TRENDS OF VEHICULAR EMISSIONS FOR CLEAN AIR ASSOCIATES PRECOMBUSTION RETROFIT DEVICE

by

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DEDICATED TO MY PARENTS

“strength behind my success”

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ABSTRACT

TRENDS OF VEHICULAR EMISSIONS FOR CLEAN AIR ASSOCIATES PRE-COMBUSTION RETROFIT DEVICE

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The research study objective was to find if there was any reduction in onboard exhaust emissions from a light duty passenger car (2007 Dodge Charger) with a Clean Air Catalytic Converter manufactured by Clean Air Associates, Inc. The research was conducted by the Civil and Environmental Engineering Department, University of Texas at Arlington as part of the North Central Texas Council of Governments Aftermarket Technology and Fuel Additive Research Program. Initially, emissions of pollutants were measured without the Clean Air Associates' retrofit device, called Baseline testing. A Horiba OBS-1300 On-Board System measured concentrations of the pollutants NOx, CO, CO_2 and HC coming out of the tailpipe of the passenger car. The baseline data constituted 40 hours of on-road collection with 20 hours on arterial track and 20 hours on highway track for peak and off-peak hours of traffic. The retrofit device was then installed in the fuel line of the car. Emissions of the pollutants NO_x, CO, CO_2 and HC were measured on road with the device for 40 hours similar to the baseline data set. The device was removed after this session and 10 hours of post removal data was collected. The data collected was analyzed in grams per mile for each pollutant using Excel sheets. The average percentage increase/reduction in the concentration of the four pollutants from the baseline to 'with device' was computed and reported for highway and arterial test tracks.

The following were the results of the data analysis:

1) The comparison of OBS 1300 accuracy values with the change in emission concentrations of each pollutant showed that the difference in emissions with and without the device exceeded the OBS 1300 accuracies for CO and CO_2 arterial peak conditions and overall CO and CO_2 conditions.
2) Overall, there is no significant difference in the four pollutant emissions after the installation of the device.
3) There was a 2.3% increase in fuel economy and on the highway and a 1.78% decrease in vehicle fuel economy with the installation of the device.
4) Dynamometer testing results were not very consistent with OBS 1300 testing results at 15 mph and 25 mph speed levels.

5) CO and CO_2 emissions were lower in the post-removal case and exceeded the OBS accuracy limits.

Conclusions were drawn based on the results and recommendations were made for future study for better evaluation of the retrofit device.

TABLE OF CONTENTS

Appendix

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Air Quality

Decades of technological development has impacted air to such an extent that its pollution is becoming a threat to life on earth. The pollutants released into the air are not desirable because they change the physical, chemical or biological components in the atmosphere. The pollutants emitted from mobile sources account for half the sources in many urban areas of the United States (Smith *et al*., 2001). Automobile emissions contribute to the majority of emissions for volatile organic compounds (VOC), nitrogen oxide (NO_x), carbon dioxide (CO_2) and particulate matter (PM) emissions. It is observed from Figure 1.1 that for the Dallas/Forth Worth area, vehicular sources contribute 56% of the total NO_x emissions and 45% of the total VOC emissions. These pollutants pose a major concern because of the risk to human health.

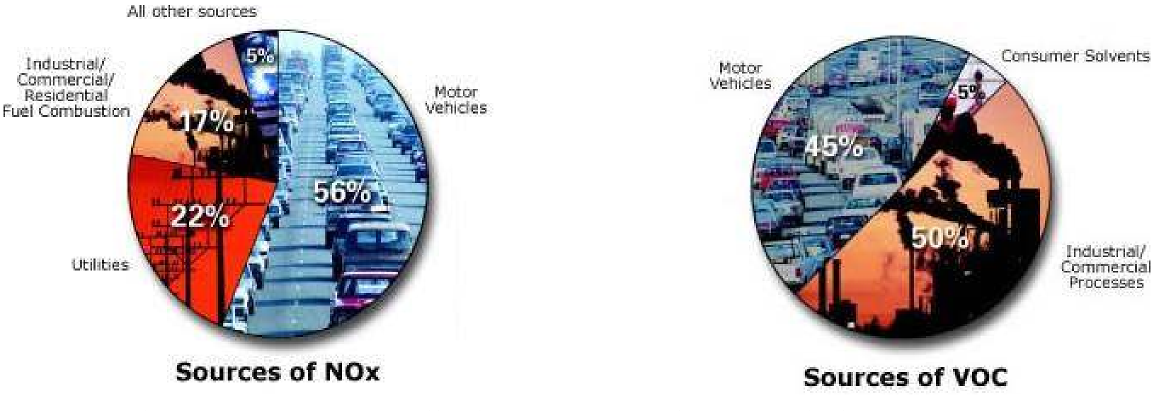


Figure 1.1 Source contributions of NO_x and VOC emissions for DFW (NCTCOG, March 2005)

1.1.1 Air Pollution Episodes (Air Pollution Its Origin and Control, 3rd Edition)

One of the very first air pollution episodes reported was a fog in London, where 268 unexpected deaths resulted due to lung-related illnesses in the year 1873. In 1931, during a nine-day period of fog in January, around 600 people died in the Manchester and Salford area of England. A four-day fog in Donora, Pennsylvania, made almost half the residents sick in 1948. The great fog of London in 1952 made the air pollution problem evident to the whole world. That fog lasted for ten days and resulted in more than 4000 deaths in Greater London. Almost all of them had records of bronchitis or heart troubles. Since then, it was recognized that this "fog" in the air pollution episodes contained pollutants that assisted in creating a dense cloud. Eventually these episodes were referred to as "smog", a combination of smoke and fog. In 2007, in the United States, there were a number of counties that violated National Ambient Air Quality Standards for pollutants - ozone, nitrogen oxide, carbon monoxide, particulate matter, sulfur dioxide and lead. Air pollution is a major problem in Latin America and the Caribbean due to rapid industrialization and expansion of urban population. The ozone concentration in the Mexico City exceeded the Mexico standard (0.11 ppm) on 307 days in the year 1991. It reached four times the concentration by the year 1992.

1.1.2 Air Pollution Sources

Different categories of sources contribute to air pollution:

- Point – Power plants, cement kilns, coal-fired boilers
- Area – Bakeries, dry cleaners, paint shops etc.

- Non-road – Lawn mowers and construction equipment
- On-road (Line sources) – Diesel trucks and passenger cars

Figure 1.2 shows various sources contributing to ozone formation

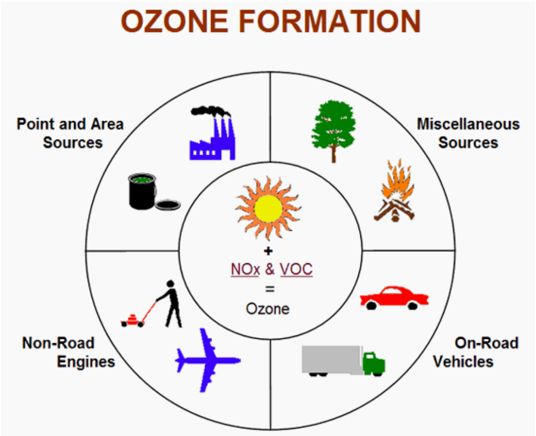


Figure 1.2 Different sources contributing to ozone formation (www.nctcog.org)

1.2 Types of Air Pollutants

There are two types of pollutants:

- Primary pollutants – These are emitted directly from the sources.

  Example: Particulate matter, carbon dioxide, sulfur dioxide and hydrocarbons
- Secondary pollutants – These are formed in the atmosphere by chemical reactions between primary pollutants and chemical compounds generally found in the atmosphere.

  Example: Ozone formed due to the multiple reactions between VOC and NO_x.

Table 1.1 Classification of Air Pollutants
(Air Pollution Its Origin and Control, Third Edition, Chapter 1, page 11)

Class	***Primary Pollutants***	***Secondary pollutants***
Sulfur-containing compounds	SO_2, H_2S	SO_3, H_2SO_4
Organic compounds	H-C compounds	Ketones, aldehydes, O_3, acids
Nitrogen-compounds	NO, NH_3	NO_2, O_3, MNO_3
Oxides of Carbon	CO	None
Halogen compounds	HCl, HF	None

The United States Environmental Protection Agency (USEPA) introduced the National Ambient Air Quality Standards. These NAAQS considers six pollutants as criteria pollutants:

1) Particulate Matter
2) Nitrogen oxides
3) Carbon monoxide
4) Sulfur dioxide
5) Lead
6) Ozone

Particulate matter exists in the atmosphere as a liquid or solid in microscopic form. If the diameter of the particle is greater than 2.5 μm, it is regarded as a coarse particle; if the diameter is less than 2.5 μm, it is a fine particle, particles with diameters less than 10 μm are PM10. Generally, particulate matter arises from fuel combustion in electric utilities, industries and through waste disposal and recycling. Fine particulate matter penetrates deep into lungs and increases risk of death from respiratory or cardiac disease in the elderly.

The major source of nitrogen oxides is combustion. Most of the NO_x is emitted as NO and then converted to NO_2 in the atmosphere. Nitrogen oxide is one of the precursors to ozone smog and also contributes to acid deposition and fine particulate formation.

Carbon monoxide is primarily the product of incomplete combustion in automobiles. Carbon monoxide when inhaled is converted to carboxyhemoglobin in blood that prevents hemoglobin from carrying oxygen to body tissues. Eighty percent of the sulfur dioxide emissions are due to coal and fuel oil combustion. Sulfur dioxide corrodes steel, iron and deteriorates ancient monuments in the form of acid rain. It causes loss of chlorophyll and damage to natural vegetation. Lead is emitted from metals processing units and also from leaded gasoline used in developing countries. Excessive exposure to lead may cause neurological impairments, such as seizures and mental retardation.

Ozone is found in the stratosphere where it shields earth from harmful ultraviolet rays. The tropospheric ozone is the photochemical smog that causes eye, throat and lung irritation. It can aggravate asthma and other respiratory problems. The process of ozone smog formation is shown in Figure 1.3.

Besides these criteria pollutants, there are chlorofluorocarbons that deplete the ozone layer. They are emitted from air conditioners and refrigerators. The depletion of the ozone layer can cause skin cancer and cataracts among humans and reduced crop yields. An other major pollutant that causes global warming is carbon dioxide (CO_2). It produces a natural warming or greenhouse effect necessary to sustain life but an increased concentration of CO_2 will produce an enhanced greenhouse effect or climate change.

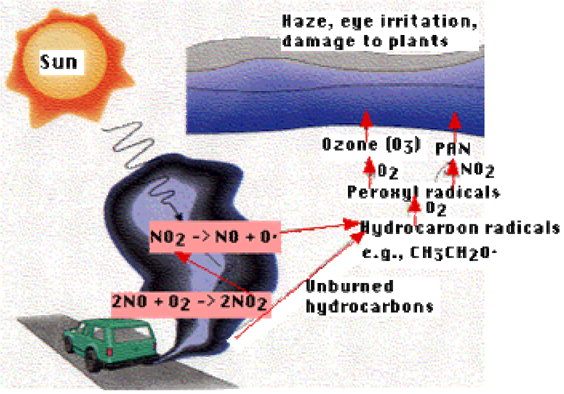


Figure 1.3 Ozone Smog Formation (www.nctcog.org)

1.3 Control Strategies for Vehicular Pollution

The control strategies available to reduce on-road pollution belong to three categories:

1) Changing vehicle design.
2) Reducing emissions through better vehicle operation.
3) Reducing miles traveled through Travel Demand Management.

Vehicle redesign can be achieved by engine design modification, alternative fuel/fuel additives and add on controls at the tailpipe. Add on controls are the kind of devices that are installed in the emission system to reduce emissions. They convert the chemical composition of the emissions to less toxic pollutants. For example, the catalytic converter is one such device that is currently used in the emission system. The Clean Air Associate's Pre-combustion Retrofit Device is other add-on control device, but it is not installed in the emissions system, instead, it is installed in the vehicle's fuel line. The device aids in the complete combustion of unburned fuel in the combustion occurs. This research assesses the effectiveness of the Clean Air Associate's retrofit device as an add-on control.

1.4 Research Objective

The main objective of this research is to determine if the Clean Air Associates pre-combustion device significantly reduced NO_x, VOC, CO and CO_2 emissions for a light duty passenger car (2007 Dodge Charger).

1.5 Clean Air Catalytic Converter

The Clean Air Catalytic Converter is a pre-combustion retrofit device manufactured and promoted by Clean Air Associates, Inc. As part of the North Central Texas Council of Government's "Aftermarket Technology and Fuel Additive Research Program-Phase II", this pre-combustion device is tested on a light-duty passenger car. According to the product literature by Clean Air Associates, Inc., the retrofit device catalytically modifies the fuel prior to its entry into the combustion chamber. It breaks down the partially burnt fuel molecules, so they readily mix with the oxygen molecules to produce more complete combustion in the combustion chamber, consequently reducing emissions. Figure 1.4 shows the Clean Air Catalytic Converter manufactured by Clean Air Associates, Inc.

Figure 1.4 Clean Air Catalytic Converter by Clean Air Associates, Inc.
(Product literature by Clean Air Associates, Inc.)

1.6 Report Overview

The overview of the thesis report is discussed in the Table 1.2. The report has major chapters such as Literature Review, Research Methodology, Results and Discussion and Conclusion and Recommendations.

Table 1.2 Thesis Report Contents Overview

Chapter	Title	Contents
2	Literature Review	This chapter consists of background literature on the similar case studies on retrofit devices.
3	Research Methodology	This chapter is about the methodology, instrument description and data analysis.
4	Results and Discussion	The final results are reported in this chapter with a comprehensive discussion.
5	Conclusion and Recommendations	In this chapter, conclusions are drawn from the results and recommendations are made for further studies and promotion of the retrofit device.

CHAPTER 2

LITERATURE REVIEW

2.1 Motor Vehicular Sources and their Impacts

Automobiles are a major source of the air pollution throughout the world and particularly in the U.S. Serious air pollution was detected in Los Angeles, in 1943, and by the year 1948, it became severe. Attempts made to reduce eye irritation by installing controls on stationary sources such as open burning, steel mills, and refineries failed. It was obvious that the air pollution in Los Angeles was of different constituents than other cities as such London and Pittsburgh. Accordingly, a research program was conducted by the State of California to discover the cause of the air pollution problem. Professor A. J. Haagen-Smit first confirmed that hydrocarbon compounds react with the nitrogen oxides using sunlight to form eye irritating compounds ozone and peroxyacetal nitrate. Studies show that highway vehicles have been responsible for a large portion of the air pollutants emitted for a number of years. In 1970, the peak year for emissions of both CO and hydrocarbons, the highway vehicles emitted 71 % of CO, 42 % of hydrocarbons and 36 % of the NO_x in the United States. Though the emissions of the highway vehicles consistently decreased over the coming decades, the emissions have continued to be a serious problem because of the increased number of vehicles.
(Air Pollution Its Origin and Control, third edition)

2.2 Air Quality Standards

2.2.1 National Ambient Air Quality Standards (NAAQS)

The Clean Air Act, last amended in 1990, requires the U.S. Environmental Protection Agency to set **National Ambient Air Quality Standards (NAAQS)** for six criteria pollutants. The Act recognizes two types of national air quality standards.

- ***Primary national air quality standards*** set concentration limits for pollutants in order to protect public health, including the health of sensitive people such as children, asthmatics, and the elderly.
- ***Secondary national air quality standards*** protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings.

2.2.2 Clean Air Act (NCTCOG, 2007)

The Clean Air Act is legislation administered by the U.S. Environmental Protection Agency (USEPA). According to the act, an area is designated as **"attainment"** for a criteria pollutant, if it complies with NAAQS. When the criteria pollutant levels in a region violate NAAQS, the region is called **"nonattainment"** for that pollutant. The EPA imposes regulations on the criteria pollutants and sets a time period for the area to reach attainment. CAA requires a State Implementation Plan (SIP) to be developed and submitted by the states with areas that fail to meet the NAAQS. The SIP describes how the state will reduce and maintain air pollution emissions in order to comply with the National Ambient Air Quality Standards. The Texas Commission on Environmental Quality (TCEQ) develops the Texas state SIP and submits it to the EPA.

Table 2.1 National Ambient Air Quality Standards (www.epa.org, 2006)

Pollutant	**Primary Standard**	**Averaging Time**	**Standard**	**Secondary Standard**
Ozone	0.08 ppm	8-hour	The 3-year annual average of the fourth-highest daily maximum 8-hour average ozone concentrations at each monitor must not exceed 0.08 ppm per year.	Same as primary
Carbon Monoxide	9 ppm	8-hour	Not to be exceeded more than once per year	None
	35 ppm	1-hour	Not to be exceeded more than once per year	None
Nitrogen Dioxide	0.053 ppm	Annual	________	Same as primary
Sulfur Dioxide	0.03 ppm	Annual	________	
	0.14 ppm	24-hour	Not to be exceeded more than once per year	
	______	3-hour	Not to be exceeded more than once per year	0.5 ppm
Particulate Matter (PM10)	150 µg/m^3	24-hour	Not to be exceeded more than once per year	Same as primary
	50 µg/m^3	Annual	Standard revoked	Revoked
Particulate Matter (PM2.5)	15 µg/m^3	Annual	The 3-year average of weighted annual mean $PM_{2.5}$ concentrations from single or multiple monitors must not exceed 15.0 µg/m^3	Same as primary
	35 µg/m^3	24-hour	The 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 35 µg/m^3	as primary
Lead	1.5 µg/m^3	Quarterly Average	________	Same as primary

2.2.3 Air Quality in the DFW Region

The DFW Metroplex region is designated as moderate nonattainment for ozone. A new 8-hour ozone standard is being implemented, which requires the area to come into attainment by June 15th, 2010. Most recently, the change in the federal ozone standard from a one-hour NAAQS to an eight-hour NAAQS required nonattainment areas to update the SIP to address the eight-hour standard. The nine counties that are nonattainment for the 8-hour ozone standard in Dallas/Fort-Worth are shown in the Figure 2.1. The TCEQ is in the process of developing an 8-Hour Ozone Attainment Demonstration SIP for the Dallas-Fort Worth nonattainment area. The Metropolitan Planning Organization for the DFW area, NCTCOG has created the North Texas Clean Air Steering Committee to provide for the issues neighboring development of the SIP. This committee consists of local elected officials, business representatives and non-profit organization representatives.

Figure 2.1 Map of Dallas-Forth Worth's ozone nonattainment counties (NCTCOG, 2007)

2.2.4 Various Strategies to Reduce Automobile Emissions

The various strategies to reduce emissions include:

- Modifications to Vehicle/Engine

  Stoichiometric combustion is avoided and combustion temperature is lowered to reduce NO_x emissions. Stoichiometric combustion can be avoided through use of a stratified charge engine, an engine designed to operate at just less than the air-to-fuel ratio, and an extra lean-burn engine. Combustion temperature is lowered through exhaust gas recirculation, water injection, changing the engine cycle for diesel engines, and fuel injection system modifications. The complete combustion of fuel lowers HC and CO emissions. Reduced flame quenching and speeding the warmup are processes to achieve complete combustion.

- Alternate Fuels

  Alternate fuels such as natural gas, propane, methanol, ethanol, biodiesel have promise to reduce NO_x and VOC emissions to some extent. Reformulated gasoline is used instead of conventional gasoline in many of the areas which are nonattainment for ozone. The other alternatives like electric or hybrid cars produce almost zero emissions. Hydrogen fuel cells when incorporated into automobiles also have zero or near zero smog-forming emissions.

- Transportation System Management (TSM)

  TSM is concerned with transportation system operation, which improves traffic flow by better managing the existing transportation facilities. The vehicle operation also reduces emissions through signal coordination; Intelligent

Transportation Systems, driver behavior education, intersection improvements and reduced speed limits.

- Travel Demand Management (TDM)

  TDM is about reducing the number of vehicles on the road, ultimately reducing emissions. The main objective of this program is to reduce the single occupancy vehicles on the road through measures such as mass transit or bicycling. The vehicle miles traveled per vehicle are reduced by better trip planning. The other strategies include carpooling, telecommuting, parking cash out and HOV lanes. Table 2.2 shows some of the Travel Demand programs implemented in the DFW region.

2.3 Emission Measurements

2.3.1 Emissions from Internal Combustion Engines

The working of emissions control technology on a vehicle can be explained by understanding the combustion process taking place in an internal combustion chamber of an automobile's engine. Combustion, an exothermic process, takes place in the presence of air at high temperatures, releasing energy that runs the car. The combustion follows two major pathways, as shown in the chemical equations below:

$$HC + O_2 \rightarrow CO + H_2O \qquad \rightarrow \text{Equation (1)}$$

$$HC + O_2 \rightarrow CO_2 + H_2O \qquad \rightarrow \text{Equation (2)}$$

The above two equations show incomplete and complete combustion resulting from fuel rich and fuel lean conditions, respectively. The other major reaction taking place in the combustion chamber is formation of nitrogen oxides.

$N_2 + O_2 \rightarrow NO_x$ → Equation (3)

Therefore, CO, CO_2, NO_x and HC are the four major pollutants coming out of the vehicle tailpipe.

Table 2.2 DFW Air Quality Emissions Control Measures for "Ozone Attainment" (www.nctcog.org, NCTCOG 2007)

Control Measure	**Description**	**Expected Emissions Reduction**	
		NO_x (Tpd)	VOC (Tpd)
CarSharing	1000 station cars used by 10 people/car resulting in reduction of 10.15 miles/day/user	0.045	0.057
Employer Trip Reduction Program(ETR)	This program is designed to reduce employee commute vehicle trips through rideshare, transit pass subsidies; operated through DART	0.023	0.026
Parking Cash Out	Employees are provided with parking cash out payments to reduce their trip to work	0.443	0.460
Pay As You Drive Insurance Programs	Mileage based Insurance programs permit drivers to pay their Auto premium on a variable scale	0.917	0.948
Speed Limit Decrease for Heavy Duty Diesel Trucks	This program explores potential emission reductions from enforcing a 55 mph speed limit for heavy duty trucks	3.25	–
Drive-Thru Service Restrictions	Prohibit drive thru service during ozone season	0.01-0.05	0.04-0.19
Bicycle and Pedestrian programs	The NCTCOG along with local governments is encouraging substitution of vehicle use with bicycle & pedestrian trips	0.07	0.04
AirCheck Texas Repair and Replacement Assistance Program	This program offers financial help to low-income vehicle owners whose vehicles failed the State Inspection. Basically to help reduce ozone forming pollutants	0.01	–

2.3.2 Why is Emissions Measurement Important?

The SIP requires that the emissions reduction for a non-attainment area be quantified. Emissions measurement avoids the situation of underestimation or overestimation of emission reductions. Underestimation of emissions leads to the application of excessive controls, and overestimation results in fewer controls, eventually increasing pollutant levels. Thus, accurate emission estimates are essential to achieve compliance with air quality standards.

Emissions Factors (EF), from emissions measurement and the Vehicle Miles Traveled (VMT) from the travel demand model are wed to come up with a regional emission estimate. Therefore, the Emission estimates = Emission Factor x Activity: Activity is VMT in this scenario.

2.3.3 Methods of Emissions Measurement

The three methods of measuring emissions are dynamometer testing, remote sensing and on-board emission measurement systems. They are briefly discussed below.

- Dynamometer Testing

  In this testing, the vehicle's rear wheels are run on two parallel cylinders under variable loads at different speeds. The emissions coming out of the vehicle's tailpipe are measured, and displayed by the computer connected to the dynamometer. Although it does not simulate the real traffic conditions, it is an easy and accurate test method. Figure 2.2 shows dynamometer testing center.

Figure 2.2 Dynamometer testing center
(http://www.deq.virginia.gov/info/program22006.html)

- Remote Sensing

  Remote sensing uses a source that emits infrared and ultraviolet radiation beams continuously across a roadway. As the vehicle passes through the beam, the infrared beam measures CO and HC emissions; the ultraviolet beam measures NO_x emissions. The system employs a freeze-frame video camera, equipment to digitize the license plate of the vehicle, which is in turn processed by a computer. Thus, the emissions measured are stored in the computer for each monitored vehicle based on the license plate number. Figure 2.3 shows emission measurements by remote sensing.

Figure 2.3 Vehicle emissions measurement by remote sensing (http://www.et.co.uk/cgi-bin/products.cgi?section=1002&productcategory=1014)

- On-Board Emission Measurement Systems

  On-board emission measurement systems measure real-world emissions under different traffic conditions while driving on-road. The current research uses an on-board emission measurement system to measure emissions from the tailpipe, while driving on the road. Generally, this system consists of a tailpipe attachment with sensors mounted on it and this attachment is connected to sensor analyzing units. The analyzers are coupled to a laptop, which records the concentrations of the pollutants. A typical on-board measuring device measures the four major vehicle exhaust pollutants; CO, CO_2, NO_x and HC.

2.4 Related Studies on Retrofit Devices

2.4.1 Aftermarket Technology and Fuel Additive Research Program – Phase I Study

As part of the Phase I testing of the NCTCOG's "Aftermarket Technology and Fuel Additive Research Program", two control technologies – Clean Air Associate's

Device and Ethos® Fuel Reformulator- were tested on UTA's very own 2000 Chevy Astro van. An on-board emissions analyzer OBS 1300 was used to measure the concentration of the pollutants NO_x, CO, CO_2 and HCs while driving. A modal approach was used for data analysis where the data was sorted out into acceleration, deceleration, cruising and idling modes and significant differences in concentrations with and without the device/additive were reported for individual modes of peak and off-peak traffic conditions.

- *Thesis by Sri Harsha Kanukolanu on the impact of the Clean Air Associate's Precombustion Retrofit device on a light-duty gasoline van*

  The Phase I testing of the retrofit device on a light-duty gasoline truck, followed the test procedure. In this phase of testing, the device was installed on the fuel line of the UTA's Chevy Astro van. The OBS 1300 was used to measure the concentrations of the four pollutants for the 'baseline' and 'with the device testing' for arterial and highway track, peak and off-peak traffic conditions. As a result, a significant impact on the NO_x emissions was observed. Kanukolanu (2006) observed in his thesis that the NO_x emissions decreased by 26.2% on the off-peak highway track for the acceleration mode. CO_2 emissions also decreased immensely on the arterial track for all the traffic conditions.

- *Thesis by Sruthi Satyanarayan on the impact of the fuel additive, Ethos® FR on a light-duty gasoline van*

  Again in the Phase I testing of Ethos® FR, on the same van, Satyanarayan (2006) observed significant reductions in the NO_x emissions in all the modes of driving that are acceleration, deceleration cruising and idling. There was a maximum reduction of 45% in NO_x concentration in the idling mode for the arterial data. There was significant reduction in CO and CO_2 emissions for all the modes except on the highway, where a slight increase in NO_x was observed. The HC emissions increased in all modes except for peak highway condition.

2.4.2 Previous Research on Aftermarket Retrofit Devices

1) EPA evaluation of the VITALIZER III Aftermarket Retrofit Device

"Vitalizer III, a copper tube whose core has percentages of precious metals which is usually placed in the fuel line. When the vehicle is in operation, it causes interruption in the flow pattern of the fuel activating an electrostatic charge within the matrix forming electrostatic colloidal matrix. When pumped into the engine's combustion chambers, it ensures more complete combustion of the fuel reducing HC & CO emissions and improving fuel economy." (EPA Evaluation of the Vitalizer III Aftermarket Retrofit Device, EPA420-99-015, August 1999)

EPA tested an aftermarket product, Vitalizer III, a retrofit device, at the National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan. Three vehicles were tested with this device, representative of the U.S. automobile fleet. The vehicles were driven on a set road route for about 1000 miles, stopping every 30 minutes. Then, the vehicles were tested without the device (baseline) using the Federal Test Procedure (FTP) [a] and Highway Fuel Economy Tests (HFET) [b]. The vehicles were tested on a dynamometer. The Vitalizer III was installed on each vehicle according to the instructions given by the manufacturer. After this session, additional road mileage of

1000 miles was accumulated. The vehicles were again tested with the device for the same tests under the same conditions.

FTP is the Standard Dynamometer testing to measure tailpipe emissions used in State Inspection of the automobiles.

HFET is the test conducted to determine the fuel economy of the vehicle under simulated driving conditions.

EPA concluded the following from the Vitalizer III testing:

- Vitalizer III increased the emissions by 72% of the observations and when this emissions data was statistically analyzed using t-test (at 95% level), the percent changes were not statistically significant. The increases ranged from 31% to 65.2%.
- Vitalizer III resulted in increases in fuel economy in six of the observations; all of them were less than 10%. The fuel economy data also showed no statistical difference.

2) EPA Evaluation of the Inset Aftermarket Retrofit Device marketed by Inset Industries, Inc.

“The Inset Device, a silver colored bar of metal of 4.25” length and 2” in diameter. The manufacturer claimed that the Inset device aligns the fuel molecules before the fuel enters the vehicle engine. The molecular alignment aids in the optimum burn of the fuel”. Figure 2.4 shows the Inset Aftermarket Retrofit Device.

Figure 2.4 Inset Aftermarket Retrofit Device
(Air and Radiation, USEPA, August 1999)

EPA's National Vehicle and Fuel Emissions Laboratory conducted the test to determine its impact on vehicle exhaust emissions and fuel economy. The device was tested on three different vehicles, a 1996 Chevrolet Lumina, a 1994 Ford Probe and a 1998 Pontiac Bonneville. The FTP and HFET tests were conducted on the vehicles without the device. The Inset device was installed in the vehicle fuel line in agreement with the manufacturer's manual. The vehicles were tested again using FTP and HFET tests.

Following are results of the Inset retrofit device testing:

- At a 95% confidence level of statistical analyses, the Inset device had no impact on total hydrocarbons, CO, NO_x emissions or on the fuel economy measured using the Federal Test Procedure and Highway Fuel Economy Test.
- It was concluded the device had no positive or negative effect on exhaust emissions or fuel economy. The use of the device on the test vehicles provided no benefit.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Standard Test Procedure

3.1.1 Installation of Clean Air Associates Device

As already discussed in Chapter 1, the Clean Air Associate's Device was installed in the fuel line of the vehicle after the secondary fuel filter and before entering the engine. It was mounted using push-on fuel hoses to the fuel line. The device was installed by the staff of the Physical-Chemical plant under the supervision of the head of the Clean Air Associates, Inc. Figure 3.1 shows the installation of the device in the vehicle.

3.1.1.1 Product Description and Use

According to the product literature, the Clean Air Catalytic Converter pre-treats the fuel, or catalytically converts it, before it goes into the combustion chamber. It breaks down and eliminates unburned fuel by converting the fuel molecules so they readily mix with oxygen molecules to produce a cleaner, faster and more complete burn in the combustion chamber, thereby reducing emissions. The device applies to both gasoline and diesel engines, both on-road and off-road vehicles. The catalyst will operate in any condition that allows fuel to flow. The purpose of this research project was to test the effectiveness of the device in reducing emissions from a light-duty gasoline vehicle while the vehicle travels on road. According to Clean Air Associates product literature, the Catalytic Converter:

- reduces emissions of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC) and nitrogen oxides (NO_x) by 40 to 80% from the exhaust of vehicles,
- reduces particulate matter and visually reduces exhaust smoke up to 100% for diesel trucks, and
- reduces fuel consumption/improves fuel economy.

Figure 3.1 Installation of Clean Air Retrofit Device in the fuel line of the Dodge Charger 2007

3.1.2 Test procedure

The NCTCOG's standard test procedure for this device was also followed in the first phase of testing on a light-duty gasoline 2000 Chevy Astro van. The Phase II testing, reported in this research, was conducted on a light-duty passenger car, Dodge Charger 2007. The test involved 40 hours of on-road data collection while driving the Charger for 20 hours on highway and 20 hours on arterial with the device, and an additional 40 hours without it. The data without the device is classified as baseline data. Among the 20 hours on each network, 10 hours of data was collected during peak traffic hours and the other 10 hours during off-peak traffic hours. Post removal testing was also done after removal of the retrofit device for 10 hours, of which 5 hours were on highway and 5 hours on arterial. This was done to compare the baseline and post-removal data to confirm the effectiveness of the device. The on-road emissions were measured using an on-board measurement system (OBS 1300) manufactured by Horiba Instruments, Inc. The testing was done throughout the week, from Monday afternoon until Friday morning. The Monday morning AM peak, Friday PM peak and weekends were not considered because on Monday morning and Friday afternoon, the conditions may differ significantly from other typical weekdays, and on the weekends the traffic volumes are usually less than that of most week days. Driving in those conditions may generate unusual data.

The peak and off-peak traffic hours used in this study are specified below:

- A.M. Peak: 6:30 am– 9:00 am
- P.M. Peak: 4:00 pm – 6:30 pm
- OFF Peak: 9:00 am – 4:00 pm

The arterial and highway test track routes are described below:

Arterial Test track: From UTA blvd, go North on Cooper to Division Street. Travel East on Division to Collins; South on Collins to Pioneer pkwy; West on Pioneer pkwy to Cooper. Now, go North on Cooper back to UTA blvd. Figure 3.2 shows the pathway for the arterial loop.

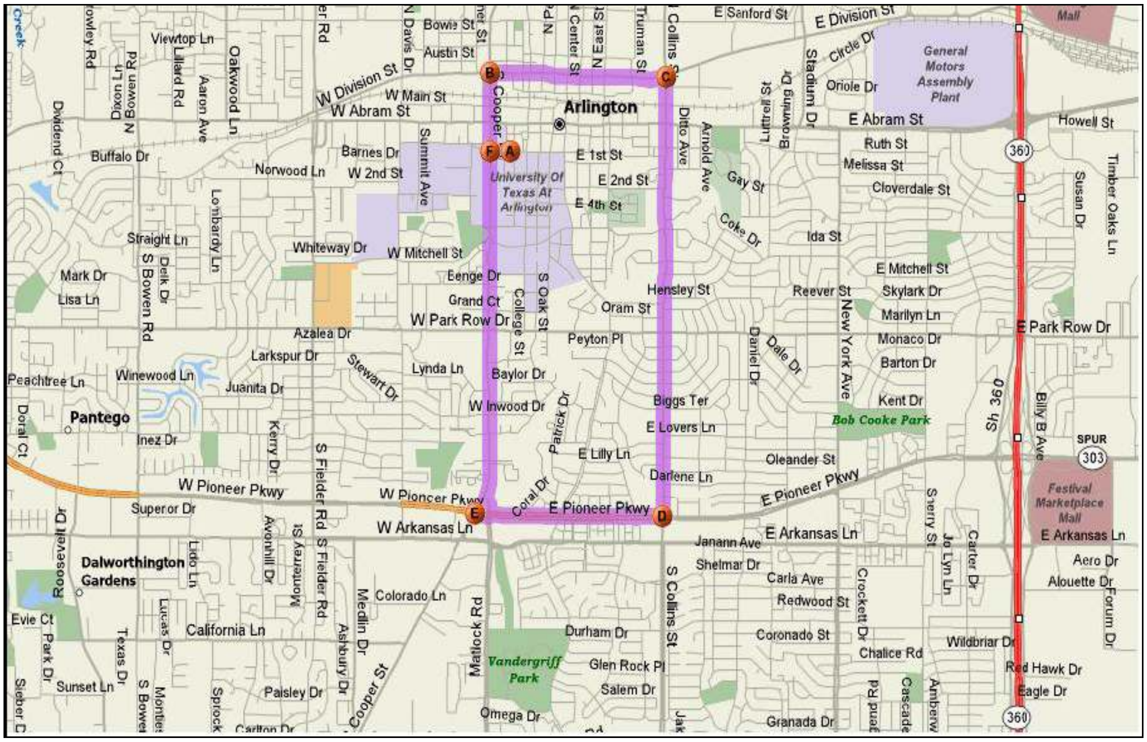


Figure 3.2 Arterial Test Track *(courtesy:* Satyanarayan's Thesis, 2006*)*

Highway Test track: From North Cooper, go West on I-30 and take exit to I-820; South on I-820 to I-20E; take an exit onto Spur 408, North on spur 408 to Loop 12. Again North on Loop 12 to I-30 Westbound. Figure 3.3 shows the path of the highway loop.

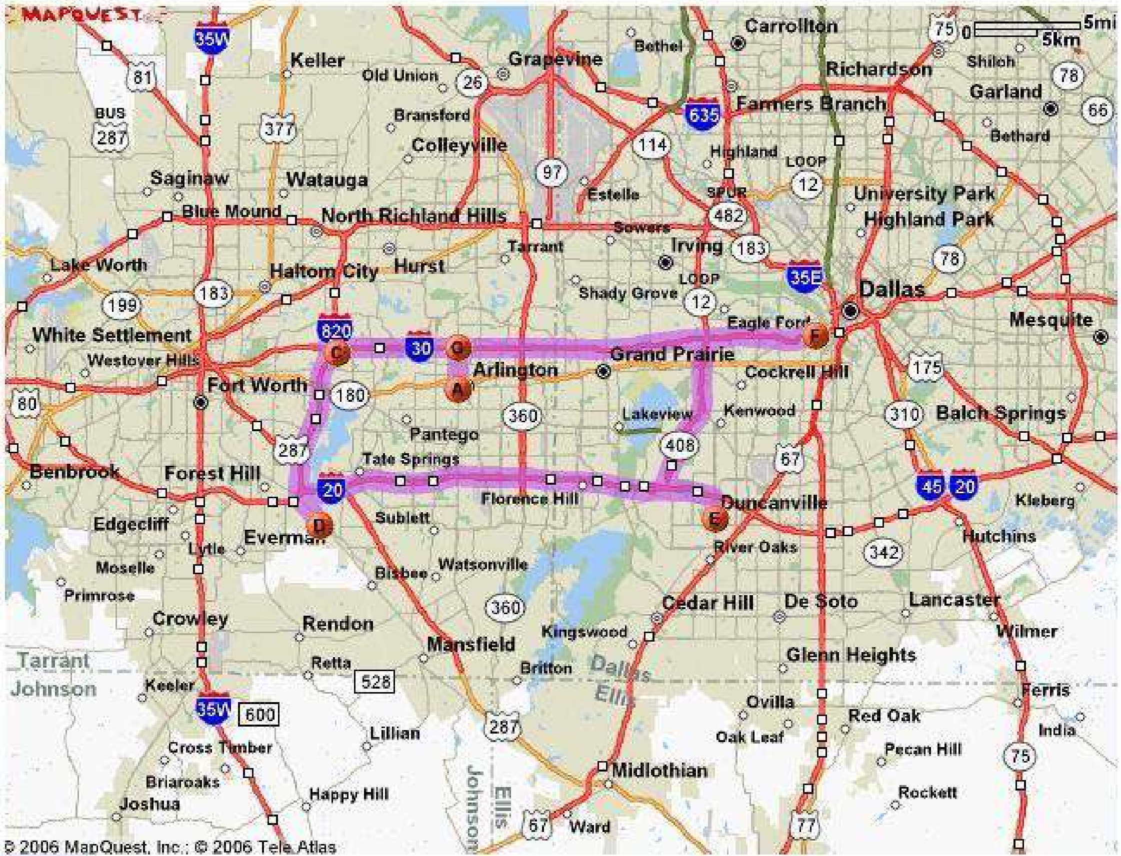


Figure 3.3 Highway Test Track *(courtesy:* Satyanarayan's Thesis, 2006*)*

3.2 Data Collection Equipment

3.2.1 Study Vehicle – Dodge Charger 2007

The light duty gasoline passenger car used in this phase II study was a 2007 Dodge Charger, as shown in Figure 3.4. It was rented from the Enterprise Inc. office, located on East Division in Arlington, Texas. Its specifications are listed in Table 3.1.

Table 3.1 Specifications of the Dodge Charger 2007

Engine Parameter	**Value**
Standard Engine	2.7 L V6
Horsepower @ RPM	190 HP @6400
Torque @ RPM	190HP @ 4000 (foot-lb)
Fuel Tank capacity	18 gallons
Fuel type/ system	Gasoline engine / Sequential electronic fuel injected
Standard transmission	4 speed automatic
Cylinders	6
Compression	9.7
Weight, lb	3820

(Dodge Charger Manual)

Figure 3.4 Dodge Charger 2007

3.2.2 On-Board Emissions Measurement System

Pollutant concentrations were measured using an on-board measuring system, OBS-1300 manufactured by Horiba Instruments, Inc. Figure 3.5 shows the entire OBS 1300 setup on the study vehicle. It measures the pollutant concentrations of HC, CO, CO_2 and NO_x, air-to-fuel ratio, GPS coordinates, GPS velocity and exhaust flow rate on a second by second basis. The sample tube that measures emissions is passed through the window and secured to the tailpipe attachment. The OBS-1300 system includes a MEXA 1170 HNDIR analyzer, a MEXA-720 NO_x analyzer, a Data Integration Unit, a Power Supply Unit, a Data Logger PC and the other accessories. The entire OBS-1300 instrument was installed in the Dodge Charger with technical assistance from Horiba Instruments, Inc. representatives.

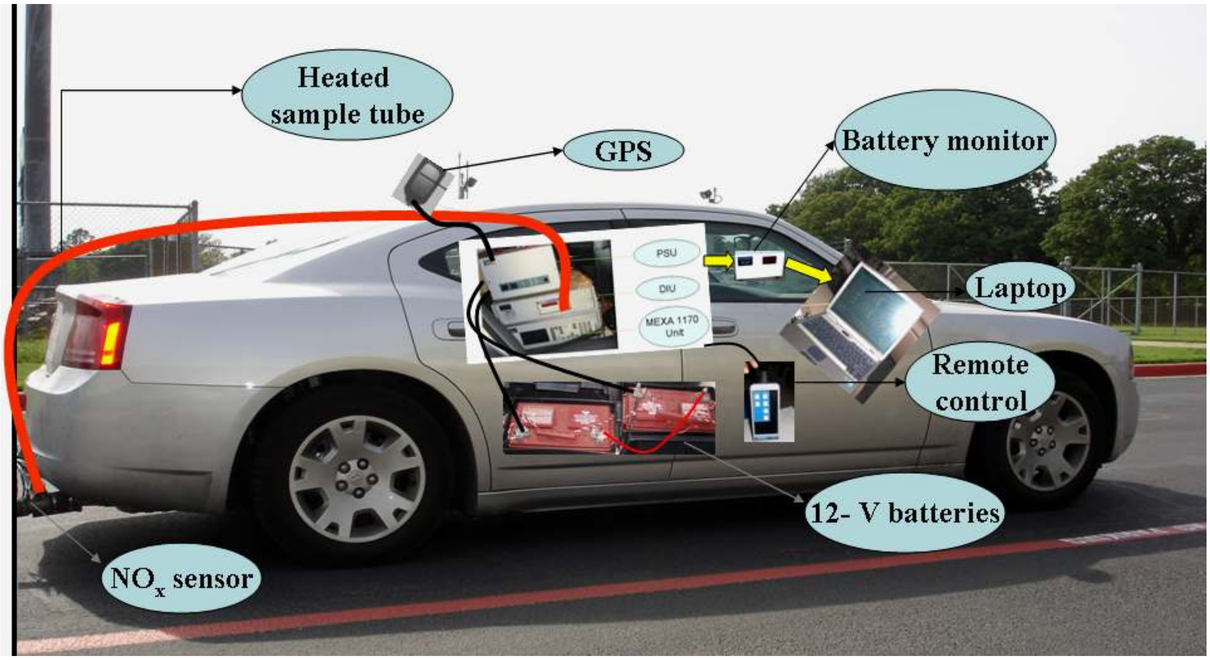


Figure 3.5 The OBS 1300 setup on the study vehicle

3.2.2.1 MEXA 1170 HNDIR Unit

This unit employs a Heated Non-Dispersive Infrared (HNDIR) detection principle to measure the emissions of CO, CO_2 and HC. The HNDIR principle uses selective absorption of infrared radiation of a certain wavelength by the exhaust gas. The exhaust gas entering the sample tube absorbs infrared radiation, in an amount directly proportional to its molecular concentration. This unit consists of a power switch and a screen that acts as an interface between the data logging laptop and the analyzer. At the rear end of this unit, there are inlets for calibration gases such as zero gas, span gas and purge gas, an inlet for sample exhaust gas, and an outlet for exhaust gas. The heated tube and remote control are connected to it. Care should be taken that no water stays in the tube as the exhaust port of the analyzer discharges it. Figure 3.6 shows the OBS device secured to the backseat of the Charger.

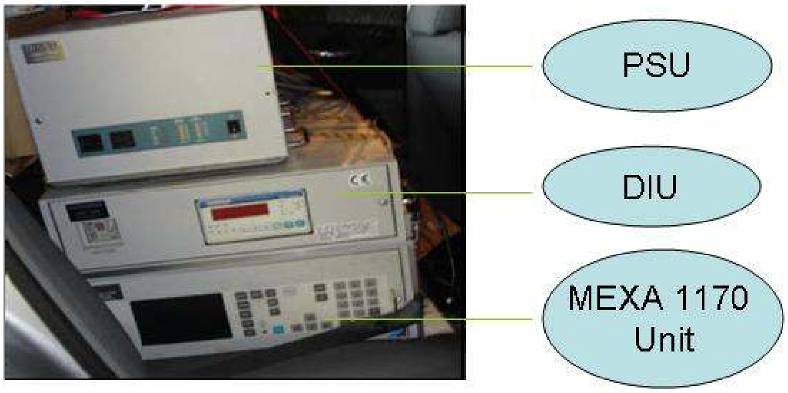


Figure 3.6 OBS-1300 device secured to the backseat of the Dodge Charger

3.2.2.2 Data Integration Unit

Data Integration Unit acts as an interface between the analyzer and the data logger PC that measures NO_x concentrations and Air to Fuel ratio. MEXA – 720 NO_x

analyzer within the unit reads information from the non-sampling zirconia sensor. Figure 3.6 shows the Data Integration Unit. The back end has various ports for exhaust pressure, differential pressure, ambient pressure, GPS, temperature and humidity connectors. The MEXA-720 NO_x analyzer and the NO_x sensor are shown in Figure 3.7.

Figure 3.7 NO_x sensor and MEXA-720 NO_x analyzer

3.2.2.3 Data Logger PC

The data logger PC connected to the two interfaces is a Latitude Laptop. It has a PCMCIA card that converts analog to digital. The software provided by Horiba enables the laptop to collect second by second data for all the vehicle parameters and pollutant concentrations. The laptop is displayed in Figure 3.8.

Figure 3.8 Data Logger PC

3.2.2.4 Power Supply Unit (PSU)

The power supply unit converts the 24V direct current from the batteries to alternating current and supplies it to the entire OBS-setup. For charging the batteries, the power supply unit can convert the AC to DC. The power supply unit is shown in Figure 3.9.

Figure 3.9 Power Supply Unit

3.2.2.5 Associated Units

The associated units include Geo Positioning System, remote controller, temperature and humidity sensor, tailpipe attachment and two sets of batteries. The two sets of deep cycle 12 V batteries are the source of power for the whole OBS setup. They are connected to the PSU, which supplies electricity to the rest of the units. The two sets of batteries are shown in Figure 3.10.

Figure 3.10 12 - Volt deep cycle batteries

A remote controller makes the functions PURGE, SPAN, ZERO, MEASURE, CAL and RESET handy to the rider who is away from the DIU and MEXA HNDIR units. It is linked to the DIU. Figure 3.11 shows the remote controller.

Figure 3.11 Remote Controller

The Geo-Positioning System device gives the coordinate (latitude & longitude) of the vehicle second by second, which is used to estimate vehicle velocity. Figure 3.12 shows the GPS device.

Figure 3.12 GPS device

The tailpipe attachment is mounted on the exhaust tailpipe. It has a flow meter (pitot tube), NO_x sensor and heated HNDIR sampling tube, as shown in Figure 3.13.

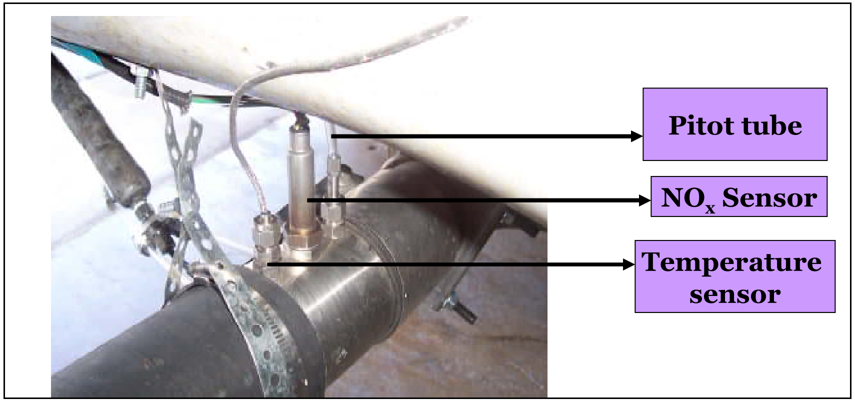


Figure 3.13 Tailpipe attachment with the NO_x sensor, Pitot tube and heated sampling tube

3.2.3 Factors Affecting the Data Collection Process

- Calibration is the main factor that affects the data collection process. The NO_x sensor should be calibrated weekly. An additional daily calibration procedure should be followed before going on-road.
- Data is not collected on rainy days, as the NO_x sensor is sensitive to water. The sensor may be damaged by the water producing aberrant data.
- While driving, the vehicle speed is maintained at the speed of the other vehicles in the traffic to be representative of the emissions of the driving fleet.
- The data collected may vary depending on the time of the day and traffic conditions, such as peak and off-peak.

- Care should be taken not to collect data when the battery power drops below 21V, which can result in erratic data. Therefore, batteries should be charged enough to complete the scheduled runs.
- As observed in the past testing, a driver's behavior also plays a part in the emissions, as the driver accelerating or decelerating roughly drastically changes emissions. Therefore, all drivers must try to limit large accelerations or decelerations.
- The parameters in the analog to digital converter (ADC) setup are to be configured to correct values as prescribed by the manual. The ADC setup in the data logging software should be configured as shown in Table 3.2.

Table 3.2 Configuration of the parameters in the ADC setup

Parameters	**Range of Values**	**Units**
NO_x	0-3000	ppm
Air to Fuel Ratio (AFR)	0-100	_
Exhaust Temperature	0-1000	^oC
Exhaust Pressure	0-200	KPa
Ambient Temperature	0-150	^oC
Ambient Pressure	0-100	KPa
Ambient Humidity	0-100	%
Velocity	0-500	kmph
Revolutions	0-5000	rpm

3.3 Calibration

3.3.1 General Calibration of OBS-1300

Calibration of the instrument should be done every day before collecting data, followed by 45 minutes of warm-up. The following steps are required in the calibration procedure:

- The two sets of 12 V deep cycled batteries are completely charged overnight.
- The DIU is turned on using AC power; and start HNDIR unit one minute later.
- Warm up the DIU and HNDIR for 45 minutes.
- After warming up, switch the power source to DC (in this case, the pair of charged 12V batteries).
- Turn on DIU and after one minute start the HNDIR unit.
- Now warm up the system for 15 minutes.
- PURGE for 5 minutes by flowing the zero gas (an inert Nitrogen gas). Figure 3.14 shows the zero gas cylinder used for purging the system.
- Press RESET and ZERO for 30 seconds.
- Meanwhile, connect the span gas cylinder and turn it on.
- RESET and SPAN for 90 seconds.
- RESET and press CAL. This will zero and span calibrate the instrument and automatically sets to RESET again.
- The above process completes the calibration of the OBS setup.

Figure 3.14 Zero gas cylinder for purging the OBS-1300 setup

3.3.2 Calibration of Flowmeter

After the general warm up and calibration process, the other major calibration is needed is that of the flow meter, in this case a pitot tube. This should be definitely done because of the past experiences of observing negative flow rate values.

- Before starting, turn the engine off and ensure the ZERO calibration of the instrument.
- Now, in the computer software, click on the CAL button that calibrates the flow rate to zero. Make sure that the values are closer to zero (-0.05 to 0.05).
- Press RESET and then PURGE; turn the engine on.
- Press MEASURE after 90 seconds of purging and start logging the data.
- The above process should be done after every run on the arterial and on the highway, and also when negative values start showing up. This calibration checks the accuracy of the pitot tube.

3.3.3 Calibration of NO_x Sensor

The NO_x sensor should be calibrated every week to ensure accurate NO_x concentration values. The calibration setup includes flow meter, sensor adapter, bubbler and water inlet, as shown in the Figure 3.16. Figure 3.15 shows the calibration gas cylinder. The calibration of the NO_x sensor follows the subsequent steps:

- Distilled water is filled into the calibration unit through the water inlet.
- The calibration unit is connected to the gas cylinder through a regulator valve.
- The calibration flow rate is in the range of 1.5 L/min to 2.5 L/min. The ball should hang between the two levels.
- The NO_x sensor switched on for calibration after the gas is allowed to flow.
- Press the CAL/SET mode for three seconds and the mode of the analyzer switches to setting mode. Ch000 appears on the screen.
- Calibration is done when the value of concentration on the calibration gas matches the concentration of NO_x on the screen.

Figure 3.15 Calibration gas cylinder used in NO_x sensor calibration

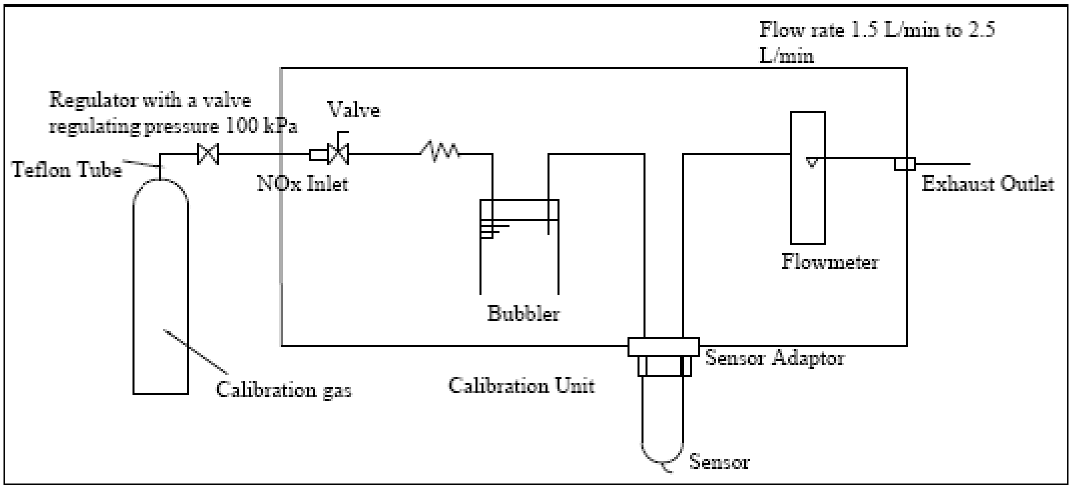


Figure 3.16 Calibration setup for NO_x sensor

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The data was stored as a text file in the note pad of the OBS-1300 software. This data was then exported to a Microsoft Excel sheet. Table 4.1 shows the parameters measured during data collection.

Table 4.1 Parameters displayed in the logging sheet

PARAMETERS	**UNITS**
Date and Time	mm/dd/yr
CO Concentration	%Vol
CO_2 Concentration	%Vol
HC Concentration	ppm
NO_x Concentration	ppm
Exhaust flowrate	L/min
Exhaust temperature	Deg C
Exhaust pressure	KPa
AFR	_
GPS Velocity	Kmph

For the data analysis, the parameters CO, CO_2, HC and NO_x concentrations, date and time were required. The time factor was very important to distinguish between peak and off-peak data.

4.2 Data Analysis

Data analysis was conducted with the device and without it. Unlike the first phase of testing, where a modal approach was used for the analysis, a gram per mile approach was used for this analysis, with the data subdivided only into highway vs. arterial and peak vs. off-peak.

Data classification and analysis was conducted according to the sequential steps discussed below:

1. The arterial and highway test track data analysis was done separately.
2. The "raw data" from the data logging text file was exported to spreadsheets.
3. After importing data, each data file was named peak or off-peak based on the timing shown on the sheet. The peak and off-peak timings were discussed in the previous chapter.
4. Subsequent to data classification as discussed in the above three steps, the concentrations of the four pollutants (CO, CO_2, HC and NO_x), exhaust flow rate, and GPS velocity were transferred to a different spreadsheet. The gram per second and gram per mile values were estimated for the four pollutants.
5. All the values were averaged for every 30 seconds of the run. Before averaging, the delay times of one second for NO_x and three seconds for CO, CO_2 and HC were incorporated into the Excel sheets. The delay time is the time taken for the pollutant concentration to be displayed on the data logging sheet from the analyzers.

6. All these averaged values were aggregated into a set for highway peak in a new Excel sheet and for highway off-peak in a different spreadsheet. Similarly, arterial data was grouped into a new set peak and off-peak, separately in new spreadsheets.
7. A final average value was calculated for all the 30 second averaged values. These final average values were considered in the percent reduction analysis.
8. The average percentage emissions reduction for each pollutant with the device was estimated for highway and arterial, peak and off-peak.
9. Scatter plots were graphed of average emissions vs. average velocity for the baseline and with the device data. T-tests were conducted to find out the statistical significance of the emissions trends.

NOTE:

Before plotting graphs, the changes made to the data to improve the data quality are listed below:

- For the highway track, the single point or multiple point data with average velocity below 45 miles/hour was omitted, as it was already considered in the arterial data set.
- On the highway test track, the very few data points with average velocity greater than 85 miles/hour were omitted since they were outliers.
- For the arterial track, the data with velocity clusters greater than 46 miles/hour were omitted, because these driving conditions were dealt with in the highway

data set and insufficient data existed to make the velocity cluster comparisons between the before and after device data sets difficult.

4.3 Results

The results obtained from the data analysis are presented in three ways:

- scatter graphs of average pollutant emissions as a function of average velocity for CO, CO_2, NOx and HC, *(section 4.3.1)*
- the average percent reductions with the device and *(section 4.3.2)*
- t-tests to identify the statistical significance of the reductions or increases in the emissions. *(section 4.3.3)*

4.3.1 Graphical Analysis

As already discussed in the above section, graphs were plotted of average emissions and average velocity for each pollutant after classifying the data. A total of 32 graphs were drawn for highway and arterial, peak and off-peak times, in gram per mile and ppm or %. Table 4.2 below shows the number of graphs plotted for each part of the data set.

Table 4.2 Number of Individual Scatter Graphs for Different Routes/Traffic Conditions

Traffic condition	Scatter Plots (g/mile)		Scatter Plots (ppm/Vol %)	
	Highway	Arterial	Highway	Arterial
Peak	4[a]	4	4	4
Off-peak	4	4	4	4

(a. Four plots for were plotted for the four pollutants, CO, CO_2, HC and NO_x)

These graphs show the emission trends with the device and without it for the four pollutants. Because of space constraints, the scatter plots in g/mile are presented here and their trends are discussed. The rest of the graphs are presented in Appendix A.

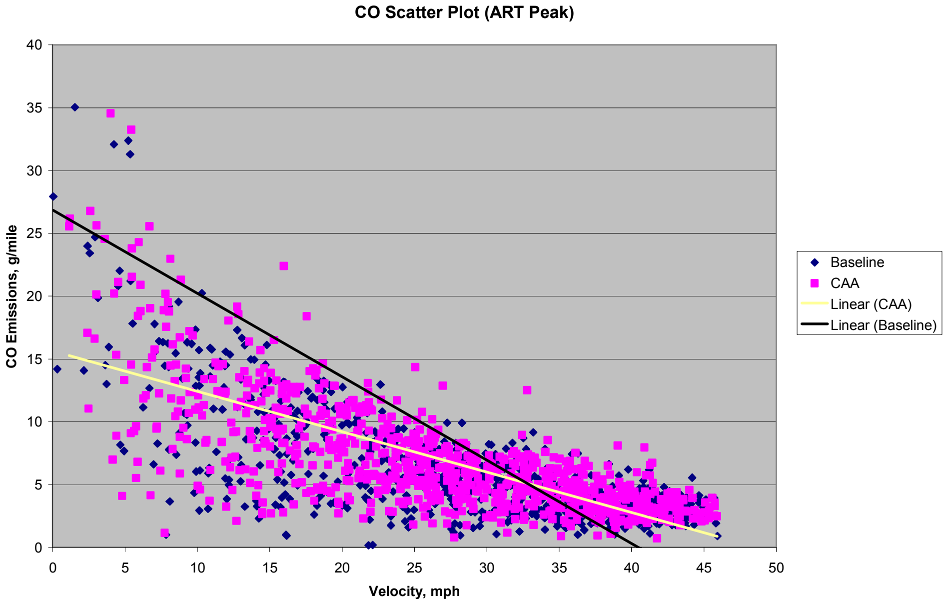


Figure 4.1 CO emission trends of arterial test track and peak time interval

Observations: Figure 4.1 shows CO emission trends of arterial test track, peak time traffic with device and baseline. A best fit linear regression line (trend line) was added to plots of baseline and CAA. It is observed from the figure that the CAA trendline generally lies below the baseline trendline.

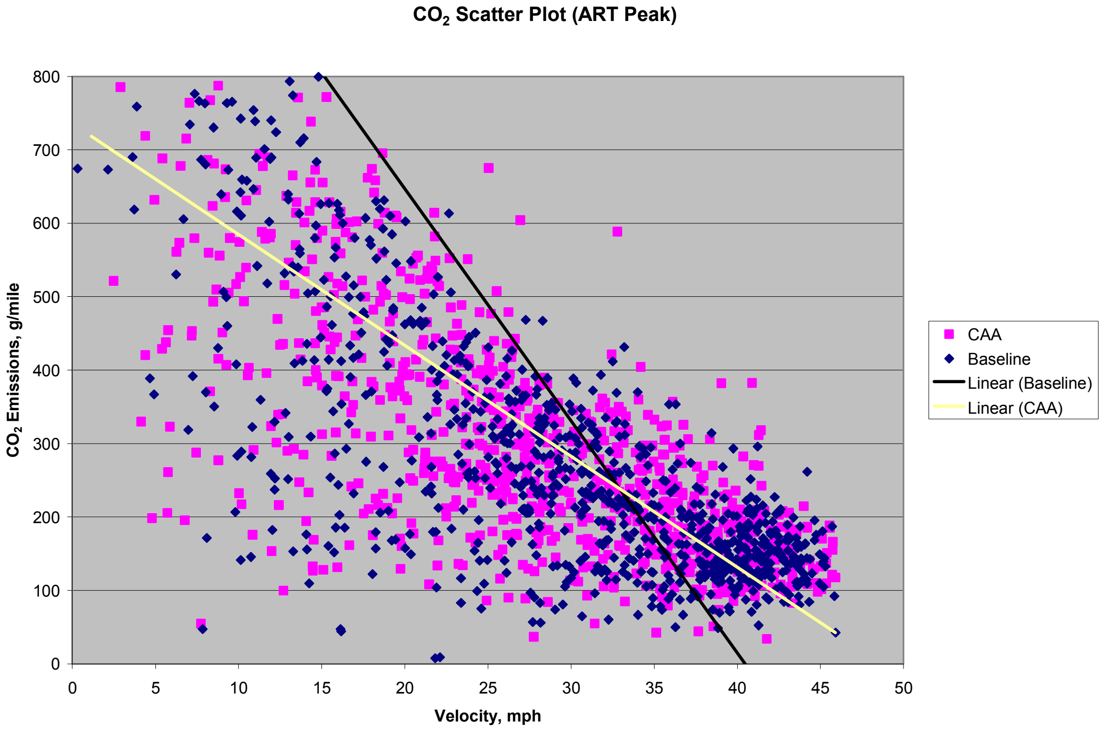


Figure 4.2 CO_2 emission trends of arterial test track and peak time interval

Observations: Figure 4.2 shows CO_2 emission trends for arterial peak traffic with and without device.

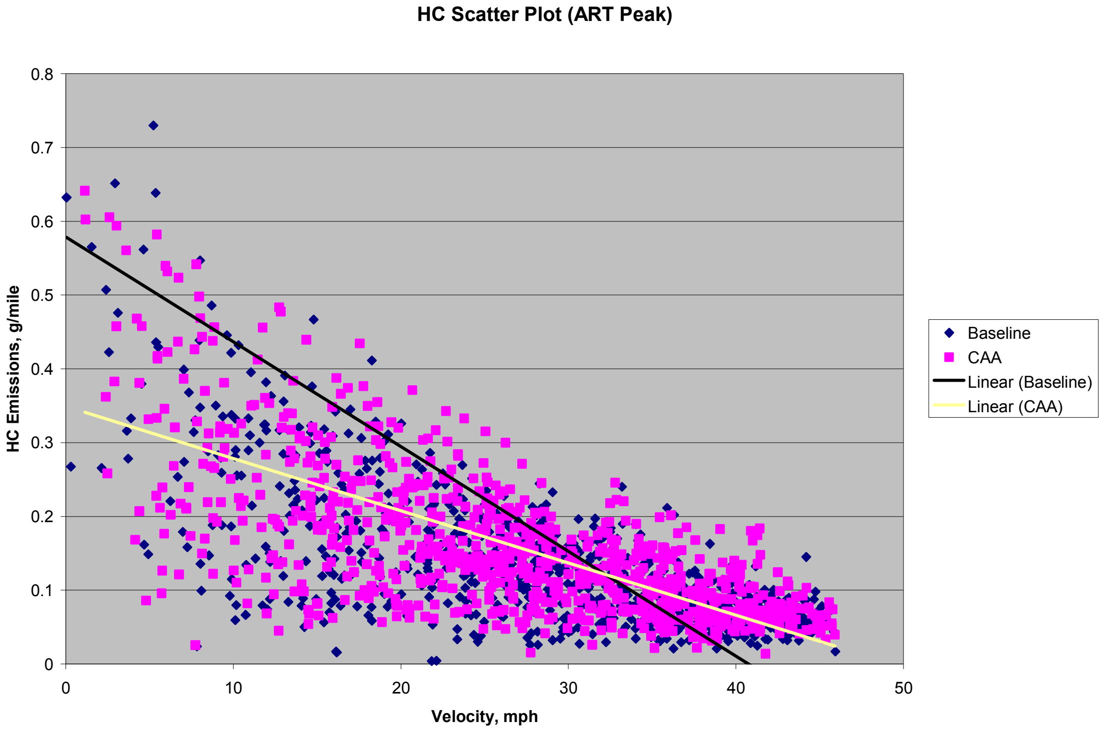


Figure 4.3 HC emission trends of arterial test track and peak time interval

Observations: Figure 4.3 shows HC emission trends of the arterial test track for peak hour traffic. It can be observed from the figure that CAA trendline generally lies below baseline trendline.

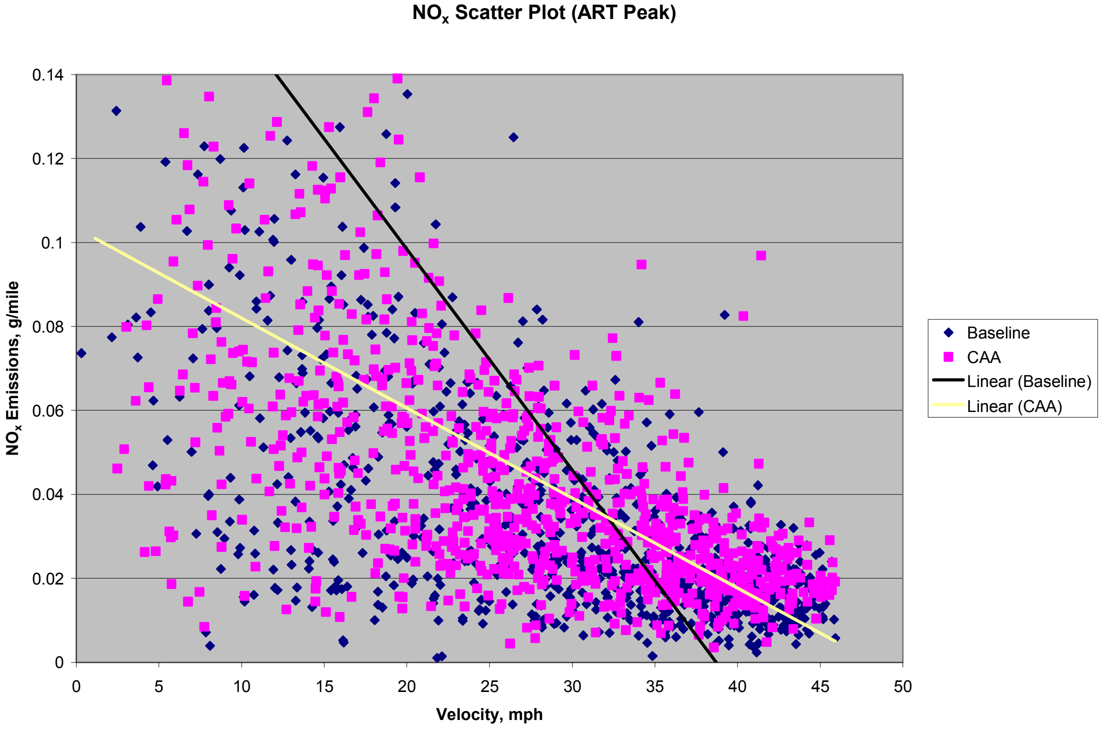


Figure 4.4 NO_x emission trends of arterial test track and peak time interval

Observations: Figure 4.4 shows NO_x emission trends for the arterial peak time traffic with device and baseline testing.

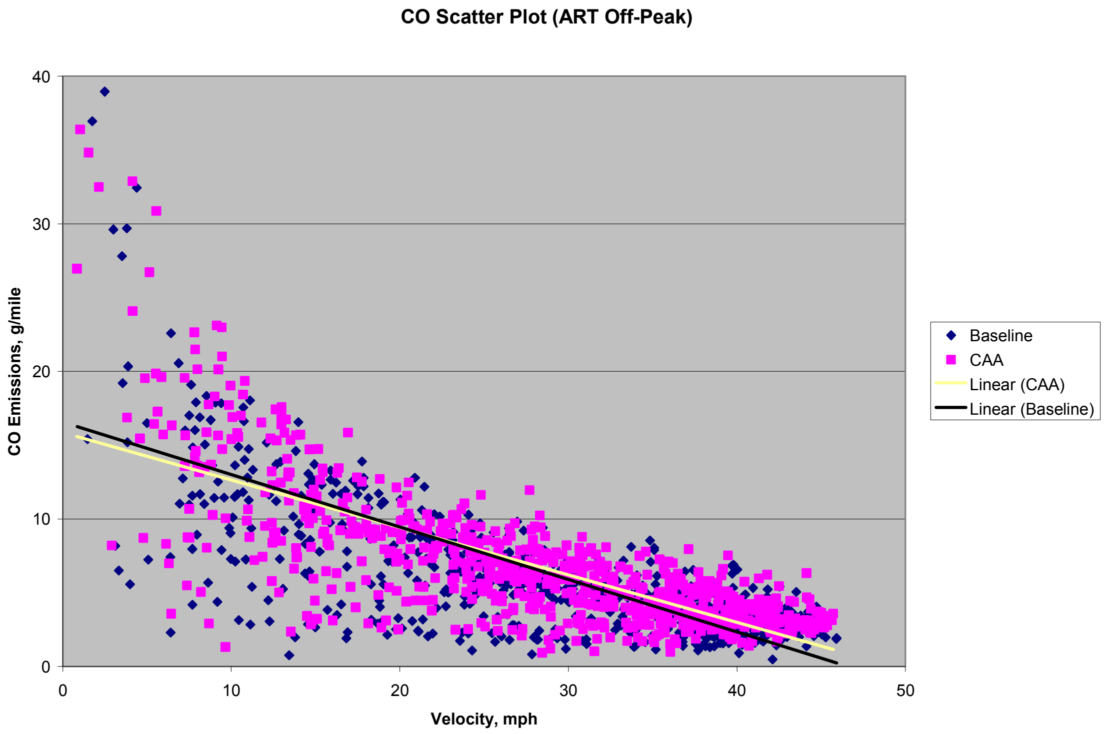


Figure 4.5 CO emission trends of arterial test track and off-peak time interval

Observations: Figure 4.5 shows CO emission trends for arterial off-peak traffic condition. CAA trendline and baseline trendline are close to each other.

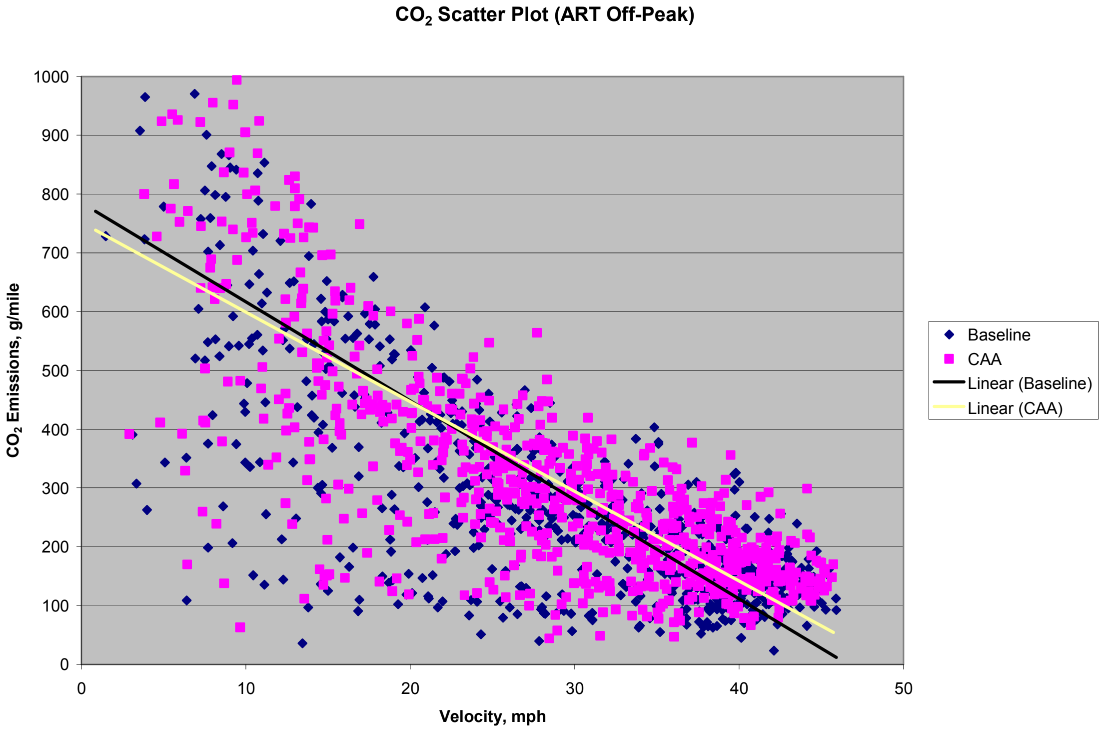


Figure 4.6 CO_2 emission trends of arterial test track and off-peak time interval

Observations: Figure 4.6 depicts a scatter plot of CO_2 emissions for arterial off-peak traffic condition, both with device and baseline. It can be observed that CAA trendline and baseline trendline are close to each other.

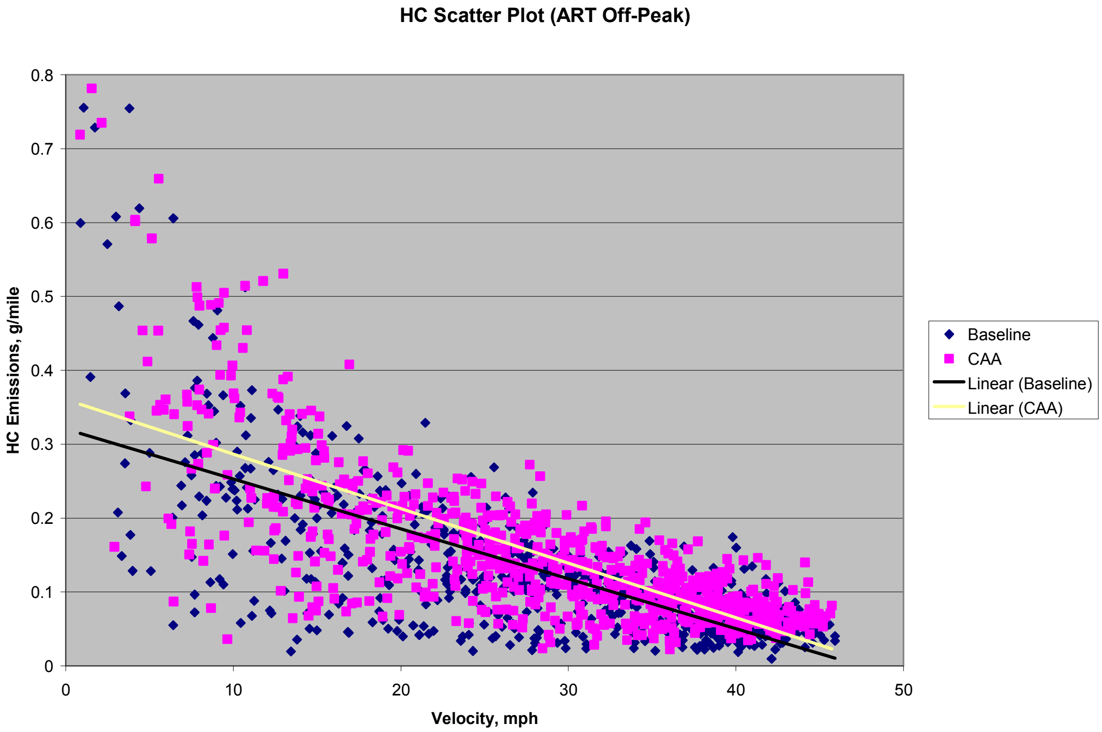


Figure 4.7 HC emission trends of arterial test track and off-peak time interval

Observations: Figure 4.7 represents HC emissions for arterial off-peak time period. It can be observed that the CAA trend line runs approximately parallel to the baseline trend line and above it.

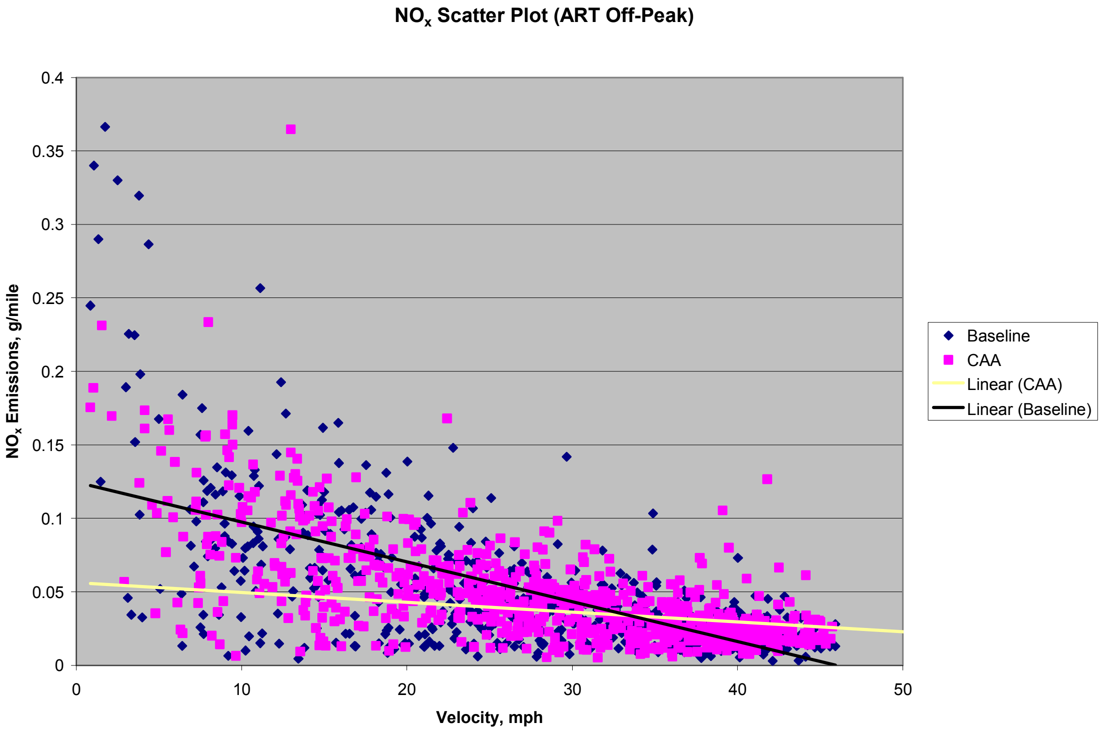


Figure 4.8 NO_x emission trends of arterial test track and off-peak time interval

Observations: Figure 4.8 shows a scatter plot of NO_x emissions for the arterial off-peak condition with device and baseline. CAA trendline lies below baseline trendline.

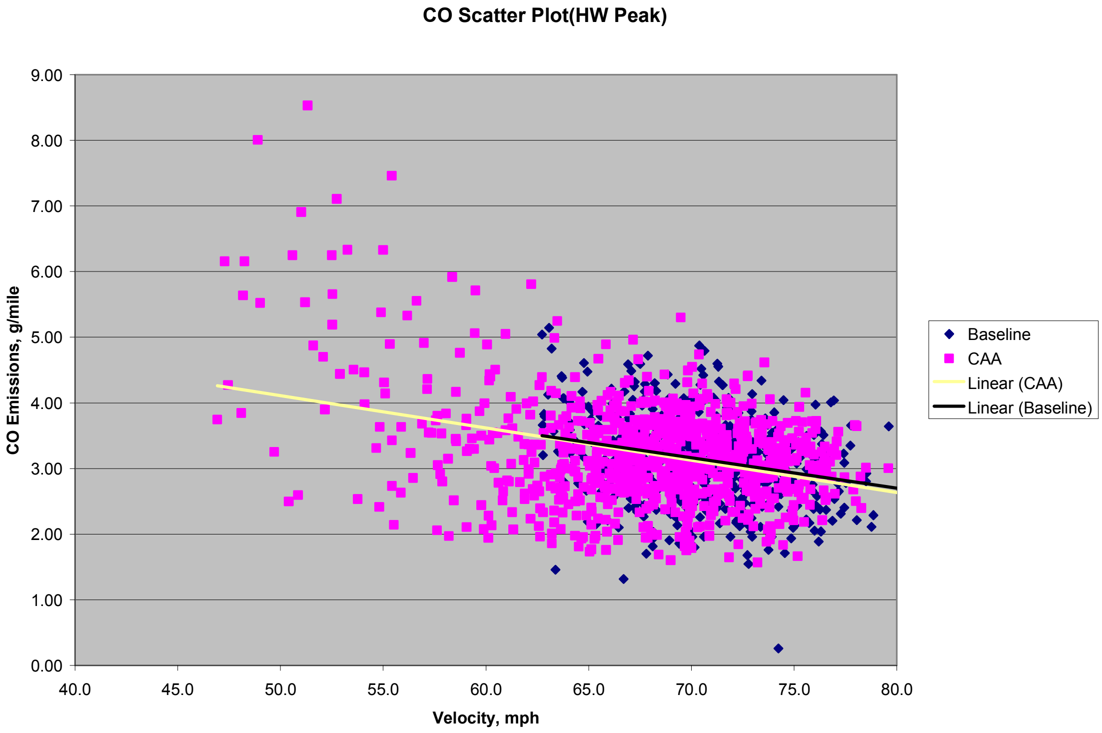


Figure 4.9 CO emission trends of highway test track and peak time interval

Observations: Figure 4.9 shows CO emission trends for highway peak time conditions with device and without it. It is observed that CAA trendline and baseline trendline are overlapping.

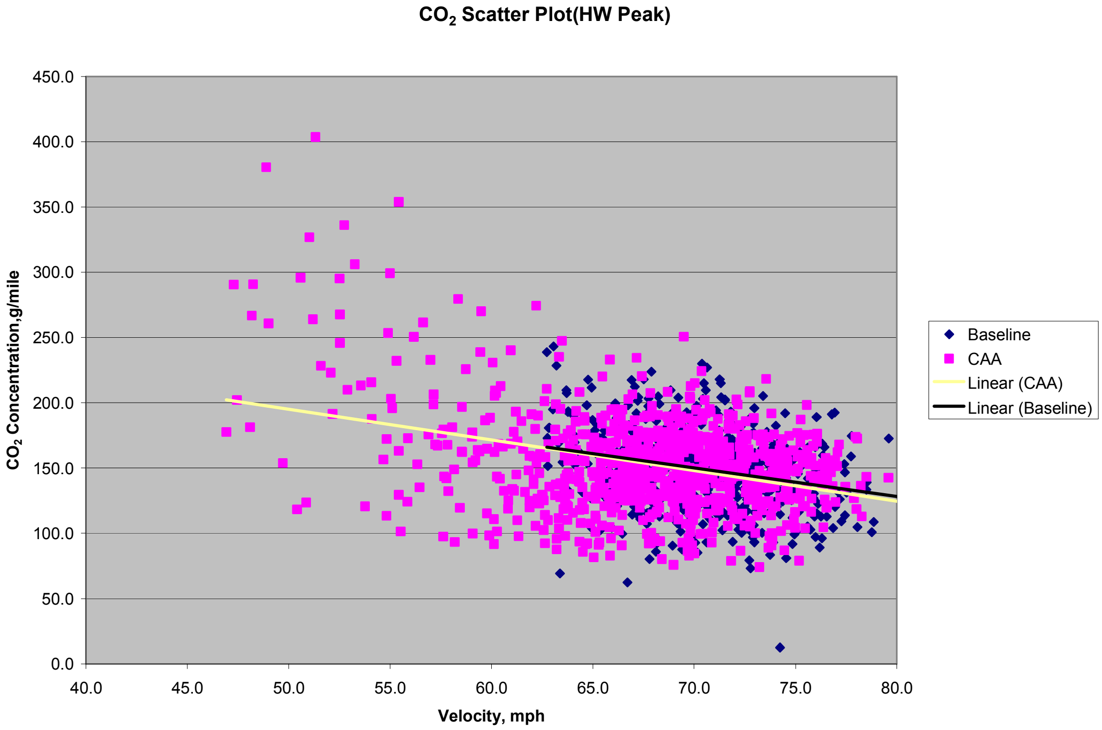


Figure 4.10 CO_2 emission trends of highway test track and peak time interval

Observations: Figure 4.10 depicts a scatter plot of CO_2 emissions for highway peak time conditions with the device and without it. It can be observed from the figure that the baseline trend line and CAA trend line overlap.

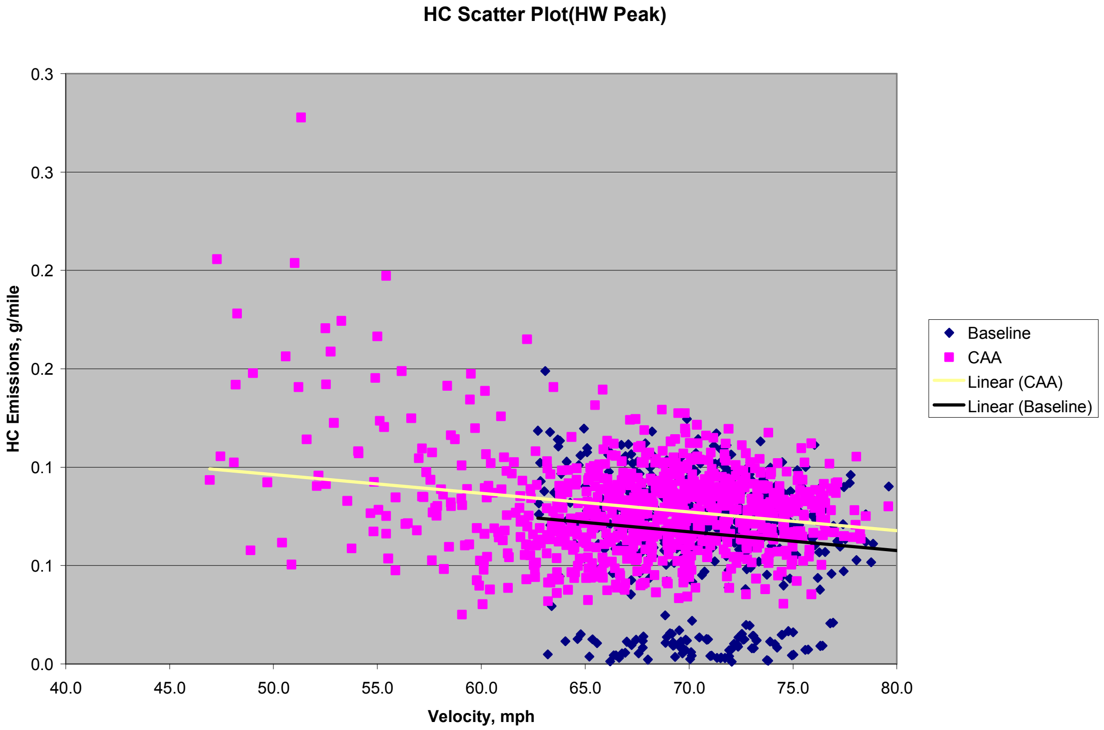


Figure 4.11 HC emission trends of highway test track and peak time interval

Observations: Figure 4.11 shows a scatter plot of HC emissions for highway peak traffic conditions, with device and baseline testing. The above figure shows that the baseline emissions and CAA device emissions overlap to great extent. The CAA trend line falls above the base line trend line.

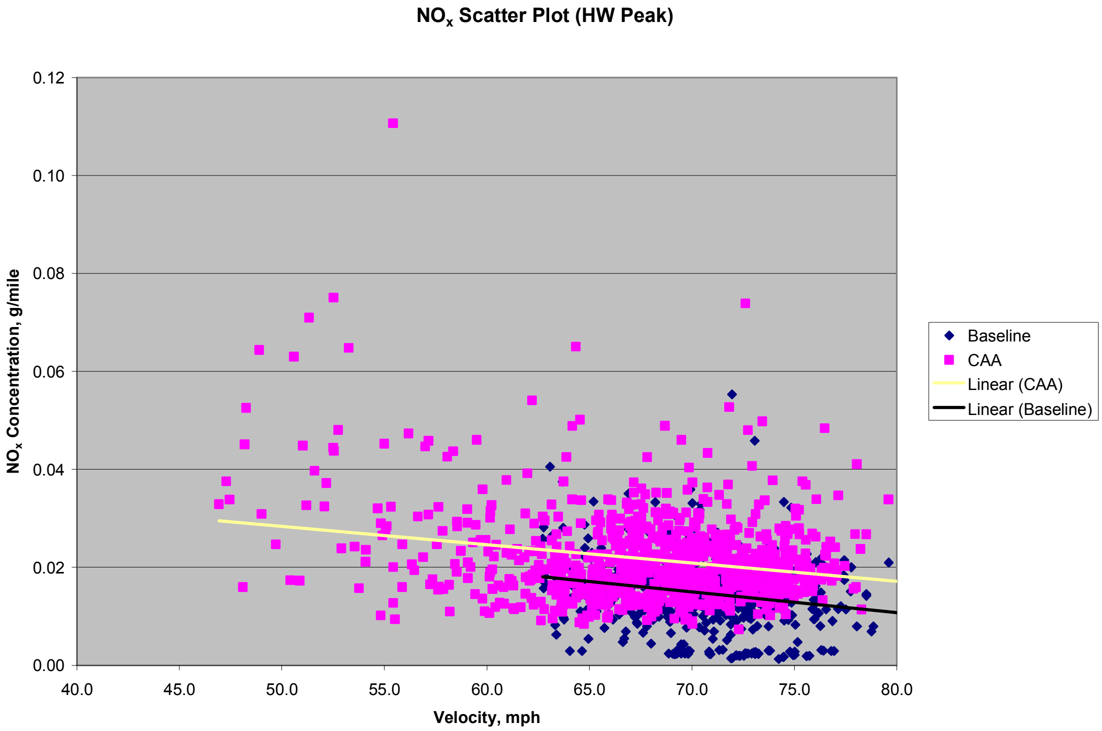


Figure 4.12 NO_x emission trends of highway test track and peak time interval

Observations: Figure 4.12 shows a scatter plot of NO_x emissions for highway peak time conditions with device and baseline testing. The NO_x scatter plot for highway test track shows that the CAA trend line lies above the baseline trend line.

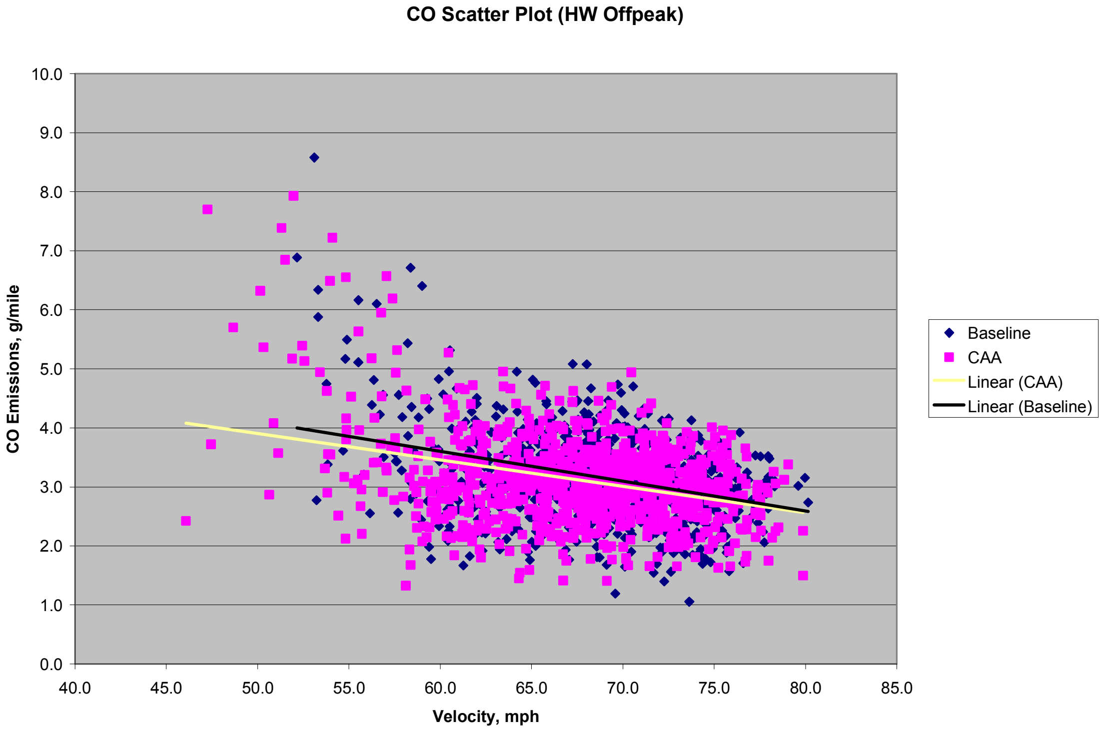


Figure 4.13 CO emission trends of highway test track and off-peak time interval

Observations: The Figure 4.13 shows scatter plot of CO emissions for highway off-peak, with device and baseline. The CAA trend line lies slightly below baseline trend line, intersecting at a point.

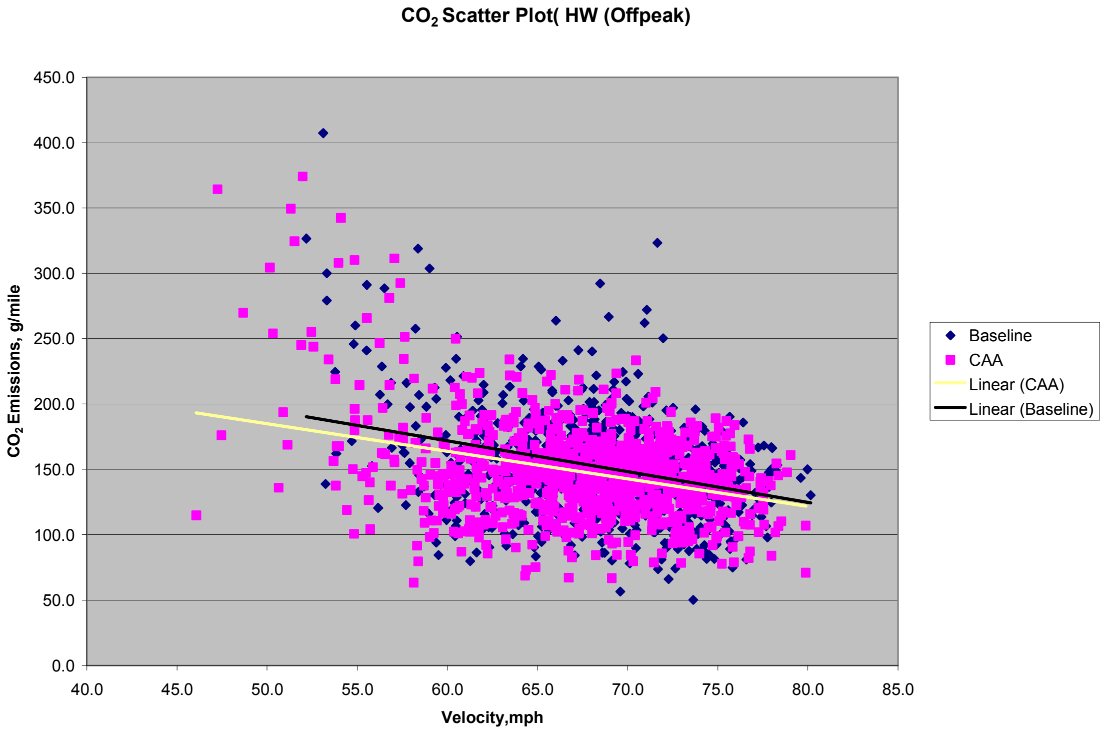


Figure 4.14 CO_2 emission trends of highway test track and off-peak time interval

Observations: Figure 4.14 shows a scatter plot of CO_2 emissions for highway off- peak conditions, with device and baseline. The CAA trend line lies below baseline trend line.

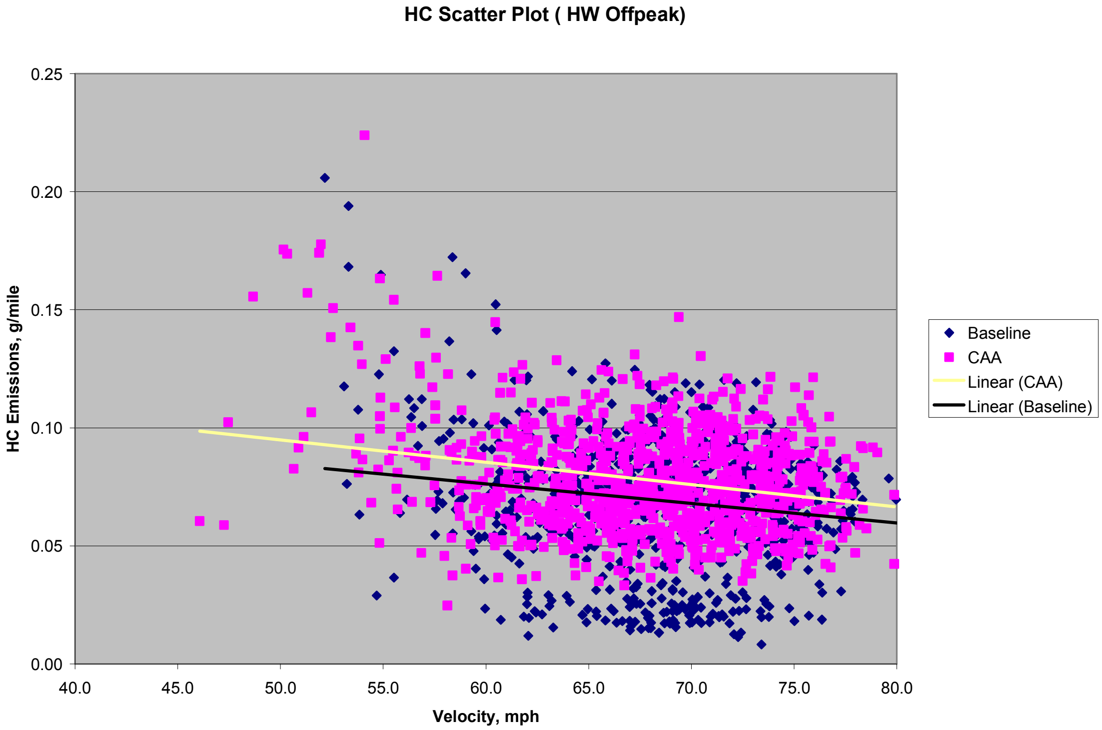


Figure 4.15 HC emission trends of highway test track and off-peak time interval

Observations: Figure 4.15 shows a scatter plot of HC emissions for highway off-peak, with device and baseline. The CAA trend line lies above the baseline trend line.

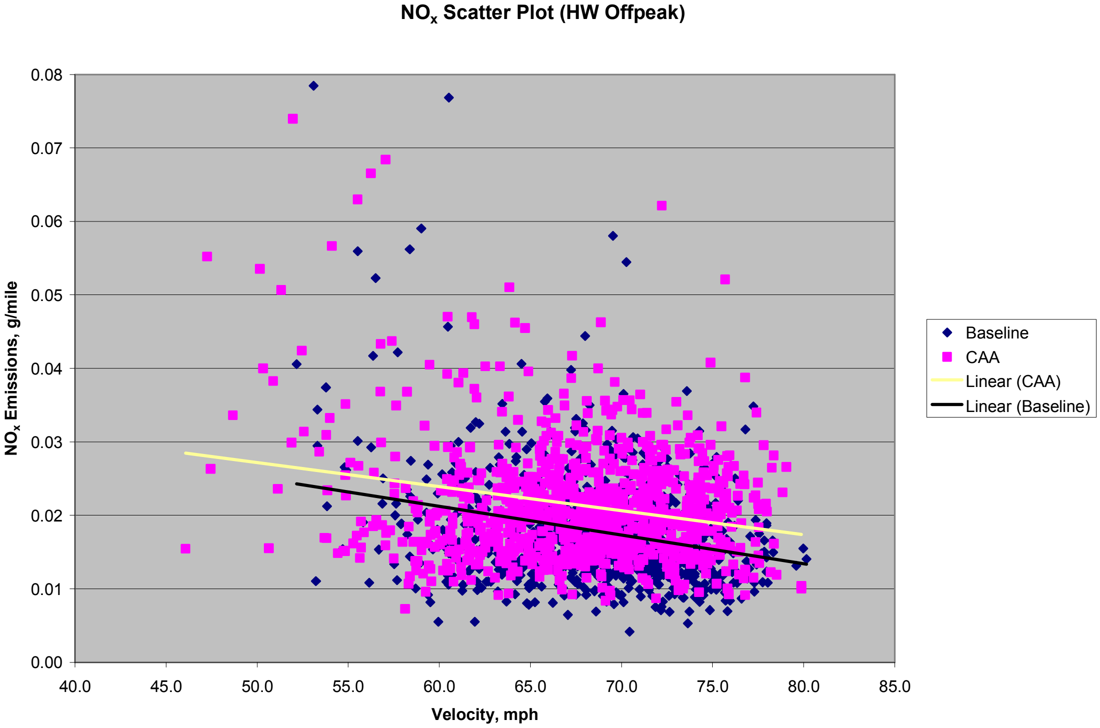


Figure 4.16 NO$_x$ emission trends of highway test track and off-peak time interval

Observations: Figure 4.16 shows a scatter plot of NO$_x$ emissions concentration for highway off-peak, with device and baseline. The CAA trend line lies above baseline trend line.

4.3.2 Percent reductions

The percentage emission reductions after device installation were calculated from gram/mile data for the four pollutants for highway, arterial, peak & off-peak conditions, as shown in Table 4.3. A negative value indicates a decrease due to installation of the CAA device. Percent reductions that are statistically significant, as discussed later in section 4.3.3 are indicated in bold.

Table 4.3 Percent Change in Emissions due to Clean Air Associates Device

Pollutant	Percentage Change (%)				
	Arterial Test Track		Highway Test Track		Average
	Peak	Off-Peak	Peak	Off-peak	
CO	-8.82	**8.48**	**2.90**	**-1.65**	-3.69
CO_2	-9.26	**8.37**	**2.74**	-2.70	-4.20
HC	-6.62	**22.0**	**18.7**	**13.1**	5.85
NO_x	-4.83	2.58	**46.70**	**19.76**	0.910

<u>Observations:</u> The following conclusions are drawn from the percent reductions estimations.

- For the arterial peak, the four pollutant emissions decreased with the device. The four pollutant emissions increased with the device for the arterial off-peak condition.
- For the highway peak condition, all the pollutant emissions increased with the device and for off-peak condition, CO and CO_2 emisisons decreased. HC and NO_x emissions increased with device.

4.3.2.1 Accuracy results

According to Horiba product literature, the instrument accuracy was taken to be 2% of full scale for HC, CO and CO_2. The instrument accuracy was taken to be 15 ppm for NO_x based on field accuracy measurements and conversations with the Horiba technical representative. The pollutant accuracies are shown in the Table 4.4.

Table 4.4 OBS 1300 assumed accuracy values

Pollutant	**OBS 1300 Accuracy Level**
CO	0.02%
CO_2	0.2%
HC	20 ppm
NO_x	15 ppm

The reduction or increase in average emissions of each pollutant was compared with the OBS-1300 accuracy value for that pollutant. Tables 4.5 - 4.8 show average emissions for each of the four testing categories - arterial peak, arterial off-peak, highway peak, and highway off-peak, with and without installation of the Clean Air Associates device. A negative difference value indicates a decrease, implying the Clean Air Associates device decreased emissions, compared to the baseline. Table 4.9 shows overall average emissions for each pollutant, with and without the Clean Air Associates device, along with the OBS 1300 accuracy values.

Table 4.5 Average Emissions for Arterial Peak, With and Without CAA Device

Pollutant	Average Measured Concentration			OBS Accuracy	Difference > OBS Accuracy?
	Without CAA device	With CAA device	Difference		
CO (%)	0.912	0.445	-0.467	0.02	Yes
CO_2 (%)	15.2	13.4	-1.8	0.2	Yes
HC (ppm)	61.4	64.8	3.4	20	No
NO_x (ppm)	23.2	24.4	1.2	15	No

Table 4.6 Average Emissions for Arterial Off-Peak, With and Without CAA Device

Pollutant	Average Measured Concentration			OBS Accuracy	Difference > OBS Accuracy?
	Without CAA device	With CAA device	Difference		
CO (%)	0.447	0.448	0.001	0.02	No
CO_2 (%)	13.5	13.5	0	0.2	No
HC (ppm)	57.2	63.5	6.3	20	No
NO_x (ppm)	26.3	25.9	-0.4	15	No

Table 4.7 Average Emissions for Highway Peak, With and Without CAA Device

Pollutant	Average Measured Concentration			OBS Accuracy	Difference > OBS Accuracy?
	Without CAA device	With CAA device	Difference		
CO (%)	0.447	0.443	-0.004	0.02	No
CO_2 (%)	13.5	13.4	-0.1	0.2	No
HC (ppm)	63	69.8	6.8	20	No
NO_x (ppm)	18.5	26.2	7.7	15	No

Table 4.8 Average Emissions for Highway Off-Peak, With and Without CAA Device

Pollutant	Average Measured Concentration			OBS Accuracy	Difference > OBS Accuracy?
	Without CAA device	With CAA device	Difference		
CO (%)	0.446	0.44	-0.006	0.02	No
CO_2 (%)	13.5	13.3	-0.2	0.2	Equal
HC (ppm)	62.5	70.6	8.1	20	No
NO_x (ppm)	21.8	26.2	4.4	15	No

Table 4.9 Overall Average Emissions, With and Without CAA Device

Pollutant	Average Measured Concentration			OBS Accuracy	Difference > OBS Accuracy?
	Without CAA device	With CAA device	Difference		
CO (%)	0.581	0.444	-0.137	0.02	Yes
CO_2 (%)	13.88	13.39	-0.49	0.2	Yes
HC (ppm)	61.4	67.5	6.1	20	No
NO_x (ppm)	22.9	25.7	2.8	15	No

Observations:

Table 4.10 shows a summary of the changes that exceed OBS accuracies. It can be observed that the difference in emissions with and without device exceeded the accuracy limits of the OBS 1300 for CO and CO_2 arterial peak. The difference in CO_2 emissions with and without device for highway off-peak was equal to the OBS 1300 accuracy limit. Also, for the overall emissions of CO and CO_2, the difference in emissions exceeded the OBS 1300 accuracy limits.

Table 4.10 Summary of Changes which exceed OBS accuracy limits

Pollutant	Arterial		Highway		Overall
	Peak	Off-Peak	Peak	Off-Peak	
CO	**Yes**	No	No	No	**Yes**
CO_2	**Yes**	No	No	**Equal**	**Yes**
HC	No	No	No	No	No
NO_x	No	No	No	No	No

4.3.3 Statistical Analysis

4.3.3.1 T-tests

Statistical analysis was also done to see if the average percent reduction or increase was significant or not. For that purpose, t-tests were done on the 30-second averaged g/mile values of all the four pollutants on the ‘baseline’ and ‘with device’ data sets to find out whether the differences were significant.

4.3.3.2 T-test procedure in Excel sheet

From the analysis tools under the Data Analysis function of the Excel sheet, “Two-sample t-test assuming equal variances” was selected.

The parameters for inputs were:

- Variable 1 Range: CAA device data
- Variable 2 Range: Baseline data
- Hypothesized Mean Difference: Zero
- Alpha: 0.05 (95% confidence level)

The outputs were:

- Mean, Variance, Observations and 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

Hypothesis testing:

For this testing, the hypothesized mean difference is zero. Therefore, the null hypothesis for conducting the t-test is "No significant difference between baseline and with the CAA device datasets", which is mathematically designated as,

$$H_o: \mu_1 \geq \mu_2$$

The alternative hypothesis is "There is a significant increase in second dataset", which is represented mathematically as,

$$H_1: \mu_1 < \mu_2$$

A one tail t-test was used for analyzing the data sets with the subsequent inputs and outputs. If | t stat | < t critical, then the null hypothesis can not be rejected and it is concluded that there is no significant difference between the data sets. If | t stat | > t critical, then the null hypothesis is rejected and it is concluded that there is a significant increase in the second data set.

Note: μ_1 = Baseline data, μ_2 = CAA device data

Table 4.11 shows the t-test results of the baseline and with device data sets for arterial test track, peak and off-peak traffic conditions. Similarly, Table 4.12 lists t-test results of the baseline and with device data sets for highway, peak and off-peak test conditions. Table 4.13 shows t-test results for baseline and with device data sets for overall percent reduction or increase in emission concentrations of four pollutants. Percent changes that are significant are shown in bold.

Table 4.11 T-tests for pollutant emissions for arterial test track, peak and off-peak time intervals

Pollutant	Peak		Off-Peak	
	Percent change	Significant difference	Percent change	Significant difference
CO	-8.82	NO	**8.48**	YES
CO_2	-9.26	NO	**8.37**	YES
HC	-6.62	NO	**22.0**	YES
NO_x	-4.83	NO	2.58	NO

Table 4.12 T-tests for pollutant emissions for highway test track, peak and off-peak time intervals

Pollutant	Peak		Off-Peak	
	Percent change	Significant difference	Percent change	Significant difference
CO	**2.90**	YES	**-1.65**	YES
CO_2	**2.74**	YES	-2.70	NO
HC	**18.7**	YES	**13.1**	YES
NO_x	**46.70**	YES	**19.76**	YES

Table 4.13 T-tests for overall percent reduction/increase in four pollutant emissions

Pollutant	**Overall Emissions Percent Reduction**	
	Percent change	Significant difference
CO	-3.69	NO
CO_2	-4.20	NO
HC	5.85	NO
NO_x	0.910	NO

Discussion: From the above tables, it can be observed that on the arterial track there is no significant difference in all the pollutant emissions with device installation for peak conditions. However for the off-peak conditions, CO and CO_2 emissions significantly increased by 8.4% and HC emissions significantly increased by 22%. On the highway test track, for the peak condition, CO emissions significantly increased by 2.9 %, CO_2 emission concentration significantly increased by 2.7%, HC emissions significantly increased by 18.7% and NO_x emissions significantly increased by 46.7%. For the highway off-peak condition, CO emissions significantly decreased by 1.65% , HC emissions significantly increased by 13.1% and NO_x emissions significantly increased by 19.7%. Overall, the HC emission concentrations increased by 5.85%, CO emissions decreased by 3.69% and CO_2 emission concentrations decreased by 4.20% and NO_x emission concentrations slightly increased by 0.91%. However, there is no significant difference in the overall emissions the four pollutants with the Clean Air Associates Device.

Table 4.14 Summary of changes which exceed OBS accuracy limits and are statistically significant

Pollutant	**Arterial**		**Highway**	
	Peak	**Off-Peak**	**Peak**	**Off-Peak**
CO	—	—	—	—
CO_2	—	—	—	—
HC	—	—	—	—
NO_x	—	—	—	—

Table 4.14 summarizes the cases with results that were statistically significant and exceeded OBS accuracy limits. It combines the information in Tables 4.10- 4.13. There is no such case that the change (an increase) is both significant and exceeded the accuracy limits of the OBS device.

4.3.4 Fuel Economy

Fuel economy of the vehicle was estimated over the 40 hours of driving with the device and a further 40 hours of driving without the device. The mileage was noted every time refueling occurred and also at the beginning and ending of each run. The fuel economy was estimated as the difference of starting mileage and ending mileage per fuel consumed in gallons. The fuel economy was averaged for both the arterial and highway test tracks. The percent reduction or increase in fuel economy of the vehicle was estimated from CAA to baseline for arterial and highway. The Table 4.15 shows data for the fuel economy of the vehicle for the arterial test track. Table 4.16 shows data for the fuel economy of the vehicle for the highway test track.

Table 4.15 Fuel economy of the vehicle on the arterial test track for the baseline and with the retrofit device

Baseline				**With CAA device**			
Mileage (miles)		Fuel consumed (gallons)	Fuel economy (miles/gallon)	Mileage (miles)		Fuel consumed (gallons)	Fuel economy (miles/gallon)
Start	End			Start	End		
1269	1331	3	21.8	2818	3055	13	18.4
1331	1692	17	21.9	3055	3333	12	23.9
				3473	3851	15	24.7
		Average	**21.8**				**22.3**

Table 4.16 Fuel economy of the vehicle on the highway for the baseline and with the device

Baseline				**CAA**			
Mileage (miles)		Fuel consumed (gallons)	Fuel economy (miles/gallon)	Mileage (miles)		Fuel consumed (gallons)	Fuel economy (miles/gallon)
Start	End			Start	End		
1895	2259	16	22.3	3333	3473	7	18.8
2259	2466	9	24.2	3856	4210	17	21
2527	2818	14	20.8	4210	4568	14	26.3
				4568	4855	15	18.6
				4855	5036	7	25.7
				5036	5304	14	18.7
				5304	5472	7	25.03
		Average	**22.4**				**22.01**

<u>*Conclusion:*</u> On the arterial there was a 2.3% increase in fuel economy and on the highway, there was a 1.78% decrease in fuel economy of the vehicle after the installation of the device.

<u>*Note:*</u> No statistical conclusion could be drawn for the fuel economy percent reduction/increase with limited data collected.

4.3.5 Dynamometer Testing

Dynamometer testing was done on the Charger by the Department of Public Safety, Irving, Texas. The test procedure was already described in the literature review. The test was conducted with the device and without it and the four pollutant emissions were measured at speeds of 15 mph and 25 mph. As dynamometer testing simulates traffic conditions on the corridor level at lower speeds, the results from the testing were compared with the emissions from the OBS arterial data at the same 15 mph and 25 mph speed levels. The changes in pollutant emission concentrations due to device installation are shown in Table 4.17, for both dynamometer testing and OBS arterial data at 15 mph and 25 mph speed levels.

Table 4.17 Percent Change in Emissions due to Device Installation

Percent Change (%)						
	Dynamometer		OBS-1300 (peak)		OBS-1300 (off-peak)	
	15 mph	25 mph	15 mph	25 mph	15 mph	25 mph
CO	0	0	1.5	-3.9	-0.3	0.2
CO_2	0.7	0	0.2	-4.1	-0.8	0.2
HC	250	250	7.2	-18.9	53.2	6.9
NO_x	0	93	10.8	-12.0	-47.0	25.5

Figure 4.17 shows dynamometer testing results without the CAA device and Figure 4.18 shows dynamometer testing results with device.

Observations:

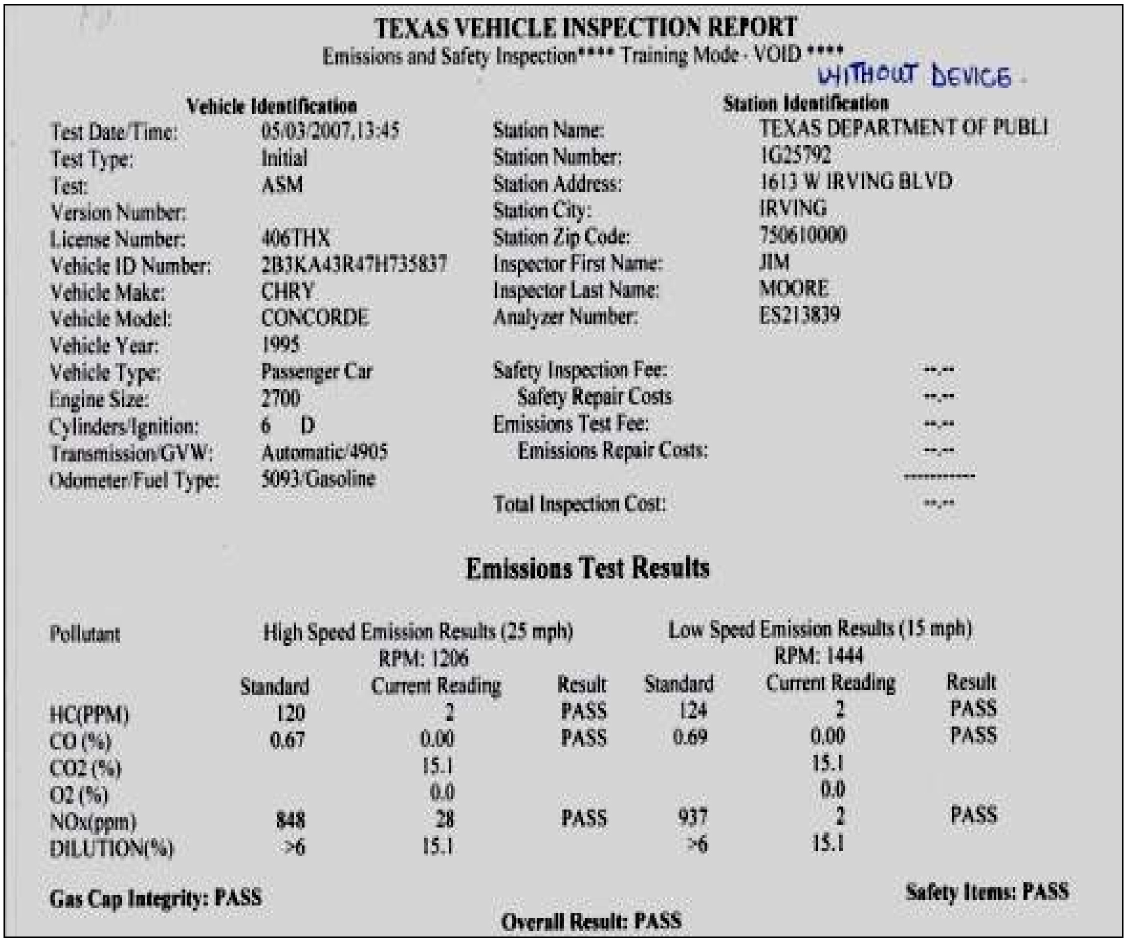
- CO emission concentrations remained the same for both 15 mph and 25 mph speed levels. CO_2 emission concentrations increased slightly at 15 mph and remained the same at 25 mph. HC emission concentrations increased by 250% at both speeds. NO_x emission concentrations remained the same at 15 mph and increased by 93% at 25 mph.

In contrast, OBS testing showed:

- CO emissions decreased a little for peak conditions at 25 mph and slightly increased for off-peak conditions at 25mph. CO_2 emissions decreased to some extent for peak conditions and vaguely increased for the off-peak condition. HC increased for both peak and off-peak conditions except for peak, 25 mph speed level. NO_x emission concentrations decreased for peak, 25 mph and off-peak 15 mph levels and it increased in rest of the cases.

Therefore, the dynamometer and OBS testing results were not very consistent.

Note: The percentage reductions/increase could not be concluded as significant because of lack of necessary sample sizes of the dynamometer testing for statistical analysis.



TEXAS VEHICLE INSPECTION REPORT

Emissions and Safety Inspection**** Training Mode - VOID ****

WITHOUT DEVICE.

Vehicle Identification		**Station Identification**	
Test Date/Time:	05/03/2007,13:45	Station Name:	TEXAS DEPARTMENT OF PUBLI
Test Type:	Initial	Station Number:	1G25792
Test:	ASM	Station Address:	1613 W IRVING BLVD
Version Number:		Station City:	IRVING
License Number:	406THX	Station Zip Code:	750610000
Vehicle ID Number:	2B3KA43R47H735837	Inspector First Name:	JIM
Vehicle Make:	CHRY	Inspector Last Name:	MOORE
Vehicle Model:	CONCORDE	Analyzer Number:	ES213839
Vehicle Year:	1995		
Vehicle Type:	Passenger Car	Safety Inspection Fee:	--.--
Engine Size:	2700	Safety Repair Costs	--.--
Cylinders/Ignition:	6 D	Emissions Test Fee:	--.--
Transmission/GVW:	Automatic/4905	Emissions Repair Costs:	--.--
Odometer/Fuel Type:	5093/Gasoline		-----------
		Total Inspection Cost:	--.--

Emissions Test Results

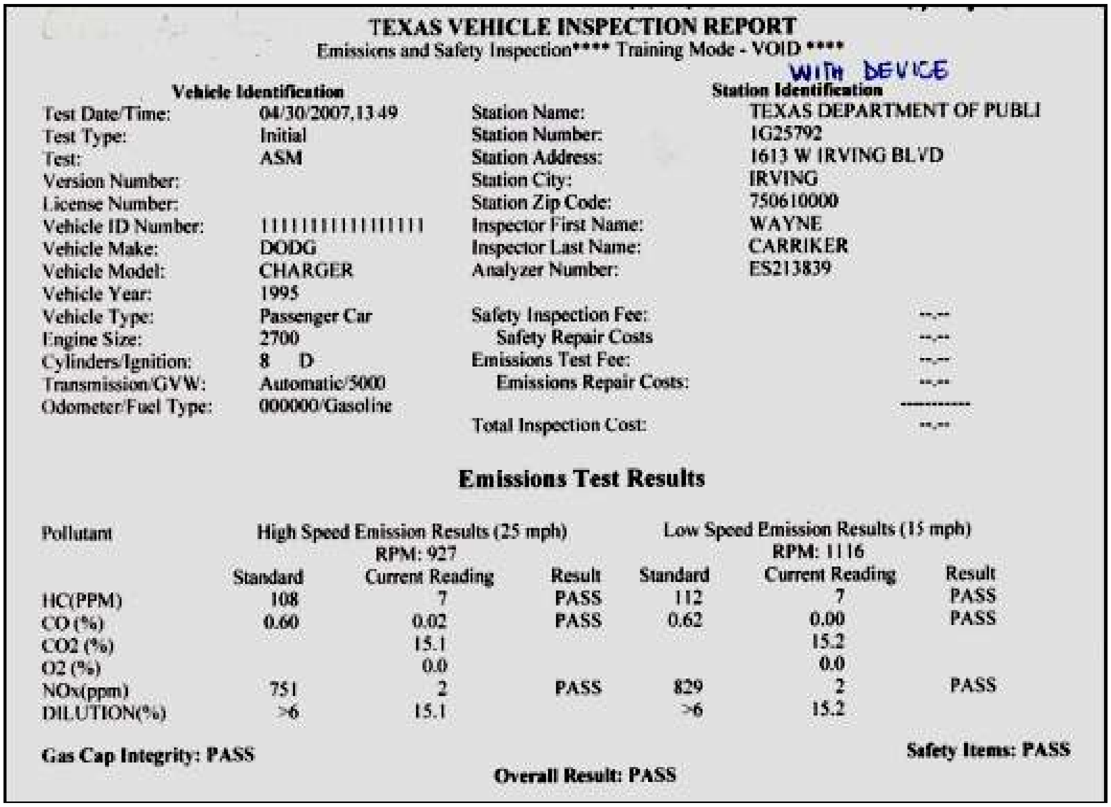
Pollutant	High Speed Emission Results (25 mph) RPM: 1206			Low Speed Emission Results (15 mph) RPM: 1444		
	Standard	Current Reading	Result	Standard	Current Reading	Result
HC(PPM)	120	2	PASS	124	2	PASS
CO (%)	0.67	0.00	PASS	0.69	0.00	PASS
CO2 (%)		15.1			15.1	
O2 (%)		0.0			0.0	
NOx(ppm)	848	28	PASS	937	2	PASS
DILUTION(%)	>6	15.1		>6	15.1	

Gas Cap Integrity: PASS

Safety Items: PASS

Overall Result: PASS

Figure 4.17 Dynamometer testing results without the device



TEXAS VEHICLE INSPECTION REPORT

Emissions and Safety Inspection**** Training Mode - VOID ****

WITH DEVICE

Vehicle Identification		**Station Identification**	
Test Date/Time:	04/30/2007,13:49	Station Name:	TEXAS DEPARTMENT OF PUBLI
Test Type:	Initial	Station Number:	1G25792
Test:	ASM	Station Address:	1613 W IRVING BLVD
Version Number:		Station City:	IRVING
License Number:		Station Zip Code:	750610000
Vehicle ID Number:	11111111111111111	Inspector First Name:	WAYNE
Vehicle Make:	DODG	Inspector Last Name:	CARRIKER
Vehicle Model:	CHARGER	Analyzer Number:	ES213839
Vehicle Year:	1995		
Vehicle Type:	Passenger Car	Safety Inspection Fee:	--.--
Engine Size:	2700	Safety Repair Costs	--.--
Cylinders/Ignition:	8 D	Emissions Test Fee:	--.--
Transmission/GVW:	Automatic/5000	Emissions Repair Costs:	--.--
Odometer/Fuel Type:	000000/Gasoline		-----------
		Total Inspection Cost:	--.--

Emissions Test Results

Pollutant	High Speed Emission Results (25 mph) RPM: 927			Low Speed Emission Results (15 mph) RPM: 1116		
	Standard	Current Reading	Result	Standard	Current Reading	Result
HC(PPM)	108	7	PASS	112	7	PASS
CO (%)	0.60	0.02	PASS	0.62	0.00	PASS
CO2 (%)		15.1			15.2	
O2 (%)		0.0			0.0	
NOx(ppm)	751	2	PASS	829	2	PASS
DILUTION(%)	>6	15.1		>6	15.2	

Gas Cap Integrity: PASS

Safety Items: PASS

Overall Result: PASS

Figure 4.18 Dynamometer testing results with the device

4.3.6 Post Removal Data Analysis

Post removal data analysis was conducted to determine whether there was any residual device effect on the emissions. The results from post removal were compared with the baseline data. The post removal data was collected after the Clean Air Associates device was removed, which included 10 hours of testing, 5 hours on arterial and 5 hours on highway. The average emissions in g/mile of each pollutant were compared with the baseline, and the percent reduction was estimated as shown in Tables 4.17 – 4.19. Statistical analysis was done on the post removal data to identify the significant differences for the four pollutant emissions. Pollutant percent changes with significant difference are indicated in bold.

Post removal data was classified as arterial, highway, peak and off-peak. The average emission vs. average velocity scatter graphs are plotted in Figures 4.19 to 4.34. Figure 4.19 shows a scatter plot of CO emissions for arterial peak post removal and baseline conditions.

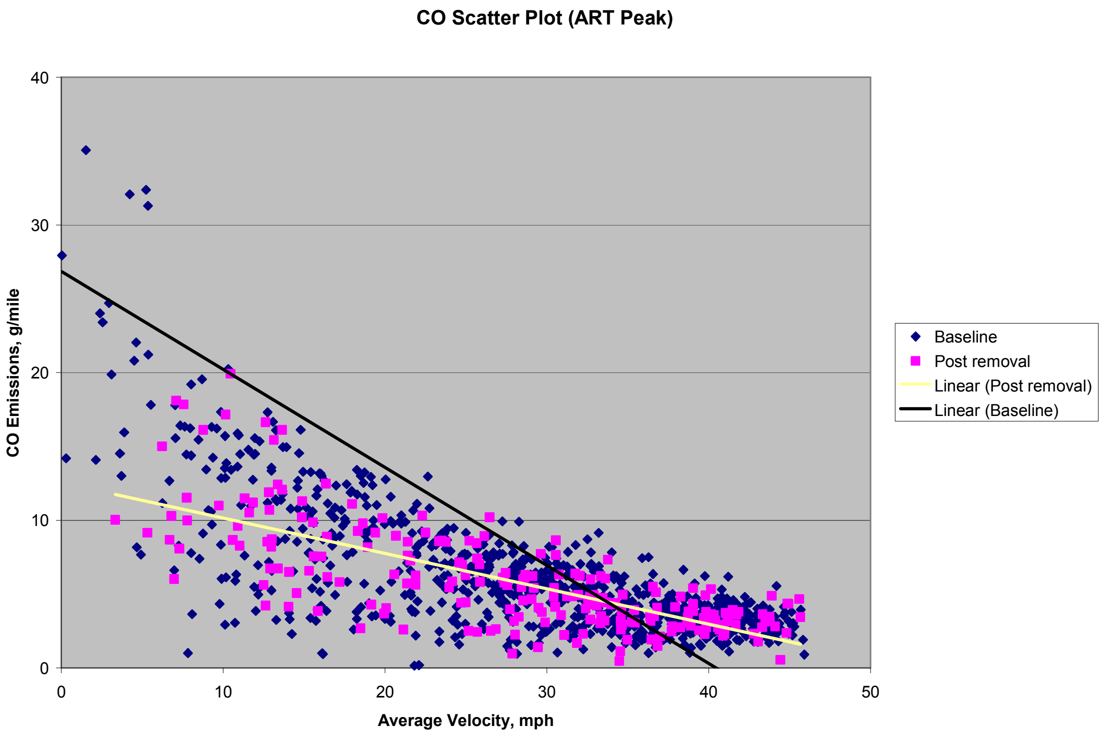


Figure 4.19 CO emissions for arterial test track, peak time traffic

Figure 4.20 shows a scatter plot of CO_2 emissions for arterial peak post removal and baseline conditions.

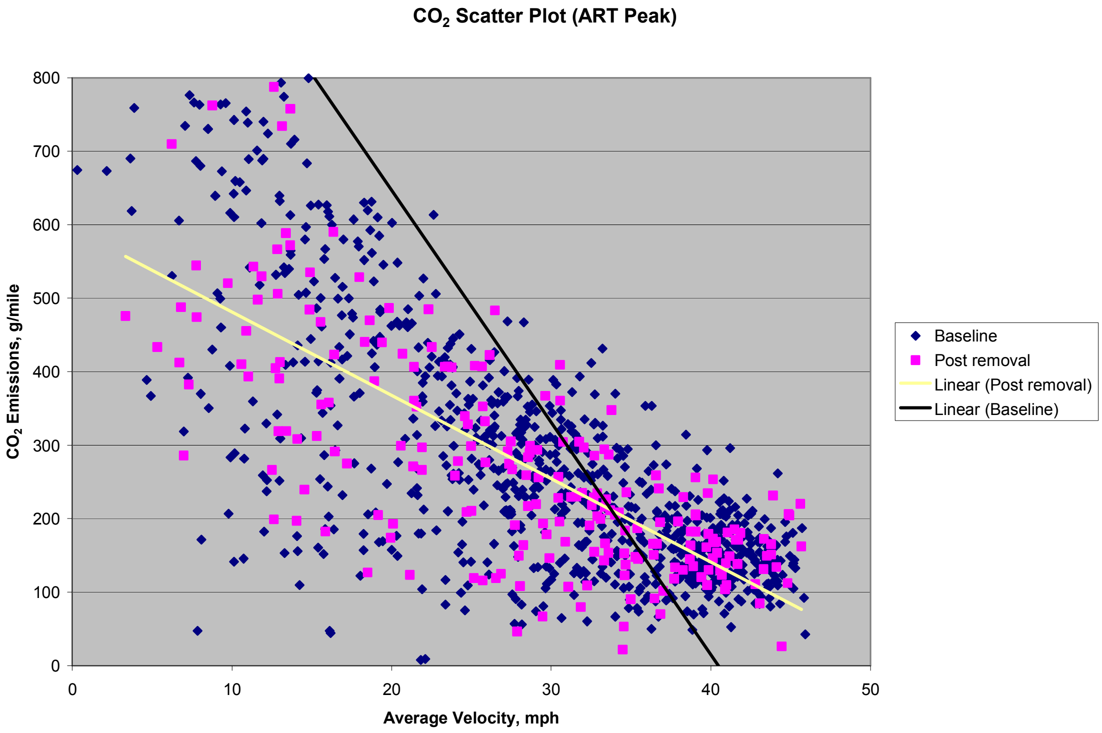


Figure 4.20 CO_2 emissions trend for arterial test track, peak time traffic

Figure 4.21 shows a scatter plot of HC emissions for arterial peak baseline and post removal conditions.

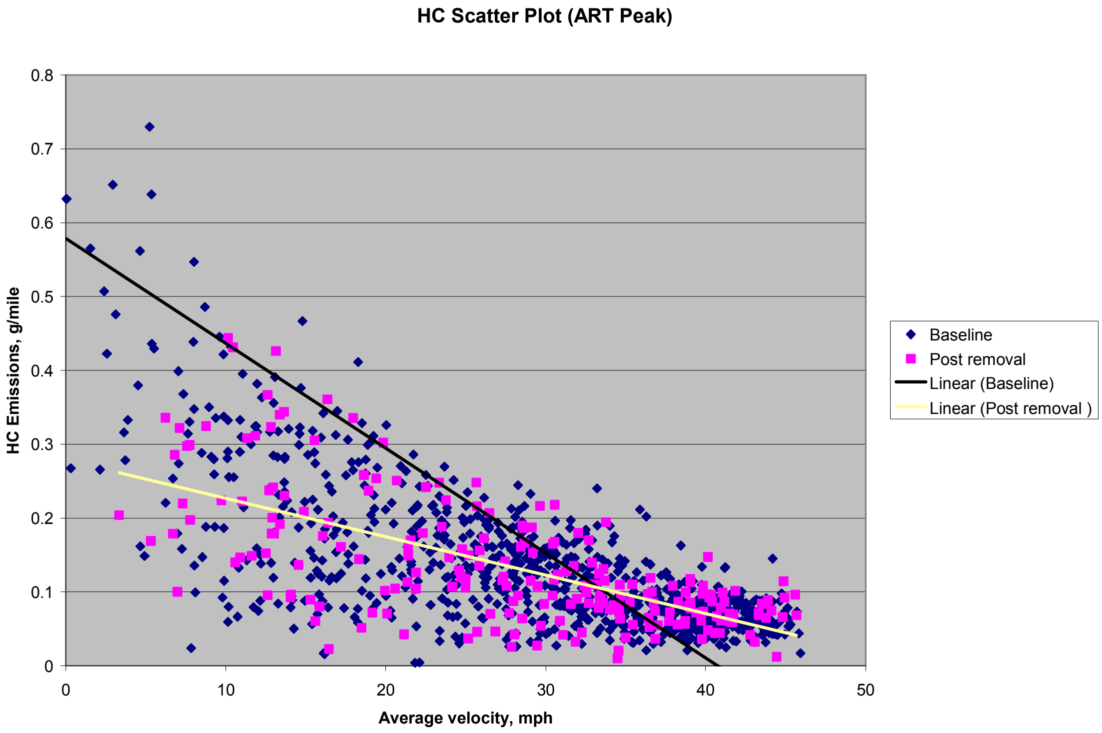


Figure 4.21 HC emissions for arterial test track, peak time traffic

Figure 4.22 shows a scatter plot of NO_x emissions for arterial peak baseline and postremoval condition.

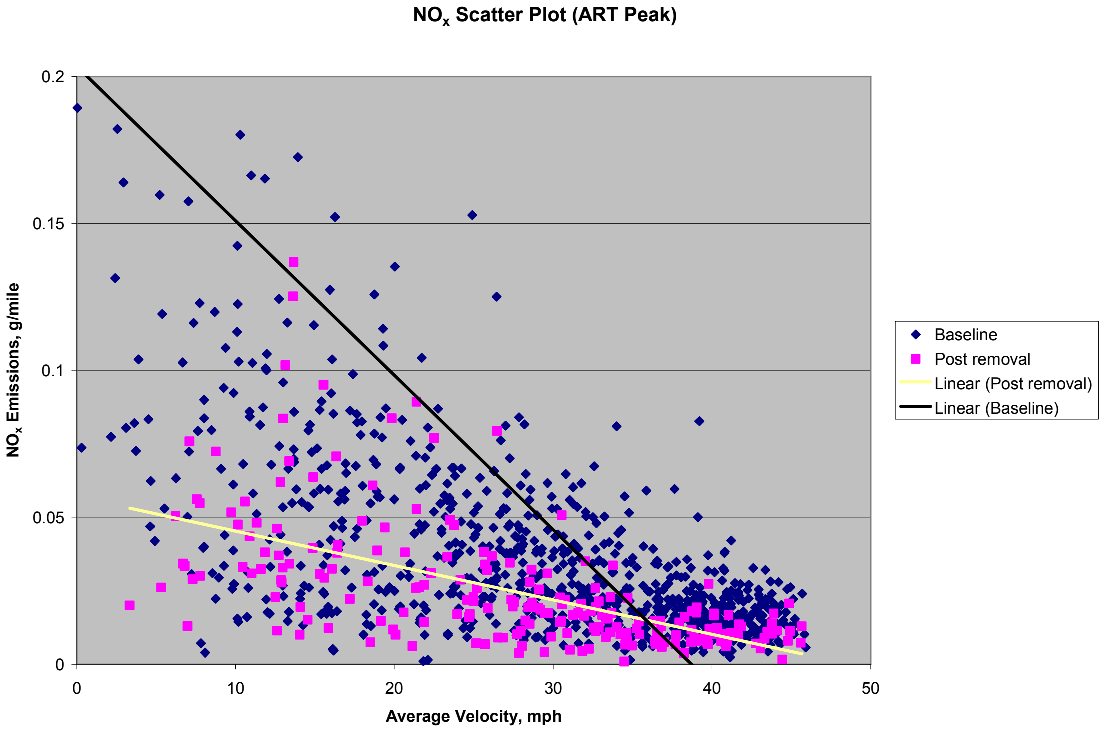


Figure 4.22 NO_x emissions for arterial test track, peak time traffic

Figure 4.23 shows a scatter plot of CO emissions for arterial off-peak baseline and post removal conditions.

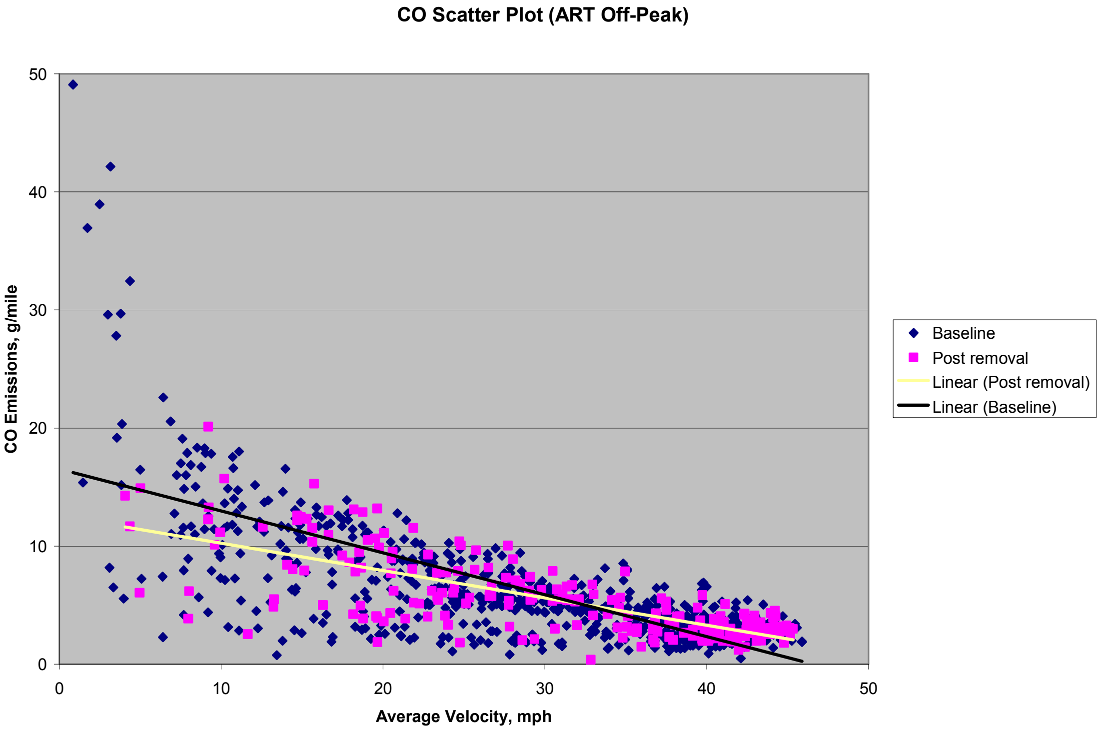


Figure 4.23 CO emissions for arterial test track, off-peak time traffic

Figure 4.24 shows a scatter plot of CO_2 emissions for arterial off-peak baseline and postremoval.

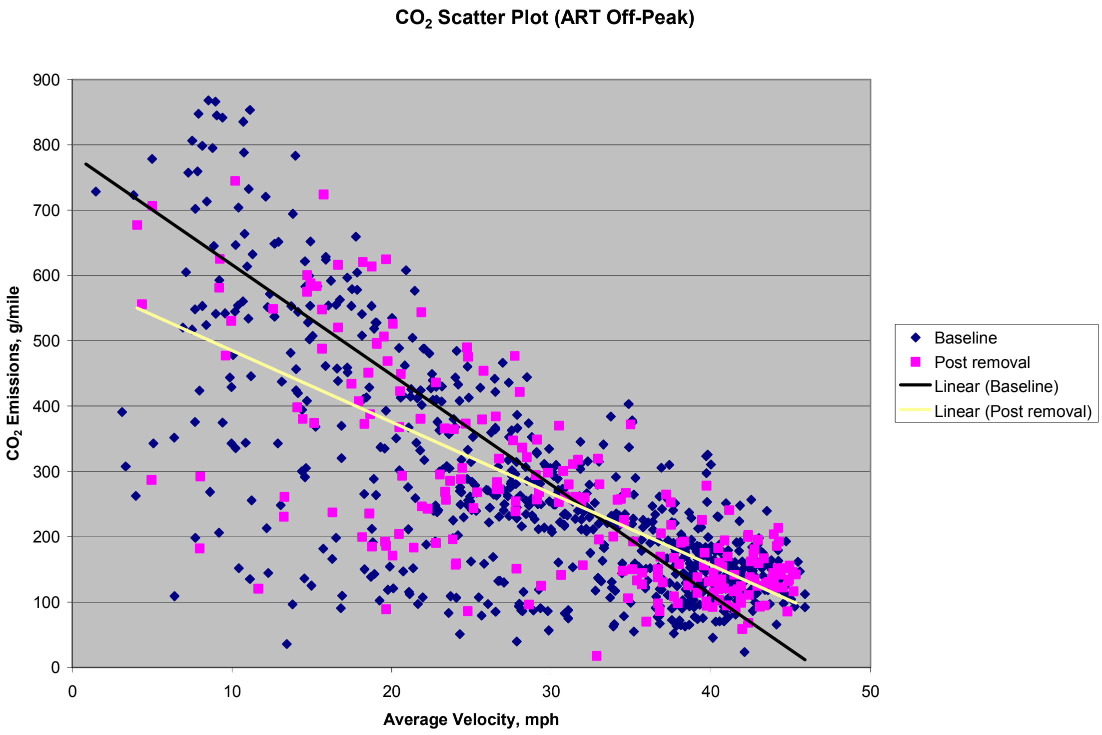


Figure 4.24 CO_2 emissions for arterial test track, off-peak time traffic

Figure 4.25 shows a scatter plot of HC emissions for arterial off-peak baseline and postremoval conditions.

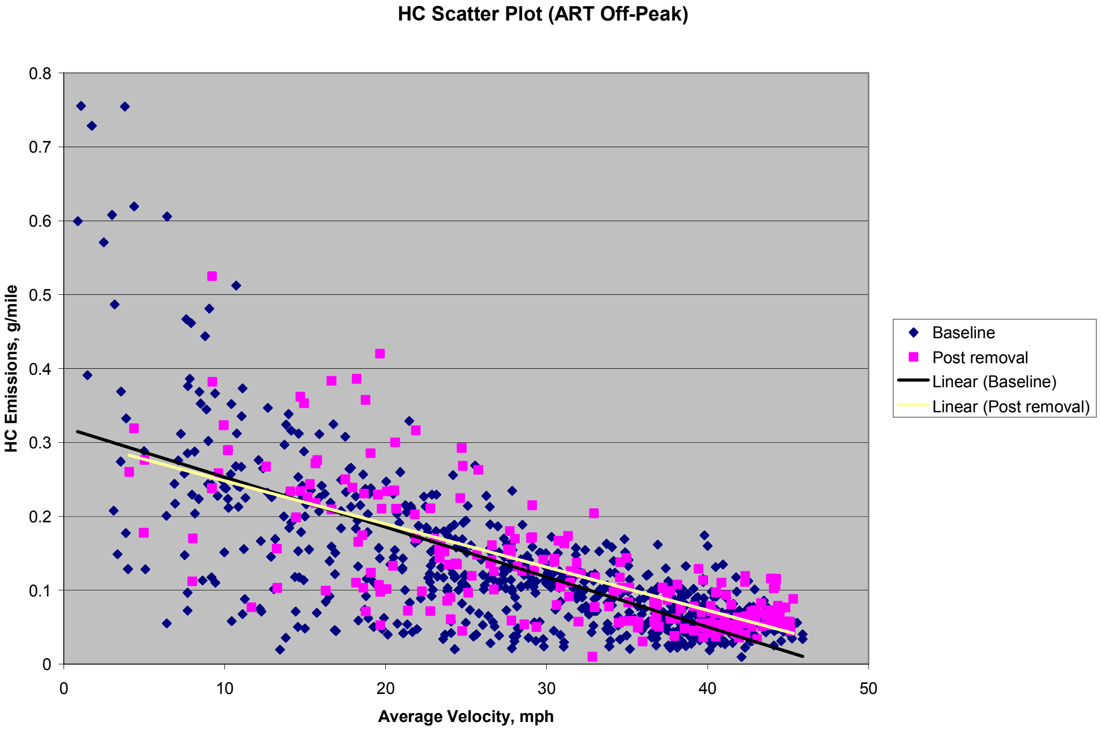


Figure 4.25 HC emissions for arterial test track, off-peak time traffic

Figure 4.26 shows a scatter plot of NO_x emissions for arterial off-peak baseline and post removal.

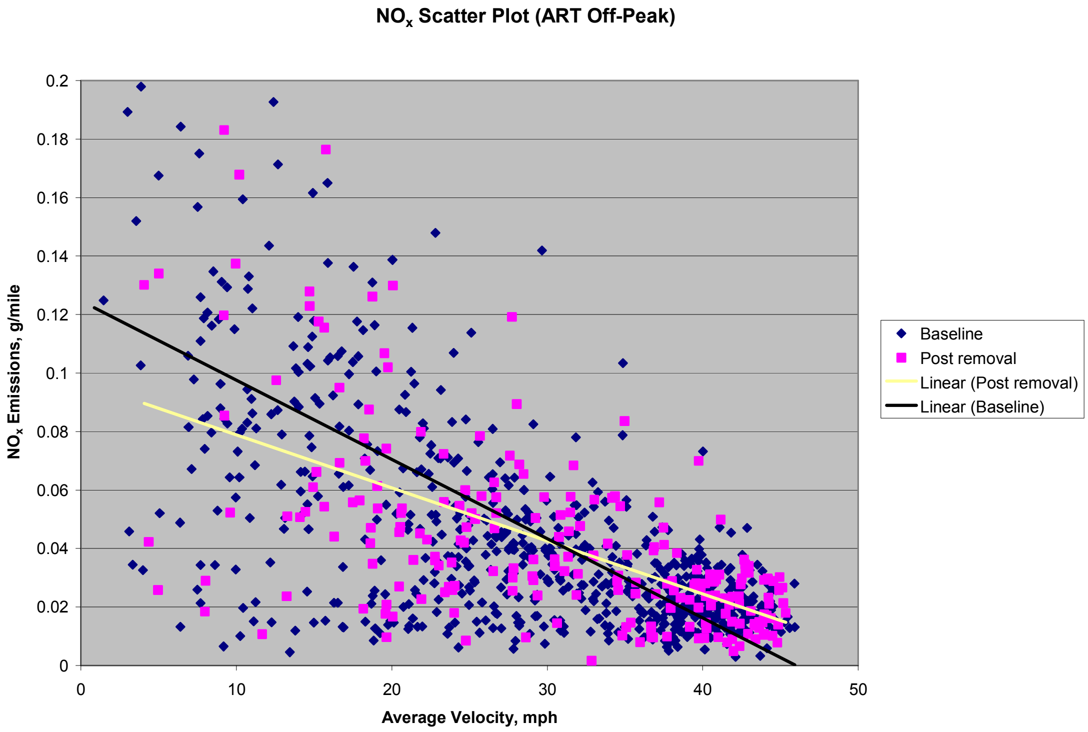


Figure 4.26 NO_x emissions for arterial test track, off-peak time traffic

Figure 4.27 shows a scatter plot of CO emissions for highway peak baseline and post removal conditions.

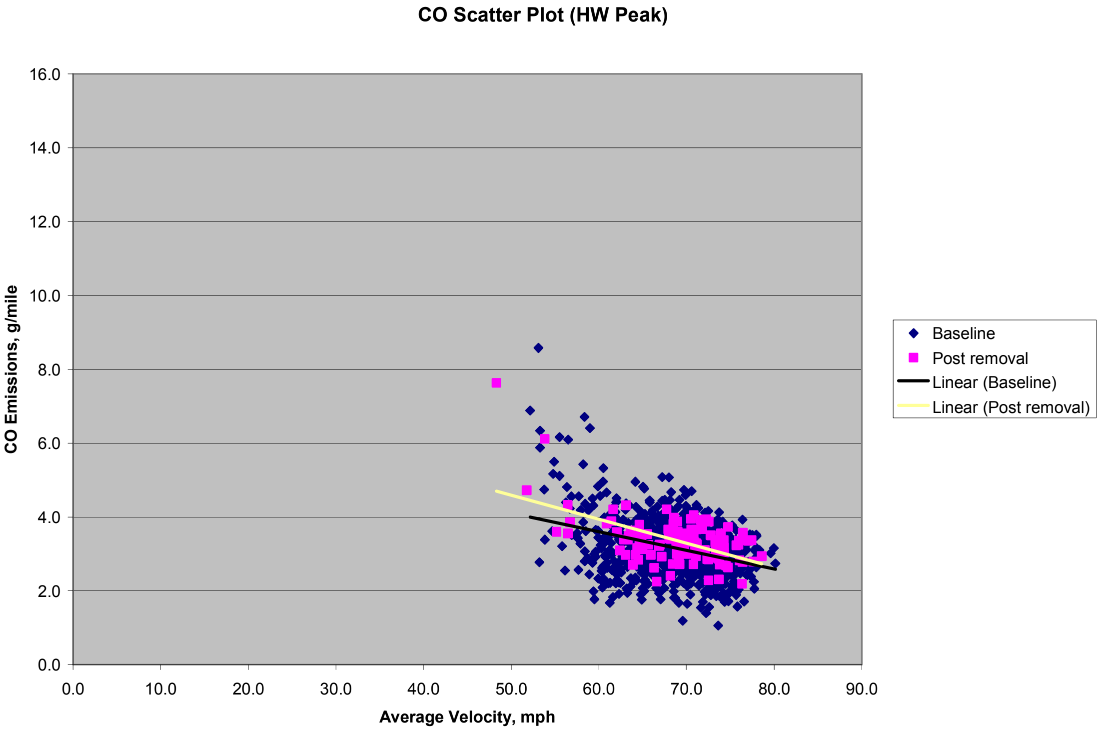


Figure 4.27 CO emissions for highway test track, peak time traffic

Figure 4.28 shows a scatter plot of CO_2 emissions for highway peak baseline and postremoval conditions.

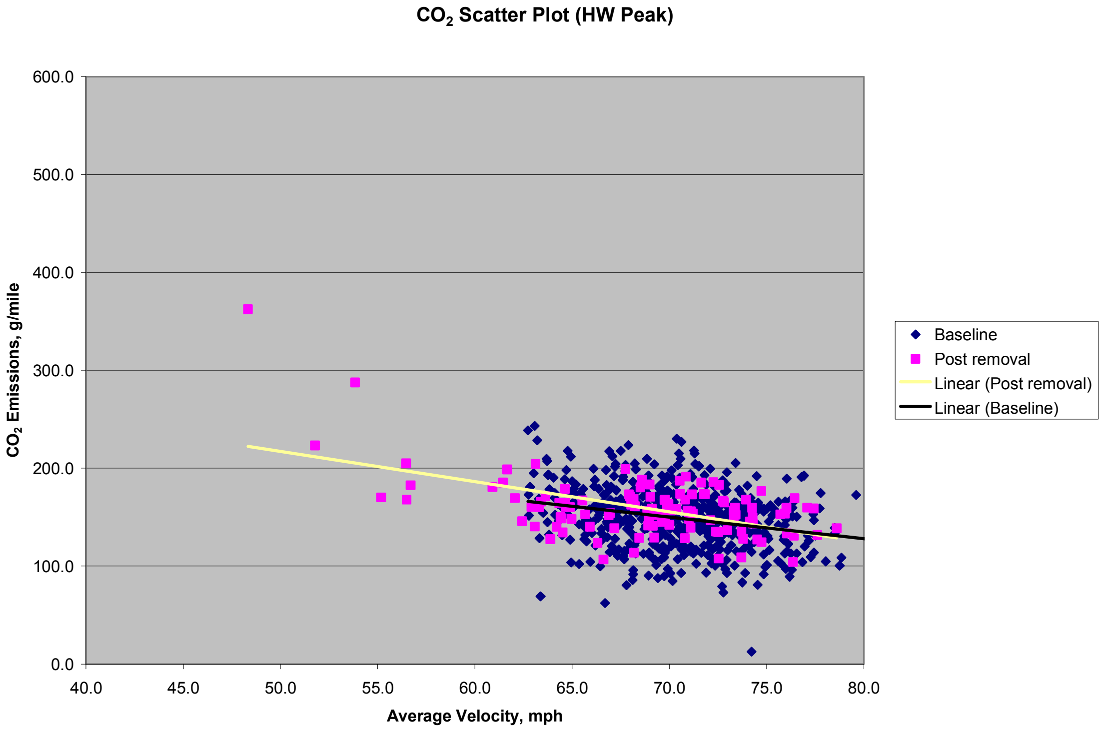


Figure 4.28 CO_2 emissions for highway test track, peak time traffic

Figure 4.29 shows a scatter plot of HC emissions for highway peak baseline and post removal conditions.

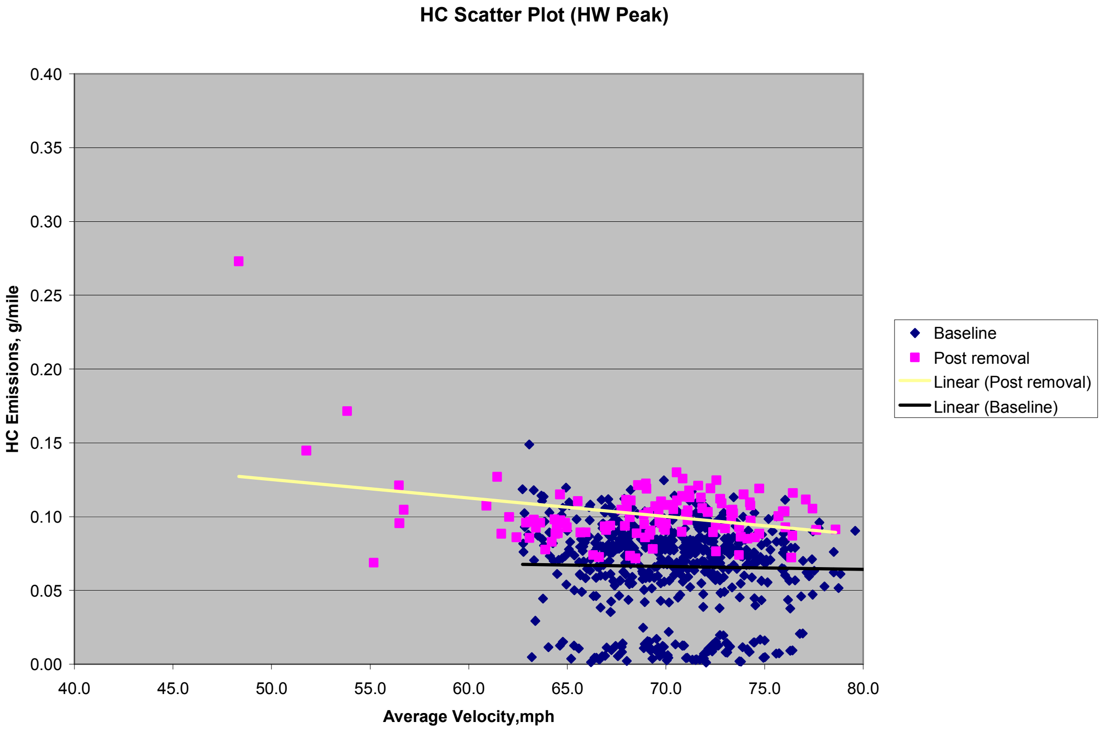


Figure 4.29 HC emissions for highway test track, peak time traffic

Figure 4.30 shows a scatter plot of NO_x emissions for highway peak baseline and post removal conditions.

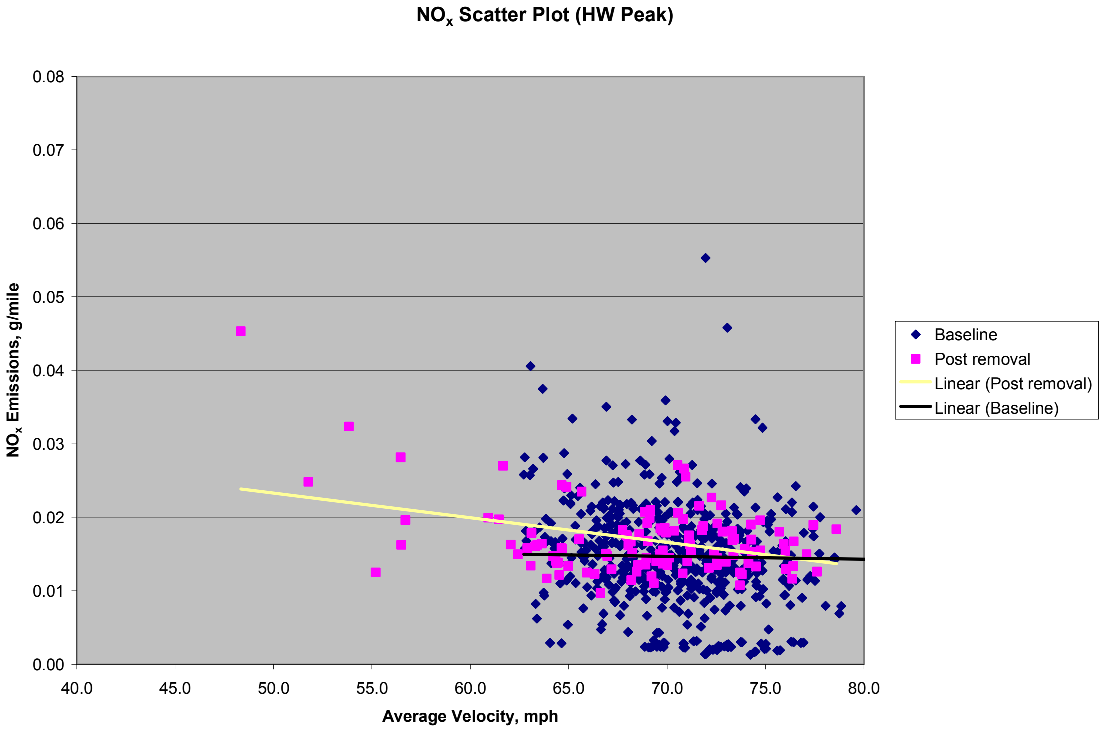


Figure 4.30 NO_x emissions for highway test track, peak time traffic

Figure 4.31 shows a scatter plot of CO emissions for highway off-peak baseline and postremoval conditions.

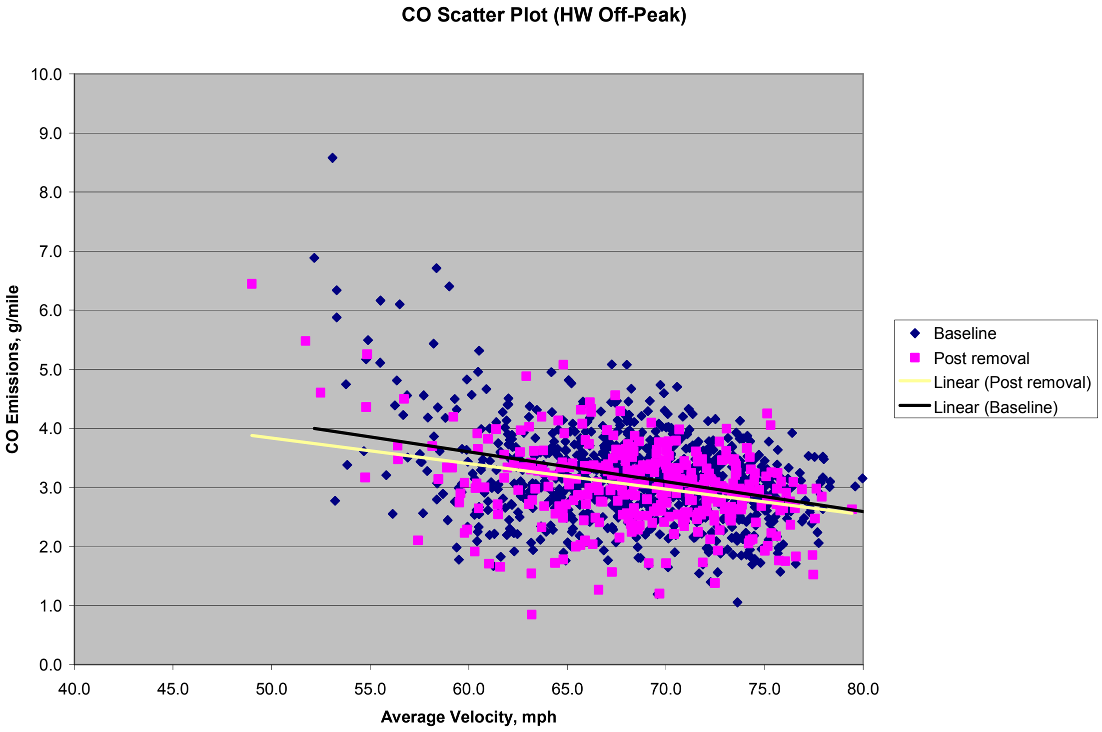


Figure 4.31 CO emission of highway test track, off-peak time traffic

Figure 4.32 shows a scatter plot of CO_2 emissions for highway off-peak baseline and postremoval.

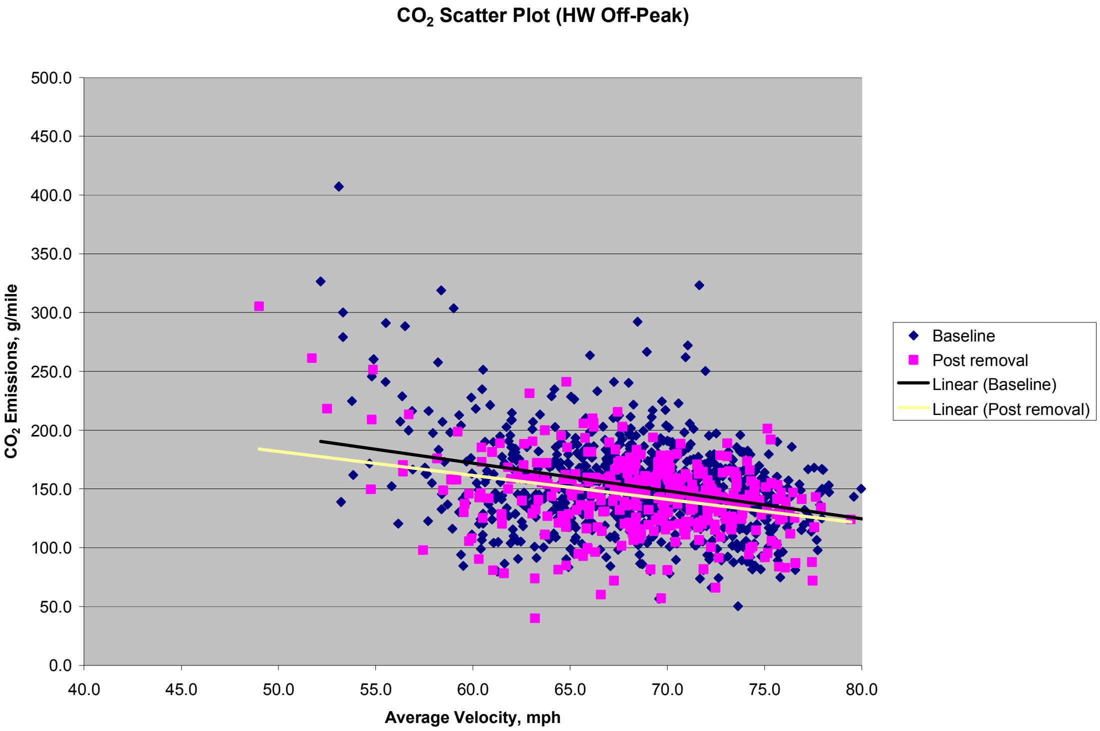


Figure 4.32 CO_2 emissions for highway test track, off-peak time traffic

Figure 4.33 shows a scatter plot of HC emissions for highway off-peak baseline and post removal.

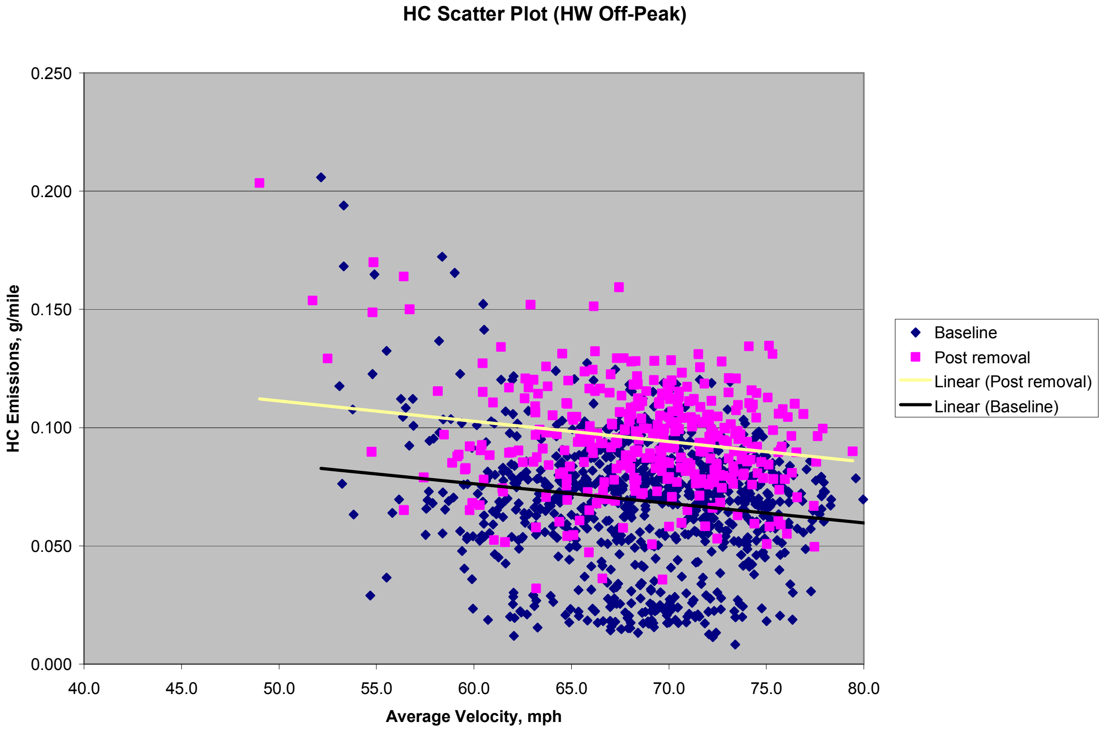


Figure 4.33 HC emissions for highway test track, off-peak time traffic

Figure 4.34 shows a scatter plot of NO_x emissions for highway off-peak baseline and post removal.

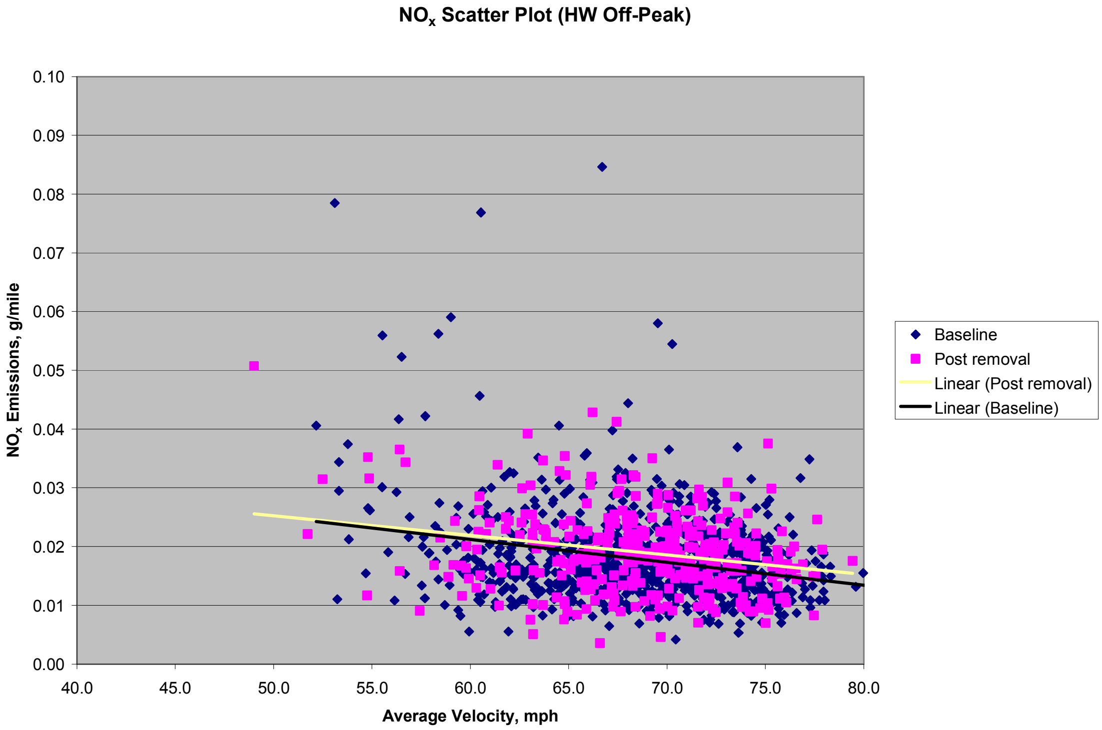


Figure 4.34 NO_x emissions for highway test track, off-peak time traffic

Percentage reductions were calculated by comparing the overall average emissions of each pollutant in g/mile, post removal vs. baseline data. Table 4.18 compares the average emission differences (measured in ppm or %) with OBS accuracies. Table 4.19 and Table 4.20 present average percent emission reductions of each pollutant, calculated from g/mile values for arterial and highway, respectively. The percent emission reductions are presented for the four pollutants categorized by highway vs. arterial and peak vs. off-peak. A negative value indicates a ‘decrease’ in emissions. Table 4.21 presents the overall percent change in emissions due to post removal condition.

Table 4.18 Overall Average Emissions, Baseline vs. Post Removal

Pollutant	**Average Concentration**			OBS Accuracy	Difference > OBS Accuracy?
	Without CAA device	Post Removal	Difference		
CO (%)	0.581	0.442	-0.139	0.02	Yes
CO_2 (%)	13.88	13.33	-0.55	0.2	Yes
HC (ppm)	61.4	76	14.6	20	No
NO_x (ppm)	22.9	22	-0.9	15	No

Table 4.19 Percent Change in Emissions due to Post removal Clean Air Associates Device for the Arterial Test Track

Percentage Change Arterial Test Track				
Pollutant	Peak	Significant difference	Off-peak	Significant difference
CO	-20.2	NO	**-9.90**	YES
CO_2	-20.5	NO	**-10.04**	YES
HC	-17.05	NO	5.54	NO
NO_x	**-50.24**	YES	-7.62	NO

Table 4.20 Percent Change in Emissions due to Post removal Clean Air Associates Device for the Highway Test Track

Percentage Change Highway Test Track				
Pollutant	Peak	Significant difference	Off-peak	Significant difference
CO	**7.1**	YES	**-4.42**	YES
CO_2	**6.9**	YES	**-5.31**	YES
HC	**52**	YES	**37.6**	YES
NO_x	14.9	NO	6.38	YES

Table 4.21 Overall Percent Change in Emissions due to Post removal Clean Air Associates Device

Pollutant	**Overall Reduction (%)**	
	Average	Significant difference
CO	**-13.88**	YES
CO_2	**-14.22**	YES
HC	5.49	NO
NO_x	**-21.62**	YES

Observations: For CO and CO_2, the overall changes in emissions/emission concentrations, baseline or post-removal, exceeded the OBS accuracy limits and were statistically significant. CO and CO_2 emissions were lowered in the post-removal phase. This could be due to continuing impacts of the retrofit device.

4.3.7 Comparison between results from the Phase I & Phase II testing for the device

The overall percent reduction emissions of the four pollutants with installation of the device was compared with Phase I testing overall percent reduction results. Table 4.22 shows comparison of Phase I and Phase II device testing results.

Table 4.22 Comparison of phase I and phase II overall percent reduction of pollutant emissions with device installation.

Pollutant (%)	**Phase I**		**Phase II**	
	Overall percent reductions	Significant difference with device and without it	Overall percent reduction	Significant difference with device and without it
CO	2.29	NO	-3.69	NO
CO_2	**-0.1**	YES	-4.20	NO
HC	4.63	NO	5.85	NO
NO_x	**-9.47**	YES	0.910	NO

<u>Discussion:</u> In the Phase I testing, the device significantly reduced CO_2 emissions by 0.1 % and NO_x emissions by 9.5%. Subsequently, HC and CO emissions increased but there was no significant difference between emissions with the CAA device and without it. In both phases of testing, HC increased by 5%. In the Phase II testing, the device slightly increased NOx emissions by 0.91% and decreased CO and CO_2 emissions by 4%. In contrast, Phase II testing showed no significant difference from the installation of device to baseline for all the pollutants and this shows that the device had no significant impact on the Dodge Charger.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of this study was to determine the impact of Clean Air Associates Pre-combustion device on the emissions of four tail-pipe pollutants HC, CO, CO_2 and NO_x for a light duty gasoline car. The following conclusions are drawn from this research study:

1) The comparison of OBS 1300 accuracy values with the change in emission concentrations of each pollutant showed that the difference in emissions with and without device exceeded the OBS 1300 accuracies for CO and CO_2 arterial peak conditions and overall CO and CO_2 emissions.
2) The fuel economy estimation concluded that on the arterial, there was a 2.3% increase in fuel economy and on the highway, there was a 1.78% decrease in fuel economy of the vehicle with the installation of the device.
3) Dynamometer testing results were not very consistent with OBS 1300 testing results at 15 mph and 25 mph speed levels. No statistical conclusions can be drawn because of the lack of necessary sample sizes for dynamometer testing.
5) The post removal analysis showed that the overall changes in CO and CO_2 emissions/emission concentrations, baseline or post-removal, exceeded the OBS accuracy limits and were statistically significant. CO and CO_2 emissions were

lowered in the post-removal case. This could be concluded as the continuing impacts of the retrofit device.

6) The comparison of Phase I and Phase II overall percent reduction results showed that the device had no significant impact on the four pollutant tail-pipe emissions of Dodge Charger.

5.2 Recommendations

The device had no significant impact on the emissions of CO_2, CO, NO_x and HC from the tailpipe of passenger car. The passenger car itself was a model 2007, which would have lower tail-pipe emissions than an older car (ex: 1996). This could be one of the reasons that the device did not show a tremendous impact on emissions. Therefore, it is recommended to test an older model gasoline car or a diesel vehicle with more accumulated mileage.

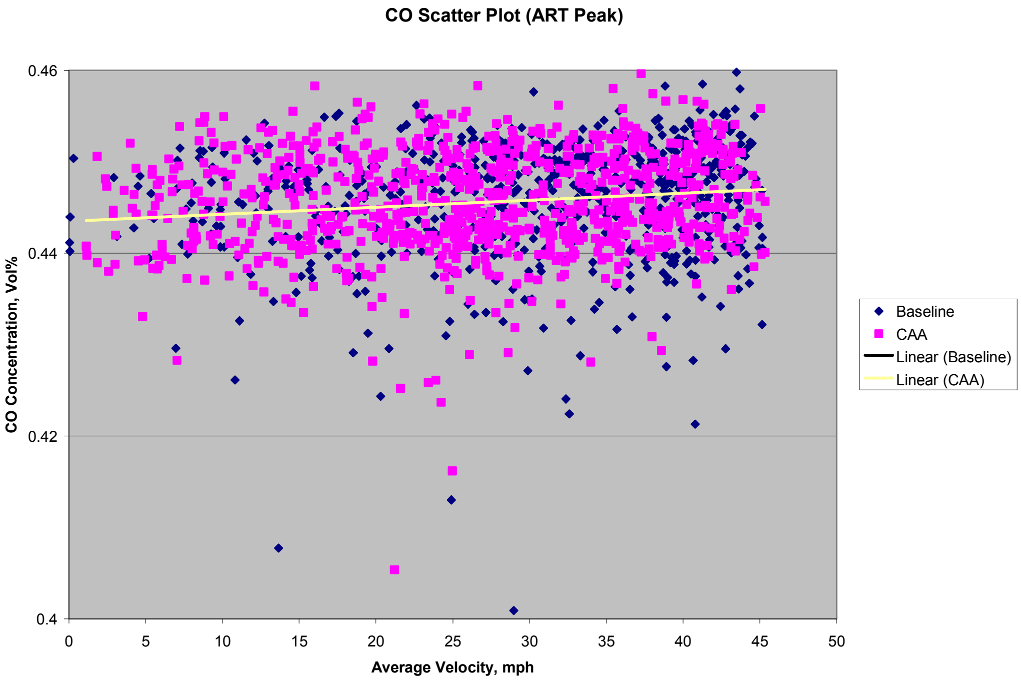
Proper training and organization is considered necessary for on-board emissions measurement of a vehicle owing to the sensitiveness of the on-board emissions measuring devices. The Calibration process should be done perfectly to obtain good data. The protocols should be strictly followed for data collection and analysis. Some amount of uncertainty should be acknowledged while interpreting the results for any kind of on-board measurement study.

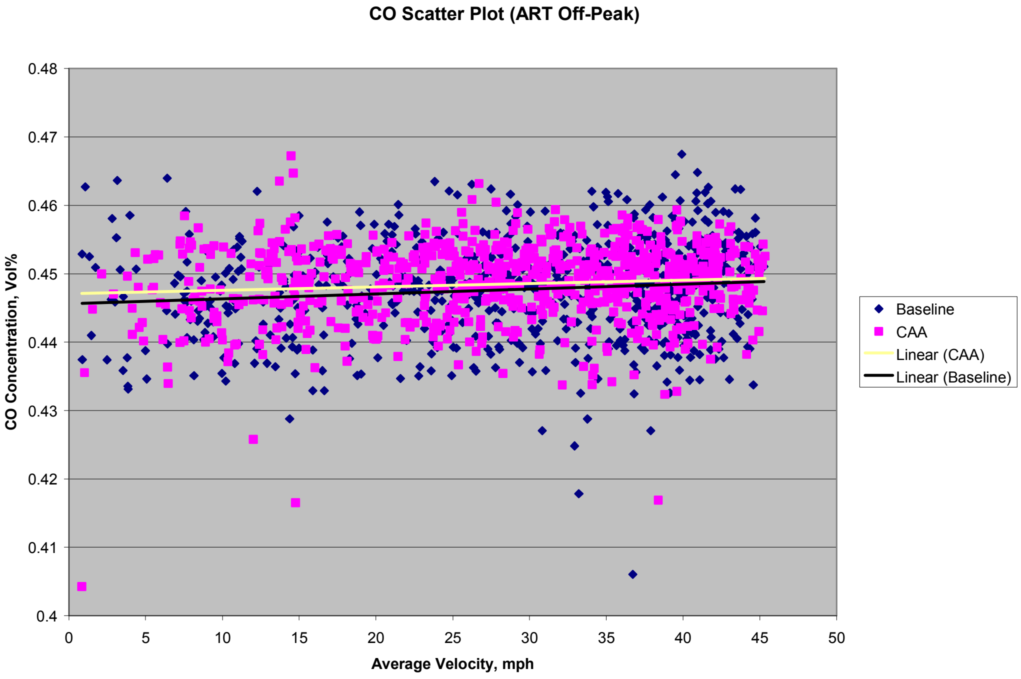
It was observed from the study that the emissions are lower when the car accelerates moderately or in a cruising mode. Therefore, it is recommended to drive at moderate accelerations, maintaining steady speed and avoiding jack-rabbit accelerations and decelerations.

APPENDIX A

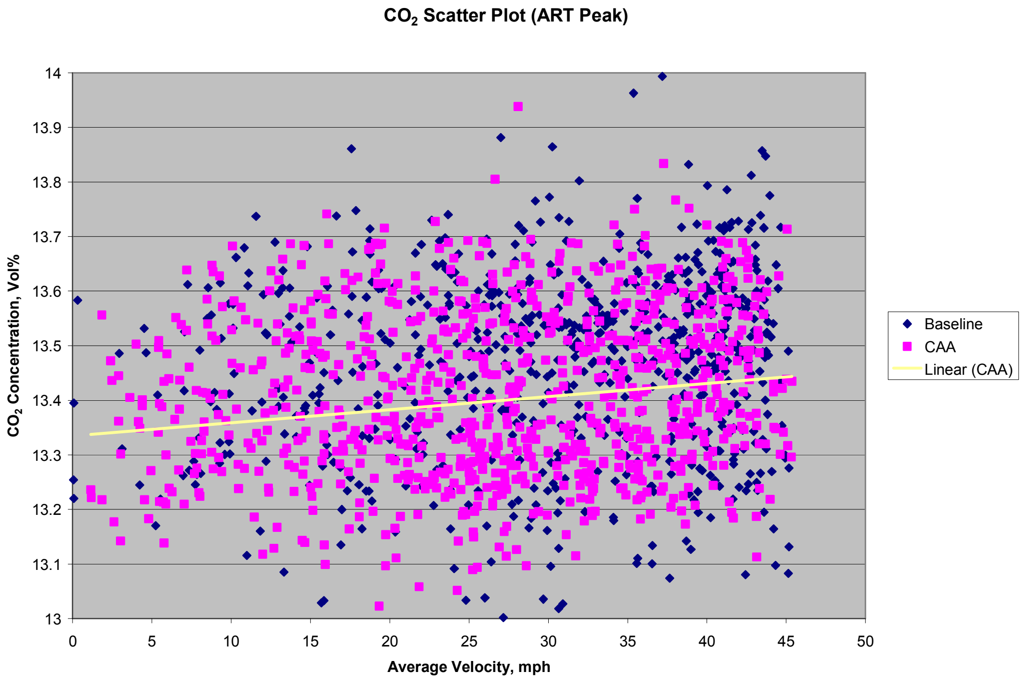
EMISSION TRENDS: GRAPHICAL COMPARISON OF BASELINE AND CAA DEVICE

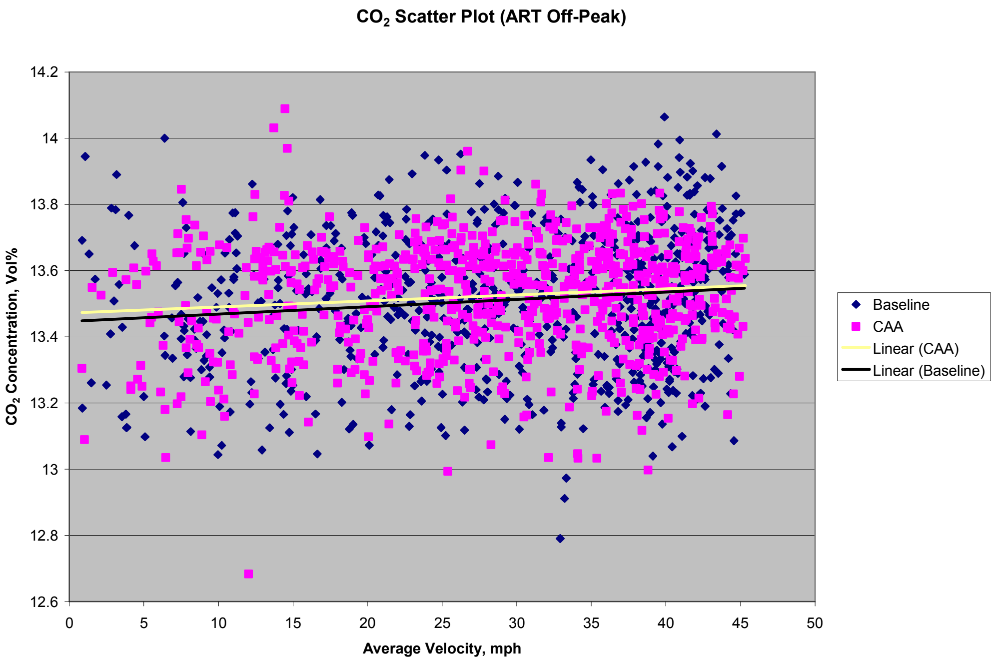
Case A: CO emission trends for arterial test track, peak & off-peak time interval



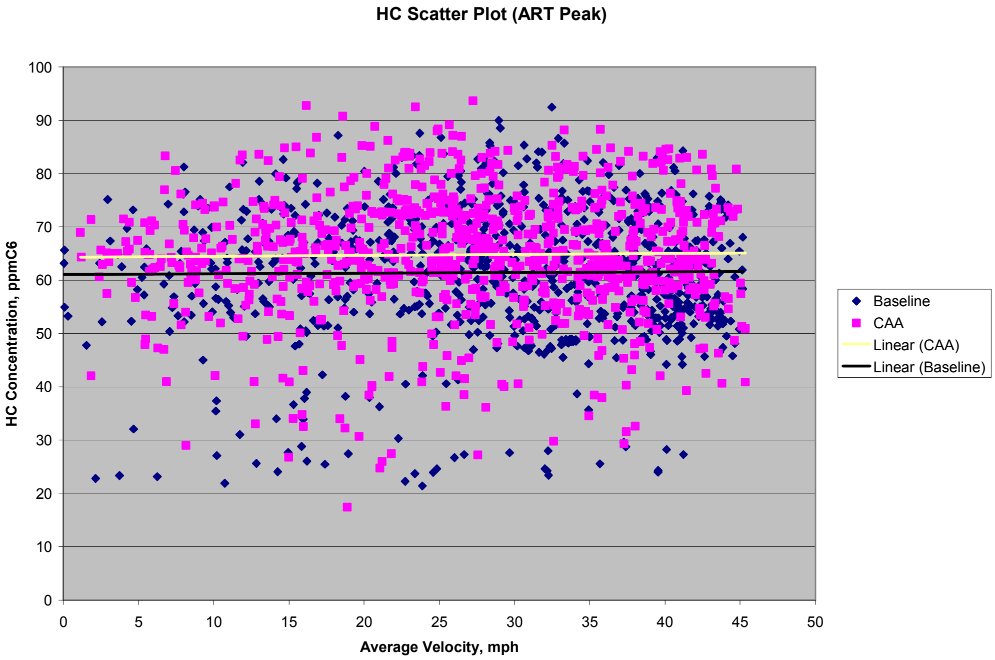


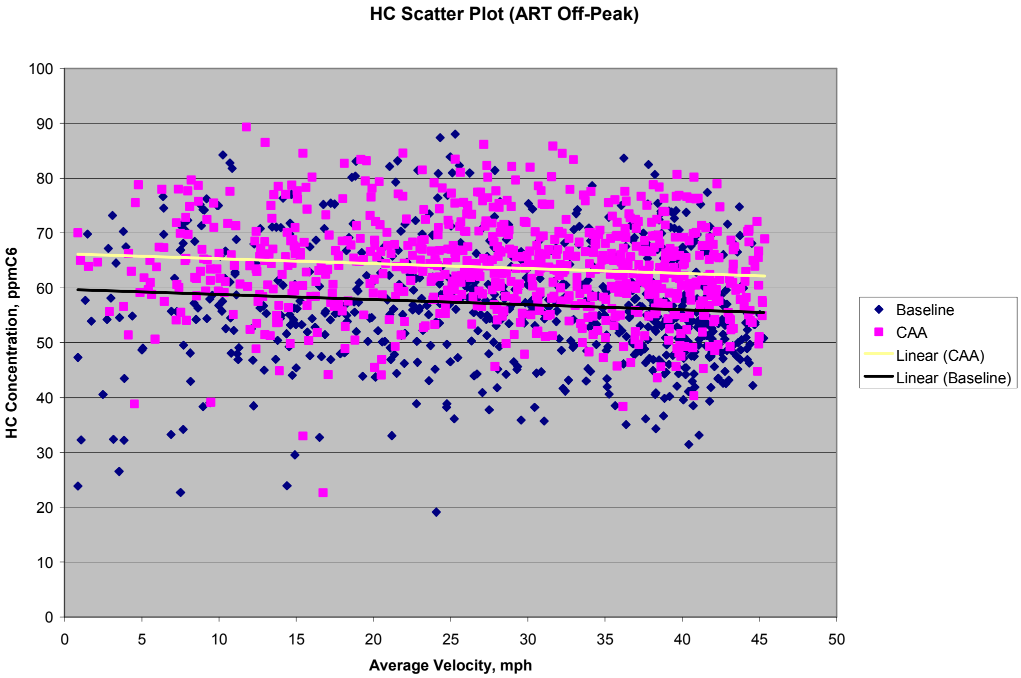
Case B: CO_2 emission trends for arterial test track, peak & off-peak time interval



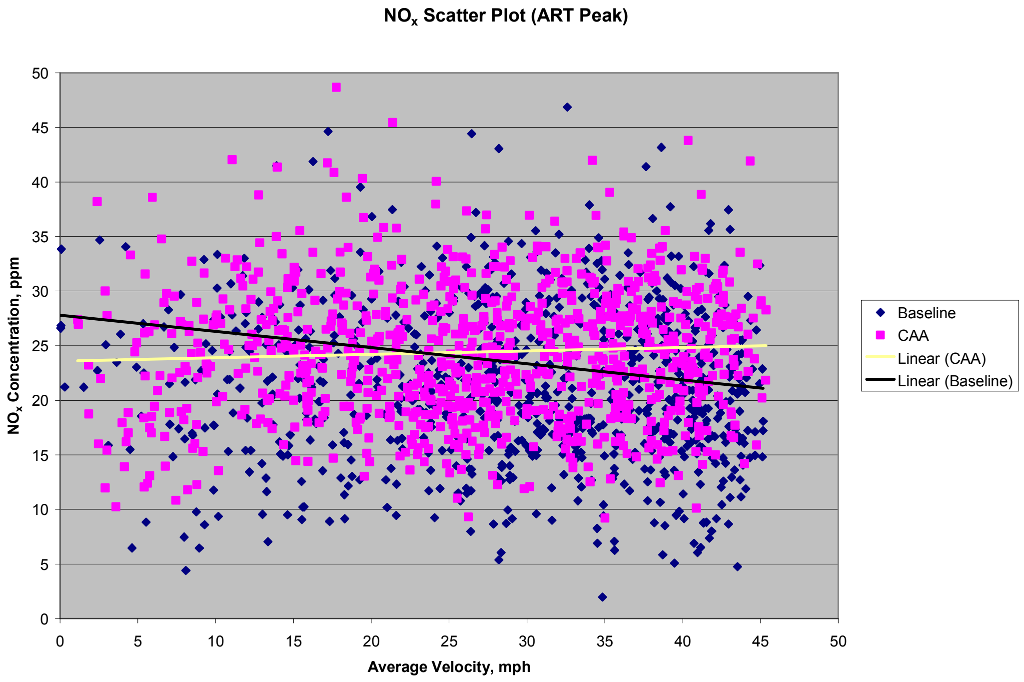


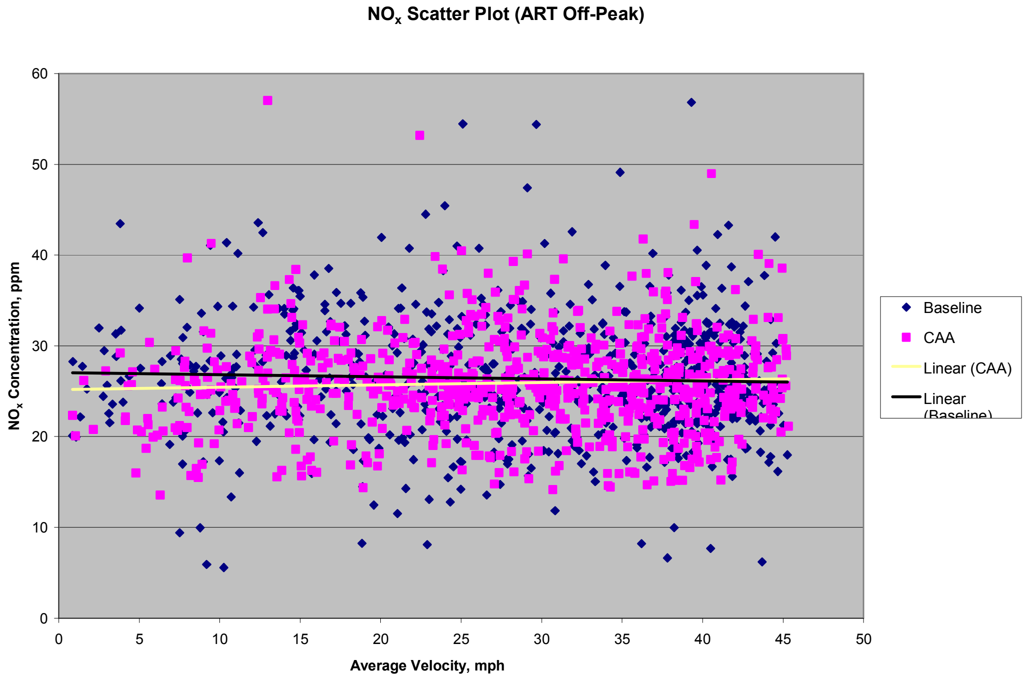
Case C: HC emission trends for arterial test track, peak & off-peak time interval



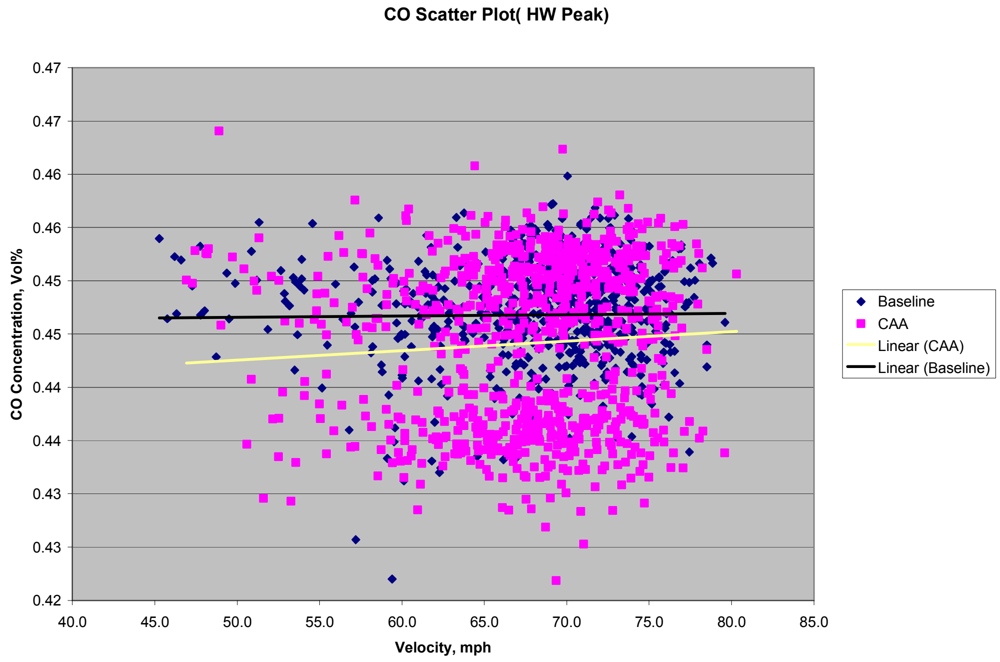


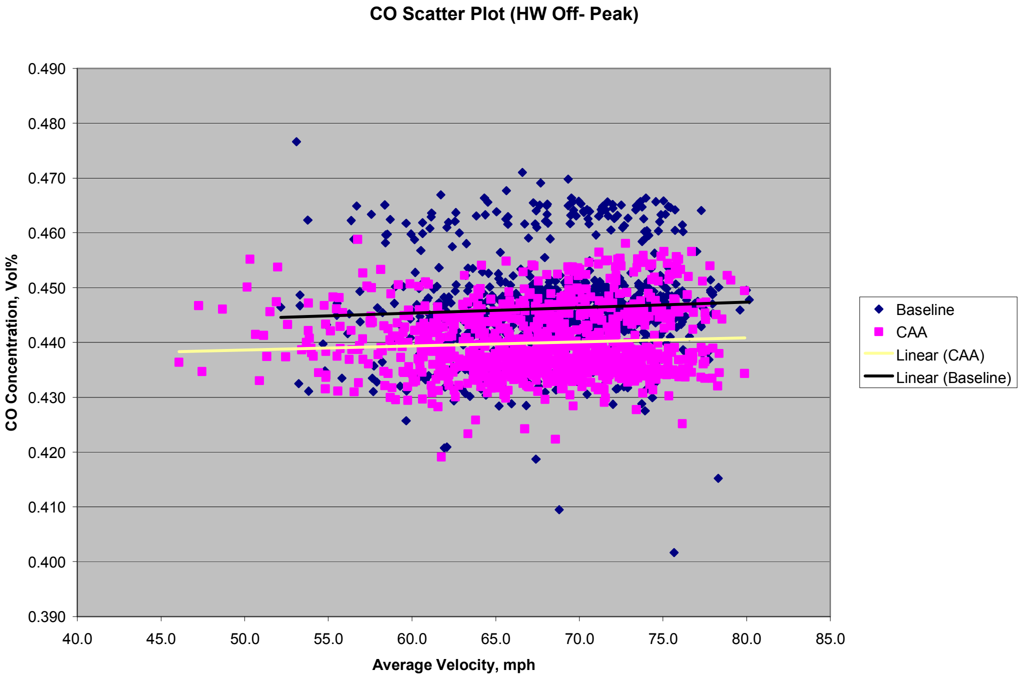
Case D: NO_x emission trends for arterial test track, peak & off-peak time interval



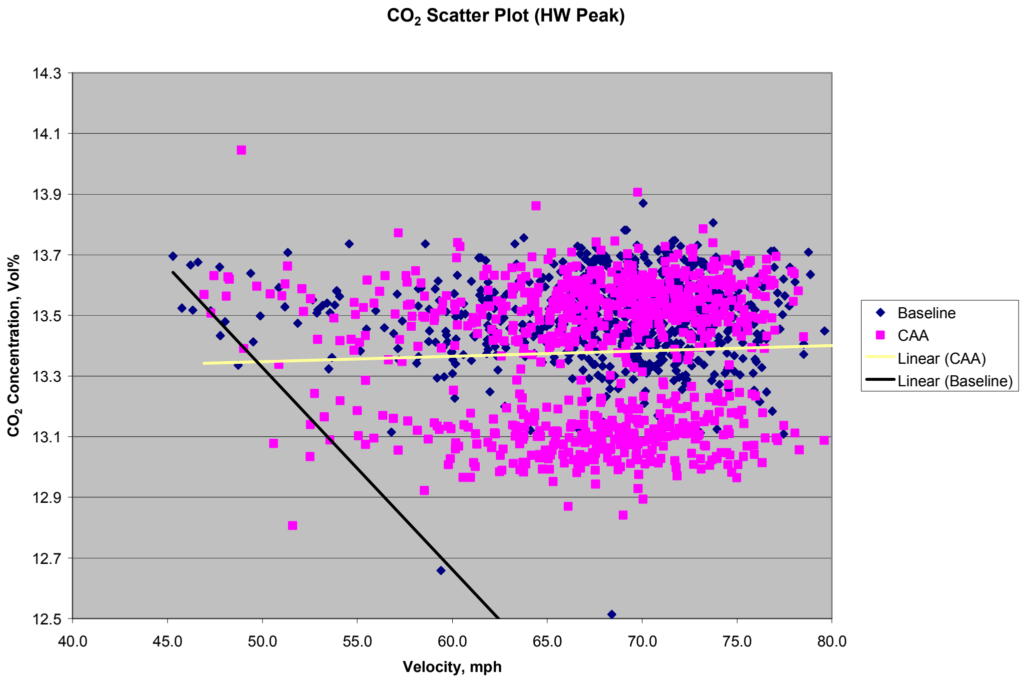


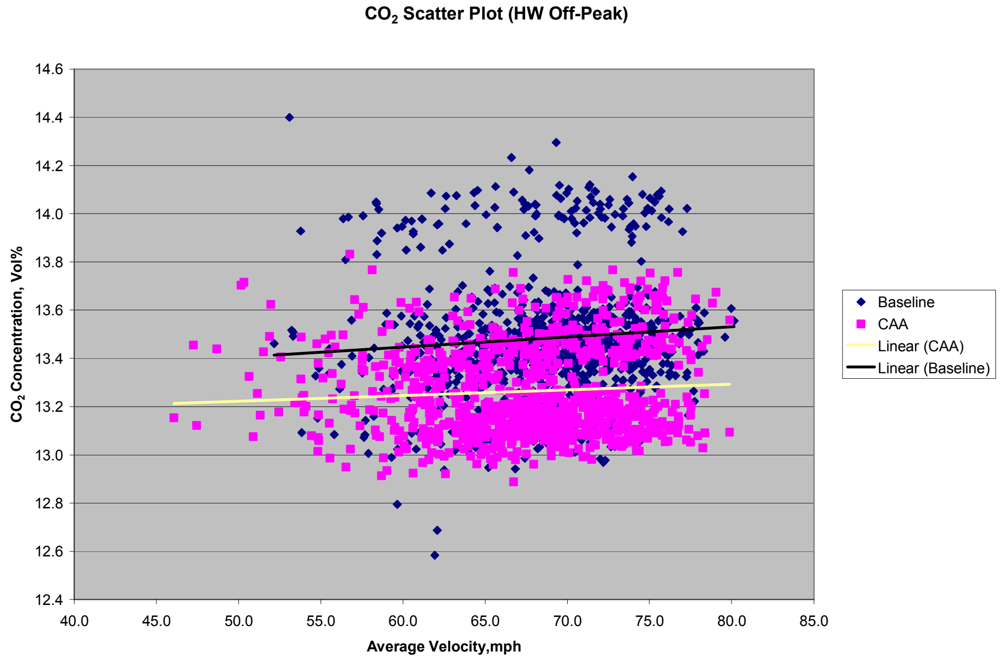
Case E: CO emission trends for highway test track, peak & off-peak time interval



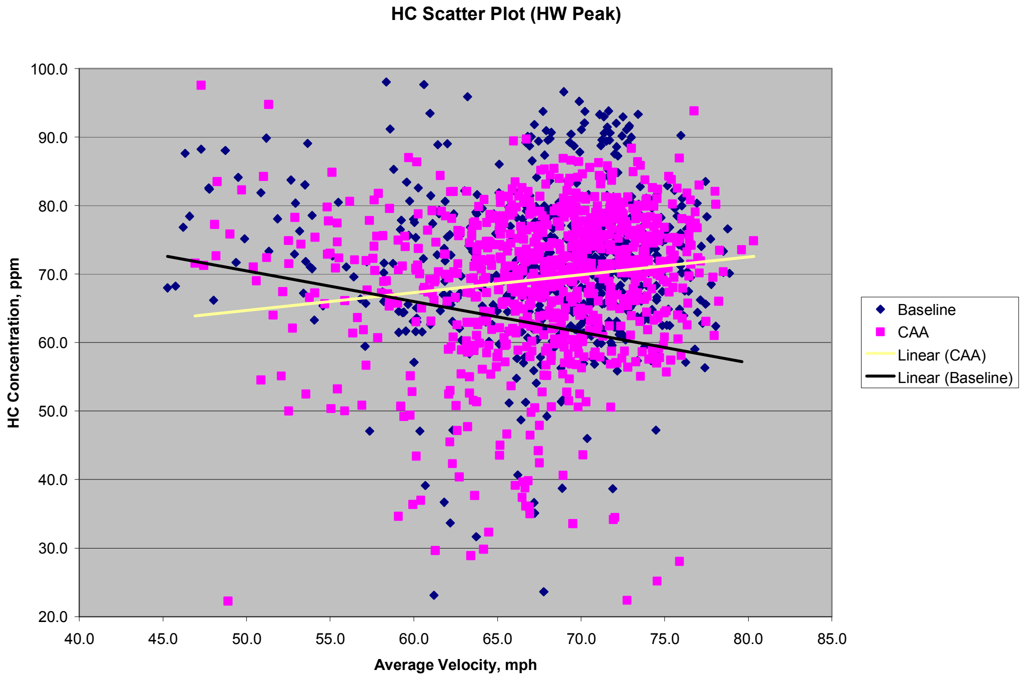


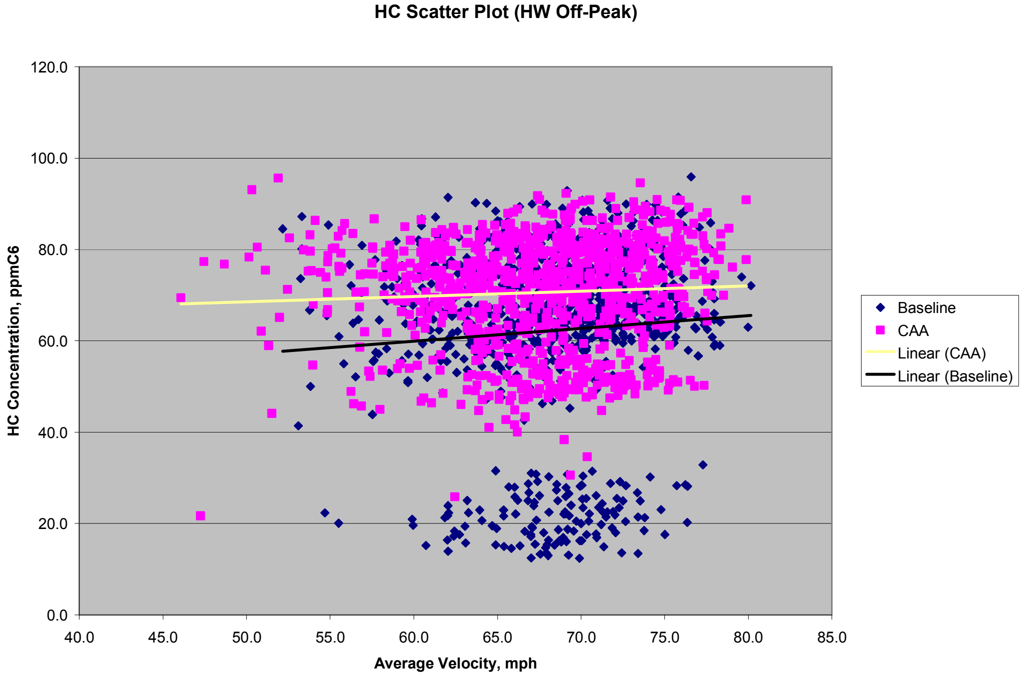
Case F: CO_2 emission trends for highway test track, peak & off-peak time interval



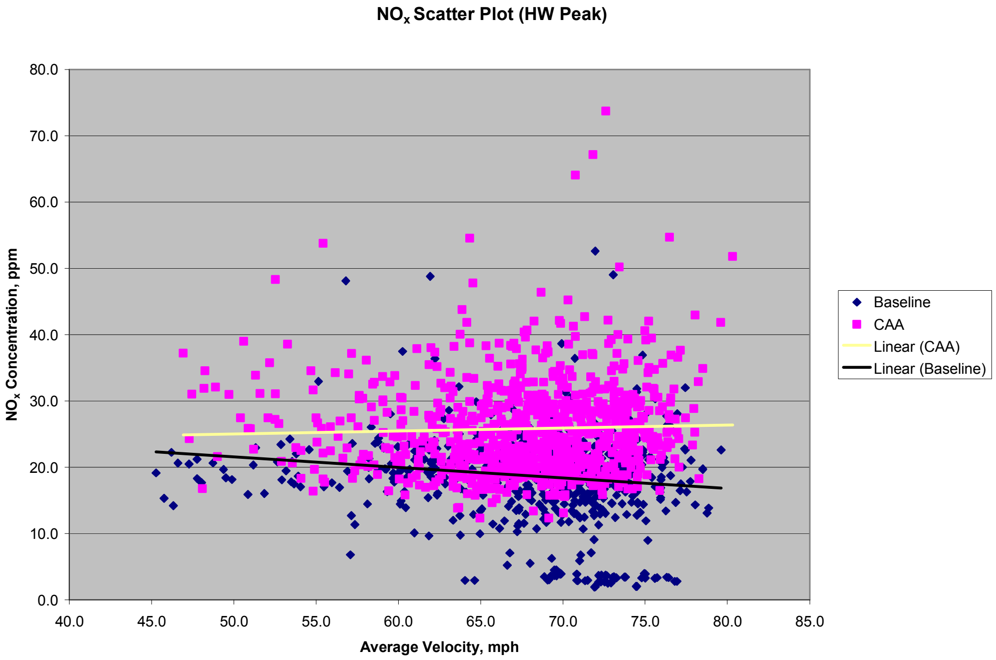


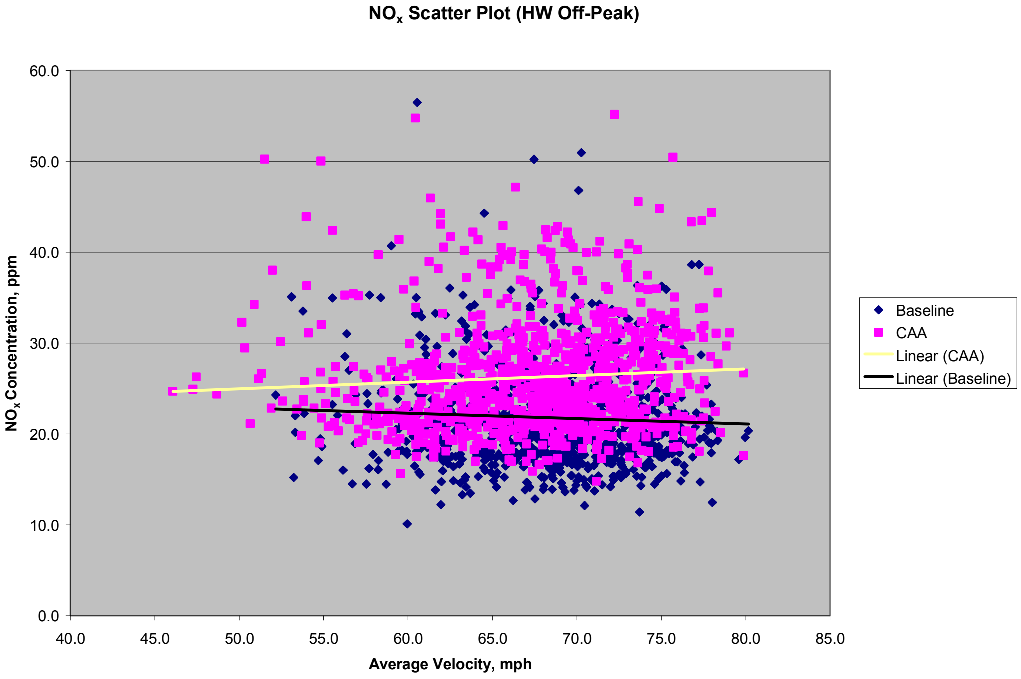
Case G: HC emission trends for highway test track, peak & off-peak time interval





Case H: NO$_x$ emission trends for arterial test track, peak & off-peak time interval





APPENDIX B

T-TESTS FOR DATA SETS IN PPM AND VOL % UNITS

Table B-1 T-tests for pollutant emissions for arterial test track, peak and off-peak time intervals

Pollutant	Peak		Off-Peak	
	Percent change	Significant difference	Percent change	Significant difference
CO	**-52.7**	YES	**0.179**	YES
CO_2	**-12.5**	YES	0.094	NO
HC	**5.41**	YES	**11.7**	YES
NO_x	**4.11**	YES	-1.87	NO

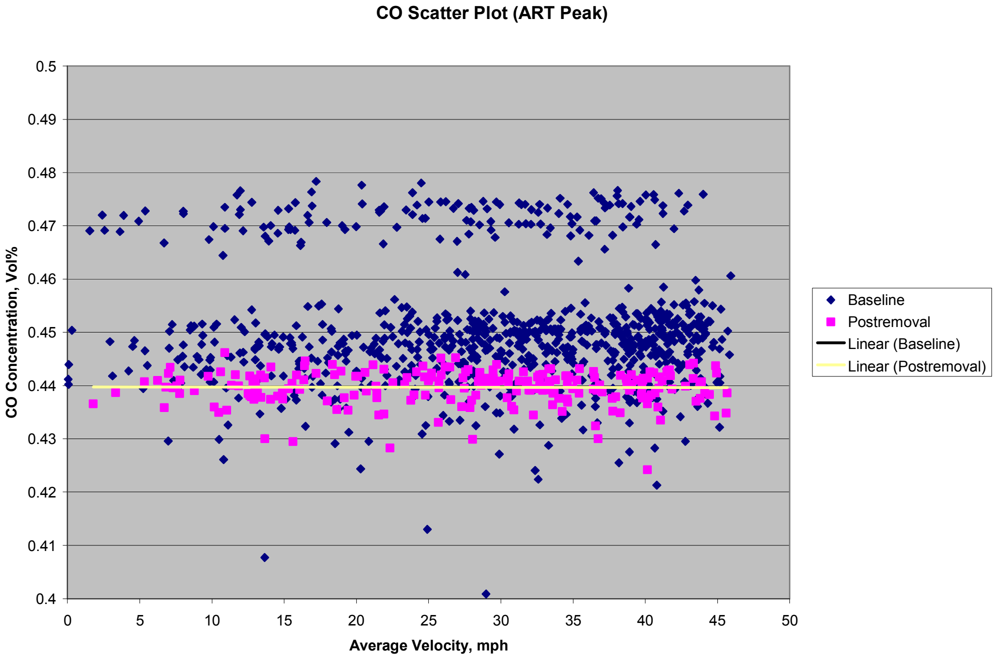
Table B-2 T-tests for pollutant emissions for highway test track, peak and off-peak time intervals

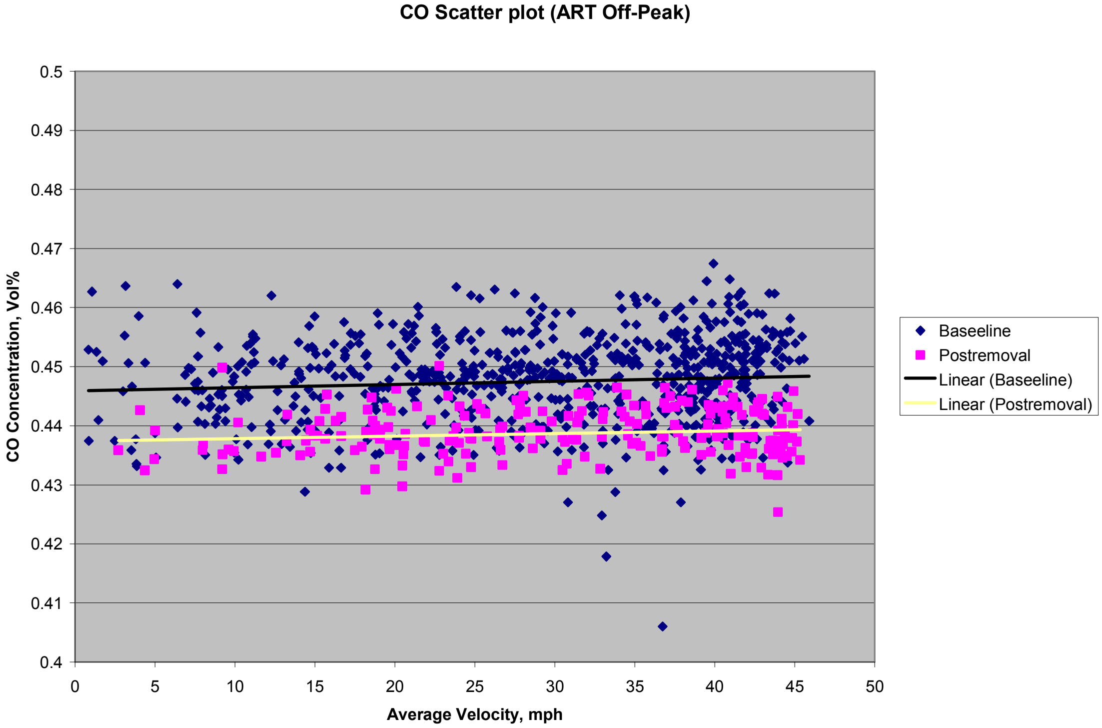
Pollutant	Peak		Off-Peak	
	Percent change	Significant difference	Percent change	Significant difference
CO	**-0.85**	YES	**1.41**	YES
CO_2	**-0.68**	YES	**1.34**	YES
HC	**10.83**	YES	**15.9**	YES
NO_x	**41.40**	YES	**20.7**	YES

APPENDIX C

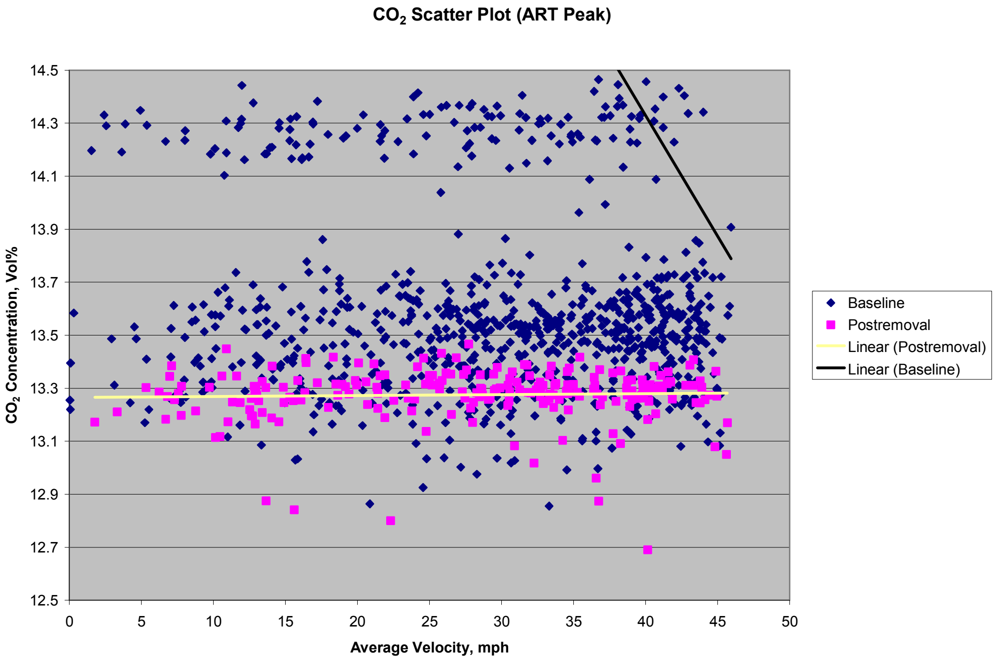
GRAPHICAL COMPARISON OF BASELINE AND POST-REMOVAL DATA

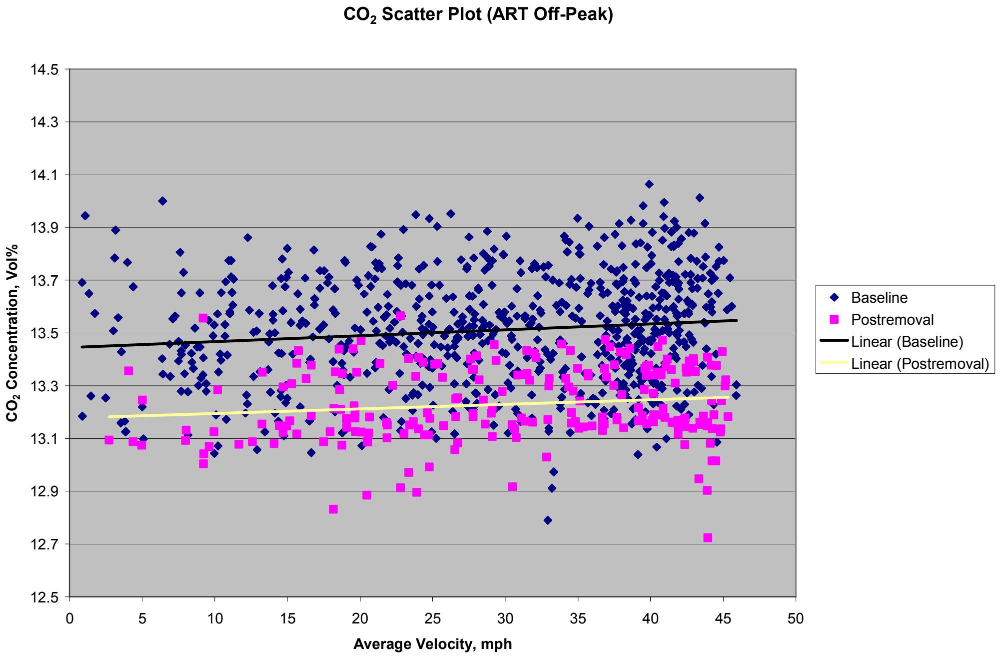
Case 1: CO emission trends for arterial test track, peak & off-peak time interval



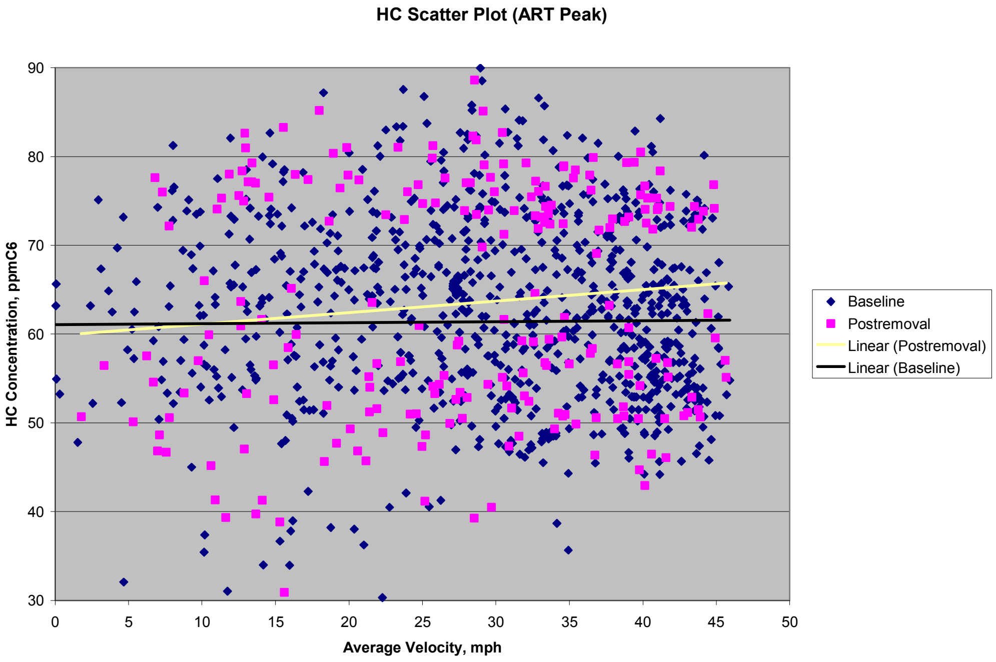


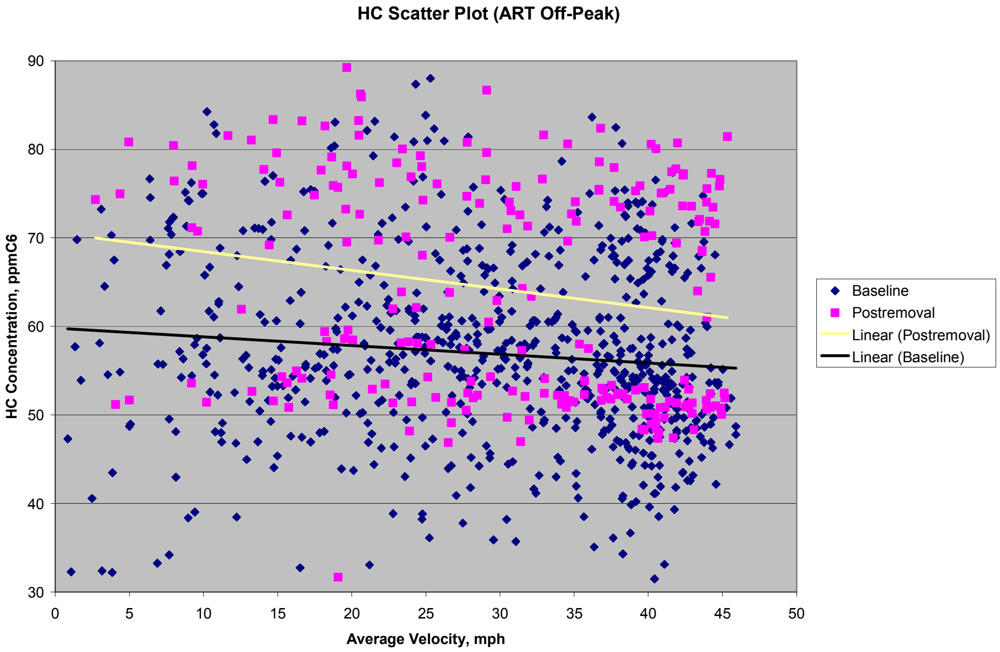
Case 2: CO_2 emission trends for arterial test track, peak & off-peak time interval





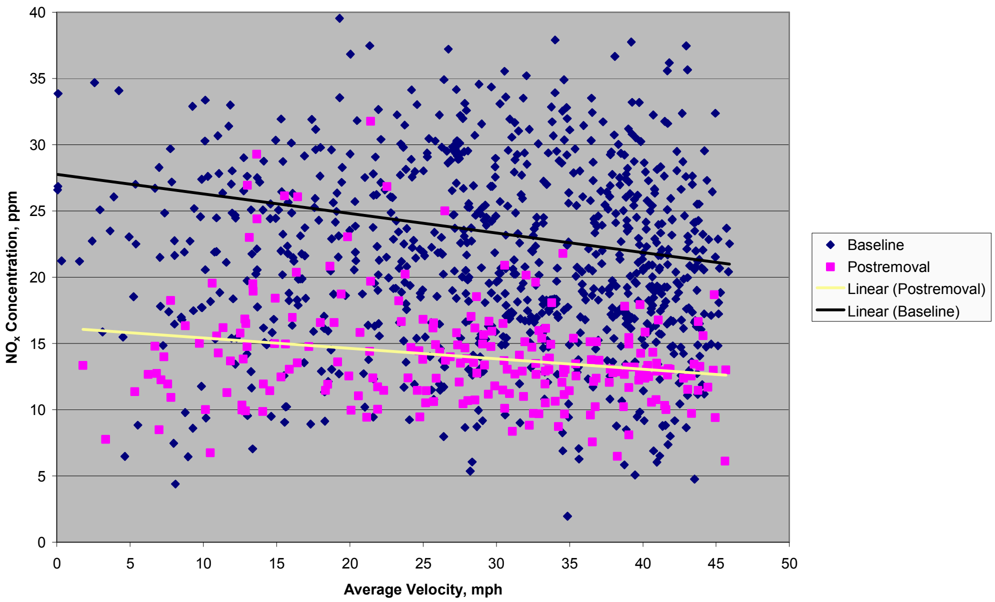
Case 3: HC emission trends for arterial test track, peak & off-peak time interval



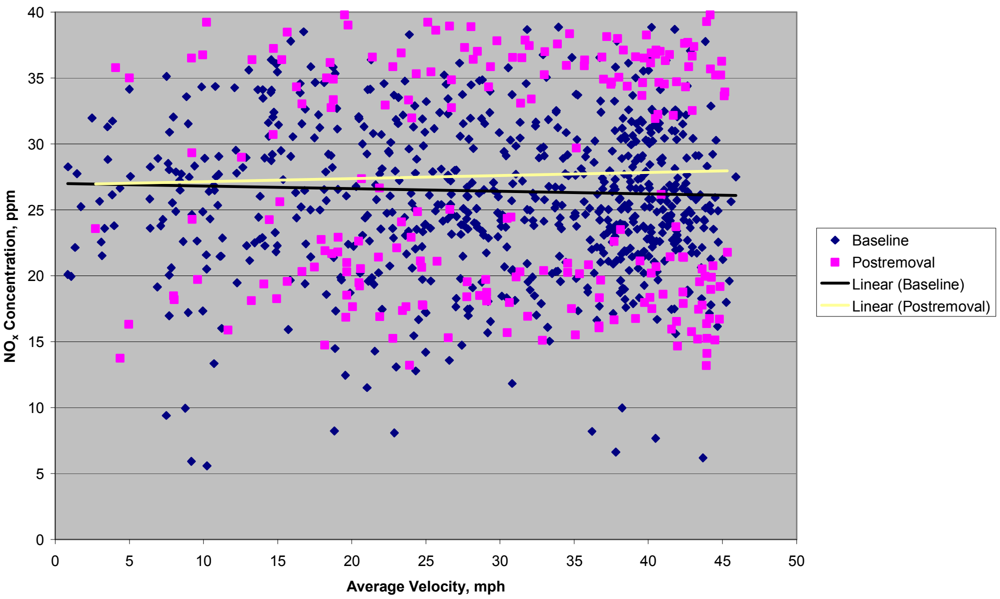


Case 4: NO_x emission trends for arterial test track, peak & off-peak time interval

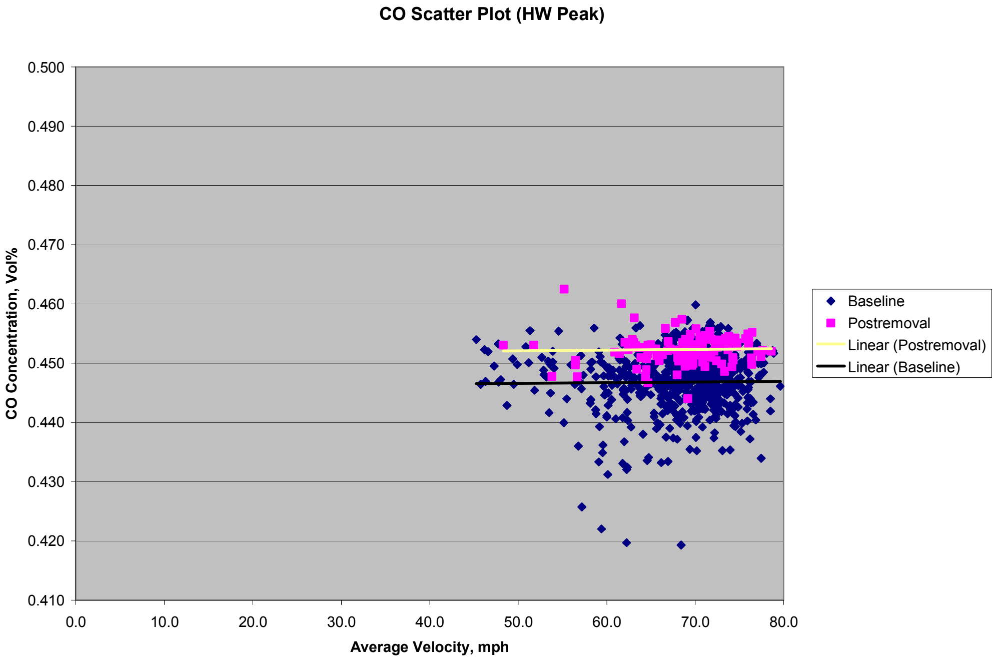
NO_x Scatter Plot (ART Peak)

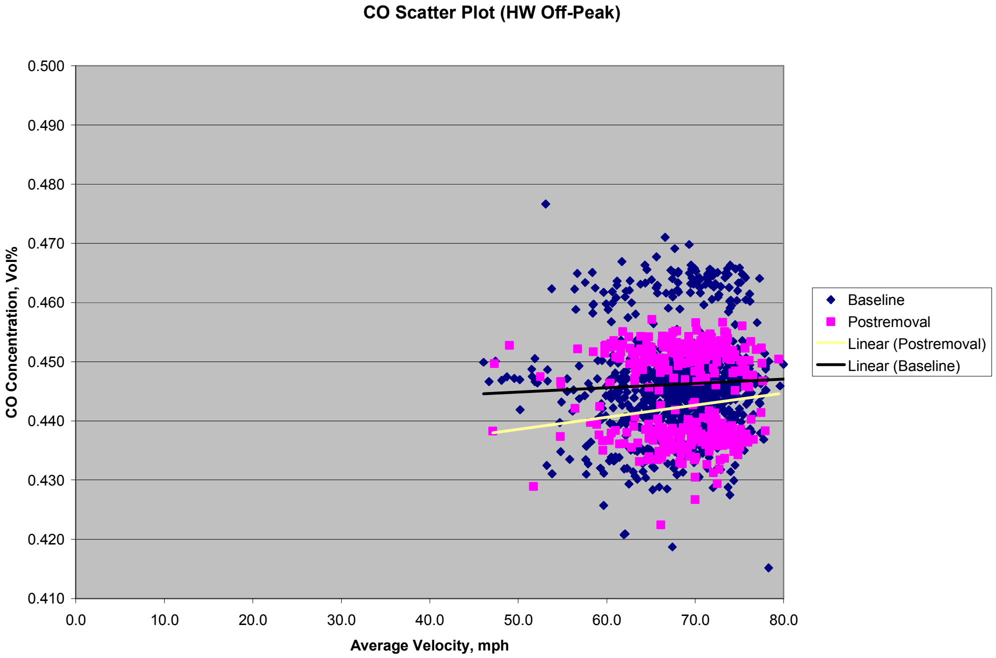


NO_x Scatter Plot (ART Off-Peak)

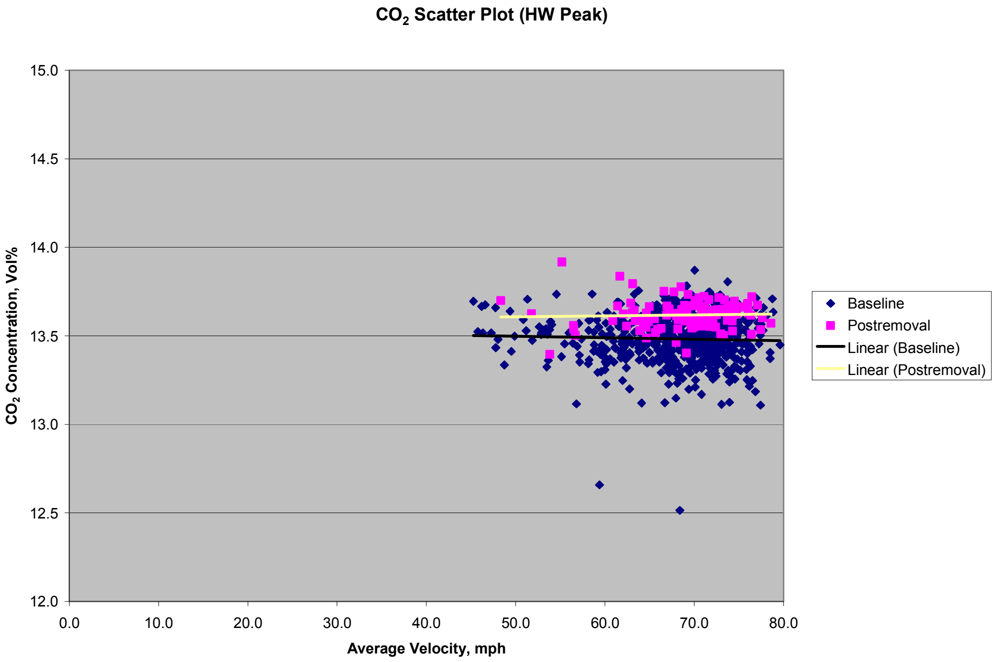


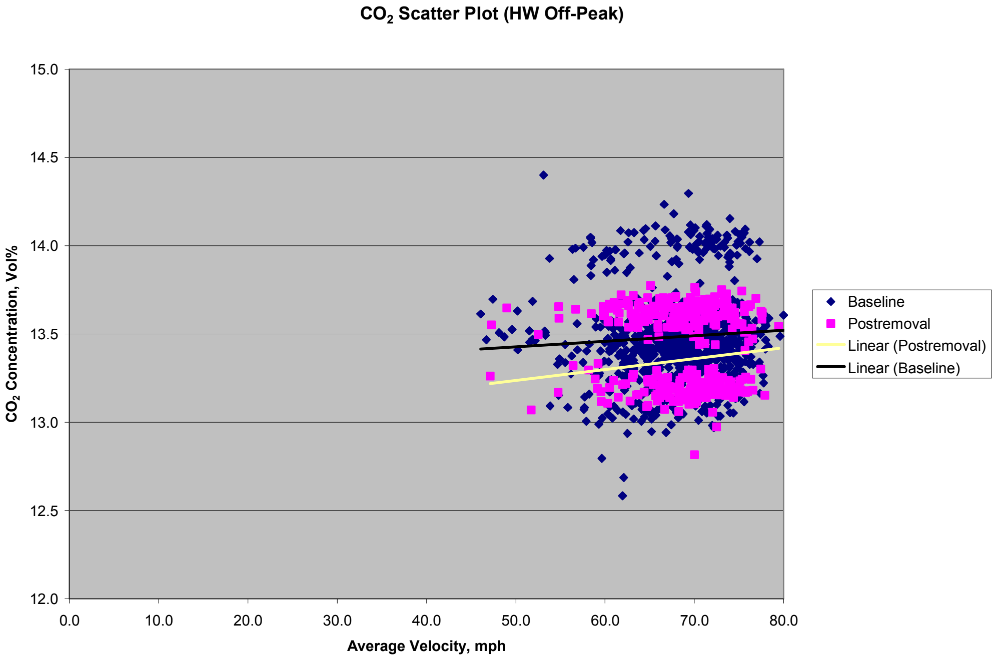
Case 5: CO emission trends for highway test track, peak & off-peak time interval



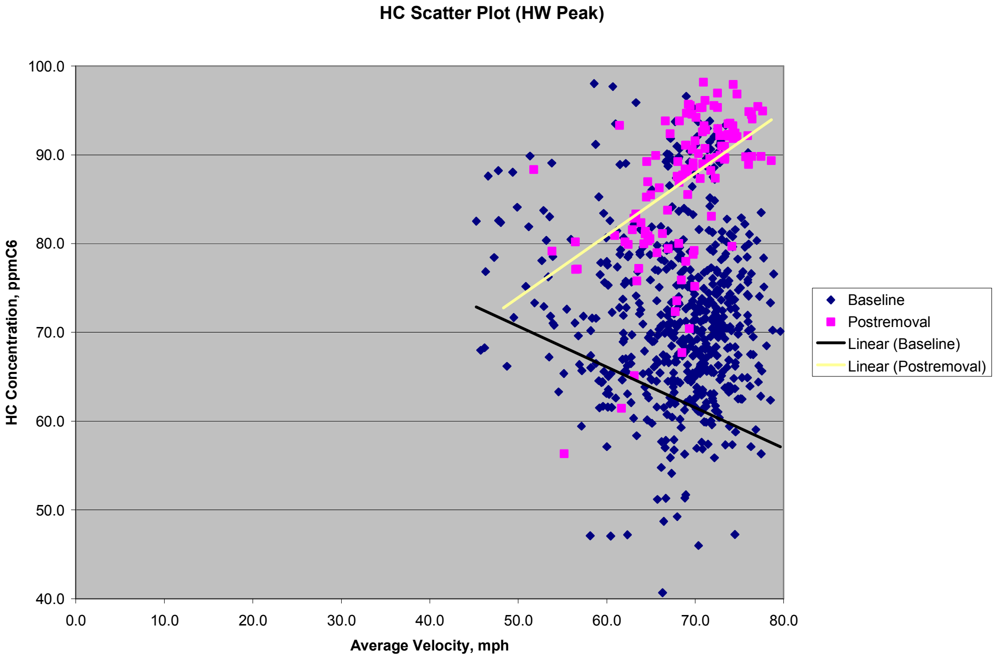


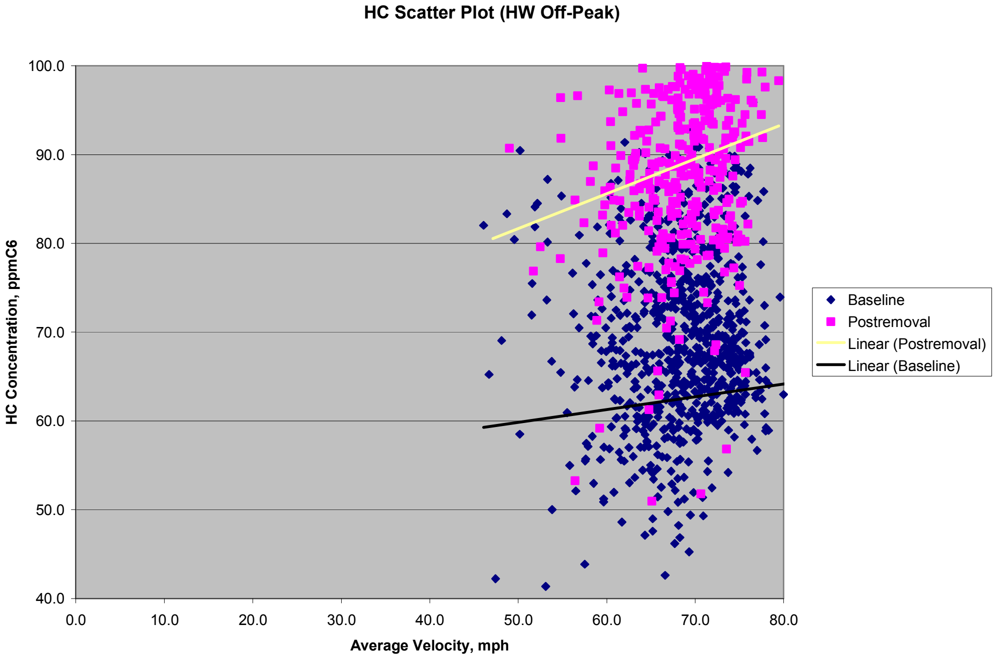
Case 6: CO_2 emission trends for highway test track, peak & off-peak time interval



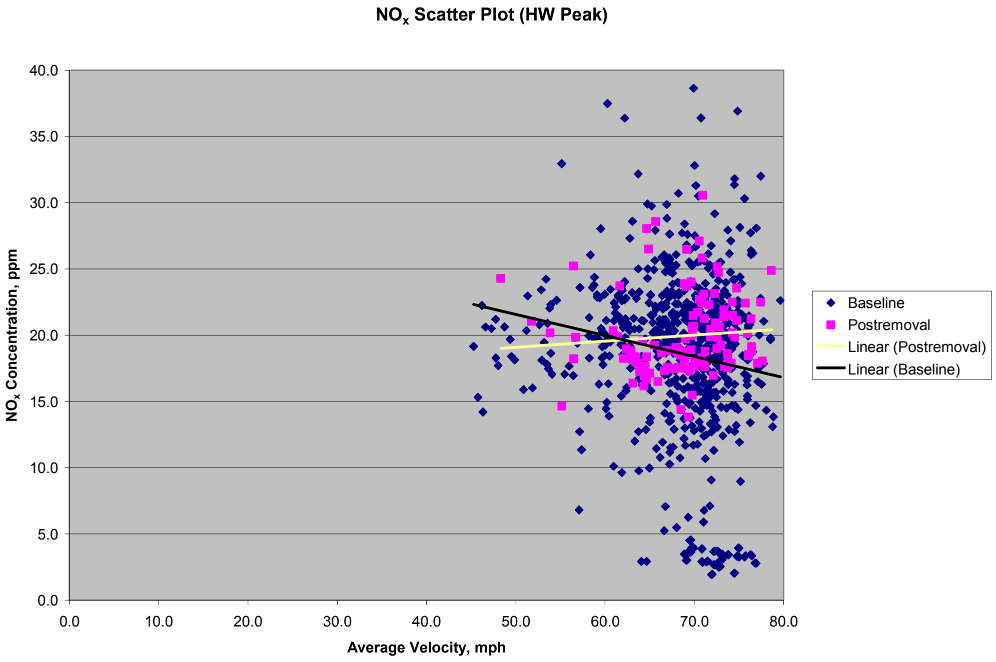


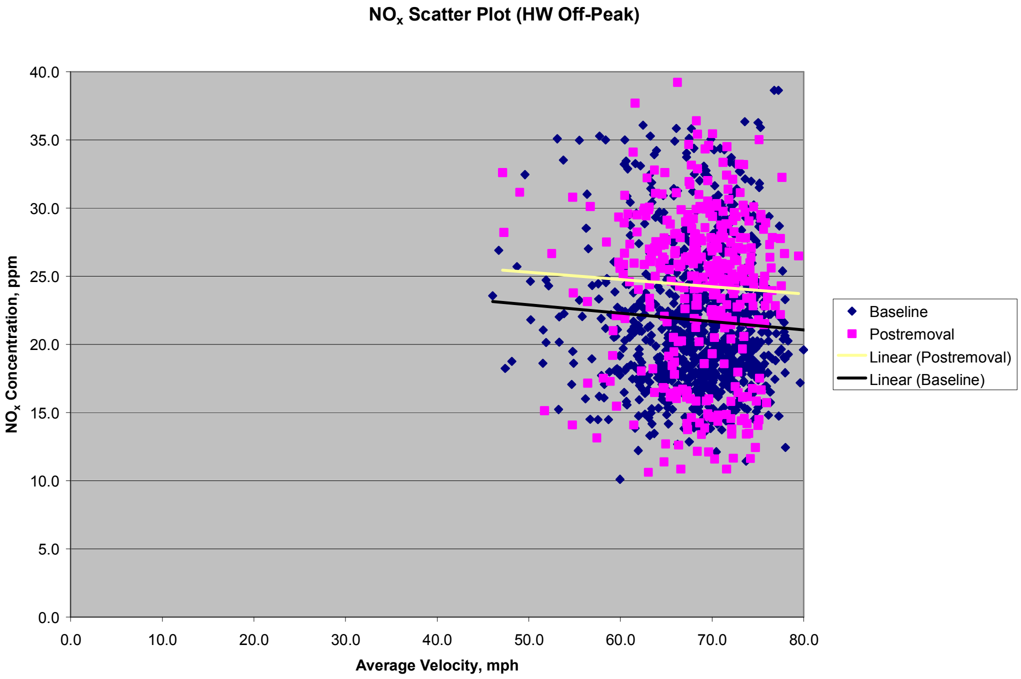
Case 7: HC emission trends for highway test track, peak & off-peak time interval





Case 8: NOx emission trends for highway test track, peak & off-peak time interval





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BIOGRAPHICAL INFORMATION

Jaya vani Nagireddi was born on January 8th 1983 in Vizag, earned her Bachelor's of Civil Engineering from M.V.S.R Engineering College, Hyderabad, India. Later on, she worked as an AutoCAD instructor for an year. In between, she developed an interest in the field of Environmental engineering and wanted to pursue higher studies in the United States.

She completed her Mater's of Science degree in Environmental Engineering under the guidance of her advisor, Dr. Sattler. Her Master's thesis dissertation was on "Vehicle Emission Trends due to the impact of Clean Air Associate's Device". In her thesis she tested a control technology, Clean Air Associate's retrofit device on a passenger car and concluded that the device had no significant impact on the four tailpipe pollutant emissions of Dodge Charger. During her course of her study she worked as a summer intern at a consulting firm, Chiang Patel & Yerby, Inc. where she worked on preliminary design report of ozone feasibility analysis for the Trinity River Authority's Wastewater treatment plant.

She was an active member of Air & Waste Management Student's chapter and motivated people to join the organization. She was also an active member of Society of Women Engineers UTA's chapter. Upon graduation, she plans to become a professional member of AWWA (America's Water Works Association). She plans to become a Professional Engineer in the area of Water/Wastewater Treatment Plant design.