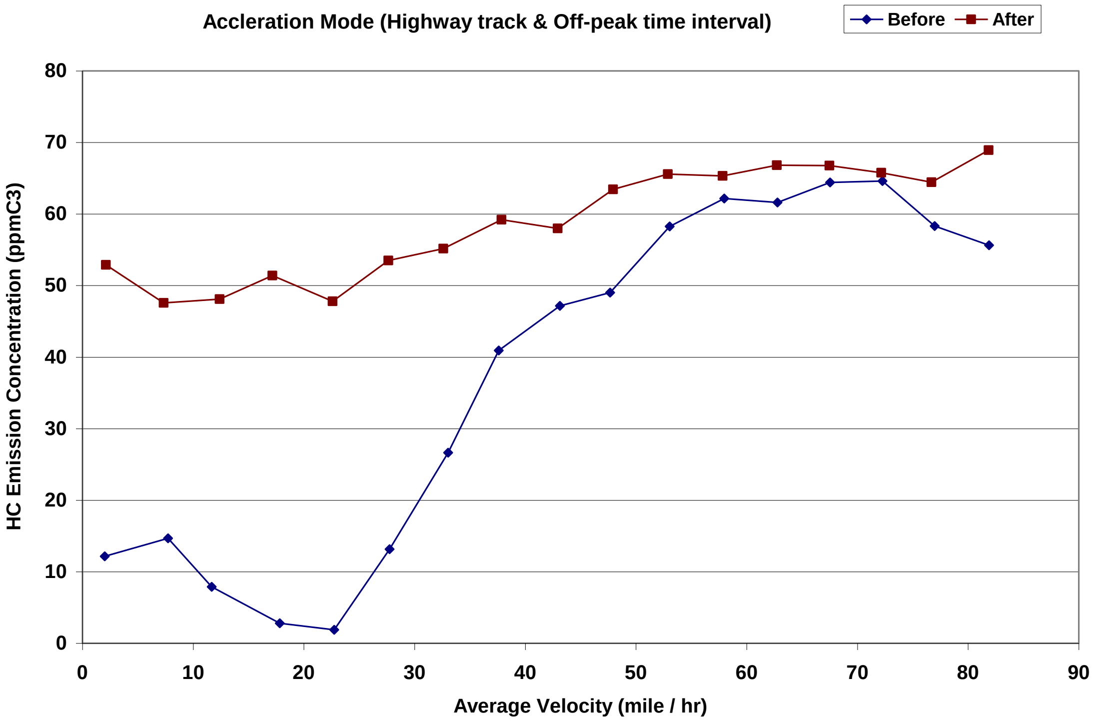

Figure 4.15 HC emission trends (ppm) for highway test track's off-peak acceleration mode

Observations:

Figure 4.15 shows that there appears to be a significant increase in HC, after the installation of the device on the study vehicle. Similar trends were observed for the CO_2 emissions in all other modes, for highway test track‟s off-peak data sets.

However, statistical analysis is required to establish or validate these observed trends.

Figure 4.16 shows the NOx emission trends in parts per million for the acceleration mode of the off-peak data collected on the Highway test track.

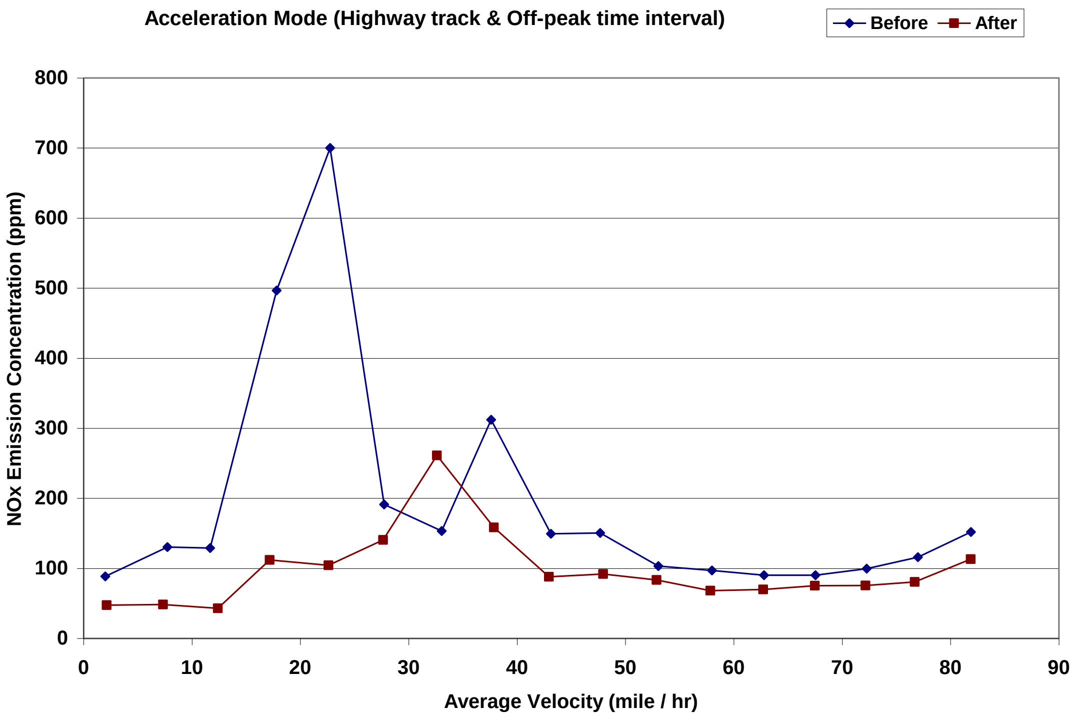

Figure 4.16 NOx emission trends (ppm) for highway test track's off-peak acceleration mode

Observations:

Figure 4.16 shows NOx emission trends, which appear to show a decrease in the „after" emissions with the device installed on the study vehicle. Similar trends were observed for all the other modes and for highway test track"s off-peak data sets.

However, to reach a certain conclusion, it is necessary to perform statistical analysis.

Therefore, from these four cases discussed, reading off the graphs, one could see that the emission concentrations of CO, CO_2, HC and NOx show an increase , a decrease or no significant difference between the „before" and „after" data lines. However, all cases needed the statistical analysis and the overall percentage reductions to be carried out to establish the observed trends. The following sections deal with this.

All the rest of the plots are presented in Appendix A for review.

4.3 Results: Percentage Reductions

After the plotting of the various comparison plots between the „before" and „after" data sets, percentage reduction calculations were carried out for all the measured pollutant concentrations to get a better understanding of the impact of the device on the emissions. The calculations were carried out for overall modal data sets, as explained in step 8 of Section 4.2.1.

4.3.1 Overall Percentage Reductions

The overall percentage reductions observed in each mode are summarized in the tables listed under this section. A negative reduction indicates an increase.

Table 4.3 summarizes the overall percentage reductions calculated for all four measured pollutants in acceleration mode.

Table 4.3 Overall Percentage Reductions Observed in Acceleration Mode.

	Overall Percentage Reductions (%)			
	Arterial Test Track		**Highway Test Track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	**-0.01**	**-0.76**	**-7.97**	**-1.84**
CO_2	2.54	2.12	**-6.00**	**-0.01**

Table 4.3 Continued

HC	5.79	**-24.5**	1.96	**-5.28**
NOx	**-7.51**	5.63	10.2	26.2

Table 4.4 summarizes the overall percentage reductions calculated for all four measured pollutants in deceleration mode.

Table 4.4 Overall Percentage Reductions Observed in Deceleration Mode.

	Overall Percentage Reductions (%)			
	Arterial Test Track		**Highway Test Track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	0.54	0.00	**-8.15**	**-2.24**
CO_2	3.12	2.73	**-5.89**	**-0.29**
HC	1.72	**-15.8**	**-0.92**	**-2.32**
NOx	2.91	8.94	11.8	20.5

Table 4.5 summarizes the overall percentage reductions calculated for all the four measured pollutants in cruising mode.

Table 4.5 Overall Percentage Reductions Observed in Cruising Mode.

	Overall Percentage Reductions (%)			
	Arterial Test Track		**Highway Test Track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	0.15	**-0.44**	**-5.45**	**-1.41**
CO_2	2.73	2.43	**-3.22**	0.79
HC	3.92	**-17.8**	0.19	**-3.37**
NOx	**-0.06**	3.18	9.79	19.4

Table 4.6 summarizes the overall percentage reductions calculated for all the four measured pollutants in idling mode.

Table 4.6 Overall Percentage Reductions Observed in Idling Mode.

	Overall Percentage Reductions (%)			
	Arterial Test Track		**Highway Test Track**	
	Peak	**Off-peak**	**Peak**	**Off-peak**
CO	**-0.38**	**-0.76**	---	---
CO_2	2.35	2.18	---	---
HC	6.05	**-15.1**	---	---
NOx	10.6	19.0	---	---

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

Observations:

The above tables show the overall percentage reductions observed across various modes, the arterial as well as highway test tracks and both peak and off-peak time intervals. They closely follow the trend patterns observed in the comparison plots discussed earlier. Of the four pollutants, one could see that only NOx emission concentrations showed a significant decrease in all the cases except for one, after the installation of the retrofit device on the study vehicle. NOx reductions varied from 3 to 26%, depending on the mode and traffic conditions.

4.4 Results: Statistical Analysis

4.4.1 General

After the plotting of the various comparison graphs showing the „before‟ data sets and the „after‟ data sets, it was felt that to positively establish whether a significant difference exists or does not exist between the „before‟ and „after‟ data sets of all the emission concentrations, statistical analysis was required. As part of that, t-tests were conducted on the „before‟ and „after‟ emission concentration data sets for all the four pollutants.

4.4.2 t-tests

These t-tests, like in the case of percentage reduction calculations, were carried out for two specific cases.

i. For overall modal data sets, as explained in step 8 of section 4.2.1.

ii. For individual modal data sets or velocity category data sets, as explained in steps 9 and 10 of section 4.2.1.

For the t-tests, the data analysis function of the “EXCEL” spreadsheet was used. The type of t-test conducted on these data sets was the “**two-sample t-test assuming equal variances**”, and a one-tail t-test was used in this analysis.

<u>Inputs in this t-test</u>

Variable 1 Range: Before data set

Variable 2 Range: After data set

Hypothesized Mean Difference: Zero (0)

Alpha: 0.05 (a 95% confidence level)

<u>Outputs</u>

Mean

Variance

Observations

Pooled Variance

Degrees of Freedom (df)

t stat (or t calculated)

P (T<=t) one-tail

t Critical one-tail

P (T<=t) two-tail

t Critical two-tail

4.4.2.1 Interpretation of the t-test results

The procedure of the t-tests conducted here is different from the normal t-tests, where one needs to manually calculate the input data set summations, their means, standard deviations etc., and input them into a formula to calculate the t stat. The output results here are interpreted a bit differently.

The Hypothesized Mean Difference is input as zero in all the t-test calculations; this means that we are saying that the probability of obtaining our given results by chance if there is no difference between the means is “zero”.

Therefore, my null hypothesis here is going to be that – “*there is no significant difference between ‘before’ and ‘after’ data*.”

Table 4.8 gives the Hypothesis testing criteria that were used for the t-tests conducted.

Table 4.8 Hypothesis testing Criteria

Hypothesis testing
H_0: $\mu_2 \geq \mu_1$ H_1: $\mu_2 < \mu_1$
H_0: $\mu_2 \leq \mu_1$ H_1: $\mu_2 > \mu_1$

where:

μ_1 = „before‟ data mean,

μ_2 = “after‟ data mean,

H_0 = null hypothesis

H_1 = alternate hypothesis

Here, alternate hypothesis will then be – “there is a significant difference between the two data sets.”

“**t stat/ t cal**” shows the t value calculated from the input data range.

P (T<=t) one-tail shows the probability of getting the calculated t value by chance alone. If this output value is extremely low, that means that the “means“” are significantly different. This implies that the inputted data sets are significantly different from each other.

t Critical one-tail shows the t value that we would need to exceed in order for the difference between the means to be significant (i.e., | **t stat** | > **t crit**).

4.4.3 Overall t-tests: Results

t-tests were conducted for all the modal data sets and the results followed the same pattern as overall percentage reduction trends. The tables listed in this section summarize the results for the various overall t-tests conducted.

16 tables are used to represent the overall t-test results for all four pollutants under various modes, arterial and highway tracks and peak as well as off-peak time intervals.

Four representative tables are provided under this section for four different pollutants. The rest of the tables are provided in Appendix B for review.

Table 4.9 lists the results of t-tests conducted for CO emission concentrations for arterial track‟s overall peak data sets.

Table 4.9 t-tests for CO Emission Concentrations for Arterial Track's Overall Peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	NO	-0.01
Deceleration Mode	YES	0.54
Cruising Mode	YES	0.15
Idling Mode	YES	-0.38

Table 4.10 lists the results of t-tests conducted for CO_2 emission concentrations for arterial track‟s overall off-peak data sets.

Table 4.10 t-tests for CO_2 Emission Concentrations for Arterial Track's Overall Off-peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	2.12
Deceleration Mode	YES	2.73
Cruising Mode	YES	2.43
Idling Mode	YES	2.18

Table 4.11 lists the results of t-tests conducted for HC emission concentrations for highway track‟s overall peak data sets.

Table 4.11 t-tests for HC Emission Concentrations for Highway Track's Overall Peak Data Sets.

Modes	**Significant Difference, (t-test result)**	**Overall Percentage Reduction Observed, %**
Acceleration Mode	YES	1.96
Deceleration Mode	YES	-0.92
Cruising Mode	NO	0.19

Table 4.12 lists the results of t-tests conducted for NOx emission concentrations for highway track‟s overall off-peak data sets.

Table 4.12 t-tests for NOx Emission Concentrations for Highway Track's Overall Off-peak Data Sets.

Modes	**Significant Difference, (t-test result)**	**Overall Percentage Reduction Observed, %**
Acceleration Mode	YES	26.2
Deceleration Mode	YES	20.5
Cruising Mode	YES	19.4

Observations on Overall t-tests:

From the above four tables, one could clearly see that the overall percentage reductions observed were being matched by the corresponding t-test results. This was observed to be the same for all the four pollutants under all conditions. Hence, we can conclude that the overall percentage reductions observed are valid results for the data collected and analyzed.

4.4.4 t-tests for Velocity Category Data Sets: Results

After carrying out the t-tests for overall modal data sets, t-tests were also carried out for certain representative velocity category data sets. This was done to validate the trends observed in the plots of the combined data sets. This also gives us a better understanding of the results of comparison between the „after" and „before" data sets. Moreover, it gives us a better understanding of the differences between „before" and „after" data sets at various average velocity ranges considered in each particular mode.

For this part of the analysis, the following representative data sets were chosen:

Peak Arterial Acceleration Mode,

Off-peak Arterial Deceleration Mode, and

Off-peak highway Cruising Mode.

For these three velocity category data sets, t-tests for all the four pollutants were conducted. This section lists some tables that show the general trends seen in the t-tests conducted. The rest of the tables are provided in Appendix C for review.

Table 4.13 shows the results of the velocity category t-tests conducted for CO emission concentrations in the acceleration mode of arterial test track"s peak data set.

Table 4.13 Velocity category t-tests for CO emissions in the acceleration mode of arterial test track's peak data set.

Velocity Ranges (mile/hr)	Significant difference	Percentage Reductions Observed, %
0 - 4.99	YES	-0.55
5 - 9.99	YES	-1.26
10 - 14.99	YES	-0.56
15 - 19.99	NO	-0.12
20 - 24.99	NO	0.24
25 - 29.99	YES	0.47
30 - 34.99	YES	0.32
35 - 39.99	NO	0.11
40 - 44.99	NO	-0.05
45 - 49.99	YES	0.45

Table 4.14 shows the results of the velocity category t-tests conducted for CO_2 emission concentrations in the acceleration mode of arterial test track‟s peak data set.

Table 4.14 Velocity category t-tests for CO_2 emissions in the acceleration mode of arterial test track's peak data set.

Velocity Clusters (mile/h)	Significant difference	Percentage Reductions Observed, %
0 - 4.99	YES	2.15
5 - 9.99	YES	1.43
10 - 14.99	YES	1.90
15 - 19.99	YES	2.32
20 - 24.99	YES	2.69
25 - 29.99	YES	2.81
30 - 34.99	YES	2.76
35 - 39.99	YES	2.69
40 - 44.99	YES	2.78
45 - 49.99	YES	3.07

Table 4.15 shows the results of the velocity category t-tests conducted for HC emission concentrations in the acceleration mode of arterial test track"s peak data set.

Table 4.15 Velocity category t-tests for HC emissions in the acceleration mode of arterial test track's peak data set.

Velocity Clusters (mile/h)	Significant difference	Percentage Reductions Observed, %
0 - 4.99	NO	-1.85
5 - 9.99	NO	-0.98
10 - 14.99	NO	2.34
15 - 19.99	YES	7.90
20 - 24.99	YES	6.71
25 - 29.99	YES	7.94
30 - 34.99	YES	12.2
35 - 39.99	YES	6.72
40 - 44.99	YES	6.15
45 - 49.99	YES	6.98

Table 4.16 shows the results of the velocity category t-tests conducted for NOx emission concentrations in the acceleration mode of arterial test track"s peak data set.

Table 4.16 Velocity category t-tests for NOx emissions in the acceleration mode of arterial test track's peak data set.

Velocity Clusters (mile/h)	Significant difference	Percentage Reductions, %
0 - 4.99	NO	2.17
5 - 9.99	NO	-6.76
10 - 14.99	YES	-7.26
15 - 19.99	NO	-3.95
20 - 24.99	YES	-12.1
25 - 29.99	YES	-9.36
30 - 34.99	YES	-6.69
35 - 39.99	YES	-9.61
40 - 44.99	YES	-8.49
45 - 49.99	NO	1.04

Observations:

From the four tables given above, one could clearly see that the velocity category t-tests conducted are closely following the percentage reductions observed at the particular velocity clusters. Similar trends were observed for the rest of the representative velocity category data sets mentioned earlier. Review Appendix C.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of this research was to measure the impact of a pre-combustion retrofit device on the emissions from a light duty gasoline vehicle. After conducting rigorous graphical and statistical analysis of the data, the following conclusions have been reached:

Graphical analysis, as discussed in Chapter 4, in this research resulted in the establishing of certain trends for the four pollutants, from the plots of „before" and „after" data. Though there were instances where an increase, a decrease or sometimes no difference was observed between the data lines, it was difficult to conclude. Hence, to conclude anything it was felt that conducting statistical analysis along with the overall percentage reduction calculations was necessary.

Overall percentage reductions showed different patterns in case of arterial and highway test tracks for CO, CO_2 and HC emissions. In some cases, emissions increased and in other cases, emissions decreased. However, NOx emissions showed a „decrease in emissions" across all the modes and traffic conditions, except in the cases of arterial track"s peak acceleration mode and peak cruising mode.

From overall percentage reduction calculations, the following results can be established:

Table 5.1 lists the summary results of the overall percentage reductions observed in case of arterial test track.

Table 5.1 Arterial Test Track's Results Summary

Pollutant	**Arterial Test Track**	
	Percentage Reductions Ranges, %	**Significant?**
CO	-0.76% to 0.54%	NO
CO_2	2.12% to 3.12%	YES
HC	-24.5% to 6.05 %.	YES
NOx	-7.51% to 19%	YES, except for two cases

Table 5.2 lists the summary results of the overall percentage reductions observed in case of highway test track.

Table 5.2 Highway Test Track's Results Summary

Pollutant	**Highway Test Track**	
	Percentage Reductions Ranges, %	**Significant?**
CO	-8.15% to -1.41%	YES
CO_2	-6% to 0.79%	YES
HC	-5.28% to 1.96%	YES
NOx	9.79% to 26.2%	YES

It can be concluded that out of the four pollutants, the device is having a major impact on NOx emissions, with a maximum decrease of 26.2% occurring at highway track‟s off-peak acceleration mode.

A significant decrease in emissions of CO_2 could also be seen in case of all the modes and both the time intervals on an arterial test track.

The above overall percentage reductions have been statistically validated by conducting t-tests on the overall modal data sets of the four measured pollutants. The tests clearly showed a statistical significance between the „before and „after‟ data sets at instances where a decrease or increase in emissions occurred and showed a statistical insignificance where no significant increase or decrease in emissions was seen.

In order to assess the impact on the various velocity categories, certain representative velocity categories were selected and the percentage reductions along with the t-tests were conducted for them, as discussed in Chapter 4.

The velocity category percentage reductions closely followed the results observed for the overall percentage reductions.

The velocity category percentage reductions observed were statistically validated by the t-tests conducted.

5.2 Recommendations

The following recommendations can be made for this particular research:

1. Since the device had a considerable impact on the NOx emissions across most of the considered cases, the pre-combustion retrofit device is recommended for further testing using different and increased numbers of vehicles to assess its full impact.
2. Greater focus of the future studies of the device should also be on its performance on highway tracks, as greater percentage reductions were observed in NOx emissions here.
3. Further study of the impact of the device on CO_2 emissions in case of arterial test track is also recommended, as it showed a significant decrease in emissions here.
4. Modifications in the device are recommended to the manufacturer to have a significant impact on the other three pollutants.

APPENDIX A

„BEFORE" AND „AFTER" TRENDS: GRAPHICAL COMPARISON

Case A: Emission Trends in for Arterial Test Track's peak Acceleration Mode.

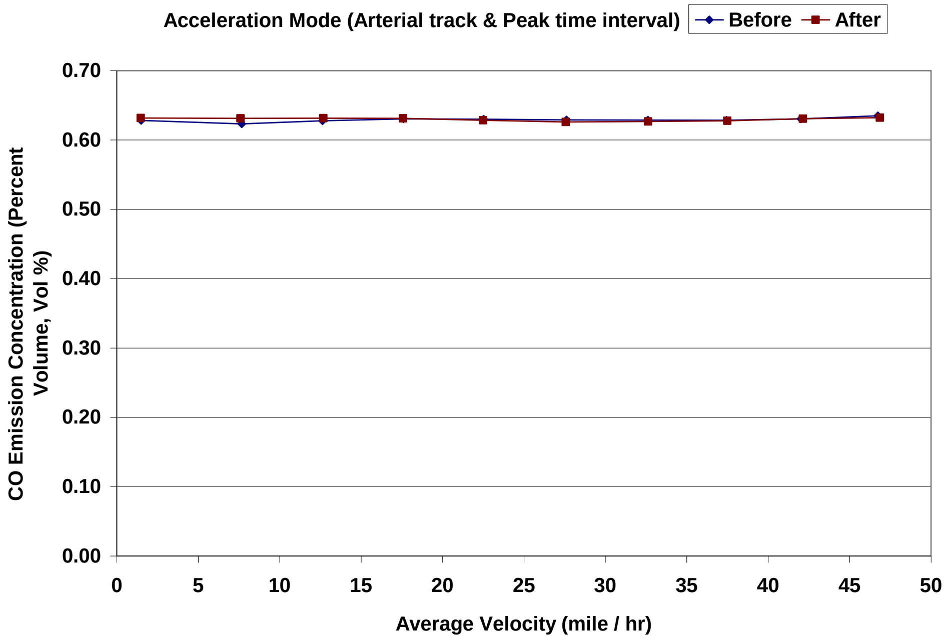

Figure A-1 CO emission trends (vol. %) for arterial test track's peak acceleration mode

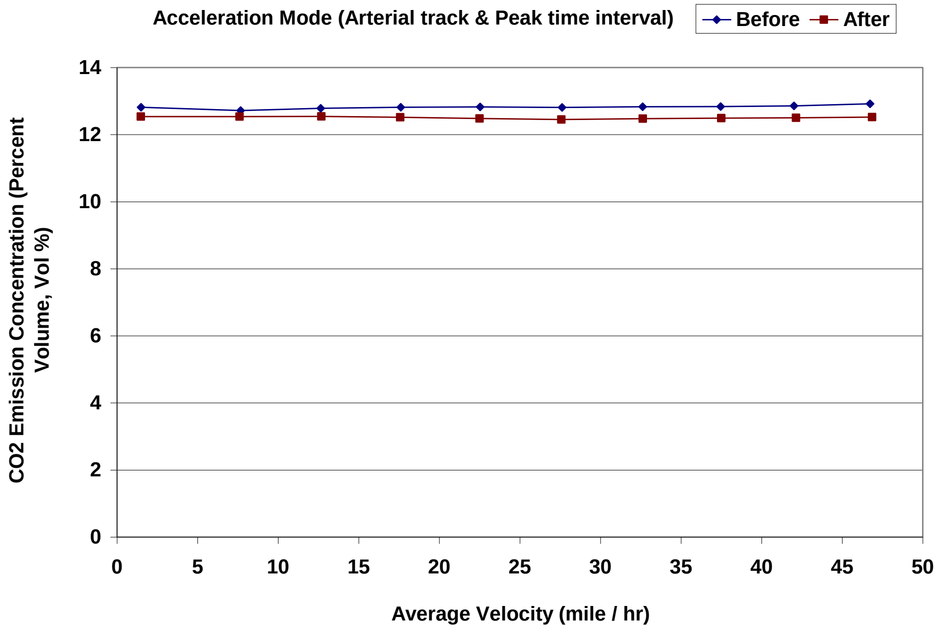

Figure A-2 CO_2 emission trends (vol.%) for arterial test track's peak acceleration mode

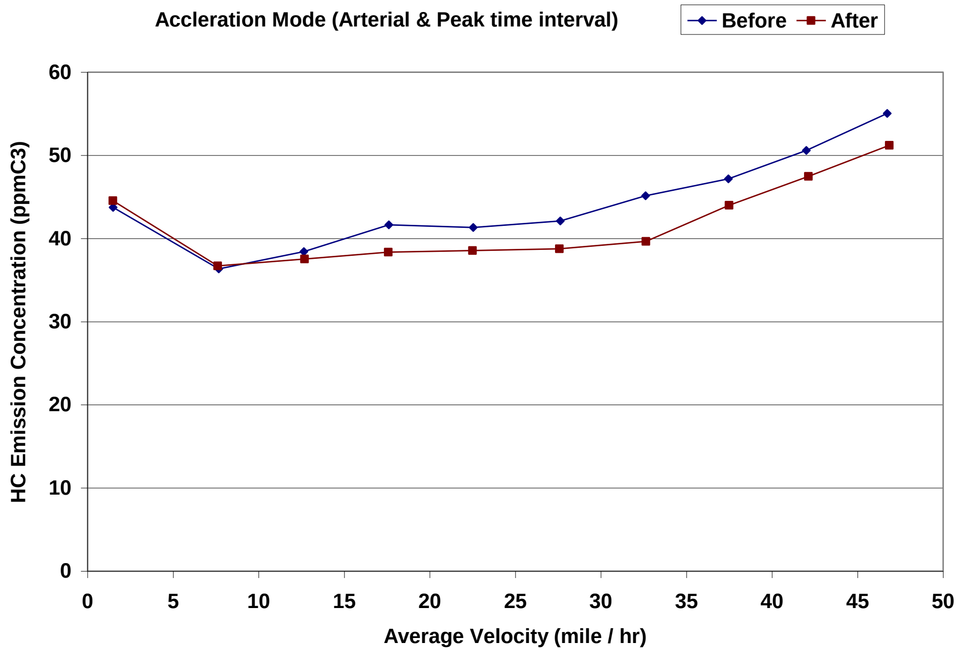

Figure A-3 HC emission trends (ppm) for arterial test track's peak acceleration mode

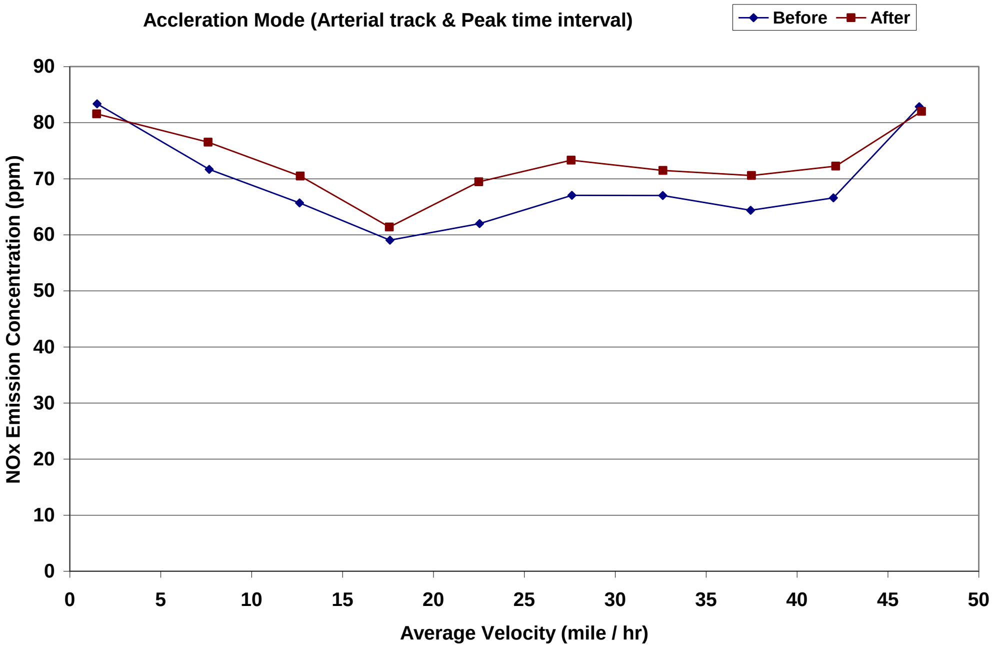

Figure A-4 NOx emission trends (ppm) for arterial test track's peak acceleration mode

Case B: Emission Trends for Highway Test Track's Peak Acceleration Mode.

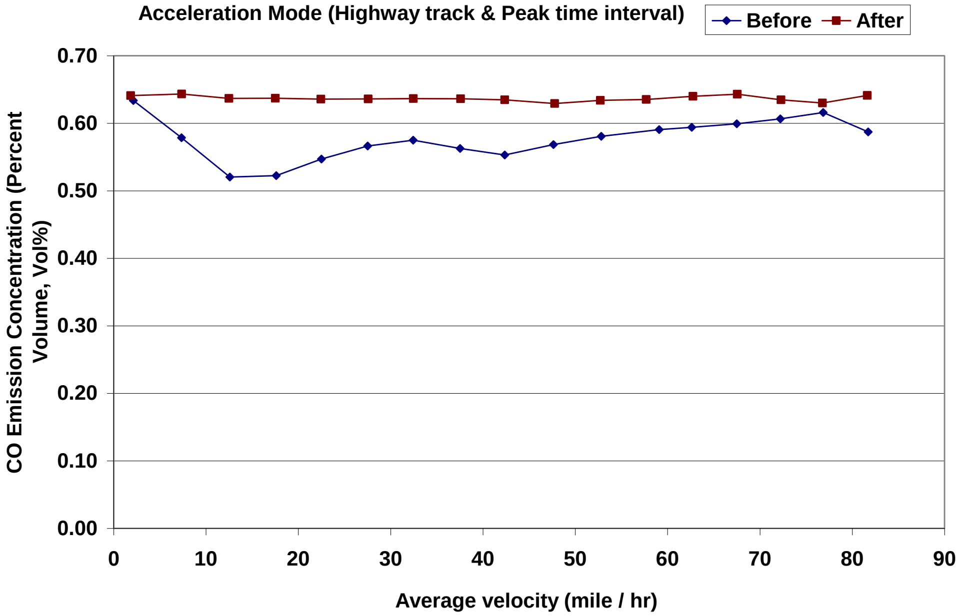

Figure A-5 CO emission trends (vol. %) for highway test track's peak acceleration mode

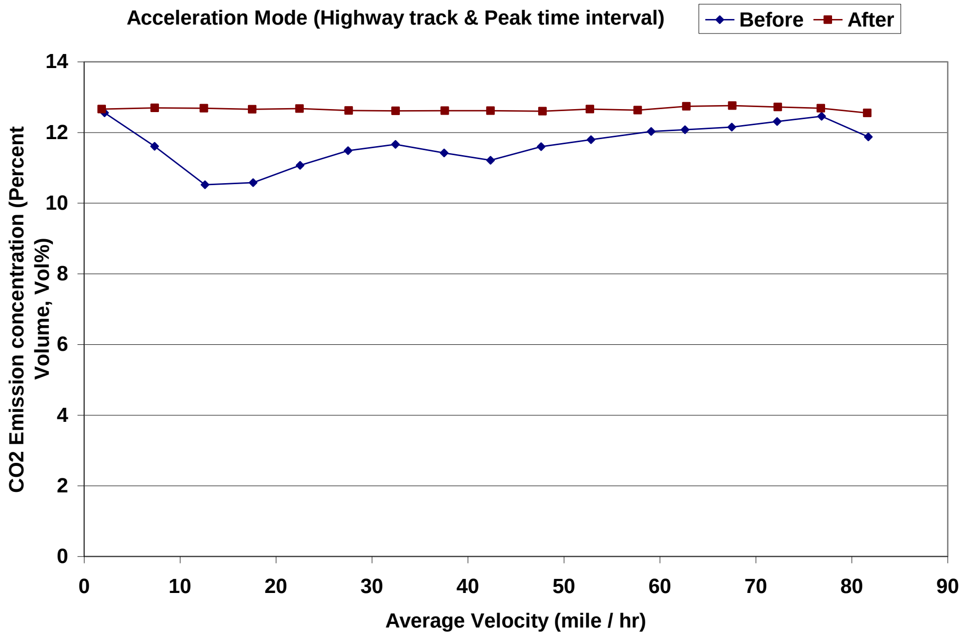

Figure A-6 CO_2 emission trends (vol. %) for highway test track's peak acceleration mode

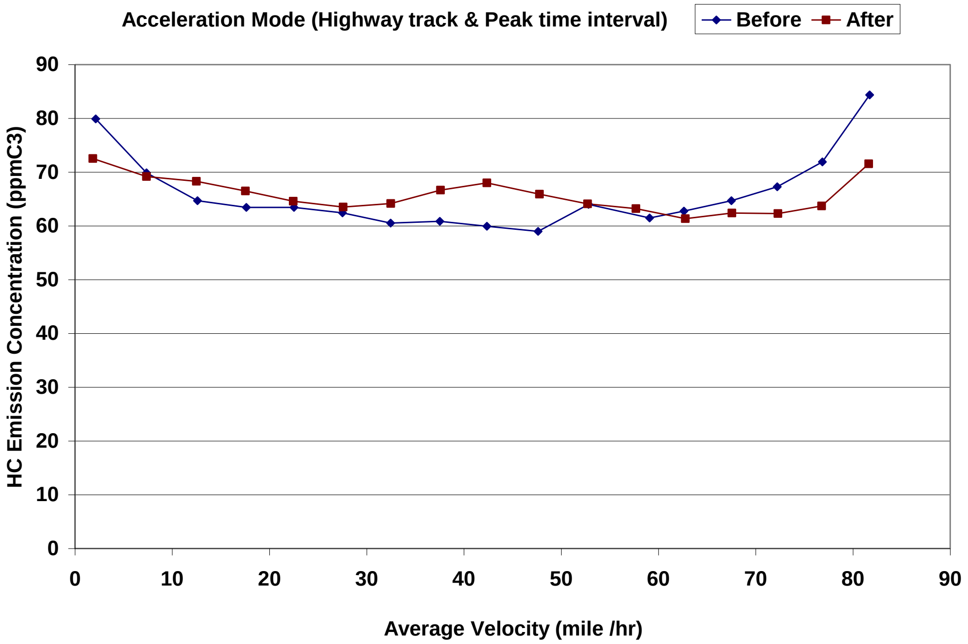

Figure A-7 HC emission trends (ppm) for highway test track's peak acceleration mode

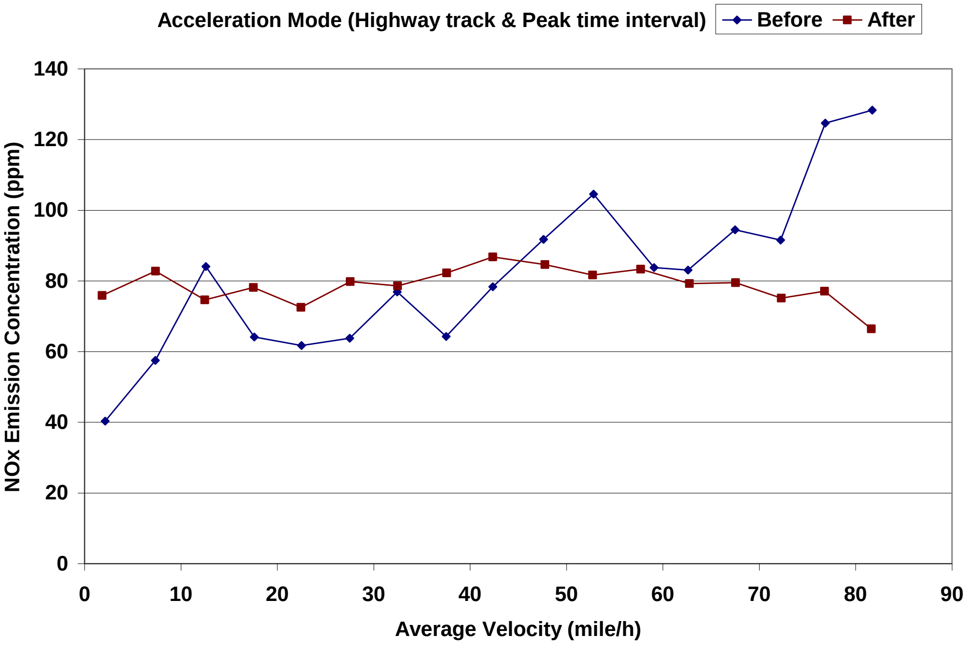

Figure A-8 NOx emission trends (ppm) for highway test track's peak acceleration mode

Case C: Emission Trends for Arterial Test Track's Off-peak Deceleration Mode.

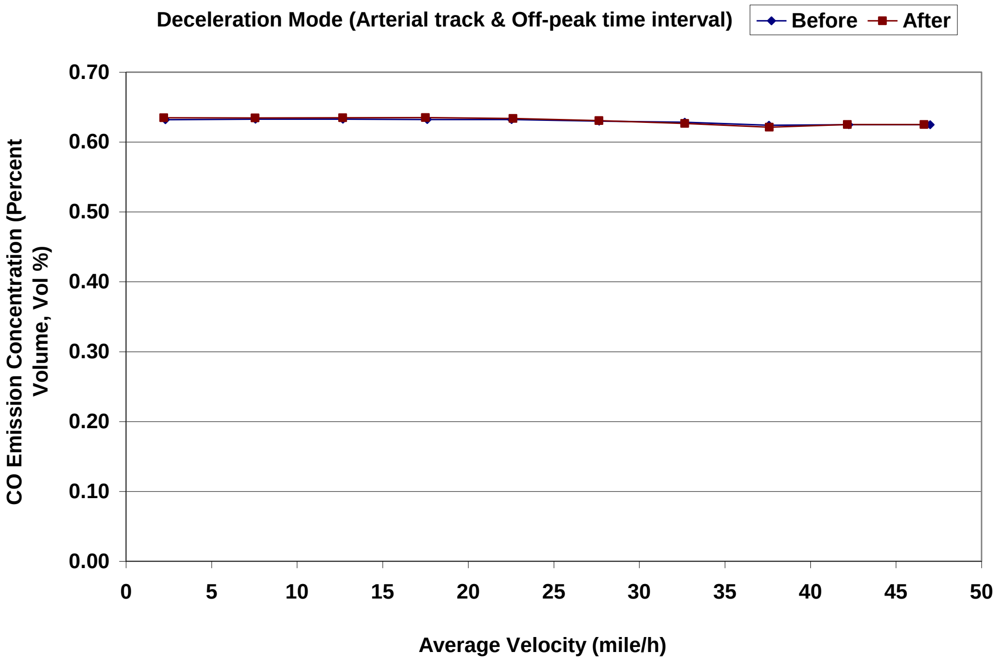

Figure A-9 CO emission trends (vol. %) for arterial test track's off-peak deceleration mode

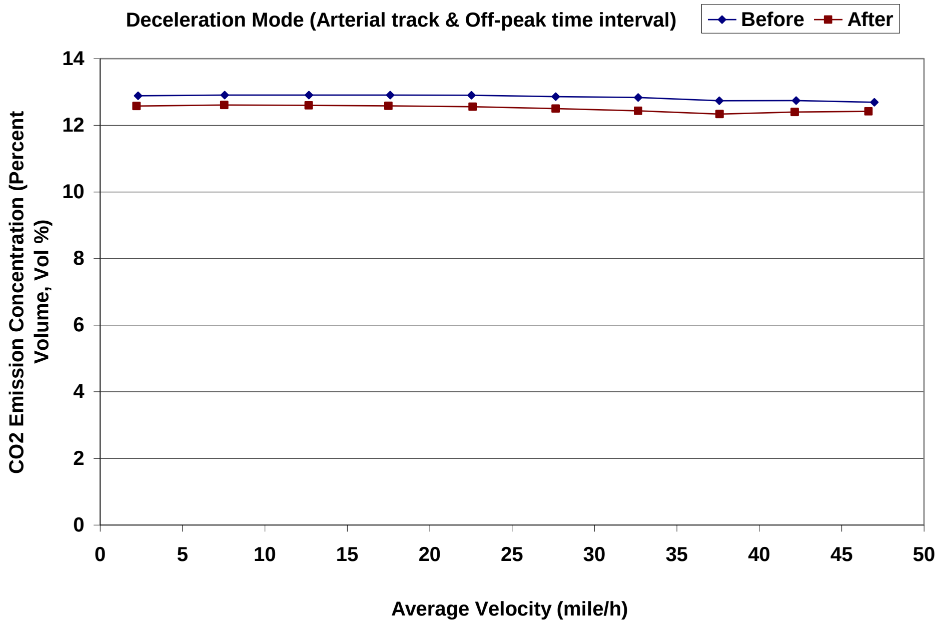

Figure A-10 CO2 emission trends (vol. %) for arterial test track's off-peak deceleration mode

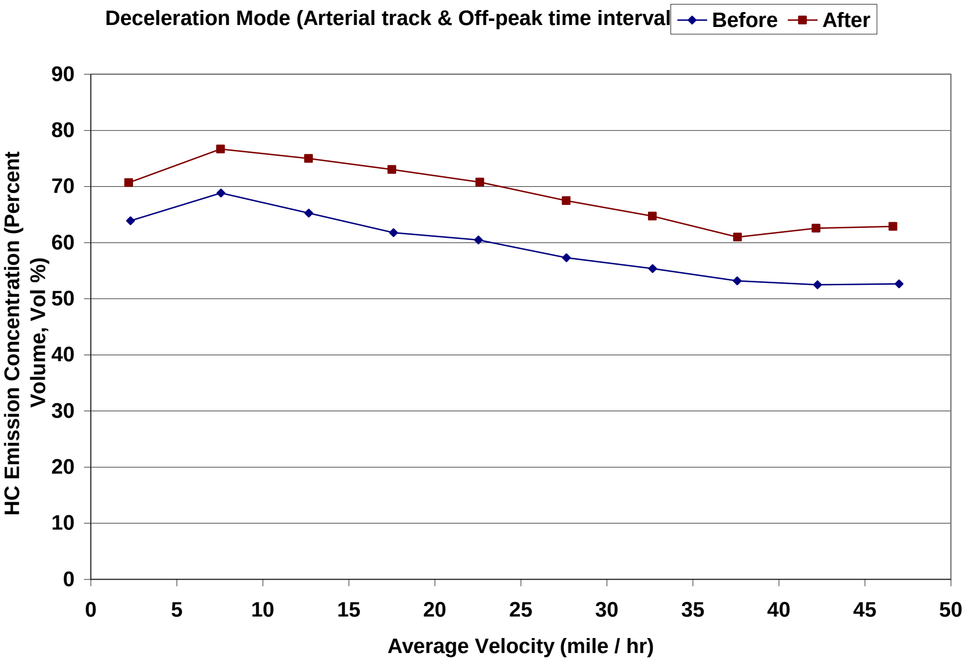

Figure A-11 HC emission trends (ppm) for arterial test track's off-peak deceleration mode

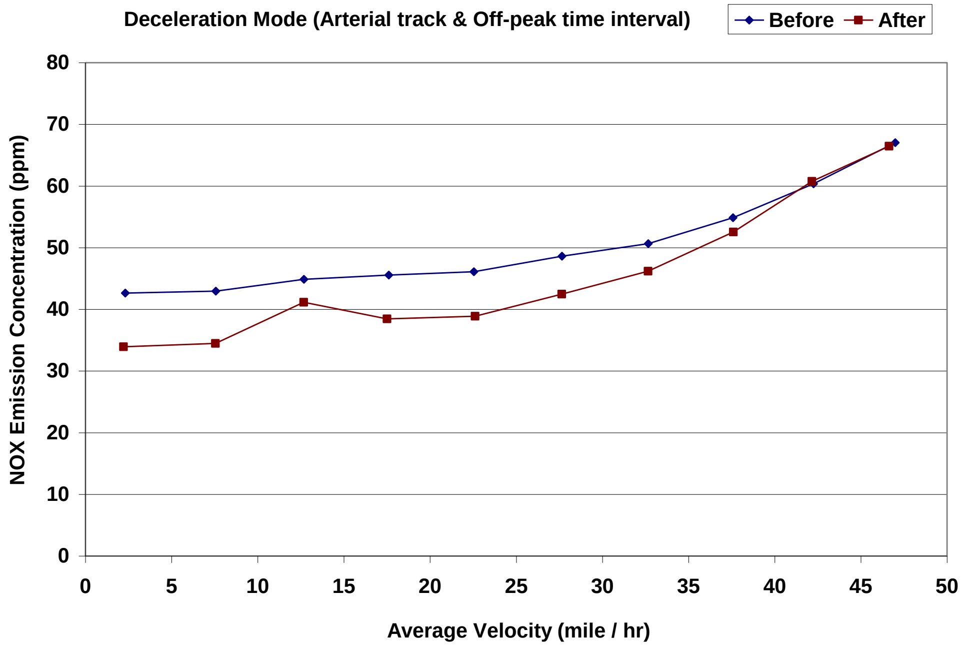

Figure A-12 NOx emission trends (ppm) for arterial test track's off-peak deceleration mode

Case D: Emission Trends for Arterial Test Track's peak Deceleration Mode.

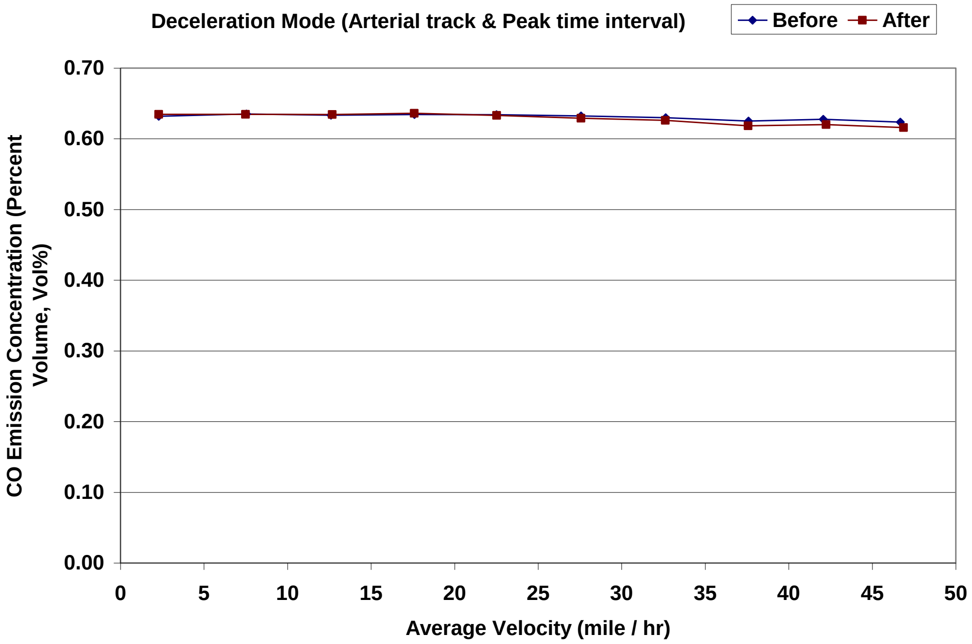

Figure A-13 CO emission trends (vol.%) for arterial test track's peak deceleration mode

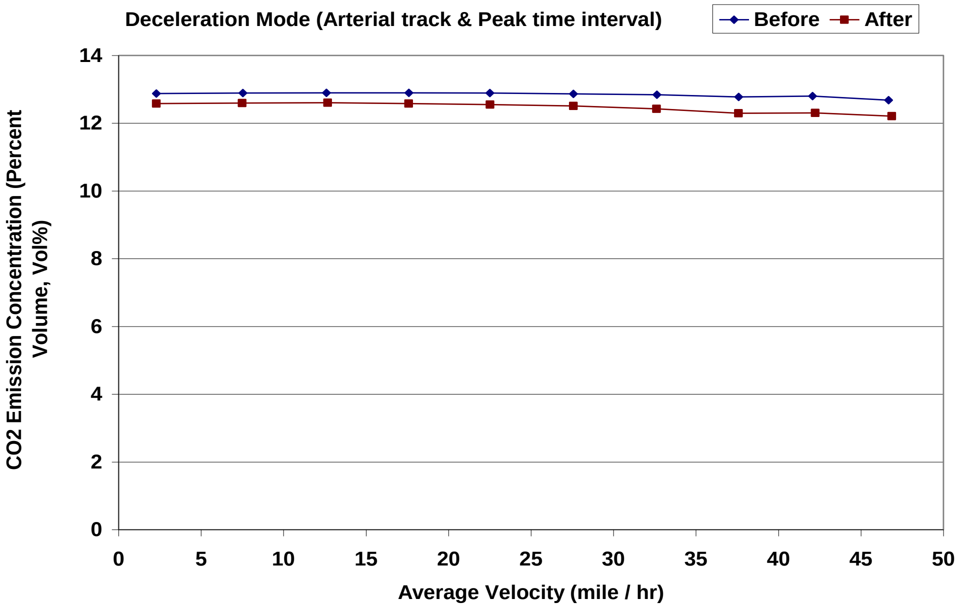

Figure A-14 CO_2 emission trends (vol.%) for arterial test track's peak deceleration mode

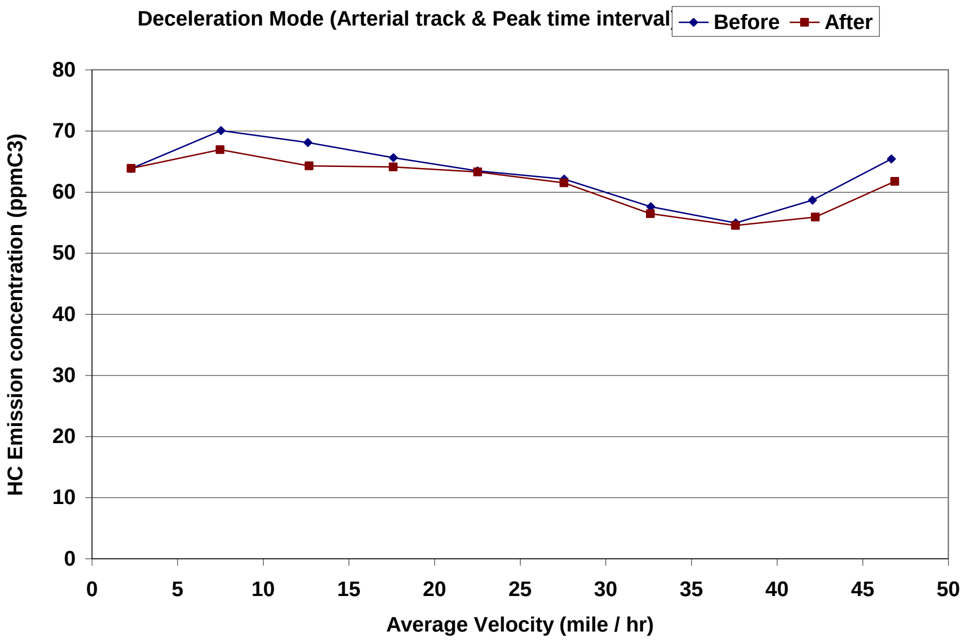

Figure A-15 HC emission trends (vol.%) for arterial test track's peak deceleration mode

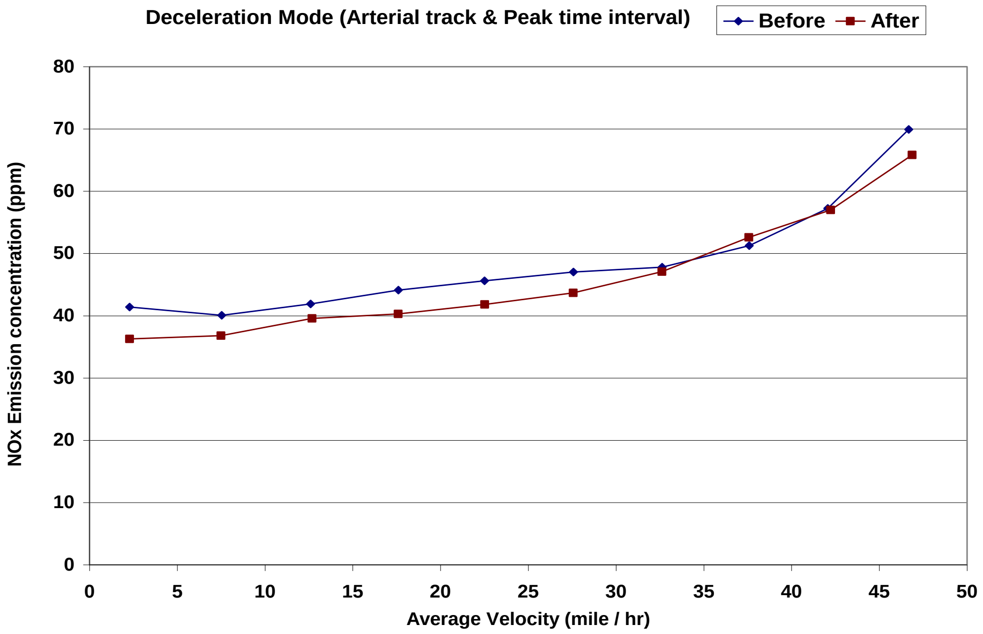

Figure A-16 NOx emission trends (vol.%) for arterial test track's peak deceleration mode

Case E: Emission Trends for Highway Test Track's Off-peak Deceleration Mode.

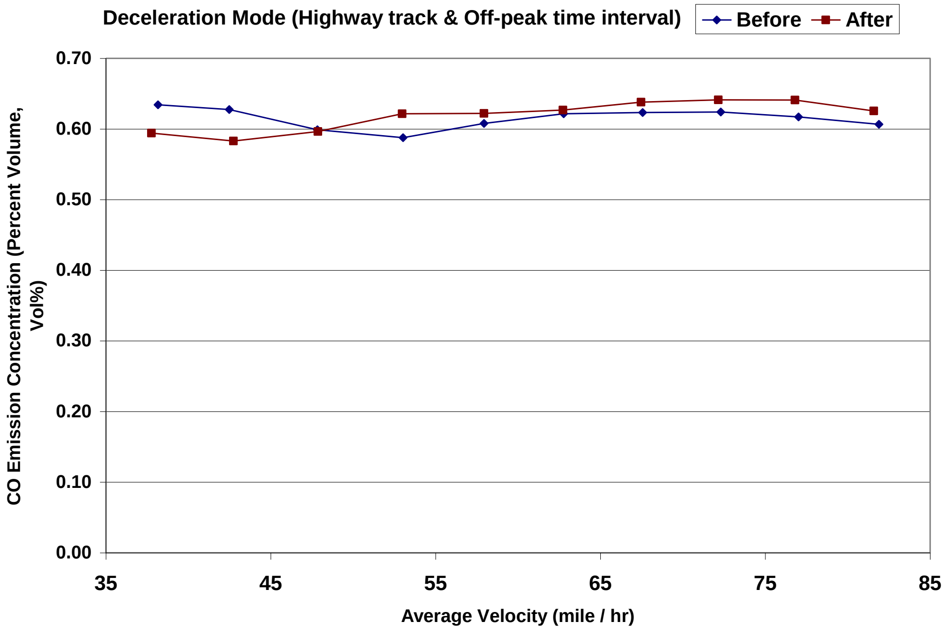

Figure A-17 CO emission trends (vol. %) for highway test track's off-peak deceleration mode

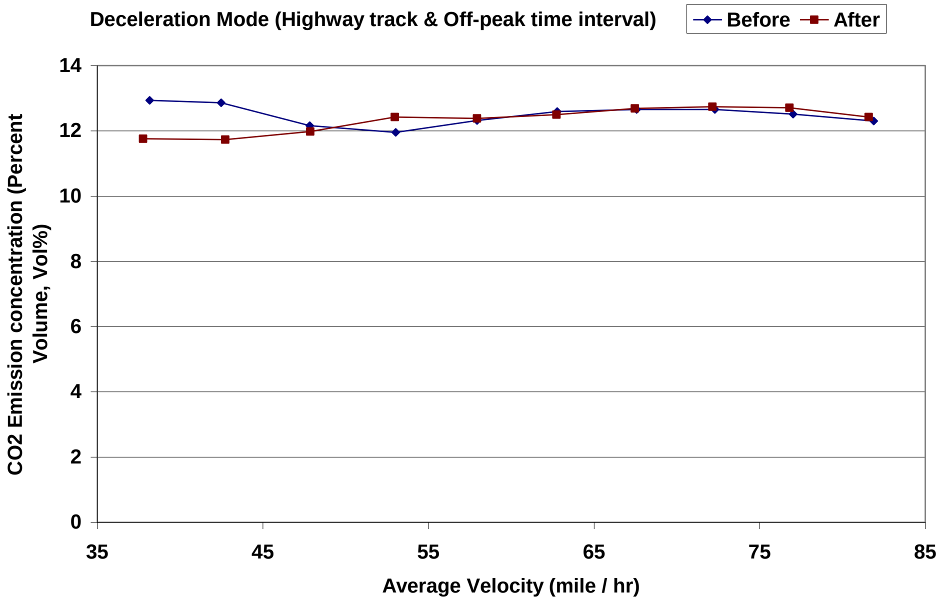

Figure A-18 CO_2 emission trends (vol. %) for highway test track's off-peak acceleration mode

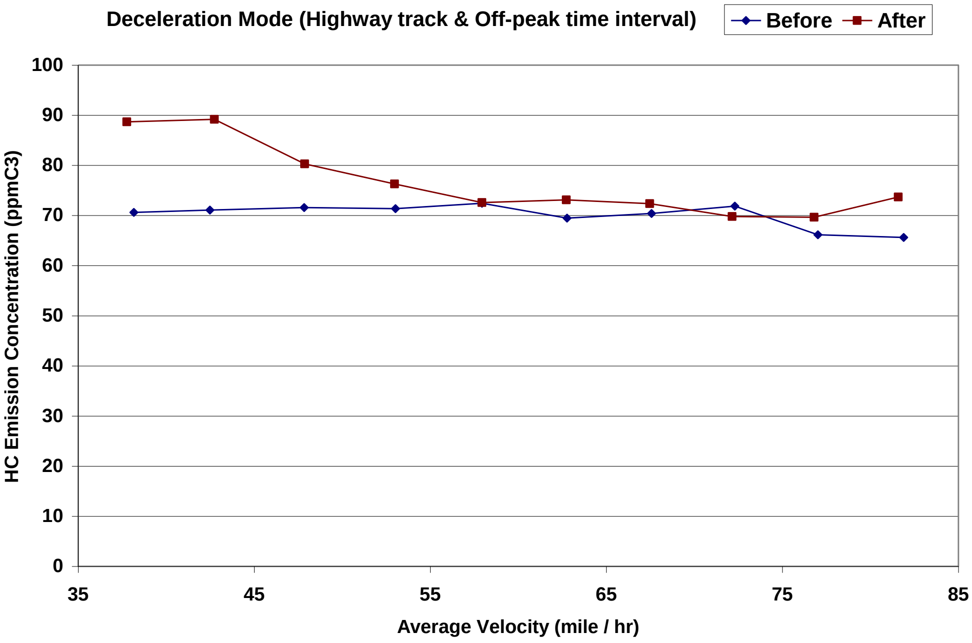

Figure A-19 HC emission trends (ppm) for highway test track's off-peak deceleration mode

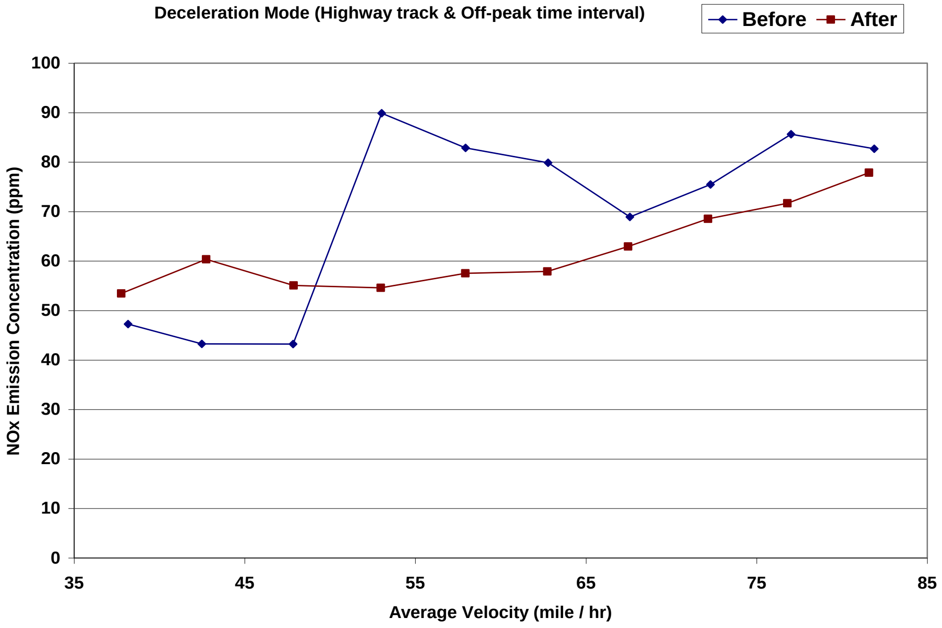

Figure A-20 NOx emission trends (ppm) for highway test track's off-peak deceleration mode

Case D: Emission Trends for Arterial Test Track's Off-peak Cruising Mode.

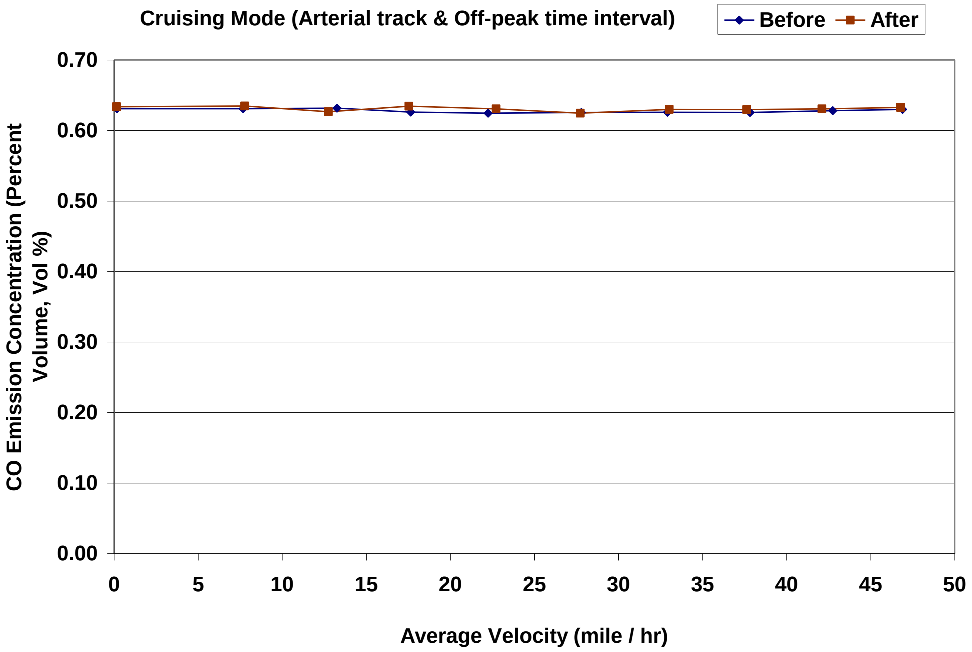

Figure A-21 CO emission trends (vol. %) for arterial test track's off-peak cruising mode

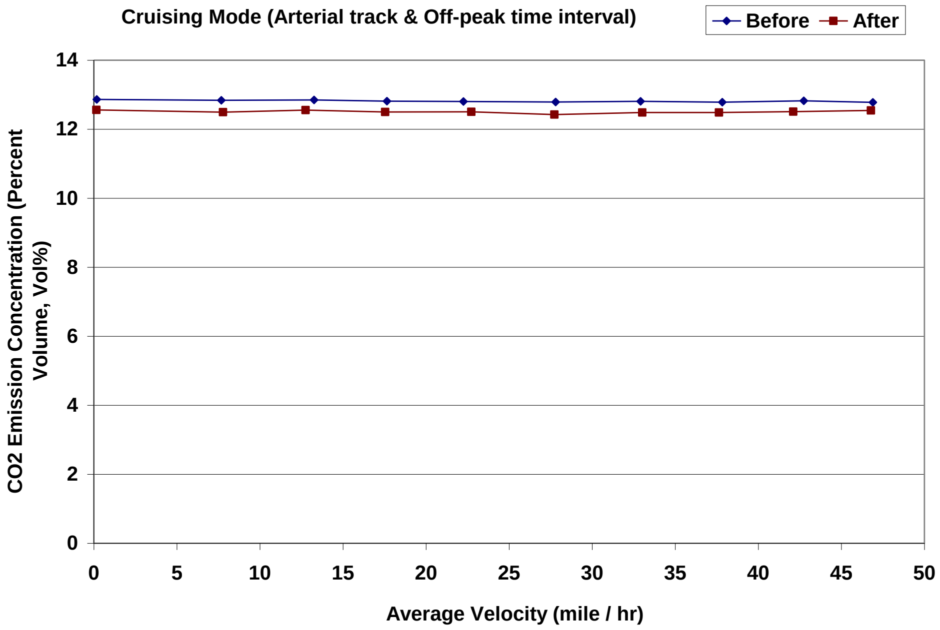

Figure A-22 CO_2 emission trends (vol. %) for arterial test track's off-peak cruising mode

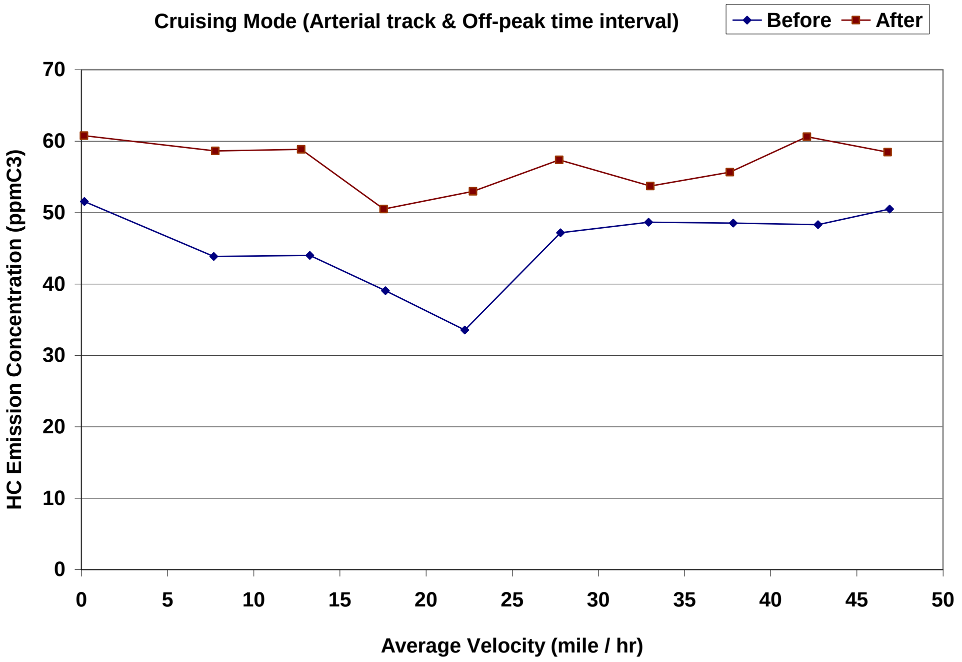

Figure A-23 HC emission trends (ppm) for arterial test track's off-peak cruising mode

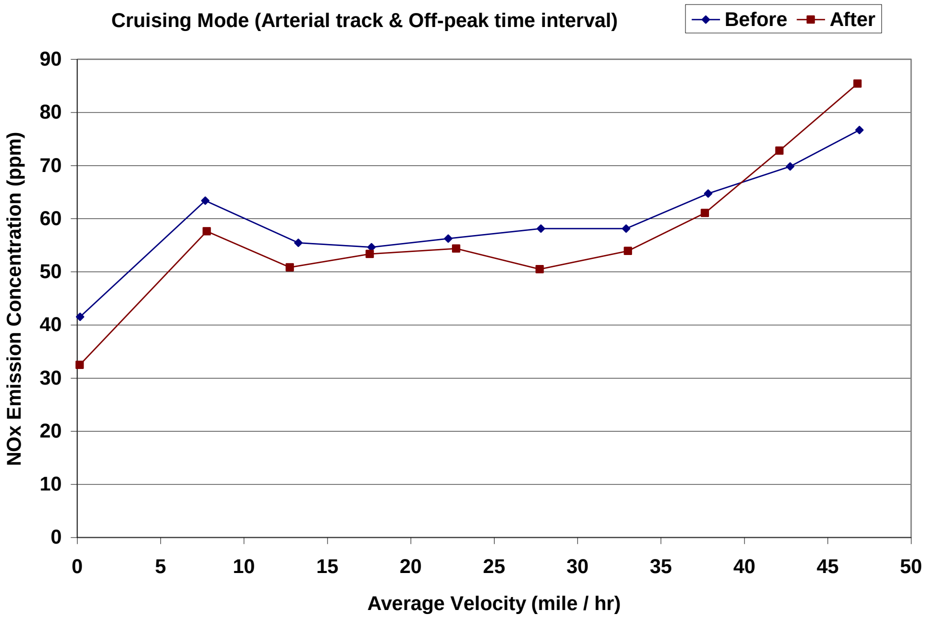

Figure A-24 NOx emission trends (ppm) for arterial test track's off-peak cruising mode

Case E: Emission Trends for Highway Test Track's Peak Cruising Mode.

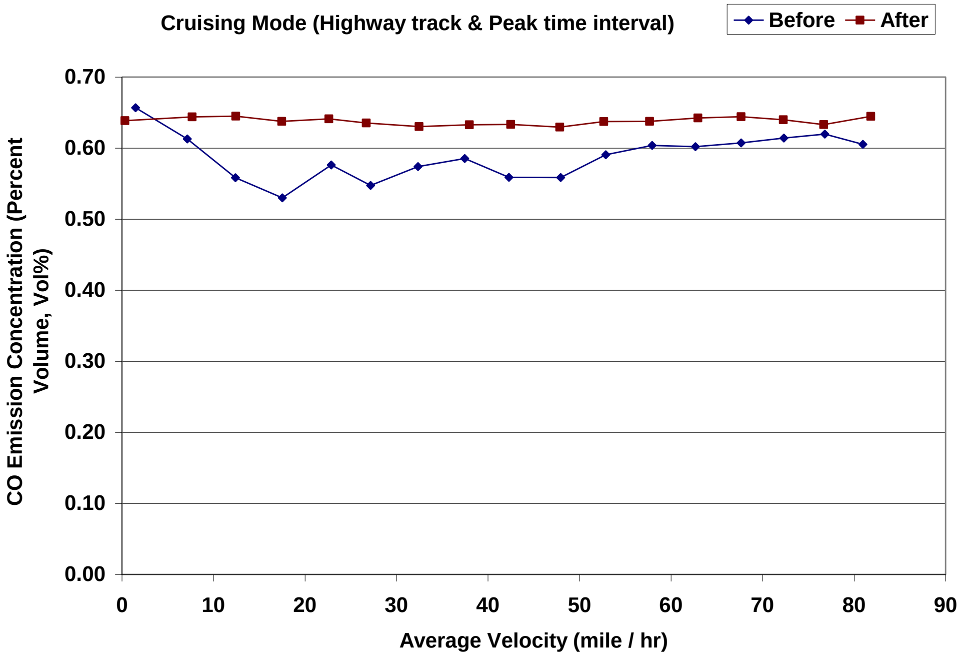

Figure A-25 CO emission trends (vol. %) for highway test track's peak cruising mode

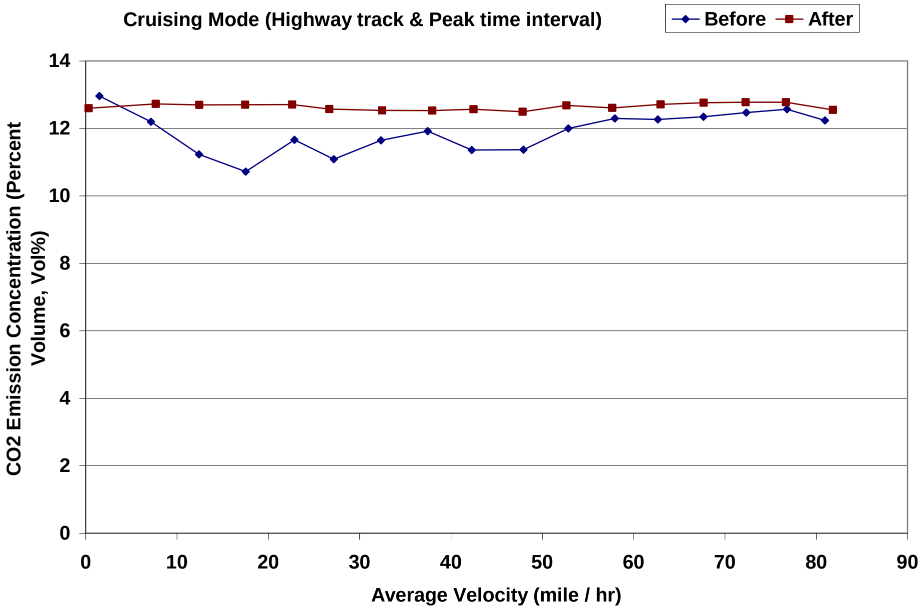

Figure A-26 CO_2 emission trends (vol. %) for highway test track's peak cruising mode

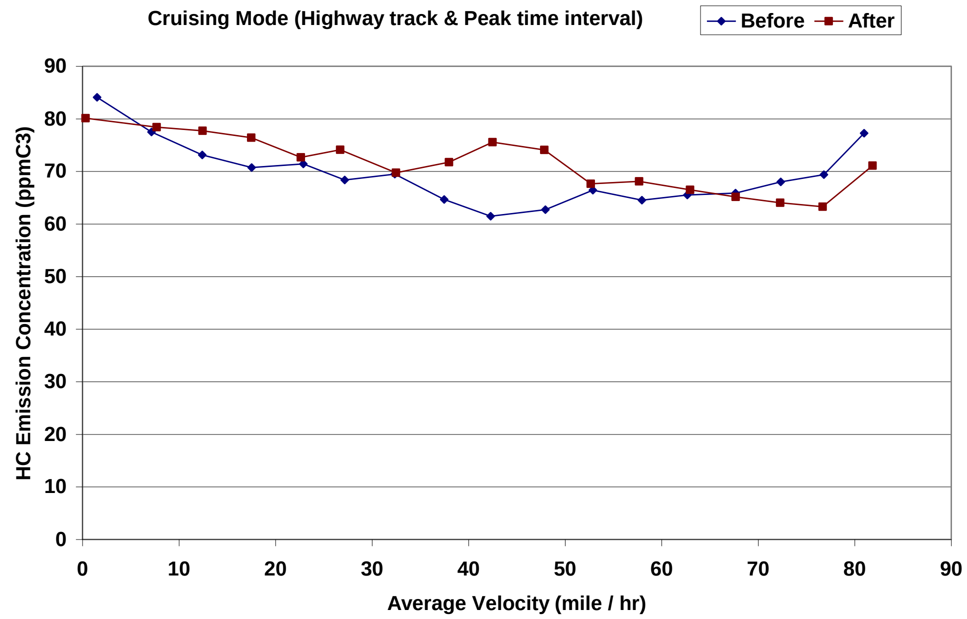

Figure A-27 HC emission trends (ppm) for highway test track's peak cruising mode

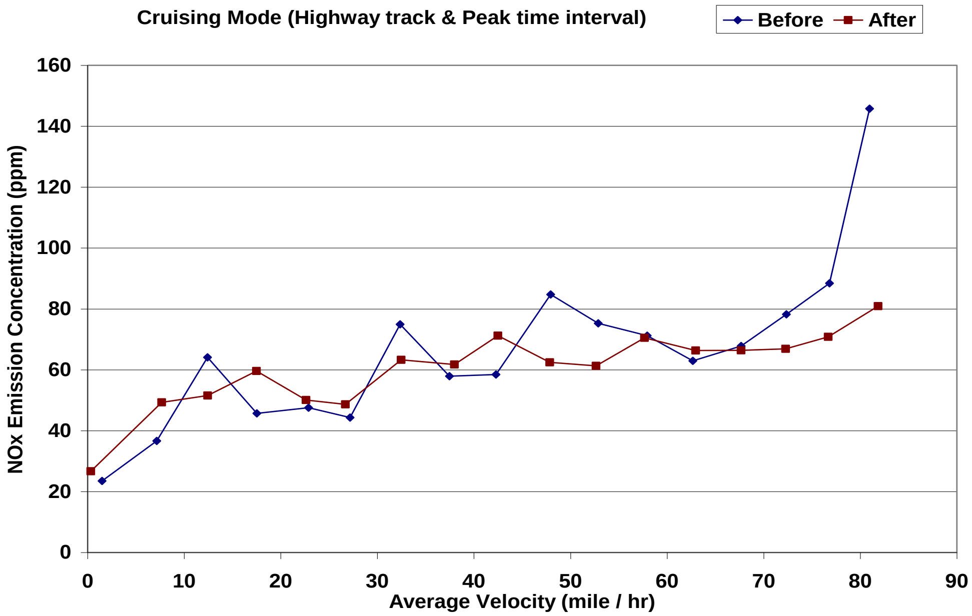

Figure A-28 NOx emission trends (ppm) for highway test track's peak cruising mode

Case F: Emission Trends for Highway Test Track's Off-peak Cruising Mode.

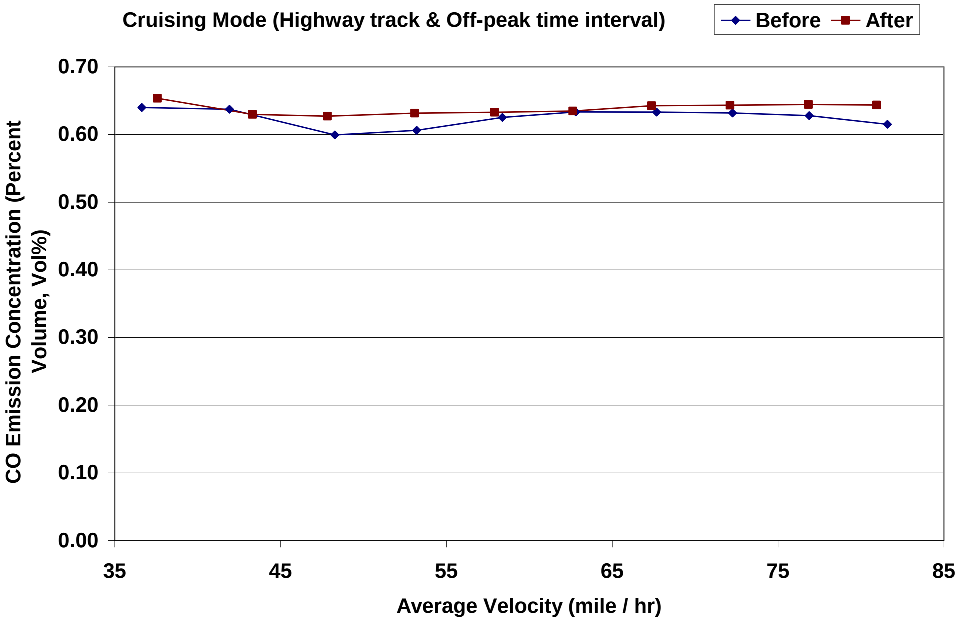

Figure A-29 CO emission trends (vol. %) for highway test track's off-peak cruising mode

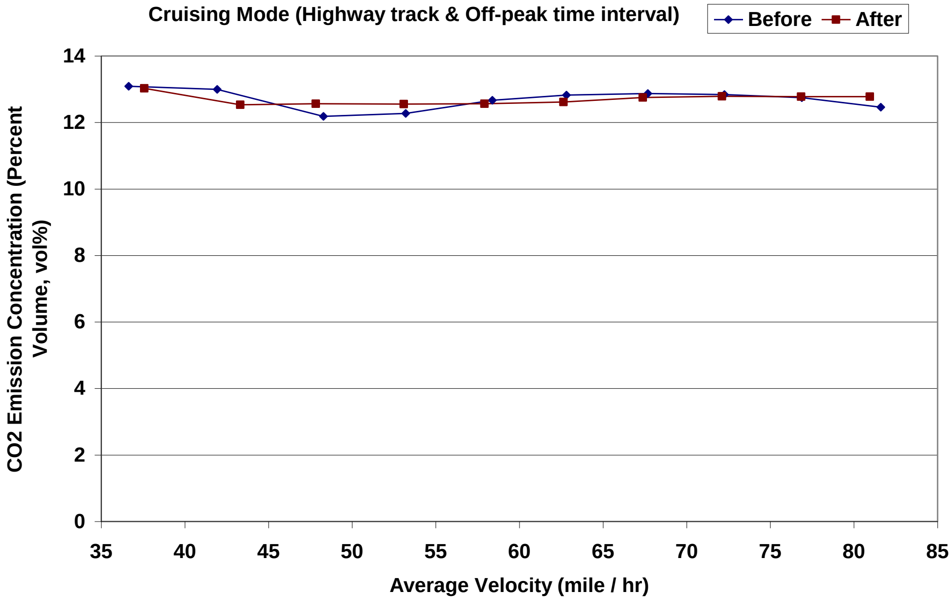

Figure A-30 CO_2 emission trends (vol. %) for highway test track's off-peak cruising mode

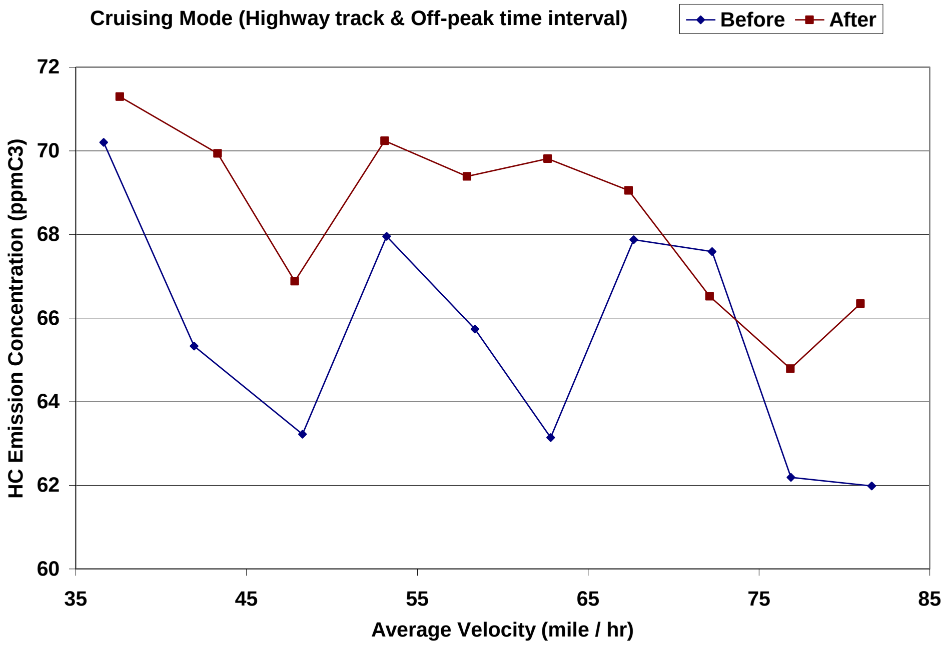

Figure A-31 HC emission trends (ppm) for highway test track's off-peak cruising mode

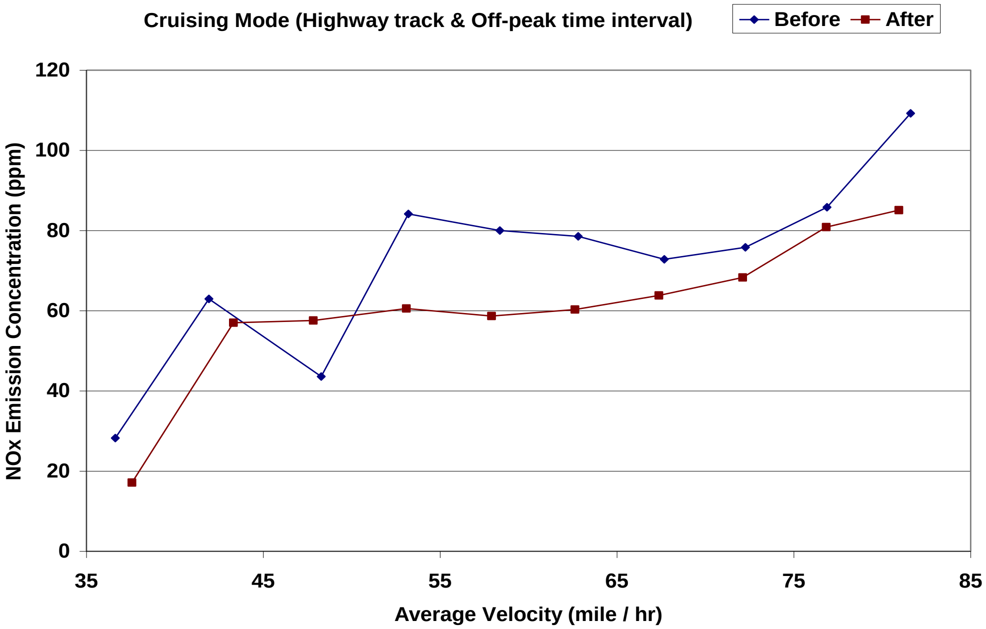

Figure A-28 NOx emission trends (ppm) for highway test track's off-peak cruising mode

APPENDIX B

T-TESTS: OVERALL MODAL DATA SETS

CASE A: CO EMISSION CONCENTRATIONS

Table B-1 t-tests for CO Emission Concentrations for Arterial Track's Overall Off-peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	-0.76
Deceleration Mode	NO	0.00
Cruising Mode	YES	-0.44
Idling Mode	YES	-0.76

Table B-2 t-tests for CO Emission Concentrations for Highway Track's Overall Peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	-7.97
Deceleration Mode	YES	-8.15
Cruising Mode	YES	-5.45

Table B-3 t-tests for CO Emission Concentrations for Highway Track's Overall Off-peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	-1.84
Deceleration Mode	YES	-2.24
Cruising Mode	YES	-1.41

CASE B: CO_2 EMISSION CONCENTRATIONS

Table B-4 t-tests for CO_2 Emission Concentrations for Arterial Track's Overall Peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	2.54
Deceleration Mode	YES	3.12
Cruising Mode	YES	2.73
Idling Mode	YES	2.35

Table B-5 t-tests for CO_2 Emission Concentrations for Highway Track's Overall Peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	-6.00
Deceleration Mode	YES	-5.89
Cruising Mode	YES	-3.22

Table B-6 t-tests for CO_2 Emission Concentrations for Highway Track's Overall Off-peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	NO	-0.01
Deceleration Mode	YES	-0.29
Cruising Mode	YES	0.79

CASE C: HC EMISSION CONCENTRATIONS

Table B-7 t-tests for HC Emission Concentrations for Arterial Track's Overall Peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	5.79
Deceleration Mode	YES	1.72
Cruising Mode	YES	3.92
Idling Mode	YES	6.05

Table B-8 t-tests for HC Emission Concentrations for Arterial Track's Overall Off-peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	-24.54
Deceleration Mode	YES	-15.80
Cruising Mode	YES	-17.77
Idling Mode	YES	-15.11

Table B-9 t-tests for HC Emission Concentrations for Highway Track's Overall Off-peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	-5.28
Deceleration Mode	YES	-2.32
Cruising Mode	YES	-3.37

CASE D: NOx EMISSION CONCENTRATIONS

Table B-10 t-tests for NOx Emission Concentrations for Arterial Track's Overall Peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	-7.51
Deceleration Mode	YES	2.91
Cruising Mode	NO	-0.06
Idling Mode	YES	10.60

Table B-11 t-tests for NOx Emission Concentrations for Arterial Track's Overall Off-peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	5.63
Deceleration Mode	YES	8.94
Cruising Mode	YES	3.18
Idling Mode	YES	19.01

Table B-12 t-tests for NOx Emission Concentrations for Highway Track's Overall Peak Data Sets.

Modes	Significant Difference, (t-test result)	Overall Percentage Reduction Observed, %
Acceleration Mode	YES	10.15
Deceleration Mode	YES	11.78
Cruising Mode	YES	9.79

APPENDIX C

T-TESTS: VELOCITY CATEGORY RESULTS

Table C-1 Velocity category t-tests for CO emissions in the deceleration mode of arterial test track's off-peak data set.

Velocity Clusters (mile/h)	Significant Difference	Percentage Reductions Observed, %
0 - 4.99	Y	-0.43
5 - 9.99	N	-0.29
10 - 14.99	Y	-0.33
15 - 19.99	Y	-0.43
20 - 24.99	N	-0.25
25 - 29.99	N	-0.10
30 - 34.99	Y	0.28
35 - 39.99	Y	0.47
40 - 44.99	N	-0.03
45 - 49.99	N	-0.06

<u>NOTE</u>: In Table C-1, Y= YES, N= NO.

Table C-2 Velocity category t-tests for CO_2 emissions in the deceleration mode of arterial test track's off-peak data set.

Velocity Clusters (mile/h)	Significant Difference	Percentage Reductions Observed, %
0 - 4.99	Y	2.40
5 - 9.99	Y	2.32
10 - 14.99	Y	2.36
15 - 19.99	Y	2.50
20 - 24.99	Y	2.66
25 - 29.99	Y	2.80
30 - 34.99	Y	3.09
35 - 39.99	Y	3.12
40 - 44.99	Y	2.69
45 - 49.99	Y	2.16

NOTE: In Table C-2, Y= YES, N= NO.

Table C-3 Velocity category t-tests for HC emissions in the deceleration mode of arterial test track's off-peak data set.

Velocity Clusters (mile/h)	Significant Difference	Percentage Reductions Observed, %
0 - 4.99	Y	-10.61
5 - 9.99	Y	-11.37
10 - 14.99	Y	-14.88
15 - 19.99	Y	-18.20
20 - 24.99	Y	-17.05
25 - 29.99	Y	-17.75
30 - 34.99	Y	-16.87
35 - 39.99	Y	-14.65
40 - 44.99	Y	-19.20
45 - 49.99	Y	-19.45

NOTE: In Table C-3, Y= YES, N= NO.

Table C-4 Velocity category t-tests for NOx emissions in the deceleration mode of arterial test track's off-peak data set.

Velocity Clusters (mile/h)	Significant Difference	Percentage Reductions Observed, %
0 - 4.99	Y	20.42
5 - 9.99	Y	19.71
10 - 14.99	Y	8.32
15 - 19.99	Y	15.56
20 - 24.99	Y	15.64
25 - 29.99	Y	12.66
30 - 34.99	Y	8.81
35 - 39.99	Y	4.27
40 - 44.99	N	-0.66
45 - 49.99	N	0.87

NOTE: In Table C-4, Y= YES, N= NO.

Table C-5 Velocity category t-tests for CO emissions in the cruising mode of highway test track's off-peak data set.

Velocity Clusters (mile/h)	Significant Difference	Percentage Reductions Observed, %
35 -39.99	Y	-2.13
40 - 44.99	N	1.21
45 - 49.99	Y	-4.63
50 - 54.99	Y	-4.19
55 - 59.99	Y	-1.19
60 - 64.99	N	-0.21
65 - 69.99	Y	-1.51
70 - 74.99	Y	-1.84
75 - 79.99	Y	-2.65
80 - 84.99	Y	-4.64

NOTE: In Table C-5, Y= YES, N= NO.

Table C-6 Velocity category t-tests for CO_2 emissions in the cruising mode of highway test track's off-peak data set.

Velocity Clusters (mile/h)	Significant Difference	Percentage Reductions Observed, %
35 -39.99	N	0.47
40 - 44.99	N	3.58
45 - 49.99	Y	-3.10
50 - 54.99	Y	-2.31
55 - 59.99	Y	0.85
60 - 64.99	Y	1.59
65 - 69.99	Y	0.90
70 - 74.99	Y	0.41
75 - 79.99	Y	-0.27
80 - 84.99	Y	-2.52

NOTE: In Table C-6, Y= YES, N= NO.

Table C-7 Velocity category t-tests for HC emissions in the cruising mode of highway test track's off-peak data set.

Velocity Clusters (mile/h)	**Significant Difference**	**Percentage Reductions Observed, %**
35 -39.99	N	-1.56
40 - 44.99	N	-7.06
45 - 49.99	N	-5.79
50 - 54.99	N	-3.36
55 - 59.99	Y	-5.56
60 - 64.99	Y	-10.56
65 - 69.99	Y	-1.73
70 - 74.99	Y	1.58
75 - 79.99	Y	-4.18
80 - 84.99	Y	-7.03

NOTE: In Table C-7, Y= YES, N= NO.

Table C-8 Velocity category t-tests for NOx emissions in the cruising mode of highway test track's off-peak data set.

Velocity Clusters (mile/h)	Significant Difference	Percentage Reductions Observed, %
35 -39.99	Y	39.38
40 - 44.99	N	9.44
45 - 49.99	N	-32.04
50 - 54.99	Y	28.03
55 - 59.99	Y	26.66
60 - 64.99	Y	23.23
65 - 69.99	Y	12.39
70 - 74.99	Y	9.91
75 - 79.99	N	5.76
80 - 84.99	N	22.10

<u>NOTE</u>: In Table C-8, Y= YES, N= NO.

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BIOGRAPHICAL INFORMATION

Sri Harsha Kanukolanu was born on February 18, 1983. He earned his Bachelor of Civil Engineering from Acharya Nagarjuna University, India in May 2004. After graduation, Sri traveled to the United States of America to pursue his higher studies.

The author completed his Master of Science in Civil and Environmental Engineering at the University of Texas at Arlington. His major being Air Quality. During his graduate studies, Dr. Melanie L. Sattler appointed him as a research assistant under her. He completed his research on the impact of a pre-combustion retrofit device on vehicular emissions and submitted a thesis on it to the university. He also served as the Vice-president for UTA’s Air & Waste Management Association Student Chapter during his graduate studies.

Sri aspires to be an Environmental Consultant in the near future with primary focus on air quality. He also intends to contribute to the development of the communities in India, his country of birth, and the United States in the future.