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16. Abstract
The objective of this document is to present the findings of the study characterizing in-use emissions of TxDOT's non-road diesel equipment. This document presents literature reviews of emission reduction technologies and emission control measures practiced by the state of Texas and other states, discusses selection of TxDOT's non-road equipment and emission reduction technologies for emissions testing, and shows the in-use emissions of TxDOT's diesel equipment before and after installing and utilizing the selected emission reduction technologies (hydrogen enrichment and fuel additive technologies) using portable emission measurement systems (PEMS). Emissions measurements and data comparison and analysis have been performed with the technologies. The selected technologies did not show statistically significant NOx emissions reductions. From additional analysis with other pollutants, both technologies did not show any benefits in terms of emissions reductions. An optimization model has also been developed as part of this research and can be used to maximize the benefit of deploying other emission reduction technologies (that are proven effective) among TxDOT's non-road diesel fleet.

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Non-road Equipment, Diesel Equipment, Grader, Rubber Tire Loader, Excavator, Exhaust Emissions, NOx, Emissions Reduction, PEMS Testing

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CHARACTERIZATION OF IN-USE EMISSIONS FROM TXDOT'S NON-ROAD EQUIPMENT FLEET – FINAL REPORT

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DISCLAIMER

The contents of this report reflect the views of the authors, who are Doh-Won Lee, Josias Zietsman, Mohamadreza Farzaneh, Jeremy Johnson, Tara Ramani, Annie Protopapas, and John Overman. The authors are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge was Josias Zietsman, Ph.D., P.E. (TX #90506). The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

LIST OF ACRONYMS

AACOG – Alamo Area Council of Governments
ASTM – American Society of Testing and Materials
B100 – pure biodiesel
B20 – biodiesel blended into petroleum-based fuel at 20 percent
BAT – best available technology
CARB – California Air Resources Board
CCV – closed crankcase ventilation
CCF – closed crankcase filtration
CFATP – Clean Fuel Advanced Technology Program
CFR – Code of Federal Regulations
CI – compression ignition
CMAQ – Congestion Mitigation and Air Quality
CO – carbon monoxide
CO_2 – carbon dioxide
DEP – Department of Environmental Protection
DOT – Department of Transportation
DOC – diesel oxidation catalyst
DF – deterioration factor
DPF – diesel particulate filter
DPM – diesel particulate matter
EAC – Early Action Compact
EF – emission factor
EFM – electronic exhaust flow meter
EGR – exhaust gas recirculation
EIA – Energy Information Administration
EPA – Environmental Protection Agency
ERG – Eastern Research Group
FA – fuel additive
FBC – fuel-borne catalyst
FHWA – Federal Highway Administration
FY – fiscal year
GPS – global positioning system
H_2 – hydrogen
H_2O – water
HC – hydrocarbons
HDDV – heavy-duty diesel vehicle
HE – hydrogen enrichment
HERS – Highway Economic Requirements System
ID – identification
IDOT – Illinois Department of Transportation
IP – integer programming
LNC – lean NOx catalyst
MECA – Manufacturers of Emission Control Association
MOVES – Motor Vehicle Emission Simulator

MPO – metropolitan planning organization
N_2O – nitrous oxide
NA – nonattainment
NCDOT – North Carolina Department of Transportation
NCSU – North Carolina State University
NNA – near nonattainment
NOx – oxides of nitrogen
NRTC – non-road transient cycle
NTIS – National Technical Information Service
O_2 – oxygen
PEMS – portable emissions measurement system
PM – particulate matter
PMC – Project Monitoring Committee
RMC – Research Management Committee
S – Sulfur
SO_2 – sulfur dioxide
SCC – source category code
SCR – selective catalytic reduction
SI – spark ignition
SOF – soluble organic fraction
SwRI – Southwest Research Institute
TAF – transient adjustment factor
TCEQ – Texas Commission on Environmental Quality
TDOT – Tennessee Department of Transportation
TERP – Texas Emissions Reduction Plan
THC – total hydrocarbon
TRIS – Transportation Research Board's Transportation Research Information Services
TTI – Texas Transportation Institute
TxDOT – Texas Department of Transportation
UCR – University of California at Riverside
ULSD – ultralow sulfur diesel
WRAP – Western Regional Air Partnership

CHAPTER 1: INTRODUCTION

DEFINING THE PROBLEM

The Texas Department of Transportation (TxDOT) operates the largest fleet of non-road equipment in Texas and one of the largest in the United States. Based on the data provided by TxDOT for this project, TxDOT owned and operated almost 3100 non-road diesel units at the end of fiscal year (FY) 2008. The emissions impact from these units is considerable, but the emissions characteristics were not well understood. TxDOT recognizes that pursuing methods to reduce emissions from non-road equipment as well as understanding the emissions characteristics are important goals.

In June 2005, the U.S. Environmental Protection Agency (EPA) issued a final rule (EPA420-F-05-021) requiring in-use testing of heavy-duty diesel engines and vehicles (*1*). In contrast to earlier emission testing programs conducted primarily in laboratory settings using engine or chassis dynamometers, the new rule requires measurement of exhaust emissions from on-road heavy-duty diesel engines under real-world driving conditions using a portable emission measurement system (PEMS).

Currently, EPA is implementing the rule for on-road heavy-duty diesel engines; a future rule expected by 2010 will establish a similar in-use testing program for non-road heavy-duty diesel engines. Thus, the characterization of emissions from non-road diesel engines during real-world operating conditions is important for TxDOT and the state of Texas.

The use of PEMS equipment in testing of non-road equipment is a cost effective and proactive approach to investigate the emissions impact of using selected engine and fuel emission reduction technologies because it enables emissions testing of TxDOT's non-road fleet under actual operating conditions.

STUDY OBJECTIVES

The overall goals of this project were to:

- understand how results from the new federal in-use testing program may affect current estimates of emissions of oxides of nitrogen (NOx) and other pollutant emissions, particularly in ozone nonattainment (NA) areas;
- evaluate the effectiveness of emerging fuels/fuel additives and retrofit technologies to reduce emissions so that TxDOT can make optimal use of funds available for emissions reductions; and
- identify emission control strategies, such as changes in operating practices, which may avoid the costs of retrofits.

Researchers achieved these project goals by:

- carefully selecting the TxDOT non-road equipment and emission reduction technologies to test,
- developing duty cycles for the selected equipment,

- measuring and analyzing baseline and treatment level emissions using the most state-of-the-art PEMS equipment in Texas, and
- comparing the results with existing data sources.

Research conducted in FY 2008 was presented in a report titled *Characterization of In-Use Emissions from TxDOT's Non-road Equipment Fleet – Phase 1 Report.* The Phase 1 report covers the background research and testing of TxDOT equipment identified as having the highest priority for emissions reduction, using two selected emission reduction technologies: fuel additive (FA) and hydrogen enrichment (HE) technologies. This report is a comprehensive report of the entire 2-year project and provides expanded results for all the testing conducted in both FY 2008 and FY 2009, including detailed analysis and comparisons for the measured emissions data.

The goals of the project have been achieved by implementing the following seven tasks as outlined in the original project proposal:

- Task 1: State-of-the-Practice Assessment,
- Task 2: Select TxDOT Equipment for Testing,
- Task 3: Select Emissions Reduction Technologies for Testing,
- Task 4: Develop Duty Cycles for Selected Equipment,
- Task 5: Measure and Analyze Baseline and Treatment-Level Emissions,
- Task 6: Compare Results with Existing Data Sources, and
- Task 7: Prepare Final Products.

In addition to the above seven tasks, researchers also developed a methodology to optimize the deployment of emission reduction technologies within TxDOT's fleet. The findings from this task are also included in this report.

CHAPTER 2: STATE-OF-THE-PRACTICE ASSESSMENT

As the first step for conducting the project, the research team performed an extensive review of available information on the following topic areas: emission reduction technologies, emissions rates, and emissions control (by other states). The state-of-the-practice assessment included searches of published materials, general web searches, information from personal contacts, and databases such as the Transportation Research Board's Transportation Research Information Services (TRIS) database, TxDOT and Texas Transportation Institute (TTI) libraries, EPA and California Air Resources Board (CARB) databases.

The collected information was analyzed and organized into four topic areas, as listed below:

- non-road emission reduction technologies,
- non-road emission reduction case studies,
- non-road emission resources, and
- practices of other states.

Each of these four topic areas are discussed in the remaining sections of this chapter.

NON-ROAD EMISSION REDUCTION TECHNOLOGIES

This section briefly covers a broad range of emission reduction technologies/combinations of technologies for non-road diesel equipment. The selection of candidate technologies and the selection criteria used are presented in more detail in Chapter 3, which deals with development of the test protocol.

Diesel emissions controls are generally achieved by modifying the engine design, treating the exhaust (also referred to as after-treatment), modifying the fuel source, or using a combination of these controls. The primary sources for information on diesel emission control devices and fuels/fuel additives are from the Environmental Protection Agency, California Air Resources Board, and Manufacturers of Emission Control Association (MECA) (*2*, *3*, *4*). Several different technologies are currently available for emissions reduction of non-road diesel equipment. As of October 2008, EPA and CARB verified one technology and a combination of two technologies for non-road diesel construction equipment. Table 1 lists the details of these verified technologies.

Table 1. Verified Technologies for Non-road Equipment/Engines.

Technology	% Reduction		Verification by	Other Information
	NOx	PM		
DOC + SCR*	80	≥ 25	CARB	Fuel with S < 500 ppm
DPF*	N/A	≥ 85	EPA** & CARB	Fuel with S < 30 ppm***

Sources: EPA (5) and CARB (6)

Acronyms used in the table are listed alphabetically: DOC: diesel oxidation catalyst; DPF: diesel particulate filter; N/A: not applicable; NOx: oxides of nitrogen; PM: particulate matter; ppm: parts per million; S: sulfur; SCR: selective catalytic reduction.

* *Verification for a product is subject to certain engine makes and certain fuel requirements.*
** *Not in EPA's Environmental Technology Verification Program.*
*** *Most products require ultralow sulfur diesel (ULSD) (S < 15 ppm) and are also verified with biodiesel blends subject to certain requirements.*

Most products for non-road diesel construction equipment are verified by CARB. Since the main focus of CARB verification is PM emissions reduction, the verified technologies are primarily targeted on PM. For NOx emissions reductions, technologies currently receiving the most attention are selective catalytic reduction, exhaust gas recirculation (EGR), and lean NOx catalyst (LNC). These technologies, as well as those listed in Table 1, are evaluated as candidates for actual testing on TxDOT's non-road fleet. Table 2 lists the most common emission reduction technologies that can be used for non-road diesel equipment. This list was assembled based on reviews of available literature, including reports of previous TTI studies conducted in cooperation with TxDOT (*7*, *8*) and information from EPA, CARB, and MECA.

Table 2. Summary of Possible Emission Reduction Technologies for Diesel Equipment.

Technology	% Reduction		Cost over 7 Years*
	NOx	PM	
Biodiesel**	−5***	20	Low
Closed crankcase ventilation	0	20	Low
Diesel oxidation catalyst	0	20	Low
Exhaust gas recirculation	40	0	Medium
Fuel additives	5	0	Low
Hydrogen enrichment	20	TBD****	Medium
Lean NOx catalyst	25	0	High
Diesel particulate filter	0	85	Medium
Selective catalyst reduction	75	25	High

* *Low: Less than $5,000; medium: from $5,000 to $10,000; high: more than $10,000.*
** *Usually used in the form of 20 percent biodiesel and 80 percent ULSD, i.e., B20.*
*** *−5 means 5 percent of NOx emissions increase.*
**** *TBD: to be determined.*

The technologies can be broadly classified as either control devices or fuels/fuel additives. The remainder of this section provides a brief description of technologies under these categories.

Emission Reduction Technologies: Control Devices

Diesel Oxidation Catalyst

In most applications, a diesel oxidation catalyst consists of a stainless-steel canister that contains a honeycomb structure called a substrate or catalyst support. The interior surfaces are coated with catalytic metals such as platinum or palladium. A DOC chemically converts diesel exhaust-gas pollutants, carbon monoxide (CO) and hydrocarbons (HC), and the liquid hydrocarbons adsorbed on carbon particles (referred to as the soluble organic fraction [SOF]) into water (H_2O) and carbon dioxide (CO_2) by using an oxidation catalyst. When the exhaust flow passes through the oxidation catalyst, unburned HC and CO are oxidized. In addition, the SOF of diesel particulate matter (DPM) is also oxidized to H_2O and CO_2. Although DOC retrofits have proven effective at reducing particulate and smoke emissions with gaseous CO and HC emissions on older vehicles, they do not reduce NOx emissions.

Currently, under the CARB and EPA retrofit technology verification processes, several manufacturers have verified that DOC products provide at least a 19 percent reduction in PM emissions. However, there are no verified DOCs for non-road diesel construction equipment.

Diesel Particulate Filter

A diesel particulate filter is a device designed to remove DPM from the exhaust gas of a diesel engine. The first type of DPF, called a wall-flow filter, consists of a honeycomb structure with alternate channels plugged at opposite ends. As the gases pass into the open end of a channel, the plug at the opposite end forces the gases through the porous wall of the honeycomb channel and out through the neighboring channel. The ultrafine porous structure of the channel walls of the filter results in collection efficiencies greater than 85 percent. It captures smoke, soot, and other PM from the exhaust by interception and impaction of the solid particles across the porous wall. These filters are commonly made from ceramic materials such as cordierite, aluminum titanate, mullite, or silicon carbide.

Since a filter can fill up over time by developing a layer of retained particles on the inside surface of the porous wall, the captured PM must be burned off during the operation of the vehicle to prevent clogging the DPF. This burn-off is referred to as regeneration. The filter regenerations occur either through the use of a catalyst (passive) or through an active technology. The passive regeneration occurs by removing the captured particulates continuously and spontaneously through catalytic oxidation on the filters, depending mainly on the filter temperature and soot load in the filter. In the event of long periods of operation at low load and temperature, however, a filter needs to burn off the loaded particulates by additional means such as a fuel burner, electric heater, and/or fuel-borne catalysts (FBCs). This burn-off by a burner is referred to as "active regeneration." The amount of soot build-up and the resulting increase in back pressure determine the frequency of regeneration. Despite the high efficiency of the catalyst, a layer of ash may build up on the filter, requiring replacement or servicing. The ash is made up of inorganic oxides from the fuel or lubricants used in the engine and will not decompose during the regular soot-regeneration process. Because sulfur in the fuel interferes with many regeneration strategies, almost all DPFs must use ultralow-sulfur diesel. There is a

1 to 4 percent fuel penalty (i.e., increase in fuel consumption) depending on catalysts and regeneration methods.

Lower levels of filtration can be achieved using a flow-through filter. In this type of device, the filter element can be made of a variety of materials and designs, such as sintered metal, metal mesh or wire, or a reticulated metal or ceramic foam structure. In this type of device the exhaust gases and PM follow a tortuous path through a relatively open network. The filtration occurs as particles impinge on the rough surface of the mesh or wire network of the filter element. These filters can be catalyzed or uncatalyzed and are less prone to plugging than the more commonly used wall-flow filters discussed previously.

To meet the stringent particulate-emissions standards that are required for heavy-duty diesel vehicle (HDDV) engines starting with the 2007 model year, the wall-flow-type DPFs are required. Currently, under the CARB and EPA retrofit technology verification processes, several manufacturers have verified that DPFs provide at least a 25 percent reduction in PM emissions. For non-road construction-equipment applications, one product is verified by EPA (Caterpillar DPF), and three products (Cleaire Horizon, Engine Control Systems Combifilter, and HUSS FS-MK filter) are verified by CARB. These products are discussed below:

- Caterpillar DPF: This product is EPA verified for model years 1996 through 2005 (subject to certain engine types and sizes) with low S diesel ($S < 30$ ppm); verification is valid until January 2010. Reduction of PM is 89 percent, CO is 90 percent, and HC is 93 percent. Detailed information is available on the EPA website (*9*).
- Cleaire Horizon: CARB (Level 3) verified for the model year 2007 or older (subject to certain engine types and sizes) with biodiesel blends (subject to certain requirements) and with standard CARB diesel; verification is valid until January 2010. Reduction of PM is 85 percent or more. Detailed information is available on the CARB website (*10*).
- Engine Control Systems Combifilter: CARB (Level 3) verified for the model year 2007 or older (subject to certain engine makes, types, and sizes) with biodiesel blends (subject to certain requirements) and with standard CARB diesel. Reduction of PM is 85 percent or more. Detailed information is available on the CARB website (*11*).
- HUSS FS-MK filter: CARB (Level 3) verified for the model year 2007 or older (subject to certain engine makes and types) with biodiesel blends (subject to certain requirements) and with standard CARB diesel. Reduction of PM is 85 percent or more. Detailed information is available on the CARB website (*12*).

Selective Catalytic Reduction

A selective catalytic reduction system uses a metallic or ceramic wash-coated catalyzed substrate, or a homogeneously extruded catalyst and a chemical reductant to convert NOx to molecular nitrogen and oxygen. For applications, an aqueous urea solution or ammonia is usually injected into the exhaust gas. When urea is used, it decomposes thermally in the exhaust to ammonia, which serves as the reductant. As exhaust and reductant pass over the SCR catalyst, chemical reactions occur that reduce NOx emissions to nitrogen and water.

SCR systems are also effective in reducing HC emissions by up to 80 percent and PM emissions by 20 to 30 percent. As with all catalyst-based emission control technologies, the use of low-sulfur fuel enhances SCR performance. SCR catalysts can be combined with a particulate filter for combined reductions of both PM and NOx. Currently, there are no stand-alone SCR systems verified by EPA or CARB. However, in conjunction with a DOC, one product is currently verified by CARB for non-road construction-equipment applications, Extengine ADEC System: CARB (Level 1) verified for model years 1991 through 1995 (subject to certain engine makes, types, and sizes) with diesel (S < 500 ppm). Reduction in PM is 25 percent or more, and NOx reduction is 80 percent. Detailed information is available on the CARB website (*13*).

Lean NOx Catalyst

A lean NOx catalyst system removes NOx from the exhaust by catalytically reducing NOx. Under lean conditions, some LNC systems use diesel fuel as a reductant, which is injected into the exhaust gas to help reduce NOx over a catalyst. The NOx is converted to nitrous oxide (N_2O), CO_2, and H_2O. Other systems operate passively without any added reductant at reduced NOx conversion rates. An LNC often includes a porous material made of zeolite (a micro-porous material with a highly ordered channel structure), along with either a precious-metal or base-metal catalyst. The zeolites provide microscopic sites that are fuel/hydrocarbon rich where reduction reactions can occur. Without the added fuel and catalyst, reduction reactions that convert NOx to N_2O would not occur because of excess oxygen present in the exhaust.

Currently, peak NOx conversion efficiencies typically are around 10 to 30 percent (at reasonable levels of diesel-fuel reductant consumption). There is only one LNC system in conjunction with a DPF that has been verified by CARB as providing a 25 percent reduction in NOx emissions and at least an 85 percent reduction in PM. However, there are no verified systems for non-road diesel construction equipment.

Exhaust-Gas Recirculation

An exhaust-gas recirculation system controls NOx emissions. Through an EGR valve, NOx emissions reductions are accomplished by allowing exhaust gases to be recirculated into the intake manifold. Because the exhaust stream is composed of inert gas, blending some percentage of that gas into the intake mixture lowers the combustion temperature and thus reduces the formation of NOx. During these recirculation processes, PM emissions usually increase so that EGR systems require other technologies such as a DPF to control the increased PM emissions.

Currently only one system in conjunction with a DPF has been verified by CARB as providing at least a 40 percent reduction in NOx emissions and at least an 85 percent reduction in PM. However, there are no verified systems for non-road diesel construction equipment.

Closed Crankcase Ventilation (CCV)

This system prevents crankcase emissions from being exposed to the cabin inside the operating vehicles and to ambient air. After closing the crankcase vent with the intake system, gases are returned to the intake system, and intake pressure is balanced with a regulator and a valve. Added filtration in the closed system further reduces crankcase PM emissions. Using a multistage filter, the emitted lube oil can be collected, coalesced, and returned to the engine's sump. Typical closed crankcase filtration (CCF) systems consist of filter housing, a pressure regulator, a pressure relief valve, and an oil check valve.

These systems greatly reduce crankcase emissions. Crankcase emissions controls are available as a retrofit technology for existing diesel engines or as an original equipment component of a new diesel engine. For 1994 to 2006 model year heavy-duty diesel engines, crankcase PM emissions reductions provided by crankcase emission control technologies range from 0.01 grams per brake horsepower-hour (g/bhp-hr) to 0.04 g/bhp-hr or up to 25 percent of the tailpipe emission standards. Currently, under the EPA and CARB retrofit technology verification processes, several manufacturers have verified CCV and CCF systems in conjunction with DOCs as providing at least a 25 percent reduction in PM emissions. However, there are no verified systems for non-road diesel construction equipment.

Emission Reduction Technologies: Fuels/Fuel Additives

This section provides summaries of selected fuels and fuel additives that may be applicable in non-road environments.

Fuel Additive

FAs are products for use in conventional gasoline and diesel fuels to improve the combustion characteristics of these fuels, reduce emissions, and increase fuel efficiency and engine power at a modest cost to the user. FA manufacturers claim that their products can reduce emissions of NOx, HC, PM, and/or CO up to 25 percent, 25 percent, 50 percent, and 30 percent, respectively. Additionally, manufacturers claim that FAs can decrease fuel consumption by up to 15 percent. However, it is also known that some products can increase emissions of one or more pollutants while reducing emissions of other pollutants and increasing fuel efficiency. Currently, there are no verified FAs.

Hydrogen Enrichment

HE systems reduce engine-exhaust emissions by creating a better flame front in the engine. Using an onboard hydrolysis device or catalytic fuel reformer, hydrogen (H_2) gas is generated from a small amount of water or diverted fuel. The enriched H_2 is added into the fuel intake manifold and delivered into the cylinders with the fuel. Because the mixture is more flammable, the hydrogen-rich intake charge creates a better flame front, which produces lower engine-out emissions. Because oxygen (O_2) is also produced during the hydrolysis or reformation, the H_2-O_2 combination provides for a better combustion on the power stroke and reduces emissions as well. The combination provides a higher energy value than just ambient air, and the fuel burns more completely in the combustion chamber, with little or no waste. This cooler but more complete burn reduces the amount of gasoline or diesel needed to power the engine, and thus fuel consumption decreases.

Manufacturers claim that their products can reduce NOx and CO emissions up to 25 percent and 35 percent, respectively. Additionally, they claim that HE systems can decrease fuel consumption by about 10 percent. However, there are currently no verified HE systems.

Biodiesel

Biodiesel fuel is composed of mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats meeting the requirements of American Society of Testing and Materials

(ASTM) D 6751. Biodiesel reduces emissions of PM, CO, and HC when used as fuel with or without blending with petroleum-based diesel (e.g., ULSD).

Biodiesel is an alternative fuel that can be used in diesel engines and provides power similar to conventional diesel fuel. It is produced by reacting vegetable or animal fats with methanol or ethanol to produce a lower-viscosity fuel that is similar in physical characteristics to diesel and can be used neat or blended with petroleum diesel for use in a diesel engine. Biodiesel is commonly blended into petroleum-based fuel at low levels, i.e., 20 percent (B20) or less. Biodiesel can be used in its pure form (B100), but may require certain engine modifications to avoid maintenance and performance problems.

Typical emissions benefits of B20 include:

- a 10 percent decrease in CO,
- up to a 15 percent decrease in PM emissions,
- a 20 percent decrease in sulfate emissions, and
- a 10 percent decrease in HC emissions.

In some tests, B20 has shown a slight increase in NOx emissions in some types of existing heavy-duty engines. The emission control technology suitable for engines operating on biodiesel blends would be similar to emission control technology used for diesel-fueled vehicles.

Currently biodiesel is in EPA's verified technologies list for highway, heavy-duty, four cycle, and non-EGR equipped engines (*4*). On the list, biodiesel provides 0 to 47 percent reductions in PM, 0 to 47 percent reductions in CO, and 0 to 67 percent reductions in HC while showing 0 to 10 percent increases in NOx emissions. However, EPA does not endorse the use of any particular company's product.

NON-ROAD EMISSION REDUCTION CASE STUDIES

This section provides a summary of the case studies for non-road construction equipment, in which emission technologies have been applied in real-world and controlled conditions. The Manufacturers of Emission Control Association reported case studies involving retrofitting diesel construction equipment (*14*). The report summarizes the following studies:

- Central Artery/Tunnel Project in Boston, Massachusetts;
- New Haven Harbor Crossing Corridor Improvement Program in New Haven, Connecticut;
- Dan Ryan Expressway Road Construction Project;
- World Trade Center (WTC) Diesel Emissions Reduction Project;
- "The Impact of Retrofit Exhaust Control Technologies on Emissions from Heavy-Duty Diesel Construction Equipment";
- Demonstration Projects for Diesel Particulate Filter Technologies on Existing Off-Road Heavy-Duty Construction Equipment; and
- City of Houston Diesel Field Demonstration Project.

The most commonly used technologies in these case studies are DOC and/or DPF with ULSD because the primary target pollutant of the studies was mostly particulate matter. Of particular note is the City of Houston Diesel Field Demonstration Project (*15*). The project's goal was to reduce NOx emissions by 50 to 75 percent. Environment Canada conducted emissions testing on a 29-unit construction fleet at Ellington Field in Houston, Texas. Several manufacturers provided emission control technologies including DOCs, passively regenerated DPFs, and SCR systems. As a result of the demonstration, the SCR system was selected as one of the technologies to be used on the fleet. The equipment retrofitted included Gradall rubber tire excavators powered by 1994–2000 Cummins 5.9-liter 190-hp engines. The SCR system has been operational for up to 3 years and has performed acceptably. Appendix A provides information on the case studies mentioned above, including the City of Houston Diesel Field Demonstration Project.

NON-ROAD EMISSION RESOURCES

Historically, EPA has produced the report *Compilation of Air Pollutant Emission Factors* (*16*). The emission factors presented in tables in Section II of "Volume II: Mobile Sources" (commonly referred to as "AP-42") for various non-road sources including construction equipment (e.g., dozers, cranes) are no longer maintained. However, more current mobile-source emissions factors are available from emission inventory models such as NONROAD. NONROAD is a non-road mobile-source emissions inventory model that provides users the ability to develop emission inventories for specific time periods (hour, day, week, month, season, and year) and for specific regions (counties, metropolitan areas, regions, states, and nationwide) for a wide variety of non-road mobile sources. Thus, in-use emissions factors for non-road mobile sources can now be estimated with much more complexity, depending upon larger numbers of parameters. With the user of the emission factors having far more options for tailoring estimates to specific areas and times, compilation and presentation of this information in tabular form, or in a single document, are no longer feasible. Therefore, non-road emissions can be obtained from resources such as emissions factors, models, and inventories.

These resources were used to calculate TxDOT's non-road diesel-equipment emissions. Researchers used calculated emissions for TxDOT equipment selection in Chapter 3. Researchers also discuss the emissions calculation methodology and the calculated emissions results in Chapter 3 in detail. Also, the resources were used in Task 6 for comparisons with emissions test results from Task 5. Additional information is also available online from EPA's Office of Transportation and Air Quality (*17*) and, in particular, the "Non-road Engines, Equipment and Vehicles" site (*18*). Appendix B lists some relevant documents including both EPA and non-EPA reports.

Non-road Emission Factors

The document EPA 420-P-04-009 contains exhaust emissions factors for compression-ignition (CI) engines used for the current NONROAD emission inventory model (*19*). It should be noted that the term "compression ignition" is synonymous with "diesel." Covered pollutants include HC, CO, NOx, PM, CO_2, and sulfur dioxide (SO_2). Brake-specific fuel consumption, a fuel rate measurement, is also discussed.

The document covers:

- zero hour,
- steady-state emissions factors,
- transient adjustment factors, and
- deterioration factors for all diesel-fueled engines.

Adjustments to emissions rates due to variations in fuel sulfur level are also included. The document also covers crankcase HC emissions factors. The relevant tables in this document to be used in this project are the input factors used in the NONROAD 2005 model. These relevant tables include:

- Table 1 – Non-road CI Engine Emissions Standards,
- Table A1 – Non-road CI Technology Distributions by HP Category and Model Year,
- Table A2 – Zero-Hour Steady State Emissions Factors for Non-road CI Engines,
- Table A3 – Transient Adjustment Factors by Equipment Type for Non-road CI Engines,
- Table A4 – Deterioration Factors for Non-road Diesel Engines,
- Table F3 – CI Transient Adjustment Factors for Various Non-road Test Cycles, and
- Table F4 – CI Cycle Transient Adjustment Factors Binned by Load Factor Category.

NONROAD Model

An area's emissions inventory consists of emissions from point, area, and mobile sources. Mobile sources are divided into on-road and non-road categories, and the non-road category consists of several subcategories, some of which are:

- mobile construction equipment,
- industrial and agricultural equipment,
- lawn and garden equipment,
- locomotives,
- port equipment,
- recreational and commercial boats,
- commercial ships, and
- off-shore platforms.

NOx (a precursor to ozone) is the criteria pollutant of most importance in Texas. In Texas the most NA and near-nonattainment (NNA) areas (eight out of a total of nine) are for ozone. Non-road sources account for about 39 percent of the mobile-source NOx emissions and about 11 percent of total emissions in the Dallas-Ft. Worth area (*20*). For the Houston-Galveston area, non-road sources make up 54 percent of mobile-source NOx emissions and 34 percent of all other criteria pollutants' emissions. Hence, non-road emissions make up a significant percentage of both mobile-source and total emissions.

Emissions rates for non-road equipment are typically contained in EPA's AP-42 documents and tables as noted in the previous section. In terms of modeling, however, non-road emissions data center on EPA's NONROAD 2005 model, commonly called NONROAD. This model estimates air pollution from more than 80 types of compression-ignition and spark-ignition (SI) non-road sources including such items as lawnmowers, motorboats, portable generators, and construction equipment. By bringing together information on equipment populations, equipment usage, and emission factors, the NONROAD model estimates mass emissions of HC, CO, NOx, SO_2, PM, and CO_2 for specific states and counties for past and future years. These emissions are estimated using a number of inputs, including:

- fuel and engine type, including gasoline, diesel, compressed natural gas, and liquefied petroleum;
- geographic area and related characteristics;
- time period, such as day, month, and season;
- climatic conditions, such as temperature and humidity;
- activity, such as hours of operation per analysis period; and
- equipment and engine types, including retrofit equipment.

In general, default values are available and used for the above characteristics that are not specifically known. Activity estimates can be made using survey data in the local area. However, the emissions rates in the current NONROAD model must be used for estimating emissions unless otherwise approved by EPA. The emissions rates included in NONROAD are based on emissions tests conducted for EPA using specified duty cycles and dynamometer testing.

Non-road Inventories

The Texas Commission on Environmental Quality (TCEQ) conducts most of the non-road emissions estimations in Texas for emissions inventory purposes. However, other entities in the state have had experiences with non-road emissions inventory and analysis. For example, the Alamo Area Council of Governments (AACOG) has produced construction-equipment emission estimates for its region. The methodology used was based on that used for the 1999 AACOG emission inventory. The study relied on local data produced from surveys and on national data used in EPA's Non-road Emissions Inventory Model in the absence of reliable local data. It was concluded that the preferred methodology for calculating construction emissions continues to involve a local survey of construction equipment use within the AACOG region (*21*). The Houston-Galveston Area Council conducted an early analysis of area-wide diesel construction emissions, concluding that NONROAD is an improvement over their previous methodologies (*22*).

However, with the advent of PEMSs, it is now possible to make direct in-use measurements for non-road equipment such as TxDOT's construction equipment. If done credibly and according to protocols acceptable to EPA, local emissions rates for the actual equipment and alternative emission reduction treatments can be tested and documented for potential use in inventories as well as evaluation of the effectiveness of treatments.

PRACTICES OF OTHER STATES

Many states have proposed or implemented various practices to encourage both on-road and non-road emissions reductions. This section summarizes those practices related to implementing non-road emission control strategies in various states. In general, these state practices fall into one of two categories: control strategies and/or incentives. Additionally, some states, most notably California and Texas, have conducted research and examined EPA emission modeling practices to more accurately determine equipment inventories and emissions factors that ultimately affect their emissions inventories.

State department of transportation (DOT) control strategies for non-road emissions generally include but are not limited to:

- operational controls such as idling restrictions and site operational controls,
- clean contracting that stipulates contract incentives and contract requirements,
- inspections and maintenance of non-road equipment,
- fuels (early deployment of ULSD),
- retrofit technologies,
- rebuilds/re-power,
- financial incentives, and
- use of congestion mitigation and air quality (CMAQ) funds.

Regulatory strategies for non-road diesel emissions generally include implementing:

- the EPA Non-Road Diesel Engines Rule,
- adoption of California’s 2007 highway diesel standards (states that have adopted this include Connecticut, Delaware, Georgia, Maine, Maryland, New Jersey, New York, North Carolina, and Pennsylvania), and
- contracting requirements for clean construction and emissions reduction on state contracts.

Appendix C provides a few examples of the control strategies and funding incentives used in various states and regions. Appendix D provides a few selected examples of state practices for estimating non-road emissions.

CHAPTER 3: DEVELOPMENT OF TEST PROTOCOL

This research involved the in-use emissions testing of TxDOT's construction equipment before and after installation of emission control devices to gauge the effectiveness of various technologies. For this, various aspects of the test protocol needed to be developed. The major components of a test protocol that needed to be determined included:

1. selection of equipment for testing among TxDOT's fleet,
2. selection of emission reduction technologies to use for testing, and
3. development of duty cycles for selected test equipment.

The Phase 1 report provided a detailed test protocol that included the selection of three types of equipment (graders, rubber tire loaders, and excavators) from TxDOT's non-road fleet, the recommendation of three types of emission reduction technologies (FA, HE, and SCR), and a methodology for identifying the most effective technology based on extensive testing. However, initial findings caused the research team to change the test protocol in consultation with the Project Monitoring Committee (PMC). An overview of these changes is presented in the next section. However, for the purpose of providing a comprehensive report, the remainder of the chapter presents the original test protocol development, including the full selection process for identifying target equipment, selection of emission reduction technologies, and duty-cycle development.

CHANGES TO TEST PROTOCOL DUE TO FURTHER RESEARCH FINDINGS

As mentioned above, findings from the initial set of testing (presented in the Phase 1 report) caused the research team to change the approach to the work performed in FY 2009. An overview of the changes and the reasoning for them are summarized below:

- Initial testing of four graders revealed that both FA and HE did not result in any significant reduction in NOx emissions. Therefore, a decision was made not to conduct testing on loaders and excavators for FA and HE. Instead, the grader testing alone was completed (for a total of six graders), along with an expansion of the analysis and results. In addition to NOx, results for other critical pollutants, namely CO, HC, and PM, and for CO_2 were included.
- The test results from both the initial and expanded testing and analysis, for a total of six graders, are presented in Chapter 5 ("Measurement and Analysis of Baseline and Treatment-Level Emissions").
- The SCR technology, which was identified as the best candidate for achieving NOx emissions reduction could not be tested within the scope of this project on account of the high price of the equipment. However, the TTI research team collaborated with TxDOT and an SCR manufacturer (Nett Technologies) and was awarded a grant for testing of SCR on TxDOT's non-road equipment fleet. This work, under EPA's Emerging Technologies Verification Program, is currently being performed. The results from this research will be made available to TxDOT.
- As an additional research task, an optimization methodology was developed for TxDOT's non-road fleet, to enable the effective deployment of emission reduction technologies among counties/areas to maximize the benefits from emissions reduction. The next chapter presents this methodology.

SELECTION OF TXDOT EQUIPMENT FOR TESTING

In the Phase 1 report, researchers developed a detailed test protocol that included the selection of the major categories of TxDOT equipment that should be included in the emission testing. In order to select the equipment for testing, TxDOT's Non-road Equipment Inventory database, provided by TxDOT, was analyzed carefully and thoroughly. Researchers developed criteria and applied them to refine the universe of equipment to those pieces that fulfilled the goals and objectives of the project. EPA guidelines were then followed to calculate the total annual NOx emissions for each unit. The equipment population was classified into categories in the source category code (SCC) that EPA defined. A further set of criteria enabled identification of priority equipment categories for emissions testing, including:

- total NOx emissions in FY 2007;
- total average NOx emissions over FY 2005–2007; and
- number of units operating statewide, in NA and in Early Action Compact (EAC) counties.

The TxDOT Non-road Equipment Inventory Database was refined based on specific criteria, and the total annual NOx emissions were estimated for a total of 11 categories of equipment. From these 11 categories, graders and rubber tire loaders were found to contribute the most to NOx emissions, followed by excavators. Details of the process of categorizing the database and estimating emissions are presented in the remainder of this section.

Initially, researchers recommended and agreed with the PMC to select three pieces of equipment from each category (graders, rubber tire loaders, and excavators) for emissions testing during both phases of the project, with a total of three proposed emission reduction technologies.

Non-road Construction Equipment Database

TxDOT provided their non-road construction equipment database in a file along with another file containing format descriptions and brief explanations of data attributes. TTI researchers examined the database to select equipment for this project.

Database Description

The database included a wealth of information for a total of 3915 pieces of non-road equipment owned by TxDOT. The equipment consisted primarily of road construction machinery along with some equipment used by TxDOT for other functions, such as sweepers. The database was last updated on August 31, 2007, and thus included complete FY 2007 information, as well as complete information for the previous 2 fiscal years, FY 2006 and FY 2005. The attributes for each piece of equipment include:

- static attributes (for example:
  - identification number,
  - classification,
  - model year,
  - fuel type,
  - engine horsepower,
  - etc.) and

- dynamic attributes, which varied by fiscal year (for example:
  - status,
  - hours of usage,
  - gallons of fuel used,
  - etc.).

A data dictionary text file accompanying the database file provides explanations of the attribute fields, codes, and abbreviations used for data entry.

Database Refinement Criteria

Researchers established criteria to refine the universe of machinery to those pieces that fulfilled the goals and objectives of this project, specifically:

- diesel equipment only (not gasoline or electric);
- equipment designated as currently in use only (status of "voucher processed");
- equipment without missing key attributes, e.g., engine horsepower data; and
- equipment that had hours of usage in at least one of the past 3 fiscal years (i.e., the years included in the database).

As a result, researchers removed 741 pieces of equipment from the initial raw population of 3915 pieces because they did not conform to one or more of these criteria, reducing the population to a total of 3174 pieces of equipment.

NOx Emissions from TxDOT Equipment

NOx emissions from the refined 3174 pieces of TxDOT equipment were calculated by the same method that is used in the EPA NONROAD 2005 model. The following sections provide a detailed methodology and the calculated results.

Emissions Calculation Methodology

Researchers followed EPA's procedures and guidelines to calculate the NOx emissions for each piece of equipment in FY 2007 and the average annual NOx emissions over the past 2 fiscal years, according to the hours of usage in each year (*18*). These are the same guidelines and data used in EPA's NONROAD 2005 model that estimates air pollution from non-road sources.

The emissions tier of each piece of equipment was determined from Table A1 of the guidelines, according to the engine horsepower and model year. Table A2 then provided the steady-state NOx emissions factor in grams/hp-hr (EF_{ss}) for each piece of equipment, according to its engine horsepower rating and tier. For pre-1988 ("Base" tier) engines greater than 50 hp, the guidelines and NONROAD 2005 use the emission factors in the Nonroad Engine and Vehicle Study (*23*).

The NOx Transient Adjustment Factor (TAF) for each piece of equipment, according to its EPA source category code and tier, was then determined from Table A3 of the guidelines. Although the equipment had already been classified by TxDOT into its own categories by type, the equipment had to be reclassified into EPA's SCCs to utilize the table and obtain the TAF.

The deterioration factor (DF) was calculated in a multi-step fashion based on data from Table A4 and two NONROAD default input files – Activity.dat and Uspop.dat – which are based on national non-road equipment activity data and which are available from EPA's NONROAD2005a Core Model and Data Files (*24*).

The DF was calculated as:

$$DF = 1 + A \times (\text{cumulative hours of activity} \times \text{load factor} / \text{median life at full load, hours})$$

where:

A = NOx relative deterioration factor (from Table A4, by tier);
Cumulative hours of activity = age × activity, hours/year (from Activity.dat, by SCC)
(*Note*: *age = 2007 – model year + 1 (equipment database)*);
Load factor (from Activity.dat, by SCC); and
Median life at full load, hours (from Uspop.dat, by SCC and horsepower).

The adjusted NOx emissions factor for each piece of equipment, EF_{adj} in grams/hp-hr, was then calculated as:

$$EF_{adj} = EF_{ss} \times TAF \times DF$$

The NOx emissions in FY 2007, 2006, and 2005 for each piece of equipment were then calculated according to the hours of usage in each year as:

$$\text{NOx emissions, grams} = EF_{adj} \times \text{horsepower} \times \text{hours of usage}$$

The average NOx emissions according to the hours of usage reported for each piece of equipment over each of the last 3 years – FY 2005, 2006, and 2007 – were then calculated.

Finally, the FY 2007 NOx emissions and the average NOx emissions in FY 2005–2007 were summed for all equipment to arrive at the total NOx emissions in FY 2007 and total average NOx emissions of the non-road equipment fleet in FY 2005–2007.

Emissions Results

Table 3 shows the total NOx emissions in FY 2007, the total average NOx emissions over FY 2005–2007, and the number of units operating statewide, in NA and in EAC counties by the equipment's SCC. Researchers used EPA attainment designations at the time this analysis was conducted (*25*, *26*).

Table 3. Total NOx Emissions by Equipment Category and County Status.

EPA Source Category Code	All Counties			NA Counties Only			EAC Counties Only		
	No. of Units *	Total NOx Emissions (Ton)		No. of Units *	Total NOx Emissions (Ton)		No. of units*	Total NOx Emissions (Ton)	
		FY 07	Average over FY 05-07		FY 07	Average over FY 05-07		FY 07	Average over FY 05-07
Pavers	14	1.4	1.7	3	0.4	0.5	2	0.0	0.0
Rollers	646	33.5	38.3	73	2.7	3.4	36	1.6	1.9
Trenchers	15	0.1	0.1	3	0.0	0.0	2	0.0	0.0
Excavators	144	56.1	56.3	25	8.3	8.5	19	7.3	7.4
Cranes	21	4.7	4.5	1	0.1	0.1	2	0.0	0.0
Graders	545	133.1	146.1	64	11.1	12.6	38	5.9	6.3
Rubber Tire Loaders	782	111.1	116.6	108	13.6	14.6	51	5.7	5.7
Tractors/Loaders/Backhoes	596	37.5	39.3	62	4.8	4.7	51	1.9	2.2
Off-Highway Tractors	55	6.0	7.4	10	1.3	1.5	9	0.8	0.9
Other Construction Equipment	54	22.7	26.7	10	2.4	3.1	2	2.4	2.4
Sweepers/Scrubbers **	298	24.0	23.8	32	1.9	2.2	15	1.0	1.0
SUM	**3170**	**430.2**	**460.8**	**391**	**46.6**	**51.2**	**227**	**26.6**	**27.8**

** Excludes three cement and mortar mixers and one scraper.*
*** Categorized as industrial equipment in EPA SCC.*

Figures 1, 2, and 3 show the total average NOx emissions over FY 2005–2007 and the number of units for each of the 11 equipment categories operating statewide (all counties), in NA counties, and in EAC counties, respectively.

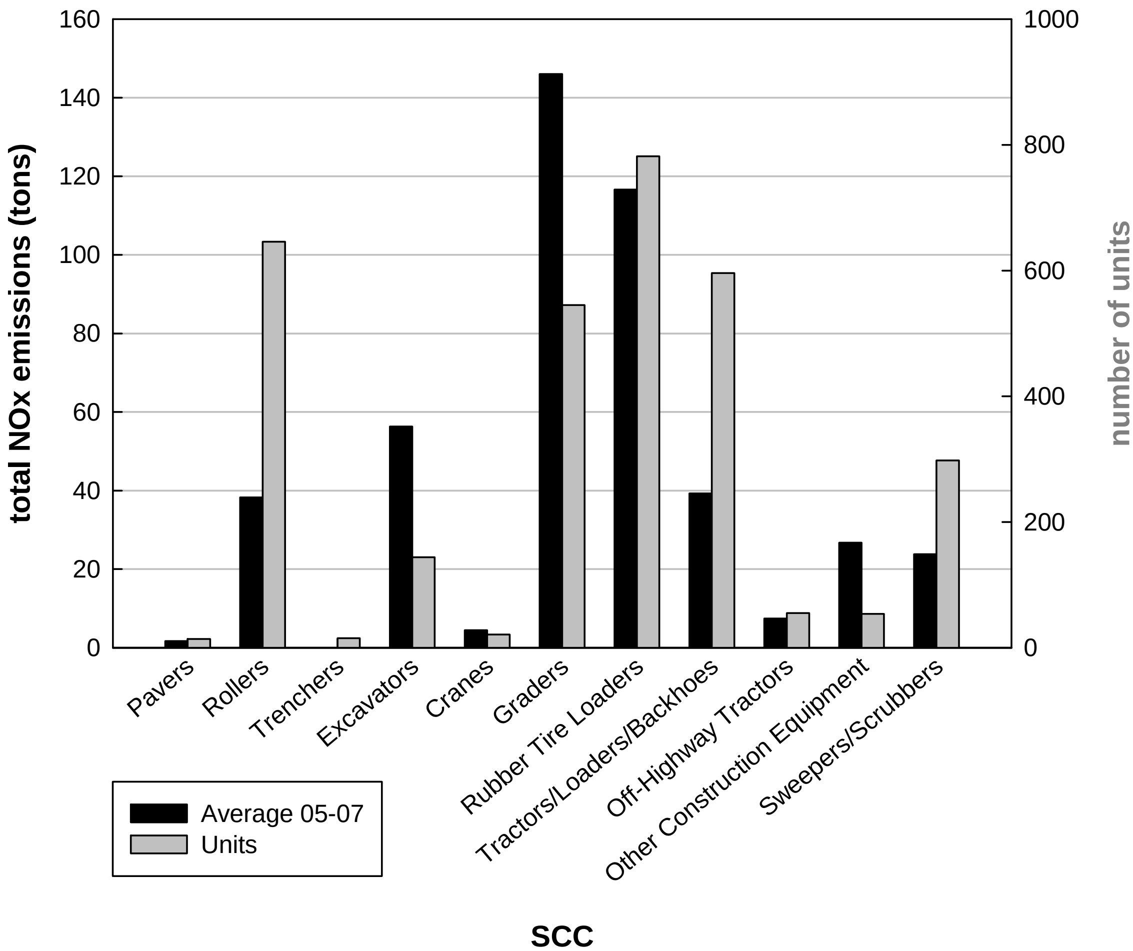

Figure 1. Total Average FY 2005–2007 NOx Emissions by Equipment Category – Statewide.

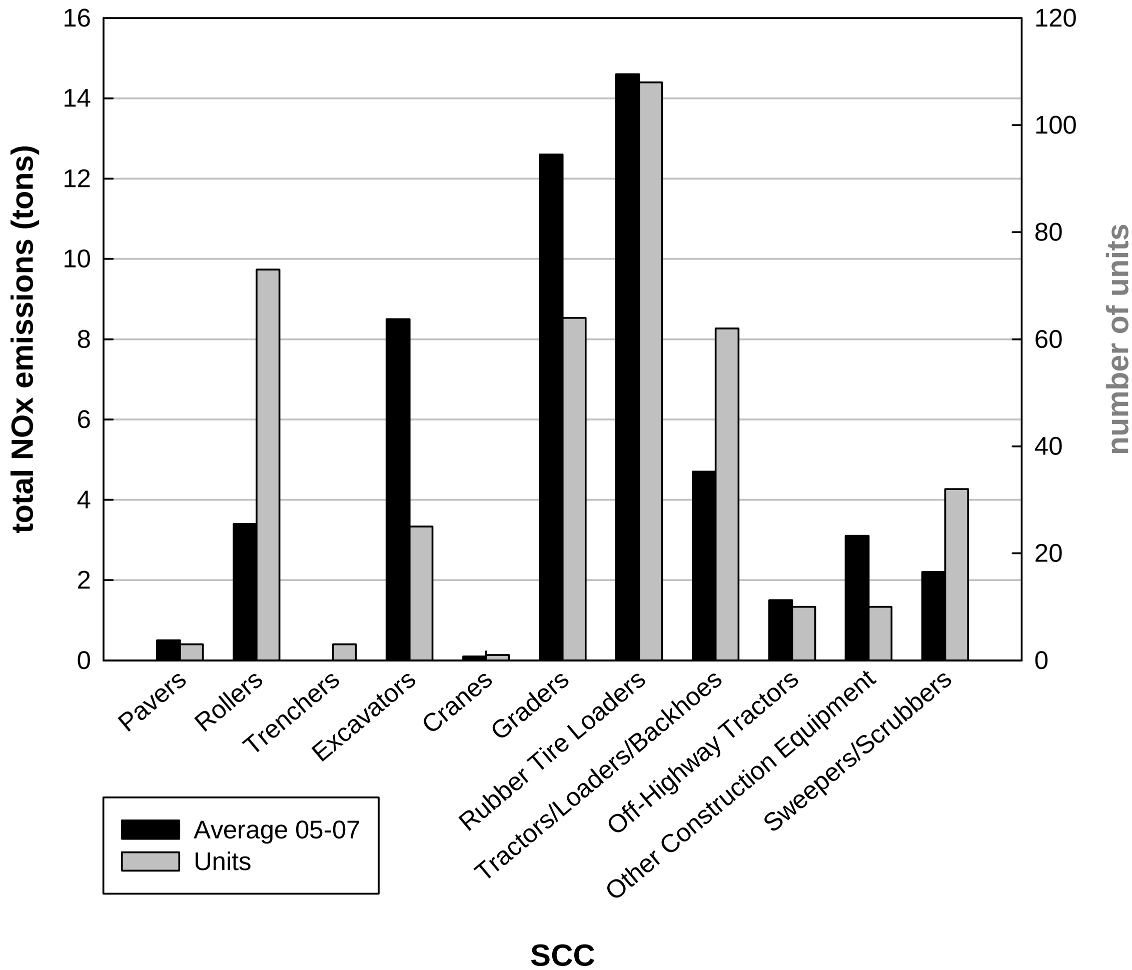

Figure 2. Total Average FY 2005–2007 NOx Emissions by Equipment Category – NA Counties.

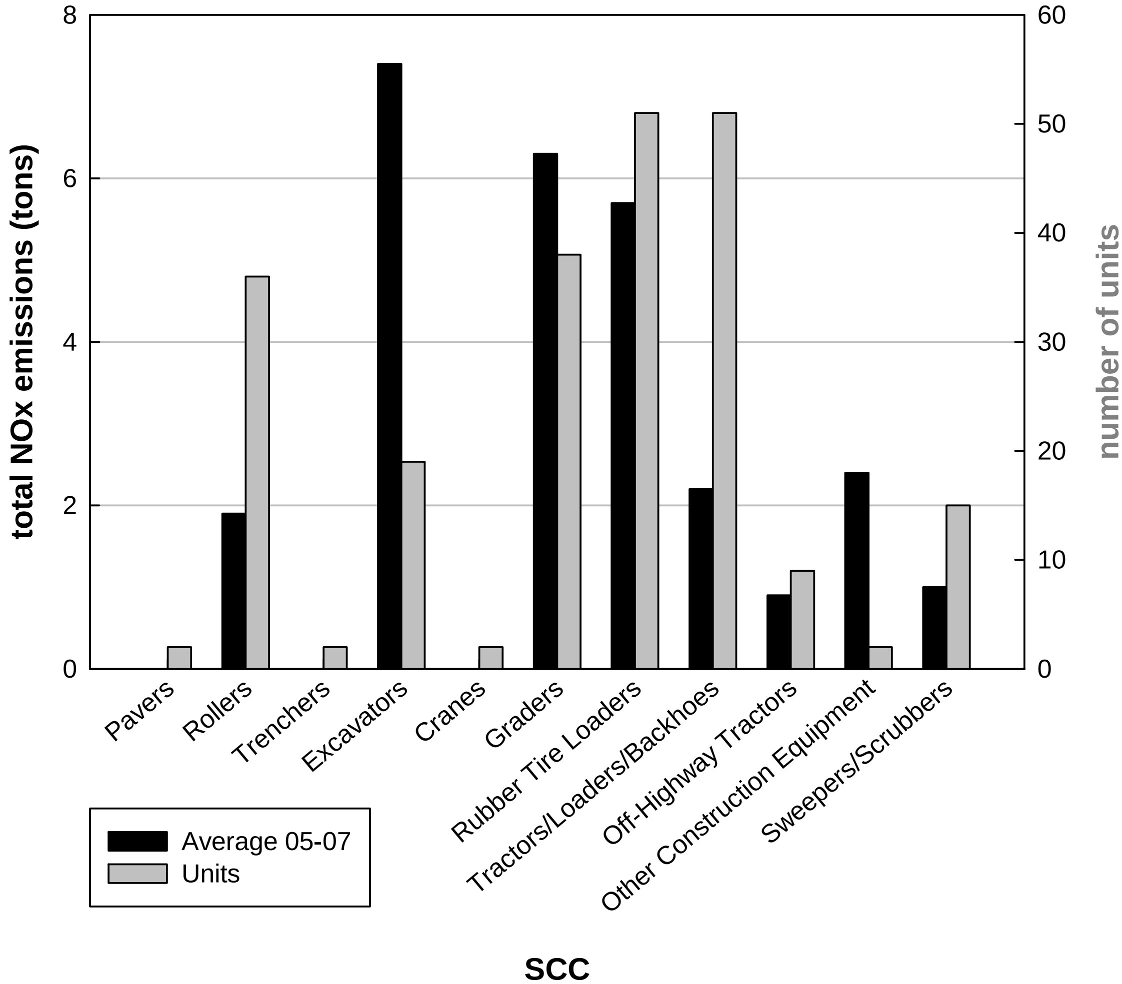

Figure 3. Total Average FY 2005–2007 NOx Emissions by Equipment Category – EAC Counties.

Criteria and Equipment Category Priority List

Researchers developed three major criteria to enable the selection of the equipment categories. In the order of importance, these criteria were:

1. total NOx emissions in FY 2007 and total average NOx emissions over FY 2005–2007,
2. number of units operating in all counties statewide, and
3. number of units operating in NA or EAC counties only.

When these criteria were applied to all 11 categories, the first two greatest NOx-emitting equipment categories (in all Texas counties as well as in NA and EAC counties) were graders and rubber tire loaders, as shown graphically in the previous section. Excavators ranked third overall but ranked first in total average NOx emissions over FY 2005–2007 in EAC counties. However, they were considered of secondary importance based on the large differences in total emissions and the lesser number of units statewide, in comparison with the first two categories. Table 4 presents the priority list and further classifies the equipment within each category by emissions tier.

Table 4. Priority Equipment Categories by Tier and County Status.

EPA SCC	**Tier**	**All Counties**			**NA Counties Only**	**EAC Counties Only**
		No. of Units (1471)*	Total NOx Emissions (Ton)		No. of Units (197)*	No. of Units (108)*
			FY 07	Average over FY 05-07		
Graders (TxDOT Classes: 90010/20/30/40)	Base	25	2.5	3.5	1	8
	Tier 0	198	51.3	57.6	24	11
	Tier 1	187	53.3	59.0	22	9
	Tier 2	114	23.9	24.0	13	10
	Tier 3	21	2.1	1.9	4	0
	Total	545	133.1	146.1	64	38
Rubber Tire Loaders (TxDOT Classes: 110010/20, 115000/10/20/30/40/50)	Base	22	2.7	2.8	1	6
	Tier 0	250	45.4	48.9	33	15
	Tier 1	312	40.4	43.3	43	22
	Tier 2	174	21.6	20.6	29	8
	Tier 3	24	1.0	1.0	2	0
	Total	782	111.1	116.6	108	51
Excavators (TxDOT Classes: 70010/20, 75010/20/30)	Base	2	0.0	0.1	0	0
	Tier 0	26	12.4	11.1	0	2
	Tier 1	75	33.3	35.9	19	10
	Tier 2	37	9.9	8.6	6	5
	Tier 3	4	0.6	0.6	0	2
	Total	144	56.1	56.3	25	19

** Total number units of all graders, loaders, and excavators are in parentheses.*

Based on the results in Table 4, TTI's original recommendation to the PMC regarding equipment selection in each category for emissions testing (baseline and after-treatment) was:

- graders: three pieces of equipment (one each from Tiers 0, 1, and 2),
- rubber tire loaders: three pieces of equipment (one each from Tiers 0, 1, and 2), and
- excavators: three pieces of equipment (one each from Tiers 0, 1, and 2).

SELECTION OF EMISSION REDUCTION TECHNOLOGIES FOR TESTING

The next step in developing a test protocol was to investigate fuel and engine technologies for non-road diesel equipment emissions reduction and to select appropriate technologies for emissions testing. The research team conducted a review of numerous technologies and selected nine of the most popular and/or promising technologies, which are briefly described in Chapter 2. Out of these nine technologies, five technologies were identified as possible candidates for NOx emissions reduction, the primary target pollutant for this project. After careful investigations of the five technologies, lean NOx catalyst technology was excluded from the candidates. With more specific information collected from vendors through the vendor-selection procedure (which is described later in this section), exhaust-gas recirculation technology was again excluded. Then, after examining the information, fuel-additive and hydrogen-enrichment technologies were recommended to the PMC and selected as the final two technologies for initial testing. Also, two vendors (one each for FA and HE) were selected. SCR technology was recommended as the third technology to be considered in this research. The remainder of this section describes the process by which these three technologies were selected, including the vendor-selection process.

Non-road Emission Reduction Technologies

Diesel emissions controls are generally achieved by:

- modifying the engine design,
- treating the exhaust (also referred to as after-treatment),
- modifying the fuel source, or
- using a combination of these controls as stated in Chapter 2.

The primary sources for information on diesel emission control devices and fuels/fuel additives are from EPA, CARB, and MECA (*1, 2, 3*).

Several different technologies are currently available for emissions reduction of non-road diesel equipment. Among numerous technologies, the most popular and/or promising emission reduction technologies were chosen and reported briefly in Chapter 2. Out of the nine technologies discussed, four technologies (diesel particulate filter, diesel oxidation catalyst, closed-crankcase ventilation, and biodiesel) are primarily targeted on PM emission reductions. These technologies were excluded from the technology selection because this project is focused on NOx reduction. The remaining five technologies, which reduce NOx emissions to various degrees, were therefore chosen as possible candidates. Table 5 summarizes the five chosen technologies.

Table 5. Candidate Technologies for NOx Emissions Reduction.

Technology	% Reduction*		Cost over 7 Years ($)**
	NOx	PM	
Selective catalyst reduction	75	25	17,000–30,000
Lean NOx catalyst	25	0	8,000–15,000
Exhaust-gas recirculation	40	0***	5,000–10,000
Fuel additives	5	0	500–2,500
Hydrogen enrichment	20	NA	6,000–10,000

** Some of the reduction percentages shown are estimates from on-road applications when no data were available for non-road construction equipment.*
*** Only limited pilot-scale projects have been applied for non-road applications. Costs presented here are based on estimates from several sources mentioned above including personal contacts with vendors.*
**** PM emissions will possibly increase so that another technology, such as a particulate filter, is needed to reduce PM emissions.*

Based on reviews of literature including reports from previous TTI studies conducted in cooperation with TxDOT (*7*, *8*) and information from EPA, CARB, MECA, and personal contacts with vendors, the five candidate technologies are described in detail in the following sections. It should be noted that, due to limited resources for non-road construction-equipment applications, some information is obtained only from on-road applications and/or non-road non-construction equipment such as emergency generators.

Selective Catalytic Reduction

Using a catalyzed substrate or a catalyst with a chemical reductant, an SCR system converts NOx to molecular nitrogen and oxygen. A reductant (ammonia or urea), which is injected into the exhaust gas, assists in the NOx conversion over a catalyst. When urea is used, urea decomposes thermally in the exhaust to ammonia, which serves as the reductant. As exhaust and reductant pass over the SCR catalyst, chemical reactions occur that reduce NOx emissions to nitrogen and water. An SCR system can be combined with a particulate filter for combined reductions of both PM and NOx. However, an SCR system is also effective in reducing hydrocarbon, carbon monoxide, and PM emissions even without any particulate filters. The performance of an SCR system is enhanced by the use of low-sulfur fuel.

Advantages. The advantages of an SCR system include:

- the system offers the greatest NOx emissions reductions among the candidates – 70 percent or more;
- it offers additional emissions reductions for PM (up to 50 percent), HC (up to 90 percent), and CO (up to 90 percent); and
- it is best suited to larger vehicles and equipment due to the need for a small separate tank of chemical reductant.

Disadvantages. The disadvantages of an SCR system include:

- the system cost is the highest among the candidates ($15,000–$25,000);
- an additional container for reductant and regular refilling of the reductant are needed;

- for best performance, an SCR system needs to be optimized by running the engine through a simulation of the operating cycle of the equipment – when actual operations are different from the simulated conditions, the effectiveness of the system decreases;
- by using ammonia as the reductant, ammonia slip (release of unreacted ammonia) may occur when catalyst temperatures are not in the optimal range for the reaction or when too much ammonia is injected into the process; and
- some manufacturers stated that they would not sell an SCR system alone but would sell an SCR with a PM reduction technology, such as a DPF, which would increase the system cost by 50 percent or more.

Products, Authentication, and Verification. Several companies are developing SCR systems, and some of these have been applied and tested in pilot-scale projects. Although stand-alone SCR systems have been successfully applied on boilers, such as large utility boilers, industrial boilers, and municipal solid waste boilers, SCR systems, in most cases, have been applied or tested with other PM technologies such as DPF and DOC for construction equipment. Currently, there are no stand-alone SCR systems verified by EPA or CARB for non-road construction-equipment applications. However, in conjunction with a DOC, one product is currently verified by CARB: the Extengine ADEC System. CARB Level 1 is verified for 1991 to 1995 model year off-road Cummins 5.9-liter 150- to 200-hp engines (applications to rubber-tired dozers, loaders, and excavators, and utility tractor rigs) with diesel (S < 500 ppm); reduction of PM is 25 percent or more, and reduction of NOx is 80 percent. Detailed information is available on the CARB website (*12*).

Cost (System). The cost of an SCR system ranges from $15,000 to $25,000. With a DPF system, the cost could range from $23,000 to $33,000.

Installation, Maintenance, and Operation. Installation time ranges from 2 to 5 days depending on the type of equipment, engine, exhaust, etc. The cost for installation ranges from $2,000 to $5,000. For maintenance, there is an additional cost for the reductant (e.g., $0.80 per gallon for urea), which needs to be refilled periodically.

Lean NOx Catalyst

An LNC system removes NOx from the exhaust by catalytically reducing NOx. Under lean conditions, an LNC uses diesel fuel as a reductant, which is injected into the exhaust gas to help reduce NOx over a catalyst. The NOx is converted to N_2O, CO_2, and H_2O. Without the added fuel and catalyst, NOx reduction reactions would not occur because of excess oxygen present in the exhaust.

Advantages. Currently, peak NOx conversion efficiencies typically are about 25 percent. However, some manufacturers have claimed conversion efficiencies of over 90 percent in theory.

Disadvantages. The main disadvantage of the system is that it has not been fully developed although some commercial products are currently available. In addition, LNC systems require supplemental fuel injection, which can cause a 4 to 7 percent fuel penalty.

Products, Authentication, and Verification. Some companies are developing LNCs. A few companies including Cummins are manufacturing commercial products. Currently, there are no LNC systems (either stand-alone or with other technologies) verified by EPA or CARB for non-road construction-equipment applications. However, in conjunction with a DPF, one product (Cleaire Longview™ System) is currently verified by CARB for on-road applications; information on this product is available from the CARB website (*27*).

Cost (System). The cost of an LNC system ranges from $6,500 to $10,000.

Installation, Maintenance, and Operation. Installation time ranges from 1 to 3 days depending on the type of equipment, engine, exhaust, etc. The cost for installation ranges from $1,000 to $3,000. For operation, there is an additional cost for fuel as the reductant – about 5 percent (up to 10 percent).

Exhaust-Gas Recirculation

Through an EGR valve, an EGR system accomplishes NOx emissions reductions by allowing exhaust gases to be recirculated into the intake manifold. Because the exhaust stream is composed of inert gas, blending some percentage of that gas into the intake mixture lowers the combustion temperature and thus reduces the formation of NOx. During these recirculation processes, PM emissions usually increase so that EGR systems require other technologies, such as a DPF, to reduce the increased PM emissions.

Advantages. The manufacturers claim the following advantages:
- NOx emissions are reduced by up to 50 percent; and
- on the basis of NOx reduction per unit cost, the EGR system is more cost effective than an SCR.

Disadvantages. The following are disadvantages of an EGR system:
- the EGR system increases PM emissions, which requires the EGR systems to be used in conjunction with other technologies, such as a DPF;
- the EGR system also increases fuel consumption (0 to 5 percent fuel penalty); and
- when used with filters, problems can occur between the engine and the EGR system that can lead to filter failure, and the cost for the system will increase.

Products, Authentication, and Verification. EGR systems are not yet widely applied. However, tests are continuously being performed for new commercial vehicles as well as retrofits. Currently, there are no EGR systems (either stand-alone or with other technologies) verified by EPA or CARB for non-road construction equipment applications. However, in conjunction with a DPF, one product (EGR/PERMIT™ DPF DECS) is conditionally verified by CARB for a stationary generator, and another product (Johnson Matthey, Inc., EGRT™ System) is currently verified by CARB for on-road applications. Information about these products is available on the CARB website (*28*, *29*).

Cost (System). The cost of an EGR system ranges from $4,000 to $8,000.

Installation, Maintenance, and Operation. Installation time ranges from 1 to 4 days depending on the type of equipment, engine, exhaust, etc. The cost for installation ranges from $1,000 to $2,000.

Fuel Additives

An FA is a product for use in conventional gasoline and diesel fuels to:

- improve the combustion characteristics of the fuels,
- reduce emissions, and
- increase fuel efficiency and engine power at a modest cost to the user.

FA manufacturers claim that their products can reduce emissions of NOx, HC, PM, and/or CO up to 25, 25, 50, and 30 percent, respectively. However, most of these claims are not officially verified or certified.

Advantages. FA manufacturers claim the following advantages. However, a single FA will have only some (but not all) of the advantages listed below:

- offers ease of use (i.e., there is no need to install an additional system and no additional installation costs);
- reduces additional emissions of other pollutants (PM, CO, and HC);
- increases the cetane number by up to six;
- decreases fuel consumption by about 3 to 15 percent;
- protects and cleans fuel injectors and pumps;
- increases engine power at the same or lower engine speed; and
- stabilizes stored fuel, especially biodiesel.

Disadvantages. The disadvantages of fuel additives could include:

- NOx reduction efficiency (about 5 percent) is the lowest among all candidates;
- emissions of one or more pollutants can be increased while reducing emissions of other pollutants and increasing fuel efficiency; and
- a predetermined amount of FAs need to be added when refueling unless an FA pre-mixed fuel is used.

Products, Authentication, and Verification. Many companies are manufacturing FAs including FBCs, which often are conjunctively used with a DPF. Manufacturers often claim that their products can reduce more than 10 percent of NOx, HC, PM, and/or CO emissions, and decrease fuel consumption by more than 15 percent. However, some product claims may be exaggerated, especially for emissions; most of their claims are not supported by verifiable data. For fuel efficiency, the manufacturers' claims are mostly not based on certified tests (e.g., reports from independent research institutes following standard procedure such as SAEJ1321) (*30*). Currently, there are no FAs verified by EPA or CARB except that EPA verifies cetane enhancers as verified retrofit technologies for on-road applications with 0 to 5 percent NOx reduction. However, EPA does not endorse the use of any particular company's product.

Cost and Operation. Costs for FAs range from $5 to $25 for each gallon. For operation, usually less than 1 percent of the product volume is needed to treat fuel. The additives are either pre-mixed with the fuel at the depot or via a dosing unit fitted to the equipment.

Hydrogen Enrichment

HE systems reduce engine exhaust emissions by creating a better flame front in the engine. Using an onboard hydrolysis device or catalytic fuel reformer, hydrogen gas is generated from a small amount of water or diverted fuel. The generated H_2 is added into the fuel intake manifold and delivered into the cylinders with the fuel. The hydrogen rich intake charge creates a better flame front because the mixture is more flammable. Because oxygen gas is also generated during the hydrolysis or reformation, the combined hydrogen and oxygen gases provide a better combustion on the power stroke, which results in emissions reductions. This cooler but more complete burn reduces the amount of diesel needed to power the engine so that fuel consumption also decreases.

Advantages. The manufacturers claim the following advantages:

- causes emissions reductions of up to 25 percent for NOx and 35 percent for CO,
- cleans the inside of the engine and removes deposits on the cylinder walls,
- decreases fuel consumption by about 10 percent, and
- increases engine power and torque.

Disadvantages. The disadvantages include:

- additional space is needed for the hydrogen generating device;
- for operations, a HE system needs battery power from the equipment or an additional generator; and
- regular refilling of deionized water is needed.

Products, Authentication, and Verification. A few companies are manufacturing HE systems. This is new technology; thus, only a limited number of tests have been performed. Currently, there are no HE systems verified by EPA or CARB.

Cost (System). The cost of an HE system ranges from $5,000 to $8,000.

Installation, Maintenance, and Operation. Installation time ranges from 1 to 3 days depending on the type of equipment, engine, exhaust, etc. The system needs battery power from equipment. The cost for installation ranges from $1,000 to $2,000. For maintenance, there is an additional cost for deionized water (e.g., $1.00 per gallon for 160 hours of operation), and the deionized water must be refilled periodically.

Technology Selection – NOx Emissions Cost Effectiveness Analysis

TTI researchers recommended three technologies (two for testing in the initial phase and an additional technology for further testing) from among five candidate technologies that were described in detail. Because this project focuses on NOx emissions reductions, costs for NOx emissions reduction were first examined through an analysis of cost effectiveness. Then, other critical factors like applicability to non-road equipment were considered based on specific information collected from vendors and other personal contacts.

For the NOx emissions cost effectiveness analysis, costs for NOx removal (C_{NOx}) are calculated using the following equation:

$$C_{NOx} = C_{tech}/(E_{NOx} \times R_{NOx})$$

where:

C_{tech} = costs for system, installation, and operation of a technology (over 7 years);
E_{NOx} = total NOx emissions of an off-road unit for 7 years; and
R_{NOx} = NOx emission reduction rate.

The 7 years in the above equation were determined based on information collected from literature and vendors, as discussed previously. Based on the information, the candidate technologies would operate for 7 years without any major failure or problems, requiring only regular maintenance, if any. Table 6 shows NOx reduction rates (taken from Table 2 in this report) and costs (average values from the cost ranges in Table 5) for the five candidate technologies. It should be noted that the analysis presented here shows preliminary results to assist with technology selection. Table 6 shows the NOx reduction rates, R_{NOx}. Note that these are estimates based on the collected information, not from actual testing. The actual costs for the technologies applied for equipment will vary from one piece of equipment to another.

Table 6. NOx Reduction Rates and Costs of the Candidate Technologies.

Technology	NOx Reduction Rate	Cost over 7 Years
Selective catalyst reduction	0.75	$23,500
Exhaust gas recirculation	0.40	$7,500
Lean NOx catalyst	0.25	$11,500
Hydrogen enrichment	0.20	$8,000
Fuel additive	0.05	$1,500

Table 7 shows the calculated costs for NOx removal over 7 years using the NOx reduction rates and the costs from Table 6 along with total NOx emissions (per year and over 7 years) for Tier 0, 1, and 2 graders, rubber tire loaders, and excavators.

Table 7. Results of NOx Removal Costs (C_{NOx}) for All Candidate Technologies.

EPA SCC	Tier	All Counties			C_{NOx} ($/1 Ton of NOx Reduced)				
		Units	Total NOx Emissions (Tons) (FY2007)	Total NOx Emissions for Each Unit over 7 Years (Tons)	SCR	EGR	LNC	HE	FA
Graders	Tier 0	198	51.3	1.81	17,274	10,337	25,360	22,052	16,539
	Tier 1	187	53.3	1.99	15,713	9,403	23,068	20,059	15,044
	Tier 2	114	23.9	1.47	21,320	12,758	31,300	27,218	20,413
Rubber Tire Loaders	Tier 0	250	45.4	1.27	24,658	14,756	36,201	31,479	23,609
	Tier 1	312	40.4	0.91	34,592	20,700	50,784	44,160	33,120
	Tier 2	174	21.6	0.87	35,994	21,539	52,842	45,949	34,462
Excavators	Tier 0	26	12.4	3.33	9,407	5,629	13,810	12,009	9,006
	Tier 1	75	33.3	3.10	10,096	6,042	14,822	12,889	9,667
	Tier 2	37	9.9	1.87	16,750	10,023	24,591	21,383	16,037
				Average	20,645	12,354	30,309	26,355	19,766

As shown in Table 7, costs for reducing 1 ton of NOx emissions, C_{NOx}, are the lowest for EGR followed by FA, SCR, HE, and LNC, respectively. From the lowest amount, the costs are $12,354 for EGR, $19,766 for FA, $20,645 for SCR, $26,355 for HE, and $30,309 for LNC for 1 ton of NOx removal (on average for graders, rubber tire loaders, and excavators combined). For an EGR system, however, an additional PM control device, such as a DOC or a DPF, is needed as discussed previously. Based on information obtained at this stage of the project, no vendors have supplied an EGR plus DOC system. Considering the addition of a DPF in an EGR system, the resulting system cost increases by about $8,000, which totals $25,532 for C_{NOx} for an EGR system with a DPF. Thus the final C_{NOx} costs considered in this analysis are $19,766 for FA, $20,645 for SCR, $25,532 for EGR plus DPF, $26,355 for HE, and $30,309 for LNC.

As previously stated, C_{tech} used for calculating C_{NOx} can vary up to about ± 30 percent depending on the ranges of C_{tech} estimates in Table 5. Comparing FA, which has the lowest C_{NOx}, SCR, EGR plus DPF, and HE are in the range of about 30 percent variation. C_{NOx} for LNC is more than 50 percent higher than that of FA. In addition, LNC has not been used much in off-road applications or on-road applications. Therefore, TTI researchers excluded LNC technology from the final selection.

Evaluation for Final Technology Selection

With limited information currently available from vendors and other sources, Table 8 lists C_{NOx}, R_{NOx}, and critical factors for technology selection of the final four candidates.

Table 8. Considering Factors for Final Candidate Technologies.

Technology	C_{NOx}	R_{NOx}	Critical Factors
FA	$19,766	0.05	R_{NOx} is mostly based on vendor's claims so that actual testing results can be smaller.
SCR	$20,645	0.75	Addition of DPF increases C_{NOx} by 34 percent.
EGR + DPF	$25,532	0.40	Some vendors stated that EGR technology is not suitable for non-road construction applications.
HE	$26,355	0.20	R_{NOx} is mostly based on vendor's claims so that actual testing results can be smaller or greater.

As shown in Table 8, TTI researchers found that the following critical issues need to be considered:

- With 0.05 of R_{NOx} (i.e., 5 percent of NOx reduction), FA shows the least amount of C_{NOx}. However, based on TTI's experience with FA testing, it is known that R_{NOx} could be much smaller, resulting in an increased C_{NOx} value. For example, 3 percent of NOx reduction instead of the 5 percent assumed increases C_{NOx} to $32,944, which is higher than that of LNC.
- SCR shows the highest R_{NOx} and the second lowest C_{NOx}. However, R_{NOx} can be decreased if an SCR system is not optimized. Additionally, depending on vendors, C_{NOx} will increase to $27,673 with the addition of a DPF, making the cost higher than that of HE.
- R_{NOx} for an EGR system (EGR plus DPF) is the second highest, and there are no additional system costs because a DPF is already included. However, EGR technology has been scarcely applied on non-road construction equipment. In addition, TTI researchers collected information that one application (among few) of an EGR on non-road construction equipment was not successful, and a vendor who sells EGR plus DPF systems for on-road applications stated his belief that EGR technology is not appropriate for non-road construction equipment.
- HE shows the highest amount of C_{NOx} with 20 percent NOx reduction. Because HE has not been applied for non-road construction equipment, the R_{NOx} values may deviate significantly from 0.20. If R_{NOx} is more than 0.2, C_{NOx} will decrease. For example, 0.25 of R_{NOx} decreases C_{NOx} to $21,084, which is close to those of SCR and FA.

Based on the current, but limited, cost information, NOx reduction rates, applicability to non-road construction equipment, and specific issues stated above, TTI researchers selected FA and HE technologies for initial testing. The two main reasons for excluding EGR plus DPF technology were the testimonial of a city official that their applications of EGR systems on non-road construction equipment had not been successful and a vendor's statement that he/she believed that EGR technology is not appropriate for non-road construction equipment. For SCR technology, TTI researchers had difficulties in finding vendors who would supply a maximum of nine SCR systems (total costs would be up to $300,000) free of charge. Therefore, SCR was excluded for initial testing but remained the best candidate for further testing, mainly because of the highest NOx reduction rate.

Vendor Selection

TTI researchers investigated vendors extensively for the five candidate technologies: EGR, FA, HE, LNC, and SCR. The researchers contacted a large number of vendors and asked them general and specific questions about their technologies and products. After careful examination of the responses, some of them were used for the technology selection, while others were used for vendor selections. For final vendor selection for FA and HE technologies, more specific questions regarding costs, emission reduction data, and willingness to participate in the project were asked to more than 10 vendors. After examining the respondents' answers, two candidates (Carbon Chain Technologies Ltd. for FA and GoGreen Fuel, Inc., for HE) were recommended to the PMC and chosen for the initial testing.

For vendor selections, TTI researchers and TxDOT participants agreed during the progress meetings that:

- TTI would prepare questionnaires for technologies and agreements between participants and TTI, and submit them to the PMC for review;
- TTI would distribute questionnaires and collect the responses from vendors; and
- based on the collected information, TTI would recommend one vendor for each technology.

The questionnaires contained both general and specific questions about technologies and vendors' products. For the FA and HE technologies, two different draft questionnaires were prepared and are provided in Appendices E and F. After careful examination of the responses (mainly costs [for technology, installation, and maintenance, if any], emission reduction data, and willingness to participate [free of charge and warranty] in this project), two candidates (Carbon Chain Technologies Ltd. for FA and GoGreen Fuel, Inc., for HE) were chosen.

After the vendors had been selected, agreements between TTI and the vendors were drafted, and submitted to the PMC for review. The following aspects were covered in the agreements:

- vendors will provide their technologies free of charge;
- vendors will install their technologies and supply any necessary parts or accessories needed for normal operations free of charge;
- if TxDOT is not satisfied with the technology, vendors will uninstall their technologies and return TxDOT equipment to its original condition free of charge;
- vendors will follow the testing schedule and protocol set by TTI; and
- test results will be available to the public — however, there will be no endorsements of the products or vendors from TxDOT or TTI.

DEVELOPMENT OF DUTY CYCLES FOR SELECTED EQUIPMENT

Duty cycles are developed to replicate actual operating conditions for the equipment selected for PEMS testing. As a part of the Phase 1 report, duty cycles were developed for both graders and rubber tire loaders. Since the final test results presented in this report only deal with graders, the duty cycle development is only presented for graders. Readers may refer to the Phase 1 report for more information on other duty cycle development.

The research team conducted interviews with TxDOT personnel, literature searches, and general web searches to obtain information on diesel-powered non-road equipment. The research team also visited TxDOT work sites and recorded the activities of selected non-road equipment during their normal operations, and developed simplified and repeatable duty cycles that would replicate actual operating conditions for the selected equipment under TxDOT's operating conditions.

The development of the duty cycles for the selected equipment categories comprised three major steps: methodology selection, site visits and data collection, and duty cycle development. In the methodology selection step, researchers concluded that a task-based approach would be more suitable for portable emission measurement system testing and recommended the approach to the PMC, and the PMC approved it for this study. After selecting the types of equipment for testing, TTI staff members visited TxDOT work sites to collect data regarding the operational characteristics of the selected equipment. These site visits included interviewing equipment operators and project managers as well as observing and recording activities of the selected pieces of equipment during their normal operations.

A portable global positioning system (GPS) was also installed on the selected pieces of equipment to track their movement and operation distance. Additionally, the research team obtained engine operation data from Eastern Research Group (ERG), a consulting firm. ERG had collected engine operation data from a sample of TxDOT non-road equipment for a previous Research Management Committee (RMC) project: 0-4576, "Emulsified Diesel Emission Testing" (*31*). The data included second-by-second readings of engine speed (rpm), engine load (percent), and throttle position (percent) for a rubber tire loader and an excavator. These data were used for quality control.

Methodology Selection

Non-road equipment relies on its engine both to operate the equipment and to provide power for attachments such as buckets, shovels, and blades. A duty cycle for non-road equipment is defined as the sequential tasks that are performed by the equipment to produce a unit of output (*32*).

The existing emission testing procedure for non-road equipment is based on testing the engines on engine dynamometers. For example, the current federal duty cycle for non-road applications is an eight mode steady-state cycle for engine dynamometer testing. The procedure is explained in 40 Code of Federal Regulations (CFR) Part 89 Subpart E (*33*). In cooperation with the authorities in the European Union, EPA has also developed a transient driving cycle for mobile non-road diesel engines named non-road transient cycle (NRTC). The NRTC is a 1200 second long transient cycle developed for dynamometer testing. The developed cycle will be used for certification type approval testing of some non-road diesel engines, with full implementation occurring over 6 years.

PEMS technology provides the capability of emissions measurement under real-world operating conditions. A duty cycle for PEMS testing of non-road equipment can use either task-based or engine-based modes. A task-based cycle is comprised of a sequence of different tasks performed by the equipment, and an engine-based cycle consists of a series of steady-state and transient engine loads.

EPA is now considering a more flexible approach for its newest emissions model, Motor Vehicle Emission Simulator (MOVES). Three potential methods using PEMS data to generate non-road emission rates for MOVES were investigated by the University of California at Riverside (UCR), Environ Corporation, and North Carolina State University (NCSU) (*34*). UCR pursued a database approach by constructing macro-, meso-, and micro-level emissions lookup tables based on individual vehicle and duty cycle results. NCSU applied a modal binning approach in which the operational modes of the non-road vehicles were defined based on changes in engine speed and exhaust flow. Finally, Environ Corporation divided the second-by-second PEMS data into a series of micro trips. The literature shows that the task-based approach is superior when using PEMS technology (*35*, *36*).

Development of Duty Cycle for Graders

A grader, also commonly referred to as a motor grader, is a construction vehicle with a large blade used to create a flat surface. TxDOT uses graders in two major operations: to maintain asphalt overlay and to spread and level base layer material to create a wide flat surface for asphalt.

In order to identify the in-use operational characteristics of TxDOT graders, the research team coordinated site visits to a sample of TxDOT work sites. The visits included a visit to TxDOT's maintenance office in Brenham followed by a visit to a road maintenance work site on FM 109 located southwest of Brenham. The TTI staff interviewed the site managers, support crew, and equipment operators at both sites.

According to the TxDOT operators, the TxDOT graders are mostly (more than 80 percent of their operation time) used for asphalt overlay maintenance operation (hot mix or reclaimed asphalt) and the rest of the time for base layer preparation. The operators stated that both types of operations are similar in terms of tasks, and the only difference would be the type of material they are working with. During both operations, the graders are used to level the material (asphalt or base material) on a surface in several runs.

The leveling task is conducted only in a forward run. If there is not enough space to make a turn at the end of a forward run, the operator lifts the blade and backs up to reach the starting point, and then repeats another forward run. Figure 4 shows the blade positions of a grader in forward and backward run maneuvers. The operators stated that when there is enough room for a U turn maneuver at the end of a forward run, they turn around and perform another forward (leveling) run.

Figure 4. Grader Blade Position in Forward (Left) and Backward (Right) Movements.

The graders that TxDOT operates mostly have six or seven forward and two or three backward gears. The interview with operators also revealed that they only use one gear during a leveling movement (forward run). The gear selection depends on the types of material they are working with. Hot mix asphalt usually needs higher speed; therefore, operators often use the third gear, while for other materials they can utilize either the second or the third gear.

The graders are usually driven to the work site unless the distance is more than approximately 25 miles. For distances farther than 25 miles, they are transported by a flatbed trailer operated by TxDOT. The top speed of the graders in driving mode varies between 20 mph and 30 mph depending on their makes and models.

TTI researchers recorded video footage of grader operation during the site visit. A GPS unit was also installed on the grader to track its movement during the operation. TTI researchers processed the GPS data, video recordings, and information obtained from the operators. Four distinct tasks were identified for a grader:

1. idling,
2. leveling maneuver: forward movement with engaged blade (blade in down position),
3. backward movement with unengaged blade (blade in lifted position), and
4. driving to/from the work site (forward movement with unengaged blade).

For tasks 2 and 3 a grader is operated at speeds lower than 5 mph. When moving to/from the work site (task 4), speeds are usually between 20 mph and 30 mph. For the purpose of this study, all tasks are assumed to occur when the testing equipment is in hot-stabilized condition. A minimum of 20 minutes of idling is considered at the beginning of the testing to ensure that test vehicles have reached hot stabilized condition.

A duty cycle was developed to represent a broad range of the operational modes of a TxDOT grader. The proposed duty cycle includes all four tasks that were identified. Table 9 describes the characteristics of the tasks in this duty cycle. Leveling and backup tasks (tasks 2 and 3) need to be executed at a constant speed for each task.

Table 9. Tasks of Proposed Duty Cycle for Motor Graders.

Task	Description	Duration (s)	Distance (yd)
1. Idling	Hot stabilized idling between leveling sub runs	30	N/A
2. Leveling	Forward move with blades engaged in leveling operation	N/A	70
3. Backup	Reverse move with blades unengaged	N/A	70
4. Driving 1	Forward move with blades unengaged at maximum speed	N/A	500
5. Driving 2	Forward move with blades unengaged at 20 mph	N/A	500

N/A: not applicable.

Two different driving tasks ("driving 1" and "driving 2") are considered to provide the necessary data for the purpose of emissions comparison. The first driving task is set to reach the maximum speed, while the second driving task is set at 20 mph. The maximum speed driving task intends to capture the emissions characteristics of the equipment at its maximum load, while the 20 mph speed intends to provide consistent emissions data for comparison purposes. The driving tests must be executed on a paved road.

After idling for about 20 minutes, a TxDOT operator will move the test grader at the beginning of the 500 yard paved portion of the test road designated for the driving task. After at least 1 minute of idling, the operator will be asked to accelerate the grader to reach the maximum speed and maintain the speed until the end of the test section. The operator will then reduce the speed at the end of the test section and turn around and stop for at least 30 seconds. Then, the operator will repeat the maximum speed driving task in the opposite direction (i.e., heading back to the starting position).

After returning to the starting point and turning around, the grader will stop and idle for at least 30 seconds. Then, there will be another round of driving from the starting position to the other end of the 500 yard paved road and back to the starting position. However, during this driving task the grader will accelerate to 20 mph and maintain this speed until the end of the paved test road. The grader will stop and idle for at least 30 seconds at the end of the road before driving back to the starting position.

After the driving portion of the duty cycle is completed, the leveling/backup parts will be tested. The leveling/backup testing will be performed in a bed of the base material, Colorado rocks. Figure 5 shows the 10 inch deep bed covered with 206 tons of Colorado rocks on a paved road. The size of the bed is 70 yards long and 10 yards wide.

Figure 5. Bed for Leveling/Backup Testing.

Each run of the developed leveling/backup duty cycle consists of three leveling sub runs and one repetition of the driving tasks. Each of the first and second leveling sub runs consists of two leveling tasks with one backup task in between. The third sub run has only one leveling task. At the end of each leveling sub run, the test grader will turn around and perform another leveling sub run. A 30 second period of idling has been considered between each leveling sub run. Figure 6 shows this process graphically.

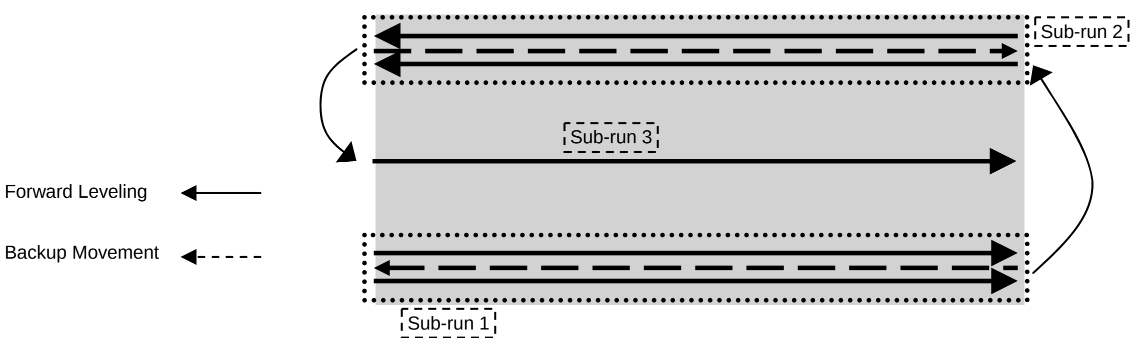

Figure 6. Leveling Portion of Graders' Duty Cycle.

After completing the leveling/backup parts of the cycle, the grader will return to the starting position for the driving tasks to repeat the entire duty cycle. The entire duty cycle (including driving 1 and 2, leveling, and backup) will be repeated at least three times to obtain statistically meaningful data.

CHAPTER 4: METHODOLOGY FOR OPTIMIZING DEPLOYMENT OF EMISSION REDUCTION TECHNOLOGIES

In addition to research on the use of emission reduction technologies for TxDOT's non-road fleet, an additional issue is one related to the actual deployment of these technologies to maximize their benefits. Usually, an agency such as TxDOT would have a fixed amount of money that could be allocated to the deployment of emission reduction technologies. In addition to budgetary constraints, the following also need to be given consideration:

- the types of technologies being applied;
- the types of non-road equipment, as well as the specific pieces selected for deployment; and
- the area of operation of the non-road equipment on which the emission reduction technologies are applied.

This chapter discusses a methodology that has been developed for a model that can optimize the deployment of emission control technologies on a fixed budget. The methodology is currently being demonstrated for three technologies; however, it can be modified to optimize deployment for any single technology or combination of available ones. The methodology also takes into account the efficiency of the various technologies; thus, results from testing can be used to further improve the deployment.

OPTIMIZATION APPROACH

The objective was to develop methodologies that will help to deploy emission reduction technologies for TxDOT's non-road equipment to reduce emissions in a cost effective and optimal manner. The study focused on the counties of Texas that have NA and NNA status. Three technologies were considered for deployment in this research: hydrogen enrichment, selective catalytic reduction, and fuel additives. Combinations of technologies were also considered in the study. Two approaches were investigated in this research. The first approach was "Method 1" in which all the technologies, i.e., FA, HE, and SCR, were deployed in the NA counties in the first stage. In the second stage the same technologies were deployed in the NNA counties with the remaining budget, if any. In the second approach all the technologies were deployed in the NA counties along with deploying only FA in the NNA counties in the first stage. Then with the remaining budget, SCR and HE were deployed in the NNA counties in the second stage. In each of these methods, two options were considered, i.e., maximizing NOx reduction with and without fuel economy consideration in the objective function. All these four options were programmed with Visual C++ and ILOG CPLEX. The alternative options described in this study will assist the decision makers to decide about the deployment preference of technologies.

PROBLEM STATEMENT

Texas has a total of 254 counties, of which 20 are NA counties and 3 are NNA counties, as shown in Figure 7. The figure also shows the TxDOT districts that contain the 8 hour ozone NA and NNA counties. These NA and NNA counties have different types and numbers of construction equipment. Given a certain budget, TxDOT can utilize the budget to deploy emission reduction technologies to minimize emissions from the equipment in these NA and NNA counties. Reducing the emission levels from the equipment fleet is a benefit to society through improved health and to public agencies through reaching conformity and attainment. However, purchasing these emission reduction technologies is a cost to TxDOT. Therefore, it is essential for TxDOT to use its budget in an optimal and effective way to deploy the emission reduction technologies to reduce emissions from its fleet in a cost effective manner.

As mentioned earlier, ozone NA is the main issue of concern to TxDOT. NOx is a precursor of ozone and is therefore the primary target pollutant for this optimization methodology. The purpose of this exercise was to develop a model for optimal deployment of emission control technologies. The goal was primarily to minimize cost-related emissions from the construction equipment fleet based on relevant economic, operational, and technical constraints. The model will enable TxDOT to quickly decide how to utilize a given budget as effectively as possible to maximize the benefit of reducing emissions from the construction equipment. For the purpose of this study, the optimization model focused on deploying a limited set of emission reduction technologies: HE, FA, and SCR for the construction equipment in the NA and NNA counties. However, the model could be easily upgraded and expanded to consider more technological options and be practically implemented and used. The model was tested through utilizing TxDOT's construction equipment fleet's data of NA and NNA counties in Texas.

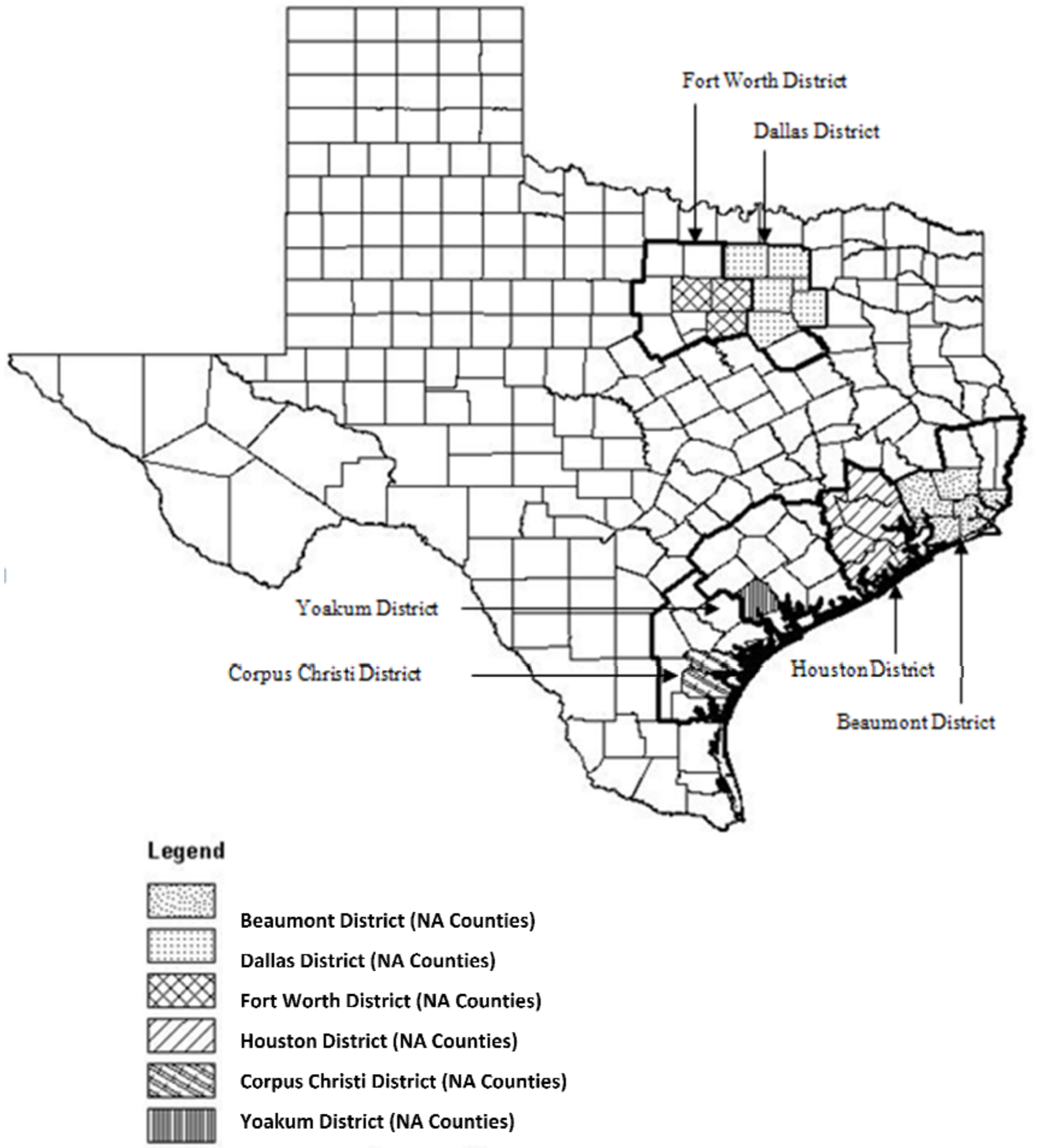

Figure 7. NA and NNA Counties of Texas.

DATA REQUIREMENTS AND DATA ASSEMBLY

This section specifies the major data needs for this optimization methodology procedure. A majority of the data required were assembled through previous tasks on this research.

TxDOT's Non-road Equipment Database

TxDOT's non-road fleet includes equipment such as graders, loaders, excavators, pavers, rollers, trenchers, cranes, and off-highway tractors. Chapter 3 describes the contents of TxDOT's non-road equipment database in detail. Information in this database was utilized to estimate the emissions from the non-road fleet using EPA's guidelines and procedure.

Emission Reduction Technologies

Three emission reduction technologies were considered in this study for demonstrating the model – HE, SCR, and FA. Two combinations of technologies were also considered, i.e., HE with FA and SCR with FA. The model is flexible enough to apply to other sets of emission reduction technologies. Literature reviews and surveys conducted in previous tasks provided information regarding the availability of the technologies, the different costs associated with them, operational requirements, fuel economy, and emission reduction efficiencies. The different categories of costs considered in this model include purchasing cost, installation cost, operation cost, and maintenance cost of each technology. Fuel cost is also considered in this investigation. The Energy Information Administration (EIA) updates the gasoline and diesel price, and the current cost of diesel was $2.216 per gallon (*37*). The combined NOx reduction efficiencies were estimated based on consultation with the HE and SCR vendors.

The vendors also provided information on other constraints that affected the model – for example, the SCR vendor mentioned that SCR was not available for equipment having horsepower less than 100 hp. They stated that the cost of the SCR system and size of the components made the system impractical to retrofit on such small mobile engines. Therefore, this consideration was also included in the model formulation stage. Table 10 summarizes the information regarding the selected technologies that were used in formulating the model.

Table 10. Data Regarding the Selected Emission Reduction Technologies.

Technology		HE	SCR	FA
Purchasing, Installation Cost ($)		8,400	17,100**	18***
Operation Cost ($)		-	0.25/hour	-
Maintenance Cost ($)		100/year	0.75/hour	-
Dosage Rate (ml)		-	-	4.25****
Fuel Efficiency (%)		8*	−1	-
Reduction Efficiency (%)	NOx	36	80	5.8
	$PM_{2.5}$	-	-	-
Combined Reduction Efficiency (%)	NOx	41.8	81.16	-

* *after 240 hours of operation.*
** *within 101 to 300 hp.*
*** *per gallon of FA used.*
**** *per gallon of diesel used.*

Air Pollution Damage Cost

The damage cost of NOx was obtained from the Highway Economic Requirements System (HERS) model developed for FHWA. HERS employs damage costs (for different pollutants) that were derived from the study performed by McCubbin and Delucchi (*38*). The damage cost for NOx used in the HERS model is $3,625 per ton. This damage cost for NOx was used in this model (*39*).

Criteria for Deployment of Emission Reduction Technologies

TxDOT's preferences were obtained regarding the deployment criteria through consultation with TxDOT's fleet management staff. They proposed that in order to retrofit a piece of equipment, it must have a remaining age and remaining usage hours equal to at least 50 percent of its expected age and expected usage hours before disposal. The data regarding the usage hours and the age at disposal of equipment were obtained from the TxDOT fleet database. About 25 percent of the equipment had sufficient remaining age and remaining usage hours for satisfying the above requirement.

In order to deploy the emission control technologies, TxDOT staff expressed that they prefer to allocate their budgets first in the NA counties. Then the remaining budgets were to be allocated in the NNA counties. All these considerations were incorporated while formulating the optimization model.

MODEL DEVELOPMENT

Overall Approach

The overall approach involved several steps that included development of the model and development of the deployment plan of emission control technologies. These steps were development, testing, and refinement of the model, and development of the deployment plan. Figure 8 presents the flow diagram of the overall process.

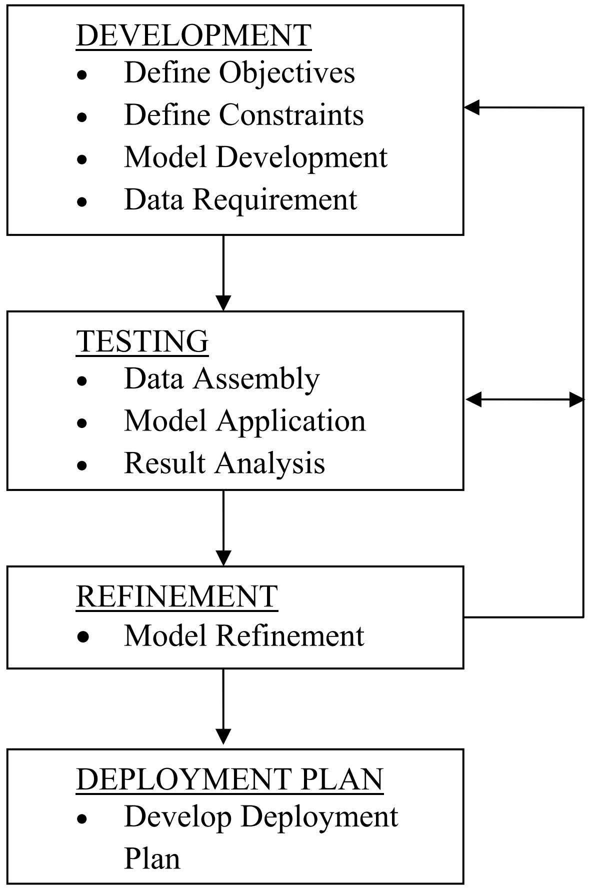

Figure 8. Flow Diagram of the Overall Approach.

Defining the Problem

The purpose of this task was to develop a model that will propose a deployment plan of emission control technologies for the selected categories of construction equipment, namely graders, loaders, and excavators. These categories of equipment were selected since they were the highest NOx emitting equipment in Texas, as shown in Chapter 3.

In addition to this, TxDOT proposed some equipment selection criteria and the location preferences for developing the deployment plan:

- For a piece of equipment to be retrofitted, it must have a remaining age and remaining usage hours equal to at least half of its expected age and expected usage hours before disposal.
- In terms of location preferences, TxDOT intended to focus on allocating the budgets in the NA counties first. Afterwards, the remaining funds were to be allocated in the NNA counties.

Three emission reduction technologies – HE, SCR, and FA – were selected for deployment. Constraints related to the technology application included:

- The SCR system was not available for equipment having horsepower less than 100 hp.
- According to TxDOT, each county has a diesel tank from which all the equipment located in that county is fueled. Therefore, FA had to be deployed in the county as a whole. In other words, if a piece of equipment of a particular county was selected for having FA, the rest of the equipment of that county would also receive FA; i.e., either the whole county receives the fuel additive, or it does not receive it at all.
- In order to estimate the total amount of fuel additive required of a county, the diesel requirement for other categories of equipment ("others") in excess of graders, loaders, and excavators also needed to be taken into consideration.
- Combinations of technologies were also considered in this problem. That is, a piece of equipment could have either HE or SCR along with a fuel additive. A combination of SCR and HE was not considered in this study. The combined reduction efficiencies of the technologies were estimated based on the recommendations of the respective vendors.

Possible Deployment Approaches

Figure 9 shows the schematic representation of the possible ways the emission reduction technologies can be deployed among different counties. The notations used in the figure are as follows:

- i = different counties; i = 1, 2…N (here N = 32).
- j = different categories of construction equipment at each counties; j = 1, 2, 3, 4 (grader, loader, excavator, and others).
- k = total unit number of j type equipment at each county.
- q = different types of emission reduction technologies; q = 1, 2…..n (here n = 3).
- I_{ijkq} = binary variable.

The ovals represent the different counties. The circles contained in each oval represent different categories of construction equipment, and at the bottom the rectangles represent the several emission reduction technologies to be deployed among each of the counties. The path shows the possible ways the technologies can be deployed. The model developed in this study helps to identify which path to select for optimal deployment of technologies.

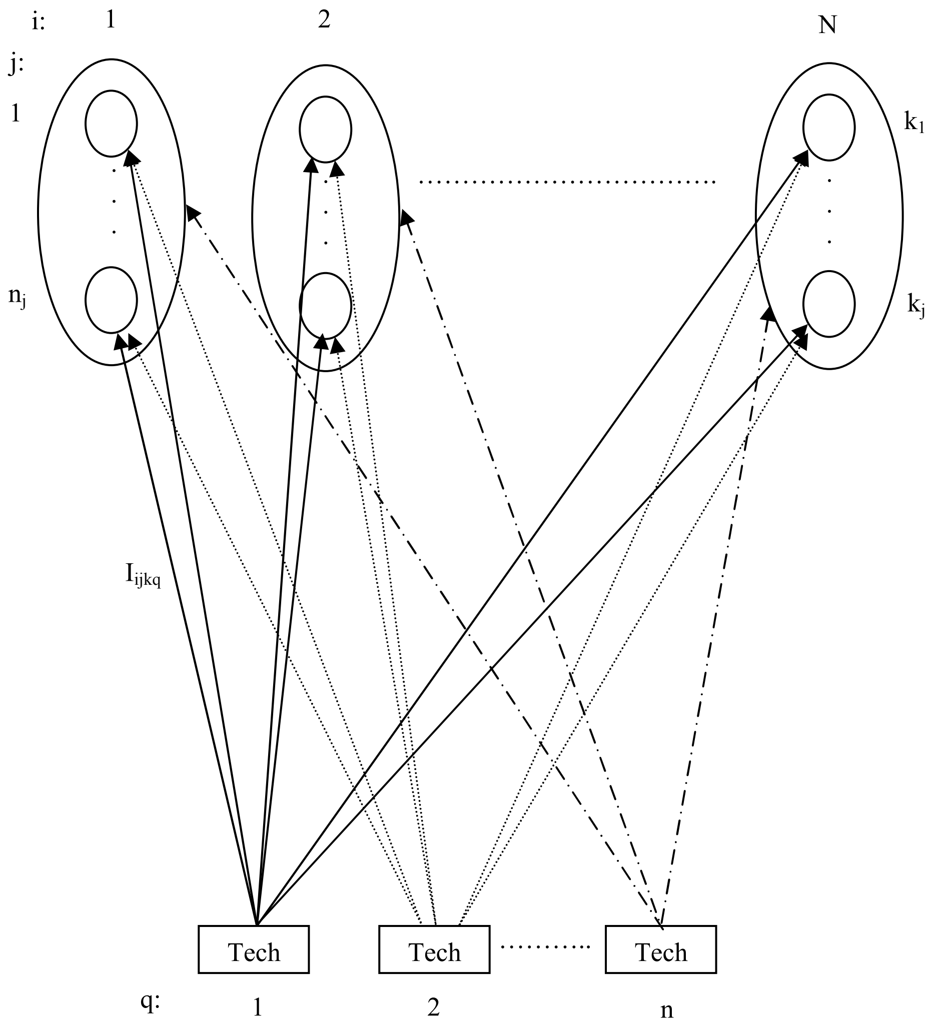

Figure 9. Possible Ways of Deploying Emission Reduction Technologies.

Two different approaches were followed for developing the model. In the first approach, Method 1, the technologies, i.e., FA, HE, and SCR, are optimally deployed only in the NA counties in the first stage. After that, in the second stage, the same technologies are deployed in the NNA counties with the remaining budget, if any. In the second approach, Method 2, all the technologies are optimally deployed in the NA counties along with the deployment of the FA only in the NNA counties in the first stage. Then with the remaining budget, SCR and HE are deployed in the NNA counties in the second stage. Method 1 strictly follows the guidelines provided by TxDOT; Method 2 has been evaluated in this research as an alternative and potentially better technology deployment policy. Fuel efficiency/penalty is another consideration that can be included in the model. HE increases fuel efficiency, whereas SCR causes a fuel penalty. The overall economic effect of a chosen deployment is therefore influenced by these effects. The two different approaches (Methods 1 and 2) can then be more precisely evaluated by considering these fuel economy benefit/penalty effects. Table 11 summarizes this analysis scheme.

Table 11. Analysis Scheme of the Study.

Approach	Options	Case
Method 1 (In first stage, deploy FA, HE, & SCR in NA counties; in second stage, deploy same technologies in NNA counties with remaining budget, if any)	NOx reduction with fuel economy	Case 1A
	NOx reduction without fuel economy	Case 1B
Method 2 (In first stage, deploy FA, HE, & SCR in NA counties and FA in NNA counties; in second stage, deploy either SCR or HE on any given equipment in NNA counties with remaining budget, if any)	NOx reduction with fuel economy	Case 2A
	NOx reduction without fuel economy	Case 2B

Model Formulation

The formulation of the model involved an approach to developing an optimization methodology based on the constraints and parameters outlined previously. This section describes the approach in detail. The set *C* is defined as the set containing the NA and NNA counties, indexed by c. Let n_c be the total number of counties in consideration. In this case, n_c is equal to 32 considering all the NA and NNA counties in Texas. The set E is the set of different categories of construction equipment indexed by e, and let n_e be the total categories of construction equipment to be considered. In this study, n_e is equal to 4, i.e., grader, loader, excavator, and others. Let n_{ce} be the total number of equipment of category e in county c, and each piece of equipment is indexed by i. Set P represents the set of different pollutants indexed by p, and n_p represents the total number of pollutants to be considered. In this case, n_p is equal to 1. Set T represents the set of emission reduction technologies indexed by t, and let n_t be the total number of emission control technologies to be considered. In this study n_t is equal to 3.

Let Em represent the emissions from a particular piece of equipment. C_p is the cost of pollutant p, and R_{pt} represents the emission reduction efficiency of technology t for pollutant p. The variable I represents a binary variable, and its value is 0 or 1. If a particular technology is selected for a piece of equipment, the value of I will be 1; otherwise, it will be 0.

The cost of emissions of pollutant p from i^{th} equipment of category e of county c is $Em_{c,e,i,p}C_p$. If technology t is applied on that piece of equipment, the emission reduction benefit would then be $Em_{c,e,i,p}C_pR_{p,t}I_{c,e,i,t}$. The final expression for total emission reduction benefit is:

$$\sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{p=1}^{n_p}\sum_{t=1}^{n_t} Em_{c,e,i,p}C_pR_{p,t}I_{c,e,i,t} \quad (1)$$

Let the fuel consumption of a piece of equipment be $F_{c,e,i}$. Let the cost per gallon of fuel be C_F, and let the fuel efficiency of technology t be FE_t. If the technology selected causes a fuel penalty, the value of FE_t will be negative. Therefore, the expression for fuel efficiency/penalty is $F_{c,e,i}\,C_F\,FE_t\,I_{ceit}$. The final expression for total fuel efficiency/penalty is:

$$\sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{t=1}^{n_t} \mathrm{F}_{c,e,i}\mathrm{C}_{F}\mathrm{FE}_{t}\mathrm{I}_{c,e,i,t} \tag{2}$$

Objective Function

Therefore, the final expression of the objective function optimizing both emission reduction benefits and fuel economy benefits is given in Eq. (3):

$$\text{Maximize Z} = w_1\sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{p=1}^{n_p}\sum_{t=1}^{n_t} \mathrm{Em}_{c,e,i,p}\mathrm{C}_{p}\mathrm{R}_{p,t}\mathrm{I}_{c,e,i,t} + w_2\sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{t=1}^{n_t} \mathrm{F}_{c,e,i}\mathrm{C}_{F}\mathrm{FE}_{t}\mathrm{I}_{c,e,i,t} \tag{3}$$

In the above equation, w_1 and w_2 are the weights associated with emission reduction benefit and fuel economy benefit, respectively. The value of w_1 and w_2 can vary from 0 to 1 depending upon which case (see Table 11) is considered. The values of w_1 and w_2 for different cases are summarized below:

- Case 1A: $w_1 = 0.5$ and $w_2 = 0.5$,
- Case 1B: $w_1 = 1$ and $w_2 = 0$,
- Case 2A: $w_1 = 0.5$ and $w_2 = 0.5$, and
- Case 2B: $w_1 = 1$ and $w_2 = 0$.

We note that w_1 and w_2 in Cases 1A and 2A can also be different than 0.5 (still summing up to 1) since the two terms in the objective function can have different values; the first term is an estimated monetary benefit to society due to emissions reduction, and the second term is a cost saving purely due to fuel efficiency. These two terms, which are both expressed in dollars, may be valued differently. However, we are treating them as equal in this study, and different values can be considered in further research.

Model Constraints

Let the cost of the technology t be represented by C_t, including purchasing cost, installation cost, operation cost, and maintenance cost. The cost associated with the technology t is $C_t I_{c,e,i,t}$. Therefore, the expression for the budget constraint is given in Eq. (4):

$$\sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{t=1}^{n_t} C_t I_{c,e,i,t} \le Budget(\$) \tag{4}$$

TxDOT indicated that for a piece of equipment to be retrofitted, it must have a remaining age and remaining usage hours equal to at least half of its expected age and expected usage hours before disposal. The remaining usage hours and the expected usage hours at disposal of a piece of equipment are represented by $ru_{d,c,e,i}$ and $U_{e,i}$, respectively. Similarly, the remaining age and the expected age at disposal of a piece of equipment are represented by $ra_{d,c,e,i}$ and $A_{e,i}$, respectively. Eqs. (5) and (6) provide expressions for the remaining usage hours and remaining age constraints, respectively:

$$ru_{c,e,i} \geq 0.5U_{e,i}$$

(Remaining usage hours) (5)

(c = 1 to n_c, e = 1 to n_e, i = 1 to n_{ce})

$$ra_{c,e,i} \geq 0.5A_{e,i}$$

(Remaining age) (6)

(c = 1 to n_c, e = 1 to n_e, i = 1 to n_{ce})

SCR systems (t = 2) are not available for equipment of horsepower less than or equal to 100 hp. Hence, the value of the variable I for a particular piece of equipment having horsepower less than or equal to 100 hp will be 0.

Constraints provided in Eqs. (7) and (8) ensure that HE and SCR technologies are mutually exclusive and not deployed together (as indicated by experts' guidelines), while other combinations are possible, such as HE (t = 1) and FA (t = 3), and SCR (t = 2) and FA (t = 3):

$$\sum_{t=1}^{n_t} I_{c,e,i,t} \leq 2 \quad (7)$$

(c = 1 to n_c, e = 1 to n_e, i = 1 to n_{ce})

$$\sum_{t=1}^{2} I_{c,e,i,t} \leq 1 \quad (8)$$

(c = 1 to n_c, e = 1 to n_e, i = 1 to n_{ce})

Another requirement regarding FA is that the FA must be applied to either all or none of the equipment within a county. The expression related to this constraint is given in Eq. (9):

$$I_{c,e,i=1,t=3}=I_{c,e,i=2,t=3}=\ldots.=I_{c,e,i,t=3} \qquad \forall c,e \quad (9)$$

Therefore, the final optimization model is an integer program. Linear programming in which all or some of the variables are required to be non-negative integers is called an integer programming problem (IP) (*40*). Under Method 1 and Method 2, the objective function is expressed by Eq. (3), which is subjected to the constraints expressed through Eqs. (4) to (9). The model result will be a deployment plan of emission control technologies with a view to maximize the emission reduction benefit with/without considering fuel efficiency. Most IP problems (such as ours) are combinatorial and non-deterministic polynomial-time hard, therefore, they are not easily solvable. The model was programmed with Visual C++ and ILOG CPLEX.

RESULTS OF MODEL APPLICATION

This section presents the results of model applications prescribing a mix of technologies to be deployed for emissions reduction of non-road equipment. Two approaches or methods have been tested, each having two options (with and without consideration of fuel economy), thus making four cases as stated earlier. Some useful definitions of selected terms are presented below:

- Total NOx reduced (first stage and second stage): The total NOx reduction includes the total NOx reduced from both the NA and NNA counties.
- Combined fuel/diesel economy (first stage and second stage): It is defined as the total fuel economy obtained from both the NA and NNA counties.
- Total combined benefit (first stage and second stage): The total combined benefit includes the total NOx reduced and the total fuel economy from both the NA and NNA counties.

Graphs of the total combined benefit (first and second stages) are plotted for budgets ranging from about $500 to $1,183,000 in order to present the sensitivity of the combined benefit with budgets. The model solutions are obtained up to a budget of $1,183,000 since both NA and NNA counties receive the maximum possible units of HE, SCR, and FA coverage at this budget, and the total benefit at the first and second stages becomes constant with further increasing of the budgets.

Comparison between Case 1A and Case 1B

Case 1A and Case 1B represent the results of the Method 1 approach with and without consideration of fuel economy, respectively. A comparison of the total combined benefit (first and second stages) between Case 1A and Case 1B, as shown in Figure 10, reveals that Case 1A exceeds or equals Case 1B for a budget starting from $200,000. Case 1A exceeds Case 1B for budgets ranging from $200,000 to $600,000 and $775,000 to $1,120,000 with a difference ranging from about $76 to $4,440 and $6 to $610, respectively.

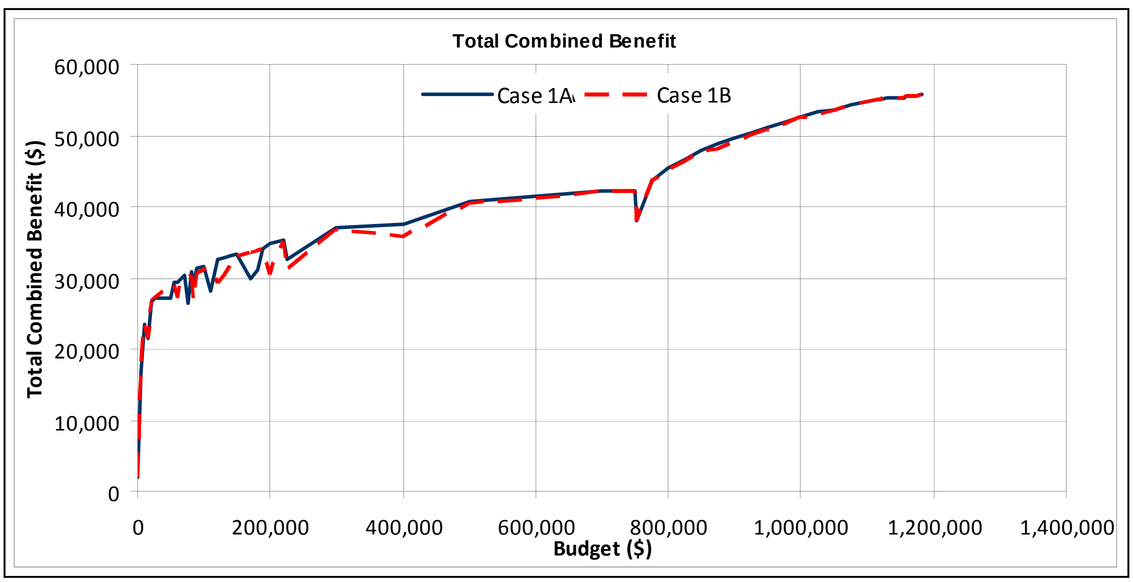

Figure 10. Total Combined Benefit in the First and Second Stages (Case 1A versus Case 1B).

Comparison between Case 2A and Case 2B

Case 2A and Case 2B represent the results of the Method 2 approach with and without consideration of fuel economy, respectively. A comparison of the total combined benefit (first and second stages combined) between Case 2A and Case 2B reveals that Case 2A exceeds Case 2B for budgets ranging from $45,000 to $6,00,000 and $775,000 to $1,120,000 with a difference ranging from $1 to $732 and $4 to $545, respectively. The only exception in this budget range is $975,000, at which Case 2B exceeds Case 2A. Figure 11 presents the total combined benefit (first and second stages combined) for both Case 2A and Case 2B.

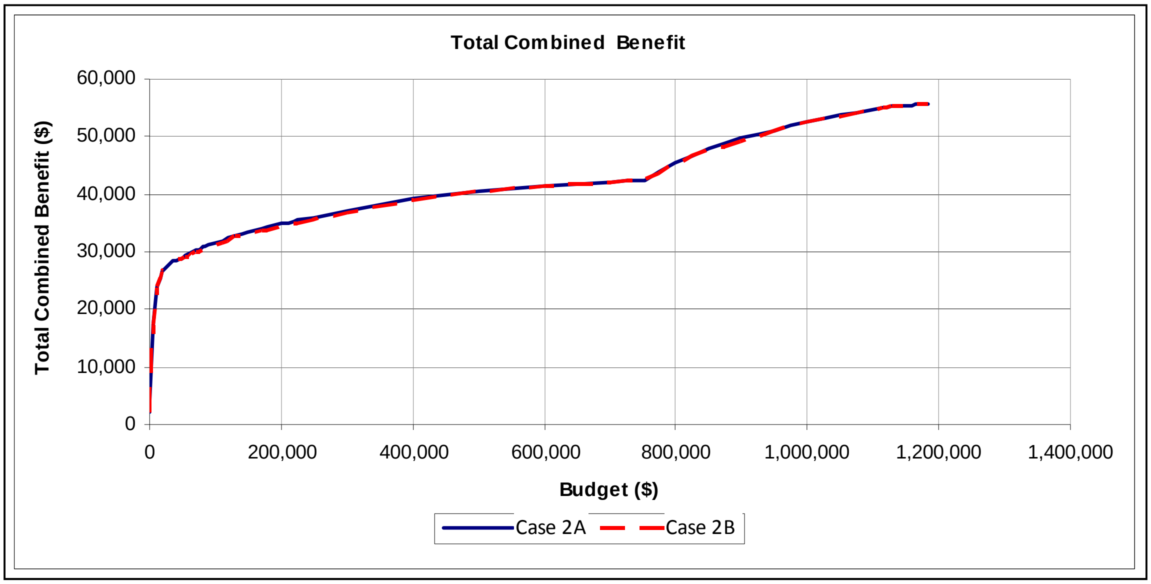

Figure 11. Total Combined Benefit in the First and Second Stages (Case 2A versus Case 2B).

Comparison between Case 1A and Case 2A

The total combined benefit (first and second stages combined) for Case 1A is greater or equal to Case 2A for budgets ranging from $500 to $825,000 with differences up to $4,207. Case 2A again exceeds Case1A for budgets ranging from $850,000 to $1,075,000. For the rest of the budgets, there are no differences between the cases. Figure 12 presents the graphs for Case 1A and Case 2A for the total combined benefit (first and second stages combined).

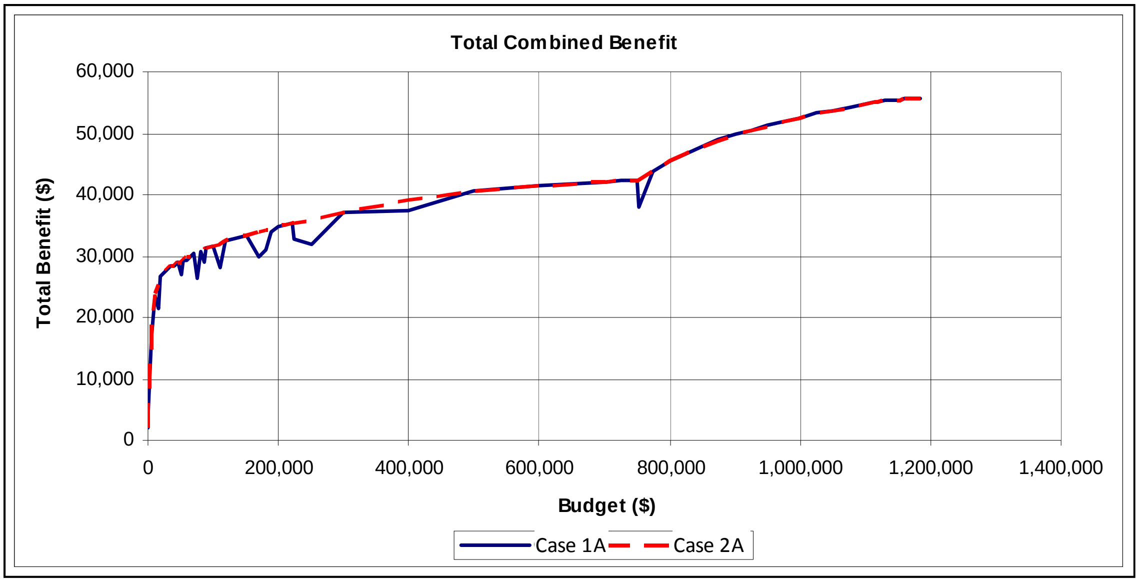

Figure 12. Total Combined Benefit in the First and Second Stages (Case 1A versus Case 2A).

Comparison between Case 1B and Case 2B

The total combined benefit (first and second stages combined) for Case 2B, presented in Figure 13, is greater or equal to that of Case 1B for budgets up to $1,130,000. At $1,135,000, Case 1B exceeds Case 2B. For rest of the budget amounts, there is no difference between the cases.

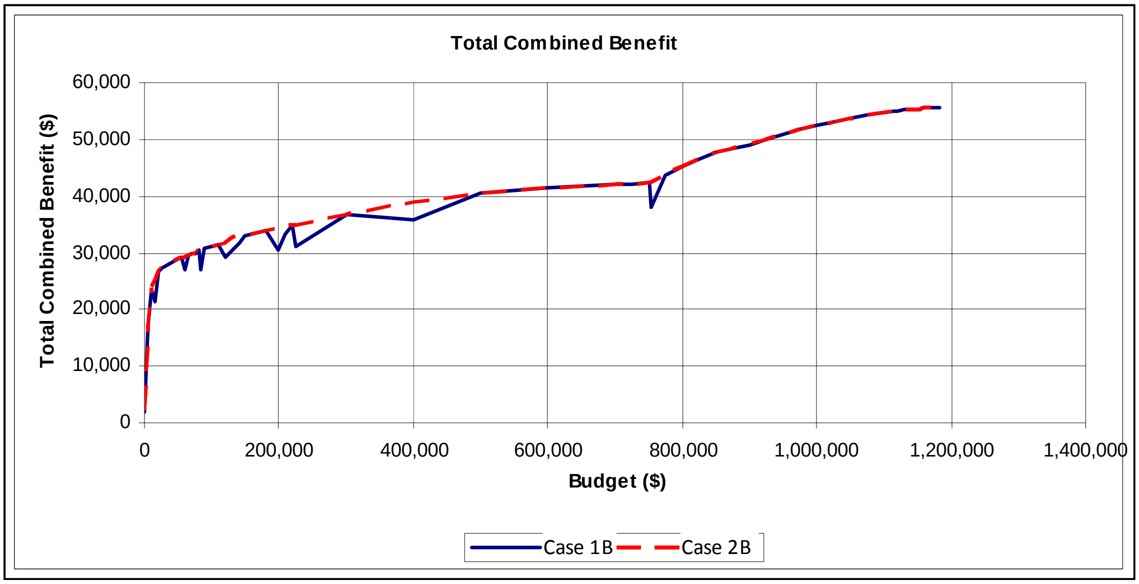

Figure 13. Total Combined Benefit in the First and Second Stages (Case 1B versus Case 2B).

From Figures 10 and 11, it can be observed that Case 2A and Case 2B (Method 2) prevent the drops that occurred in Case 1A and Case 1B (Method 1) for the total combined benefit (first and second stages). The graphs for total combined benefit (first and second stages) of Case 2A and Case 2B progress upward without any drop with further increases in the budget amounts.

DISCUSSION OF FINDINGS

The aim of this task was to develop a model for devising an optimal deployment plan of emission reduction technologies for TxDOT's construction equipment. Three different technologies were selected, namely HE, SCR, and FA considering such factors as data availability, cost of technologies, and emission reduction efficiencies. However, the model is quite general and allows the user to simply include other technologies if and when necessary. Four categories of construction equipment – grader, loader, excavator, and others – were included in the analysis. Graders, loaders, and excavators are the higher emitting pieces of equipment in Texas. An "other" category was considered involving all the remaining equipment for estimating the FA requirement of a county.

Model Development and Evaluation of Results

Method 1 was developed based on criteria specified by TxDOT. In Method 1, NA counties were given the first priority over NNA counties for deploying the emission reduction technologies (HE, SCR, and FA), i.e., allocating the resources in the NA counties first and then allocating the remaining resources in the NNA counties. But this pattern of deployment often caused the total NOx reduction and the total combined benefit to drop (e.g., see Figure 10) with increasing budget amounts. Therefore, the concept of Method 2 was developed to overcome the situation faced in Method 1. In Method 2, FA deployment in the NNA counties was given equal priority as the deployment of technologies in NA counties, i.e., allocating the resources in the NA counties with FA deployment in NNA counties first, and afterward allocating the remaining resources for SCR and HE deployment in the NNA counties. Comparing the graphs for Method 1 and Method 2 for total combined benefit (first and second stages), it can be concluded that Method 2 prevents any drop in the graphs for this variable, and the graphs for Method 2 progress upward without any drop with increasing the budget amounts.

The initial steep portion of the budget versus total benefit graphs for the total combined benefit for all the four cases indicates that the benefit increases very sharply for a slight increase in the investment at lower budget amounts. This is conceivable as FA is inexpensive, and at lower investment or budget levels, more expensive technologies such as SCR or HE are not affordable. FA usage becomes beneficial by covering more counties, thereby making the total combined benefit higher. Thus, at a lower investment, deploying FA is the most beneficial option. Also, it can be seen that the benefit cost ratio is poor except for lower budget amounts.

There were differences in the total combined benefit among the alternative cases investigated in this study. Often the difference was small, or there was no difference at all. The difference range for overall benefit was $1 to $4,440. The differences were primarily dependent upon the available budget, emissions, horsepower, usage hours, fuel consumption, location wise distribution of the equipment, and total number of NA and NNA counties.

The graphs for Case 2A and Case 2B for overall benefit traveled in the same direction. Thus, it can be concluded that the objectives of maximizing NOx reduction and maximizing fuel economy benefit are almost parallel. This fact causes the concerned graphs for Case 2A and Case 2B to follow a similar path and direction.

Applicability for TxDOT

The models developed here can be used as a tool by decision makers in TxDOT to decide about the deployment preference of technologies. The models developed were demonstrated with three emission reduction technologies, and other parameters such as emission reduction efficiencies, cost, etc. can be changed accordingly. The model is flexible enough to expand and include other sets of technologies. For a given budget, the decision maker can run this model and obtain the results for total NOx reduction, combined diesel economy, and total combined benefit. This will enable the decision maker to devise the required deployment plan given a choice of emission reduction technologies in the NA and NNA counties. The sensitivity analysis for total NOx reduction and total combined benefit can easily be performed by varying the budget amounts. By observing the pattern of the budget versus total benefit graphs, TxDOT can make a decision about how much investment would be beneficial.

CHAPTER 5: MEASUREMENTS AND ANALYSIS OF BASELINE AND TREATMENT LEVEL EMISSIONS

This chapter presents a detailed analysis of the in-use testing conducted using PEMS for selected TxDOT non-road equipment. Changes to the test protocol made since the Phase 1 report were discussed in Chapter 3. This chapter describes the basic test setup, including the test site, the tested TxDOT equipment, and instruments used for testing. A detailed analysis of test results from the testing of six graders is also included.

TEST SITE

The emission measurement testing took place at TTI's test track located at the Riverside Campus of Texas A&M University in Bryan, Texas. The Riverside Campus is a 2000 acre former Air Force base that is used for research and training purposes. The available test roads consist of a roadway network surrounding old barracks and other base buildings plus the former runways (longest straightaway of 7500 feet). Figure 14 shows an aerial view of the available road network at the Riverside Campus and pictures of the runway on which testing was performed. A section of one runway (marked as a white box in Figure 14[a] and shown in Figures 14[b] and 14[c]) was used for testing in this study.

(a)

(b)

(c)

Figure 14. Test Site: (a) Aerial View of the Riverside Campus at Texas A&M University, (b) Section of the Runway (Marked as White Box in [a]) Where Testing Took Place, and (c) Section Covered with Base Material for Leveling and Backup Testing.

Baseline tests of the graders were performed in the section of the runway shown in Figure 14. In this section, driving, leveling, and backup testing were conducted as per the duty cycles described in Chapter 3. Figure 15 shows pictures taken during the actual driving testing of a grader on the 500 yard long paved runway and the leveling testing on the 70 yard long, 20 yard wide, and 10 inch deep Colorado rock bed on a portion of the runway.

(a)  (b) 

Figure 15. Pictures of (a) Driving Testing and (b) Leveling Testing.

TEST EQUIPMENT

After examination of TxDOT's non-road construction equipment inventory (described in Chapter 3), six graders were selected for testing. Table 12 provides the details of these graders. After the baseline testing, these six TxDOT graders were returned to their office locations. Then, the FA and HE technologies were applied to the graders (FA for graders 1112A, 1468, and 1166G and HE for the other three), and they continued performing their normal operations. After approximately 100 hours of normal operations with the technologies installed, the graders were tested again for degreened (after installation of emission reduction technologies) testing.

Table 12. Information for TxDOT Graders Tested.

Equipment No. (ID)	Model Year	Engine Tier	Total Accumulated Usage Hours before Testing	Applied Technology
1112A*	1999	1	3764	FA
1468*	1994	0	4695	FA
1100A*	1998	1	2575	HE
1453*	1993	0	3171	HE
1106G**	2003	2	2192	HE
1166G**	2004	2	2091	FA

* *GALION-DRESSER 830B graders with six cylinder 5.8 liter KOMATSU engines with 144 hp.*

** *Caterpillar 120H graders with six cylinder 4.08 liter CAT engines with 125 hp.*

TEST INSTRUMENT

Researchers used two PEMS units simultaneously in this study – one to collect gaseous emissions (NOx, HC, CO, and CO_2) and another one to collect PM. For the gaseous emissions, TTI's SEMTECH-DS unit manufactured by Sensors, Inc., was used along with TTI's electronic exhaust flow meters (EFMs). TTI's Axion system manufactured by Clean Air Technologies International, Inc., was used to measure PM. Figure 16 shows photographs of the two PEMS units used in the testing and a photograph of installed PEMS units along with EFM on test equipment.

Figure 16. Emission Measurement Instruments: (a) SEMTECH-DS Unit, (b) Axion Unit, and (c) Both Units along with EFM Installed on a TxDOT Grader.

SEMTECH-DS

The SEMTECH-DS unit includes a set of gas analyzers, an engine diagnostic scanner, a GPS, an exhaust flow meter, and embedded software. The gas analyzers measure the concentrations of NOx (NO and NO_2), total hydrocarbons, carbon monoxide, carbon dioxide, and oxygen in the vehicle exhaust. The SEMTECH-DS uses the Garmin International, Inc., GPS receiver model GPS 16 HVS to track the route, elevation, and ground speed of the vehicle on a second-by-second basis. TTI's SEMTECH-DS uses the SEMTECH EFM to measure the vehicle exhaust flow. Its post processor application software uses this exhaust mass flow information to calculate exhaust mass emissions for all measured exhaust gases.

Axion

The Axion system is comprised of a gas analyzer, a PM measurement system, an engine diagnostic scanner, a GPS, and an onboard computer. For this study, only the PM measurement system was used. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. The PM concentrations were converted to PM mass emissions using concentration rates produced by the Axion system and the exhaust flow rates produced by the SEMTECH-DS unit.

TEST RESULTS

The test data collected were from the baseline and degreened testing of a total of six graders in TxDOT's fleet. The data recorded by the two PEMS units were in a second-by-second format. From the entire array of information that was recorded (emissions, ambient conditions, and vehicle parameters), the following information was extracted and used in this study:

- engine speed (if recorded) for data quality checking,
- second-by-second vehicle speed from the GPS in mph, and
- emissions mass rates in grams per second (g/s).

Second-by-second emissions data were carefully aligned with the instantaneous speed obtained from the GPS. The second-by-second emissions rates were then grouped into operating modes (idling, driving at maximum speed and at 20 mph, and operation including leveling and backup). Two types of analyses were performed on these data; the first analysis examined the average modal emissions rates, while the second analysis was a fuel-based approach to normalize the emissions data. The average emission rate approach provided basic knowledge of emissions during each mode; however, since the operation of non-road equipment was highly variable, the average emissions rates were not a suitable statistic for treatment comparison purposes. For the comparison purposes, the research team examined fuel-based emissions rates. Using this approach the researchers were able to apply regression analysis to determine whether the tested technologies had a statistically significant impact on emissions from graders.

Average Modal Emission Rates

The average emissions rates and the corresponding standard deviations for each mode of operation were calculated using all the data points that belonged to each mode. Figures 17 and 18 show the test results of two graders for all tasks (idling, driving at maximum speed and at 20 mph, and operation). The results of the rest of the graders are qualitatively similar and are shown in Appendix G. Figures 17 and 18 show average emissions rates of gaseous pollutants (CO_2, CO, NOx, and HC) and PM during all of the tasks along with their associated standard deviations shown in error bar form.

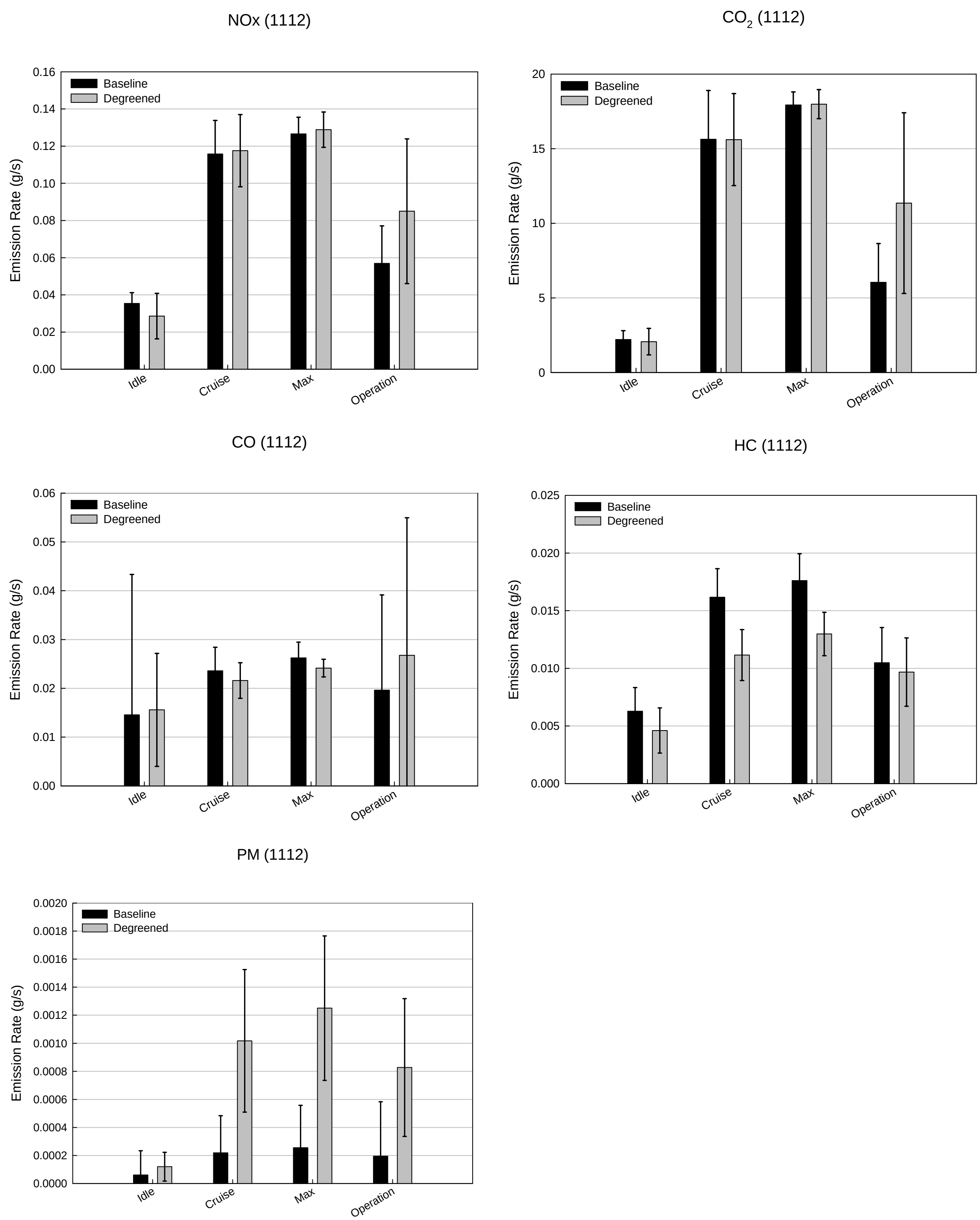

Figure 17. Testing Results of Grader 1112A (Tier 1, Fuel Additive).

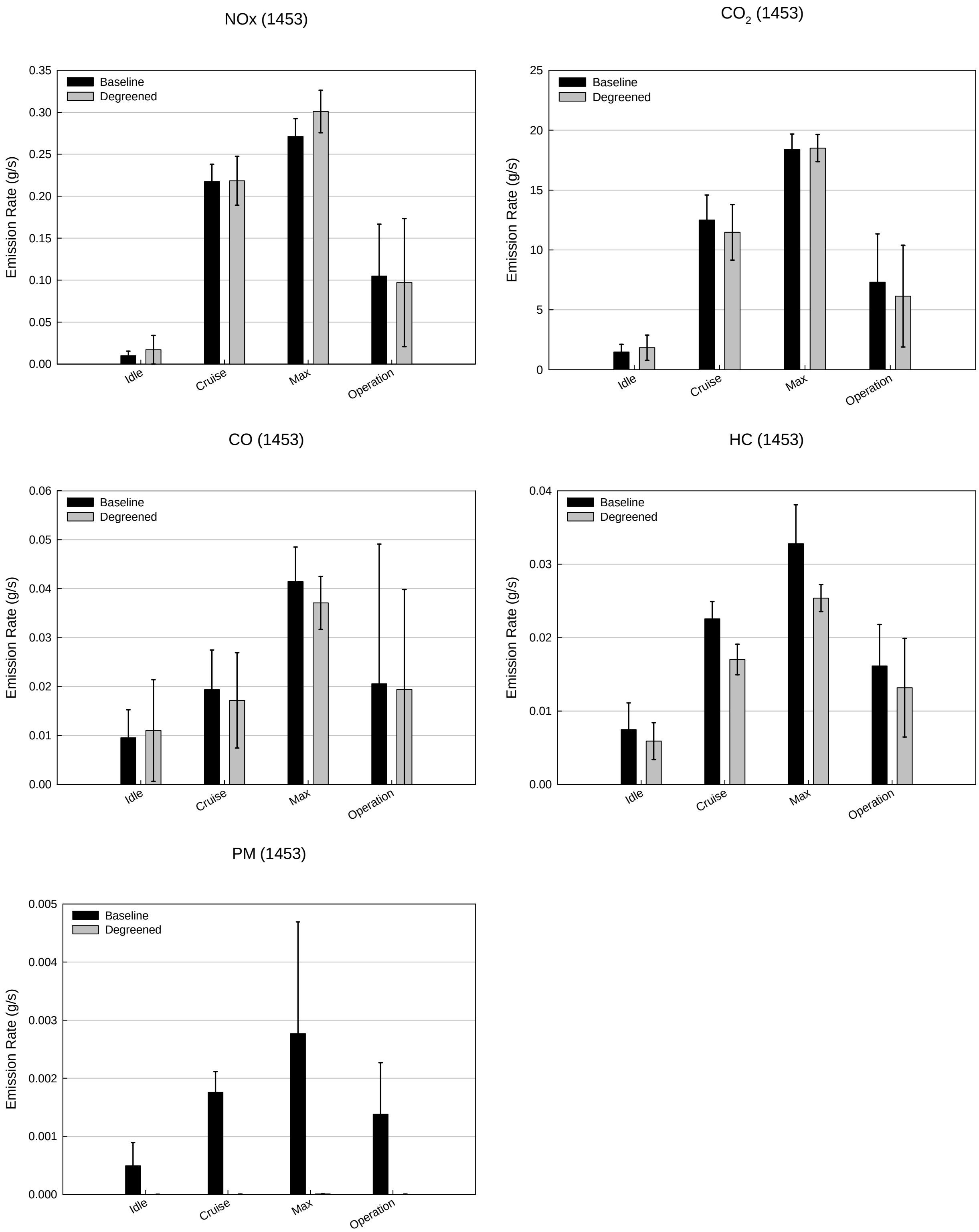

Figure 18. Testing Results of Grader 1453 (Tier 0, Hydrogen Enrichment).

Emissions rates were highest during driving at maximum speed and lowest when idling. This indicates that driving puts the highest load on graders' engines. This is expected since graders' transmissions are only designed for driving at low speeds as is the case for the majority of non-road equipment. Graders with the same tier engines show similar emissions characteristics. With the exception of idling, the NOx emissions rates of the graders equipped with newer tier engines are lower than those equipped with older tier engines. This trend indicates the expected improvement as a result of implementation of EPA's emissions standard for non-road diesel engines.

Because NOx was the focus of the study, the research team also compared the observed average baseline NOx emissions rates with estimated emission rates following EPA guidelines as described in Chapter 3. Estimated emission rates based on EPA's estimation methodology were calculated using the following equation in which EF_{adj} is the NOx emissions factor from EPA guidelines:

$$Emissions\ rate\ (g/s) = EF_{adj}\ (g/hp\text{-}hr) \times horsepower\ (hp) \times 3600\ (s/1\ hr)$$

Table 13 shows these results. They show that the observed NOx emissions rates were lower than calculated emissions rates from EPA guidelines for any of the testing tasks including driving at the maximum speed. This indicates that all the tested equipment emitted less NOx emissions than the expected average emission rates according to EPA guidelines. Tables 14 through 17 summarize the average modal emissions rates for the other pollutants.

Table 13. Baseline NOx Emission Rates: Observation versus Estimation (g/s).

	Fuel Additive			**Hydrogen Enrichment**		
Equipment ID	**1166G**	**1112A**	**1468**	**1106G**	**1100A**	**1453**
Engine Tier	**Tier 2**	**Tier 1**	**Tier 0**	**Tier 2**	**Tier 1**	**Tier 0**
Idle	0.020	0.035	0.009	0.022	0.024	0.010
Driving at Maximum Speed	0.108	0.127	0.311	0.065	0.097	0.271
Driving at 20 mph	0.055	0.116	0.213	0.053	0.080	0.217
Operation (Leveling & Backup)	0.048	0.057	0.097	0.035	0.067	0.105
EPA Guidelines	**0.135**	**0.217**	**0.323**	**0.136**	**0.217**	**0.322**

Table 14. Baseline CO_2 Emission Rates (g/s).

	Fuel Additive			Hydrogen Enrichment		
Equipment ID	**1166G**	**1112A**	**1468**	**1106G**	**1100A**	**1453**
Engine Tier	**Tier 2**	**Tier 1**	**Tier 0**	**Tier 2**	**Tier 1**	**Tier 0**
Idle	2.103	2.201	1.259	2.263	1.467	1.472
Driving at Maximum Speed	18.011	17.932	18.440	15.850	17.026	18.380
Driving at 20 mph	11.174	15.633	11.495	13.598	11.957	12.489
Operation (Leveling & Backup)	12.807	6.041	6.249	9.025	7.319	7.304

Table 15. Baseline CO Emission Rates (g/s).

	Fuel Additive			Hydrogen Enrichment		
Equipment ID	**1166G**	**1112A**	**1468**	**1106G**	**1100A**	**1453**
Engine Tier	**Tier 2**	**Tier 1**	**Tier 0**	**Tier 2**	**Tier 1**	**Tier 0**
Idle	0.010	0.015	0.011	0.012	0.009	0.010
Driving at Maximum Speed	0.039	0.026	0.041	0.046	0.027	0.041
Driving at 20 mph	0.032	0.024	0.021	0.042	0.020	0.019
Operation (Leveling & Backup)	0.036	0.020	0.020	0.039	0.016	0.021

Table 16. Baseline Total Hydrocarbon (THC) Emission Rates (g/s).

	Fuel Additive			Hydrogen Enrichment		
Equipment ID	**1166G**	**1112A**	**1468**	**1106G**	**1100A**	**1453**
Engine Tier	**Tier 2**	**Tier 1**	**Tier 0**	**Tier 2**	**Tier 1**	**Tier 0**
Idle	0.0014	0.0063	0.0064	0.0015	0.0040	0.0075
Driving at Maximum Speed	0.0047	0.0176	0.0265	0.0069	0.0172	0.0328
Driving at 20 mph	0.0037	0.0162	0.0184	0.0060	0.0136	0.0225
Operation (Leveling & Backup)	0.0075	0.0105	0.0134	0.0060	0.0088	0.0161

Table 17. Baseline PM Emissions Rates (g/s).

	Fuel Additive			Hydrogen Enrichment		
Equipment ID	**1166G**	**1112A**	**1468**	**1106G**	**1100A**	**1453**
Engine Tier	**Tier 2**	**Tier 1**	**Tier 0**	**Tier 2**	**Tier 1**	**Tier 0**
Idle	0.0004	0.0001	0.0002	0.0006	0.0001	0.0005
Driving at Maximum Speed	0.0032	0.0003	0.0020	0.0039	0.0010	0.0028
Driving at 20 mph	0.0016	0.0002	0.0008	0.0028	0.0012	0.0018
Operation (Leveling & Backup)	0.0019	0.0002	0.0006	0.0024	0.0006	0.0014

As it is clear from the results shown in Figures 17 and 18, the standard deviations of the modal emissions rates are very large, indicating a high level of variability in results. This makes it impossible to make valid comparisons between baseline and after installation (degreened) testing. The variability shows an inverse relationship with the power demand associated with each mode; i.e., driving at the maximum speed that requires high power has the lowest variability while idling, and operation modes that have lower power demand have higher variability.
It is quite well known that as the engine works harder, there is little variability in the engine's operational characteristics, which translates to less emission rate variability. On the other hand, when the engine is under low load, there are wider operational conditions that the engine works in, which in turn results in higher emissions variability. In addition, graders' operation mode has higher variability because it consists of various tasks with different load demand, most notably grading at different speeds/depths and backup. Therefore, the operation mode results in even higher emission rate variability than the other modes, which mostly consist of one simple task, e.g., driving at a certain speed or idling.

After careful examination of the results and with consultation of a statistician, the research team decided to use a fuel-based analysis to perform the statistical analysis between baseline and after installation results. The following section explains the methodology and the results of this analysis.

Fuel-Based Analysis

In order to normalize the results for each mode of operation, the second-by-second modal emissions rates in g/s were plotted against second-by-second fuel consumption rates in gal/s. Figure 19 shows a sample of these plots demonstrating baseline and after installation results for driving at the maximum speed for the grader 1106.

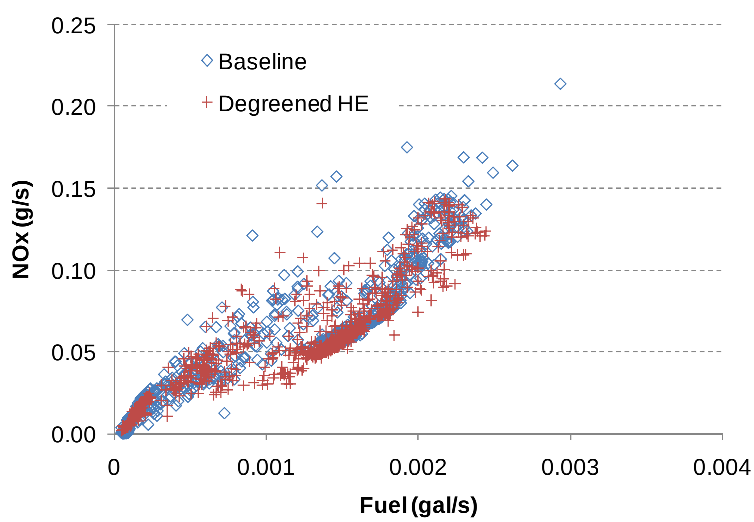

Figure 19. NOx versus Fuel Rate for Driving at Maximum Speed: Grader 1106.

The analysis uses the following two step approach (Figure 20 shows this process in graphical format):

- In the first step a prediction interval analysis was applied, and the 95 percentile prediction intervals of the dataset for each mode were compared between baseline and after installation results (*41*). First and second degree polynomial curve fitting was used in this step.
- If the results from the first step were inconclusive, the dataset was divided into 20 equally spaced subsets based on their fuel consumption rates, and the 95 percentile prediction intervals of each subset were calculated and compared.

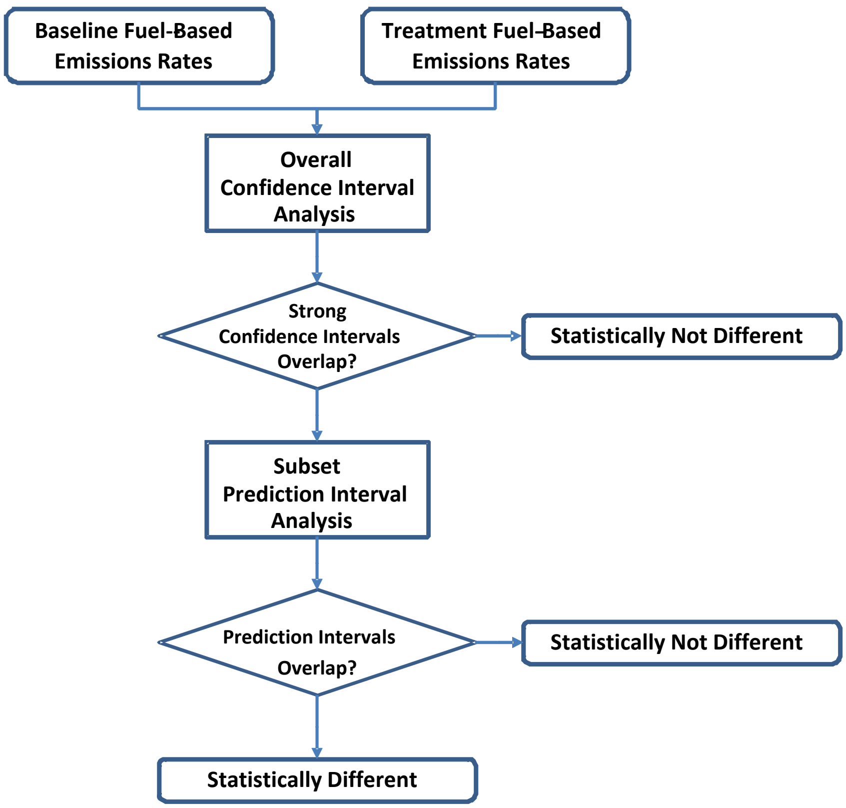

Figure 20. Flowchart of the Fuel-Based Analysis.

This methodology was applied to all tested units and their operational modes. As was the case for modal average emission rate analysis, the variability is the highest for idling and grading operation, while both driving modes had low variability. Therefore, the results of the two driving modes, driving at the maximum speed and at 20 mph, are considered the main determinants of the tested technologies' effectiveness, and the results of idling and grading operation are considered for verification. The analysis includes NOx (as the primary focus of this study), CO, THC, and PM. CO_2 is excluded from this analysis because it is the direct result of fuel combustion. In fact close to 98 percent of carbon in diesel fuel transforms to CO_2 during the combustion, and thus CO_2 has an almost perfect linear relationship with fuel consumption.

Figure 21 shows the results of the first step of this analysis (overall confidence interval). NOx emissions results in Figure 21 clearly show that there is no significant difference in NOx emissions as the result of applying hydrogen enrichment. The results for other pollutants on the other hand show a weaker overlap. The wide band areas in the graphs are usually associated with the subsets that have a low number of observation points with high variability. This is more prevalent for boundary bins, which represent the extremes of the dataset. Further investigation of the data indicated that the data are more nonlinear and had higher variability and therefore required a subset analysis (step 2). Figures 22 and 23 show the results of this analysis for driving at the maximum speed and at 20 mph, respectively.

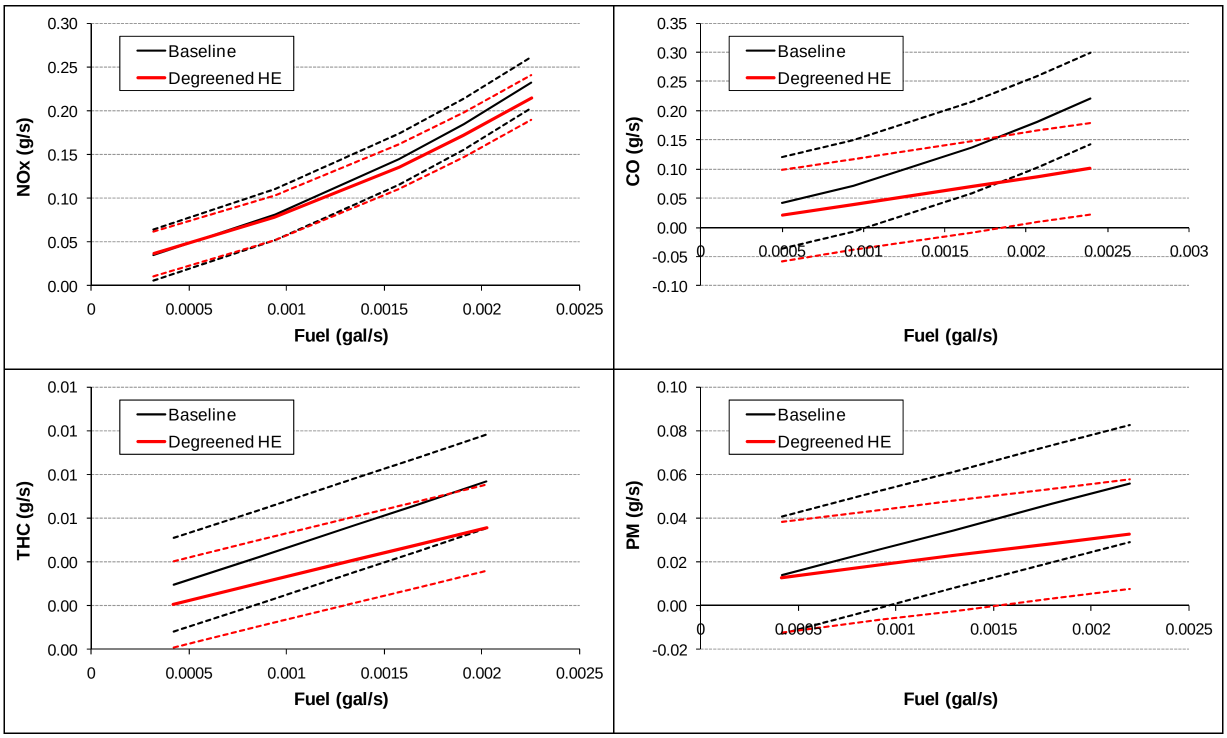

Figure 21. Results of Overall Confidence Interval Analysis (Step 1), Grader 1106 with Hydrogen Enrichment – Driving at the Maximum Speed.

The NOx results in Figure 22 are generally consistent with results in Figure 21 except for a small area in the mid-range of fuel consumption rates. Data in Figure 19 show that there is no difference in the general trend, and the concentration of observations with lower NOx values for the after installation case at that region creates this issue. NOx results in Figure 23 (driving at 20 mph) also confirm that the HE did not change the NOx emissions level from the grader. CO results in Figures 22 and 23 also indicate that the hydrogen enrichment did not have any significant impact on the CO emissions of the grader. THC and PM results, on the other hand, indicate that HE decreased the emissions of these pollutants. The reduction seems to be greater at higher fuel consumption rates, which represent higher engine load operations.

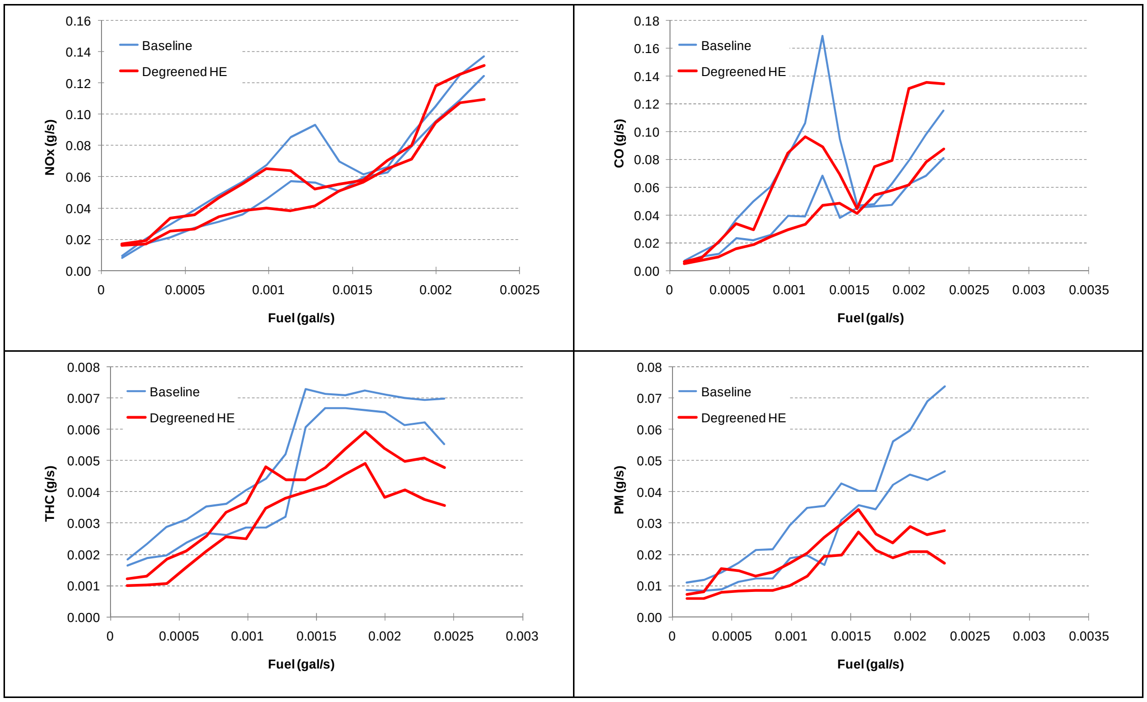

Figure 22. Results of Subset Confidence Interval Analysis (Step 2), Grader 1106 with Hydrogen Enrichment – Driving at the Maximum Speed.

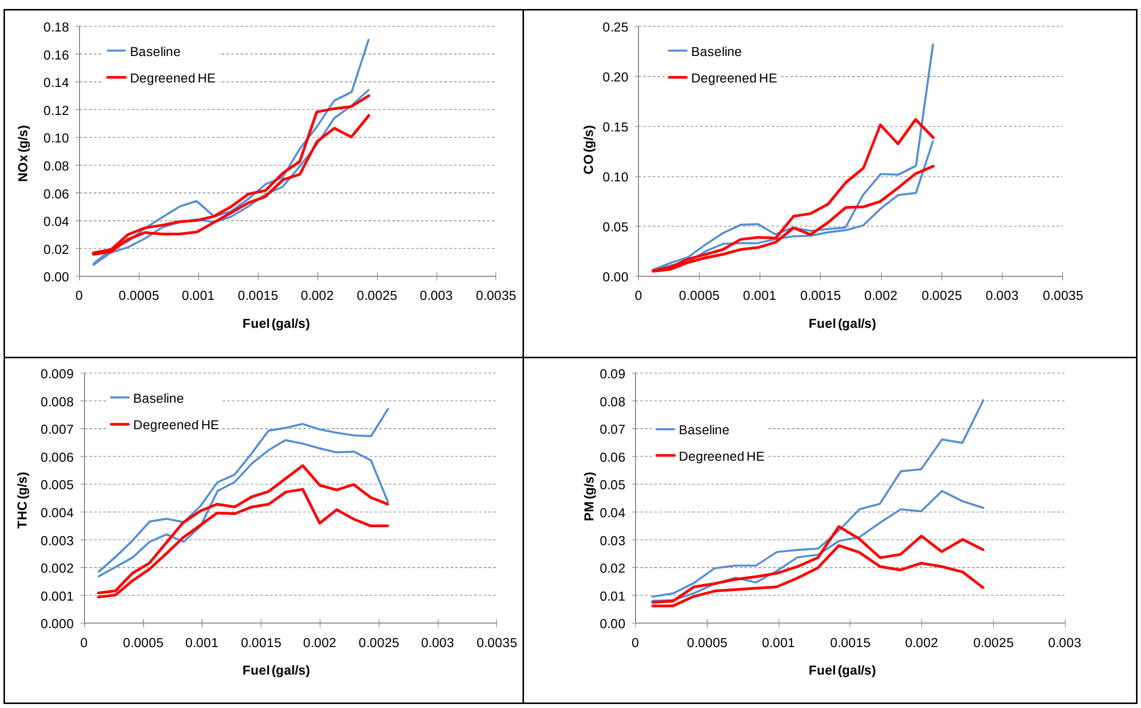

Figure 23. Results of Subset Confidence Interval Analysis (Step 2), Grader 1106 with Hydrogen Enrichment – Driving at 20 mph.

In order to make a conclusion on the effectiveness of each technology, the results of all three graders with the same technology applied were taken into consideration. These results are shown in Appendices H and I. The following summarizes the conclusion of the research team on the impact of each of the tested technologies on the emissions from tested graders:

- Neither of the tested technologies had any impact on the NOx and CO emissions from the graders of all tiers.
- Hydrogen enrichment appears to decrease the emissions of hydrocarbon emissions from the tested equipment by 10 to 30 percent on average.
- The tested fuel additive provides hydrocarbon emissions reduction of 10 to 50 percent.
- PM emissions were reduced by 20 to 50 percent by using hydrogen enrichment. The PM reduction effect appears to be greater for higher engine load conditions.
- The tested fuel additive appears to reduce the PM emissions at the high end of engine load conditions for the Tier 1 grader, while no benefit is observed for the Tier 2 grader.
- The percentage improvements mentioned here are presented based on a few observations under the in-use testing conditions and thus should be treated only as indicators of the direction of the changes in emissions levels. Unlike on-road vehicles whose main purpose is moving along a roadway, non-road equipment operates under different conditions, and their engines provide power for multiple tasks, causing a very high variability of engine operation conditions and, as a result, their exhaust emissions readings. Because of this high variability, the exact amount of reduction in each case should be determined using engine dynamometer testing.

CHAPTER 6: FINAL REMARKS

The overall goals of this study were to:

- understand how results from the new federal in-use testing program may affect current estimates of NOx and other pollutant emissions in particular ozone NA areas;
- evaluate the effectiveness of emerging fuels/fuel additives and retrofit technologies to reduce emissions so that TxDOT can make cost effective use of funds available for emissions reductions; and
- identify emission control strategies, such as changes in operating practices, which may avoid the costs of retrofits.

In order to achieve the goals, TTI researchers performed the following seven tasks outlined in the original project scope:

- Task 1: State-of-the-Practice Assessment;
- Task 2: Select TxDOT Equipment for Testing;
- Task 3: Select Emission Reduction Technologies for Testing;
- Task 4: Develop Duty Cycles for Selected Equipment;
- Task 5: Measure and Analyze Baseline and Treatment Level Emissions;
- Task 6: Compare Results with Existing Data Sources; and
- Task 7: Prepare Final Products.

In addition to this, researchers also developed a methodology for optimizing the deployment of emission control technologies in TxDOT's fleet to maximize the benefits in NA and NNA areas.

The following presents a brief summary of completed tasks and the observed results:

- TTI researchers performed an extensive investigation to obtain information on emission reduction technologies, non-road emission reduction case studies, and non-road emissions resources. Based on the analysis of the collected information, FA and HE technologies were selected for initial testing, while SCR technology was proposed for further testing. Findings from seven selected studies relevant to this research are also presented in this report. The NOx emissions of TxDOT non-road diesel equipment were calculated in Task 2. Also, various practices proposed and/or implemented for non-road emissions reductions by other states as well as by Texas were investigated and presented.
- In consultation with the TxDOT PMC, the research team modified the test protocol developed and presented in the Phase 1 report. The changes were made as a result of preliminary findings that indicated that FA and HE were not effective for NOx reductions. Additional constraints also did not allow for testing with SCR, which is to be carried out as a separate research project. Thus, emissions testing of a total of six graders were conducted and the results discussed in this research.
- Baseline and degreened (treatment level) NOx, HC, CO, CO_2, and PM emissions for the selected equipment were measured using SEMTECH-DS and Axion portable emission measurement units.
- The research team performed a series of analyses to characterize the emissions from the tested equipment. The operation of the graders were broken down into four operational modes:

    - driving at the maximum attainable speed,
    - driving at 20 mph,
    - leveling/grading, and
    - idling.
- An average modal analysis was performed to quantify the average emissions impact of each unit. The NOx emissions rates from EPA guidelines were calculated and compared to the observed modal emissions rates. The results indicate that the tested TxDOT equipment (all tiers: Tier 0, 1, and 2) emitted less NOx emissions than estimated from EPA guidelines for non-road diesel equipment. Because of the high variability of data, the average modal results were found unsuitable for comparison purposes.
- A two step prediction interval analysis was applied to second-by-second fuel-based emissions data. The analysis results indicate that neither hydrogen enrichment nor the selected fuel additive had any impact on NOx and CO emissions from graders. Both options appear to provide moderate reductions of hydrocarbon and PM emissions; however, the reduction of PM emissions happened at higher engine load conditions.
- The results here are presented based on a few observations under the in-use testing conditions and thus should be treated only as indicators of the direction of the changes in emissions levels. Non-road equipment operates under conditions where the engine is required to power multiple tasks. Therefore, there is a very high variability of engine operation conditions, which affects the exhaust emissions. Due to this high variability, the exact amount of reduction in each case should be determined through engine dynamometer testing.
- Since NOx is the focus of TxDOT emission reduction efforts and the two tested technologies did not show significant results for NOx emissions, neither of the technologies are recommended to be utilized in TxDOT's non-road fleet. However, the findings from the SCR testing (which is to be conducted in a separate research project) may prove promising in achieving NOx emissions reductions.
- The research team also developed an optimization methodology that could be used for future deployment of emission reduction technologies. This methodology is flexible and can recommend the most beneficial deployment of technologies (or combination of technologies) for a fixed budget. These findings have applicability at a later stage if TxDOT finds suitable technologies (such as SCR) for deployment in the non-road fleet.

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APPENDIX A:
NON-ROAD EMISSION REDUCTION CASE STUDIES

THE CENTRAL ARTERY/TUNNEL PROJECT, BOSTON, MASSACHUSETTS

Commonly known as the "Big Dig," this project was one of the first wide-scale efforts to reduce non-road construction emissions. Approximately 25 percent of the long-term non-road diesel equipment used on the Central Artery/Tunnel project ("Big Dig") was retrofitted with DOCs. More than 200 pieces of equipment (most of the equipment was model year 1999 or 2000) were retrofitted including:

- Nichi, Caterpillar, SIC, Terex, and JLG lifts;
- Mantis cranes;
- John Deere and Caterpillar dozers; and
- Cradel excavators.

The equipment was fueled using ULSD and emulsified diesel fuels. DOCs did not experience any adverse operational problems, such as loss of power or additional fuel consumption. Environment Canada used a portable emissions-testing device and will perform further tests of DOCs. Currently, preliminary area-wide emissions reductions for 2000-2004 were estimated at:

- 36 tons/year of CO,
- 12 tons/year of HC, and
- 3 tons/year of PM.

More detailed information can be obtained from the website: www.massturnpike.com/bigdig/background/airpollution.html.

I-95 NEW HAVEN HARBOR CROSSING CORRIDOR IMPROVEMENT PROGRAM, NEW HAVEN, CONNECTICUT

Known as the Q-Bridge Project, DOCs were installed on approximately 70 pieces of construction equipment. The project is being used as a model for statewide efforts to reduce mobile-source emissions. The objective was to protect workers and residents from harmful construction emissions along a populated corridor. The contractor requirements included:

- emissions-control devices on non-road diesel-powered construction equipment with engine horsepower ratings of 60 hp and above that are on the project or assigned to the contract for more than 30 days; and
- truck staging zones, idling restrictions, and avoidance of sensitive areas.

Contractors voluntarily used low-sulfur diesel (500 ppm sulfur) on all of their non-road equipment. During the program, estimated emissions reductions were:

- 20 tons/year of CO,
- 8 tons/year of HC, and
- 2 tons/year of PM.

More detailed information can be obtained from the website: http://www.i95newhaven.com/poverview/environ_init.asp.

DAN RYAN EXPRESSWAY ROAD CONSTRUCTION PROJECT

The Illinois Department of Transportation (IDOT) implemented this pollution-reduction initiative. During the project, all heavy construction equipment on the Dan Ryan project was required to be either retrofitted with emissions-control devices or to use ULSD. Approximately 290 pieces of construction equipment in use on the Dan Ryan project had emissions-control devices or used ULSD. Also, IDOT implemented idling limits and dust controls to reduce air emissions. With these tactics in place no significant environmental impacts due to road construction were identified from 2004 to date. More detailed information can be obtained from the website: http://dnr.wi.gov/air/pdf/danryancasestudy.pdf.

WORLD TRADE CENTER DIESEL EMISSIONS REDUCTION PROJECTS

The seven World Trade Center Diesel Emissions Reduction Projects will demonstrate clean construction by retrofitting non-road, heavy-duty diesel construction equipment with DOCs and DPFs and using ULSD. The first investigation with ULSD and DPFs included two Caterpillar 966G wheel loaders.

Using two PEMS units, a Clean Air Technologies International Montana system and the Environment Canada DOES2 system, Environment Canada measured the emissions of the loaders. Results from using just ULSD showed that reductions of PM and CO were 13 to 17 percent and 2 to 10 percent, respectively, while HC emissions increased. When DPFs were used with ULSD, the results showed that reductions were more than 97 percent for PM, more than 87 percent for CO, and 97 percent for HC.

This project did not target NOx reductions. Although test results indicated NOx reductions (16 to 30 percent), this reduction may be related to engine backpressure effects associated with operations utilizing a DPF. More detailed information can be obtained from the website: http://www.cleanaircommunities.org/projects/wtc.html.

THE IMPACT OF RETROFIT EXHAUST CONTROL TECHNOLOGIES ON EMISSIONS FROM HEAVY-DUTY DIESEL CONSTRUCTION EQUIPMENT

The testing program was conducted to study the in-use emissions and duty cycles from five heavy-duty construction vehicles and to examine the emissions-reduction potential of retrofit control technologies on construction equipment, such as DOCs and DPFs. Test results showed that a:

- dump truck, equipped with a DOC, showed PM reductions of 17 percent – however, the conversion of the gaseous emissions was low;
- backhoe, equipped with an active DPF, showed PM reductions of 81 percent;
- bulldozer DOC system showed PM reductions of 24 percent – CO emissions were also significantly reduced, while HC was not reduced;
- Caterpillar wheeled loader, equipped with a catalyzed DPF, showed a combination of 97 percent PM reductions and excellent gaseous control; and
- Volvo wheeled loader, equipped with a DOC, showed PM reductions of 52 percent (during the tests a leak developed in the mass-flow controller and made it difficult, if not impossible, to determine the absolute emissions rates).

Based on the results, retrofitting 200,000 pieces of construction equipment with DPFs would reduce PM emissions up to 15,000 tons/year, CO up to 109,000 tons/year, and HC up to 17,000 tons/year; with DOCs, reductions would be up to 4000 tons/year, 45,000 tons/year, and 7000 tons/year for PM, CO, and HC, respectively. More information along with detailed test results are available from SAE paper no. 1999-01-0110.[1]

DEMONSTRATION PROJECTS FOR DIESEL PARTICULATE FILTER TECHNOLOGIES ON EXISTING OFF-ROAD HEAVY-DUTY CONSTRUCTION EQUIPMENT

The South Coast Air Quality Management District and CARB conducted a project to evaluate the durability and effectiveness of passive DPF technology installed on existing non-road diesel construction equipment. The project installed PM filters on 15 diesel engines that are used on 12 heavy-duty construction vehicles – six scrapers and six dozers. After operating these pieces of equipment with DPFs for a period of one year, they were tested at the West Virginia University Engines and Emissions Research Laboratory. Dynamometer tests were performed on a Caterpillar engine using both transient and eight-mode steady-state duty cycles. DPFs showed that more than 90 percent of PM reductions were achieved during both pre- and post-demonstration testing along with 65 percent or greater reductions of CO and HC emissions. More detailed information can be obtained from the website: http://www.meca.org/galleries/default-file/SCAQMD_Trap_Construction%20Project%20Study_v11%20edited%20lm.pdf.

CITY OF HOUSTON DIESEL FIELD DEMONSTRATION PROJECT

The Diesel Field Demonstration Project evaluated diesel emissions-control devices on various vehicles and equipment, including construction equipment, during the summer of 2000 through the fall of 2001. The project identified retrofit emissions-control systems that can achieve 75 percent NOx reductions and at least 25 to 33 percent reduction in fine particulates. The following summarizes this project:

- Environment Canada performed emissions testing on the City of Houston fleet.
- From the demonstration testing on a Gradall G3WD excavator, the SCR system was selected among DOC plus emulsified diesel fuel (DOC+E), an SCR system, and a combined DPF + SCR system (DPF+SCR). Test results are 35 percent, 78 percent, and 84 percent in NOx emissions reductions for the DOC+E, SCR, and DPF+SCR, respectively, and 76 percent, 27 percent, and 92 percent in PM reductions for the DOC+E, SCR, and DPF+SCR, respectively.
- As a result of the demonstration, 33 rubber-tire excavators were retrofitted with SCR systems. In addition, the City of Houston has retrofitted about 30 to 40 non-road engines such as backhoes and water pumps with DOCs.
- A total of 33 ditch excavators were equipped with an initial-design SCR system, and the SCR system will be upgraded to increase the level of emissions reduction. The SCR systems that were installed included a DOC and a warning signal to indicate when the ammonia supply was getting low.

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[1] Cooper, C., and G. R. Rideout. *The Impact of Retrofit Exhaust Control Technologies on Emissions from Heavy-Duty Diesel Construction Equipment*, SAE paper no. 1999-01-0110.

More information on this project is available
at http://www.arb.ca.gov/msprog/ordiesel/Documents/houston_demo_project.pdf.

APPENDIX B:
NON-ROAD EMISSIONS-RELATED DOCUMENTS

The following documents discuss non-road emissions:

- the report *Diesel Retrofit Technology: An Analysis of the Cost-Effectiveness of Reducing Particulate Matter and Nitrogen Oxides Emissions from Heavy-Duty Nonroad Diesel Engines through Retrofits* (EPA420-R-07-005, May 2007, http://www.epa.gov/otaq/diesel/documents/420r07005.pdf);
- the report *The Cost-Effectiveness of Heavy-Duty Diesel Retrofits and Other Mobile Source Emission Reduction Projects and Programs* (EPA-420-B-07-006, May 2007, http://www.epa.gov/otaq/stateresources/policy/general/420b07006.pdf);
- the guidance document *Diesel Retrofits: Quantifying and Using Their Benefits in SIPs and Conformity – Guidance for State and Local Air and Transportation Agencies* (EPA420-B-06-005, June 2006, http://www.epa.gov/otaq/stateresources/transconf/policy/420b06005.pdf);
- the fact sheet "EPA's Diesel Retrofit SIP and Conformity Guidance" (EPA420-F-06-034, June 2006, http://www.epa.gov/otaq/stateresources/transconf/policy/420f06034.pdf);
- the report *Diesel Retrofit Technology and Program Experience: Final Draft* (July 2005, http://www.epa.gov/cleandiesel/documents/retrofit-tech-prog-exp.07-2005.pdf);
- the report *Diesel Construction Equipment Activity and Emissions Estimates for the Dallas/Ft. Worth Region* (August 2005, http://files.harc.edu/Projects/AirQuality/Projects/H043.T163/H43.T163FinalReport.pdf); and
- the report *TxDOT Emulsified Diesel Final Report* (January 2004, http://www.bp.com/liveassets/bp_internet/bp_ecd/bp_ecd_us/STAGING/local_assets/downloads_pdfs/t/Texas_DOT4576_3.pdf).

APPENDIX C:
PRACTICES OF CITY/STATES – STRATEGIES AND INCENTIVES

TEXAS

Texas has statewide initiatives to reduce mobile-source emissions. Under the Texas Emissions Reduction Plan (TERP), several monetary incentive programs were established to improve air quality (intentionally, NOx emissions reduction) in the state's nonattainment areas. Among those, the TCEQ's Emissions Reduction Incentive Grants Program offers grants and other financial incentives for emission reductions and alternatives to the selected applicants. The grants are issued for the repowering or replacement of non-road and on-road vehicles and equipment. The $30 million allocated to the Rebate Grant Program under the latest round of funding (FY 2008) has been awarded, and the new FY 2009 rebate grant notice was on schedule to be released on September 10, 2009. More information is available at http://www.tceq.state.tx.us/implementation/air/terp/.

CONNECTICUT

The Connecticut General Assembly directed the Department of Environmental Protection (DEP) through Special Act 05-7 to develop diesel emissions-reduction strategies. The act addressed transit buses, school buses, and construction equipment. The entire report is available at http://www.ct.gov/dep/lib/dep/air/diesel/docs/ctcleandieselplanfinal.pdf.

The plan listed numerous strategies for reducing emissions including:

- continue to encourage retrofits and clean fuels;
- call on state agencies (including the DOT, Department of Public Welfare, Office of Personnel Management, Department of Economic and Community Development, and University of Connecticut) to adopt Clean Air Construction Contract Specifications for state construction contracts greater than $5 million;
- revise DEP's regulations governing indirect sources of air pollution to allow for retrofits as a compliance option for applicable DOT projects;
- provide retrofits for equipment rental agencies;
- mandate requirements for emissions-control technology, ULSD fuel, and best available technology (BAT) to be used with diesel construction equipment; and
- fund incentives (in the form of sales tax waivers) to contractors to reduce emissions through purchase and use of retrofitted equipment, clean fuels, and engine re-builds.

TENNESSEE

The Tennessee Department of Transportation (TDOT) created the Clean Transportation Initiative to reduce on- and off-road mobile-source emissions. TDOT dedicated $4.8 million in CMAQ funds over three years to a Clean Transportation Innovations Incentives Fund for reducing emissions from heavy-duty diesel trucks using retrofit control equipment and idling-reduction technology.

TDOT manages the Innovations Incentives Fund and funds public/private partnerships focusing on:

- emissions-control solutions,
- replacement,
- repowering,
- rebuilding, and
- encouragement to reduce idling and use cleaner fuels.

TDOT is currently implementing three pilot partnership projects.

As with the national apportionment formula, TDOT does not account for $PM_{2.5}$ nonattainment status in its CMAQ distribution to metropolitan planning organizations (MPOs). However, TDOT is providing resources to address $PM_{2.5}$ issues by creating a statewide fund for $PM_{2.5}$ CMAQ projects. More information about TDOT's Environmental Policy Office can be found at http://www.tdot.state.tn.us/environment/policy/.

ILLINOIS

Illinois has statewide initiatives to reduce mobile-source emissions. These initiatives include the Alternate Fuels Rebate Program and the Green Fleets program.[2] The most notable effort is the Clean Air Construction Initiative undertaken by IDOT in the last year; most of the heavy construction equipment on the Dan Ryan project will either be retrofitted with devices designed to reduce harmful emissions or will use ULSD fuel. IDOT has also instituted idling limits and dust controls in order to reduce construction-related air emissions.

As noted in the case studies, approximately 290 pieces of equipment in use on the Dan Ryan project will have emissions-control devices or will use ULSD fuel. These emissions-control strategies are a contract requirement for equipment operating on the Dan Ryan project. The initiative is funded in part through a $60,000 grant from EPA that was secured by the Illinois EPA. More information is available at http://www.dot.state.il.us/press/airbear.html.

NORTH CAROLINA

In 2004, the North Carolina Department of Transportation (NCDOT) announced changes in its CMAQ program guidelines, for the first time giving MPOs the authority to determine project priorities. North Carolina receives approximately $20 million in CMAQ funds annually. Roughly 20 percent of this amount is retained for statewide projects with the rest being divided among North Carolina's 21 nonattainment counties. Both statewide and MPO-programmed CMAQ dollars included diesel retrofit projects during North Carolina's most recent approval of new CMAQ projects.

NCDOT also awarded $1.6 million over three years to the North Carolina Solar Center at North Carolina State University to establish a three-year Clean Fuel Advanced Technology Program (CFATP). A 20 percent match was provided by the North Carolina Division of Air Quality and the State Energy Office. Under the CFATP, public and private entities in ozone or PM

[2] Illinois EPA. http://www.epa.state.il.us/air/, accessed November 2007.

nonattainment and maintenance areas can apply for funding of on-road and non-road diesel retrofits.

NEW JERSEY

In September 2005, New Jersey enacted a new Diesel Risk Reduction Law, which set the framework for a program to control PM from diesel-powered mobile sources. According to this law, garbage trucks (publicly owned or used in a public contract), transit buses, and other publicly owned on-road and off-road vehicles are and will be required to install exhaust emissions-control devices. Retrofit technology and installation costs will be reimbursed by the state of New Jersey through the Corporate Business Tax as approved through a constitutional amendment in November 2005. Retrofit requirements will be phased in over 10 years based on the availability of funding. Annual funding levels are anticipated to be in the range of $14 million.

Other provisions of the law required the use of ULSD by all on- and off-road diesel vehicles by January 2007 and extended authority to local police to enforce existing idling regulations. The New Jersey Department of Environmental Protection provides further guidance on how to comply with the law, with more information at http://www.nj.gov/dep/airworkgroups/diesel_workgroup.html.

WISCONSIN

The Wisconsin Department of Natural Resources has federal grant funds available for diesel retrofit projects done in the state's eastern ozone nonattainment counties. The Wisconsin retrofit program applies to on-road and non-road municipal vehicles, as well as private or public-owned school buses and other non-road equipment. All vehicles must use EPA- or CARB-verified technologies and remain in the fleet for at least five years after being retrofitted.

OREGON

Oregon created a tax credit to help compensate for the cost of installing pollution-control devices on EPA's verified technology list. The provision provides a maximum 35 percent credit against Oregon income taxes (rates may be less for equipment not used exclusively in Oregon).

NEW YORK CITY

New York City Local Law No. 77[3] requires the phase-in use of ULSD and BAT for emissions control in all diesel-powered non-road vehicles used in city construction projects. It applies to all diesel non-road vehicles with an engine rated at 50 hp or greater that is owned by, operated by, operated on behalf of, or leased by a city agency. Public-works contracts less than $2 million must specify that the contractors use BAT.

[3] The City of New York. www.nyccouncil.info/pdf_files/bills/law03077.pdf, accessed November 2007.

APPENDIX D:
PRACTICES OF OTHER STATES – NON-ROAD EMISSIONS

WESTERN REGIONAL AIR PARTNERSHIP (WRAP)

The following states are involved in WRAP: Alaska, Arizona, California, Colorado, Idaho, Montana, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming. All the western states in the WRAP, except California, use NONROAD default values for estimating non-road diesel mobile-source emissions. Many states in WRAP consider non-road construction emissions a very small fraction of their inventory. More detailed information is available at http://www.wrapair.org/index.html**.**

ARKANSAS

Arkansas used the NONROAD model with the exception of the defaults used in growth factors. NONROAD default equipment populations are mostly based on either 1996 or 1998 data from Power Systems Research, a private marketing research company.[4] ENVIRON decided not to use the default NONROAD growth factors because questions have been raised concerning their validity. Instead, ENVIRON developed alternative state-level growth factors using different surrogates for each non-road equipment category and assumed linear growth to forecast the 1996 or 1998 base year data to 2002. More detailed information is available at http://www.adeq.state.ar.us/AIR/branch_planning/pdfs/sip_crittenden_county.pdf.

LOUISIANA

Louisiana's non-road mobile emissions data were derived from the "Emission Inventory Development for Mobile Sources and Agricultural Dust Sources for the Central States" produced by Sonoma Technology, Inc., for the Central States Air Resource Agencies in October 2004. The inventory was developed using NONROAD 2004. For other source categories, NONROAD default activity data were used in conjunction with region-specific fuel information to estimate emissions. More detailed information is available at http://www.deq.louisiana.gov/portal/tabid/2542/Default.aspx.

NEW YORK

Non-road mobile-source emissions were estimated using two separate methodologies. New York is modeled for all 62 counties separately on a monthly basis. In addition, New York is separated into two areas due to the federally mandated Reformulated Gas Program. This program is in place in the New York City Metropolitan Area, which consists of Bronx, Kings, Nassau, New York, lower Orange, Queens, Richmond, Rockland, Suffolk, and Westchester Counties.

Emissions from two-stroke and four-stroke gasoline-fueled, and four-stroke diesel-fueled off-highway vehicles as well as emissions from recreational marine vessels were estimated using the EPA draft NONROAD model. Using the EPA NONROAD model, non-road emissions from New York were estimated for each individual county for each month of the year. Temperature and fuel-blend data varied by month for each county across the state.

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[4] EPA. *Nonroad Engine Population Estimates*, Report no. NR-006A, 1998.

Temperature data for 1999 was acquired from the National Oceanic and Atmospheric Association, which included historical weather data from 17 airport locations across the state of New York as well as surrounding locations. This information was used to develop average high and low temperatures for each month on a county-by-county basis. The results were input into the NONROAD model.

Fuel-blend data for 1999 were acquired from the New York State Department of Agriculture and Markets. These data are based upon thousands of samples collected across the state from fueling stations and retention areas. These samples are then analyzed for many profiles including oxygen content, Reid vapor pressure, and sulfur content. The data provided average monthly fuel profiles on a county-by-county basis. The results were then used as inputs to the NONROAD model. More detailed information is available at http://www.glc.org/air/inventory/1999/mobile/AppendixE_NY_mobile.pdf.

APPENDIX E:
QUESTIONNAIRE FOR FUEL ADDITIVES

Emissions Reduction

Do you have any emissions test data* for your FA that can be shared with us?

Yes ______ No ______

If yes, who performed the test(s)?

EPA ______ CARB ______ Southwest Research Institute (SwRI) ______ Yourself ______

Others ______; please specify: ____

Based on the data, please specify the average emissions-reduction rate (%)

on construction equipment for: NOx _____ PM _____ HC _____ CO _____

on all applications, if different, for: NOx _____ PM _____ HC _____ CO _____

* Please attach copies of such test data that you believe are relevant to this project.

Experiences

Do you have any commercially available FA products?

Yes ___ No ___; if no, will any products be available in three months? Yes ___ No ___

If yes, approximately how much have you sold or applied in the field?

Total ______: Construction equipment ______ On-road vehicles ______ Others ______

Is (Are) your FA product(s) certified?

Yes ______ No ______; if yes, by EPA ______ and/or CARB ______

Applications

How much does your product cost?

$____/gallon (G) when sold for 1 G; $____/G for 100 G; $____/G for 1000 G or more

What is the mixing ratio?

1 G of your product in ______ G of diesel

Does your product need to be pre-mixed or just added to the fuel?

Add ______ Pre-mix ______

Others ______; please specify: ____

How will your product be purchased and stored (e.g., 1-G containers, drums, 8-oz. bottles for 50 G of diesel fuel, or pre-mixed fuel tanks)?

Please specify: ____

____

____

Do you have any general or specific requirements, instructions, and/or cautions in applying your FA technology to any of TxDOT's off-road diesel construction equipment?

Yes ______ No ______

If any, please specify: ____

____

____

____

Contact(s)

Please provide contact information below (name, title, e-mail, phone, and fax):

____

____

APPENDIX F:
QUESTIONNAIRE FOR HYDROGEN-ENRICHMENT SYSTEM

Emissions Reduction

Do you have any emissions test data* for your HE that can be shared with us?

Yes ______ No ______

If yes, who performed the test(s)?

EPA ______ CARB ______ Southwest Research Institute (SwRI) ______ Yourself ______

Others ______; please specify: ____

Based on the data, please specify the average emissions-reduction rate (%)

on construction equipment for: NOx _____ PM _____ HC _____ CO _____

on all applications, if different, for: NOx _____ PM _____ HC _____ CO _____

* Please attach copies of such test data that you believe are relevant to this project.

Experiences

Do you have any commercially available products using HE technology?

Yes ___ No ___; if no, will any products be available in three months? Yes ___ No ___

If yes, how many units (or systems) approximately have you sold or applied in the field?

Total ______: Construction equipment ______ On-road vehicles ______ Others ______

Is your HE technology certified?

Yes ______ No ______; if yes, by EPA ______ and/or CARB ______

Do you have any products commercially available now or in three months using other technologies than HE?

Yes ______ No ______

If yes, please name the technologies:

____

How many units have you sold or applied in the field for all of the technologies excluding HE?

Total ______: Construction equipment ______ On-road vehicles ______ Others ______

Are any of the technologies other than SCR certified?

Yes ______ No ______; if yes, by EPA ______ and/or CARB ______

If yes, please name them: ____

Applications

What is the cost of your system?

$____________ when sold for 1; $____________ for 10; $____________ for 100 or more

What is your cost estimate(s) to install your system on non-road diesel construction equipment such as graders, rubber-tire loaders, and excavators (please include all necessary costs for parts, labor, etc.)?

$____________ when installed on 1; $____________ on 10; $___________ on 100 or more

What is the maintenance/operation cost for each system?

$____________ for 1 year of operation (at 40 hours/weeks for 25 weeks)

Is there anything that needs to be specified for the cost and/or cost estimates above?

If any, please specify: ____

____

____

Do you have any general or specific requirements, instructions, and/or cautions to apply your SCR technology to any of TxDOT's off-road diesel construction equipment?

Yes ______ No ______

If any, please specify: ____

____

____

____

Contact(s)

Please provide contact information below (name, title, e-mail, phone, and fax):

____

____

APPENDIX G:
AVERAGE MODAL EMISSION RESULTS

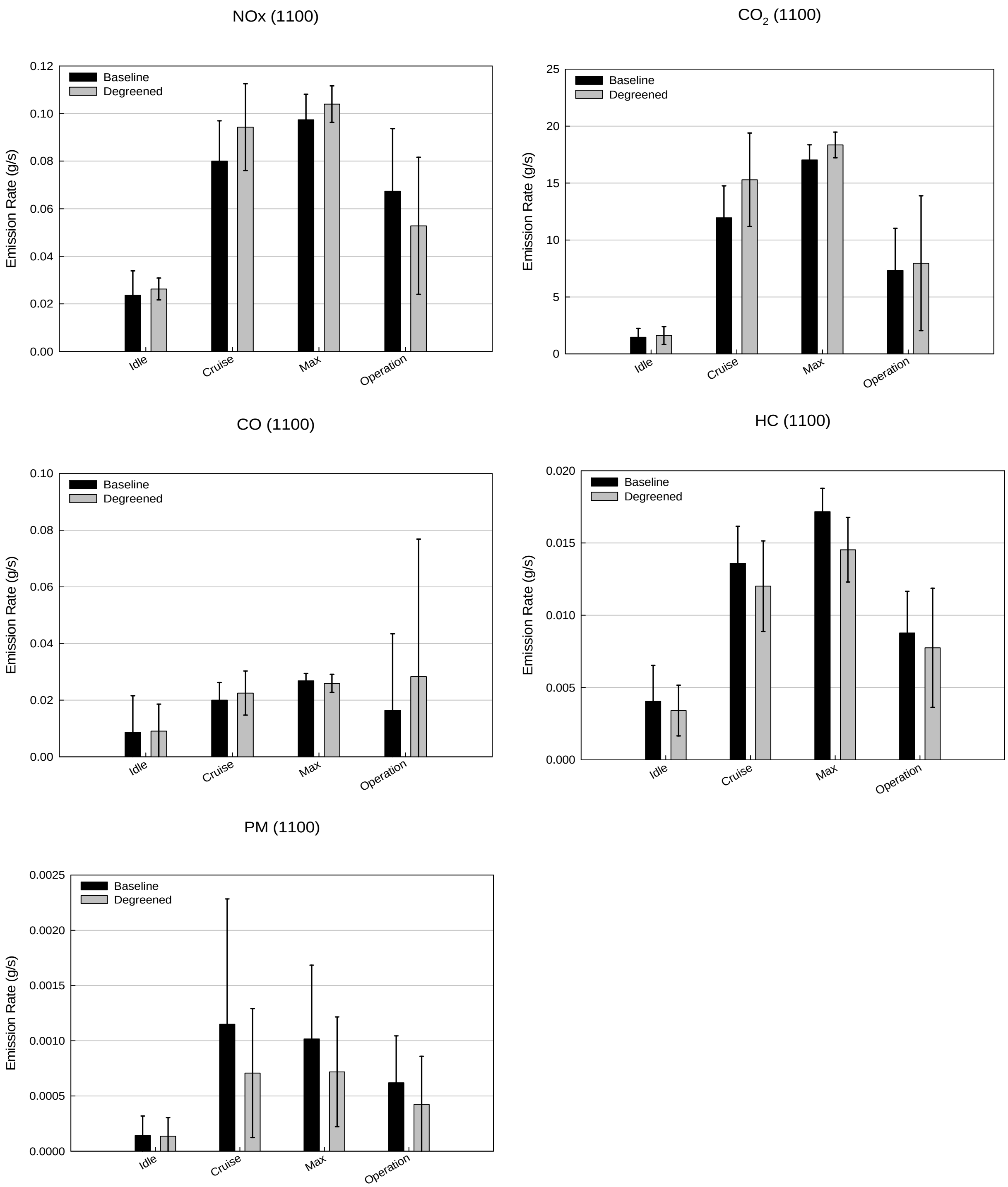


Figure G.1. Baseline Testing Results of Grader 1100A (Tier 1, Hydrogen Enrichment).

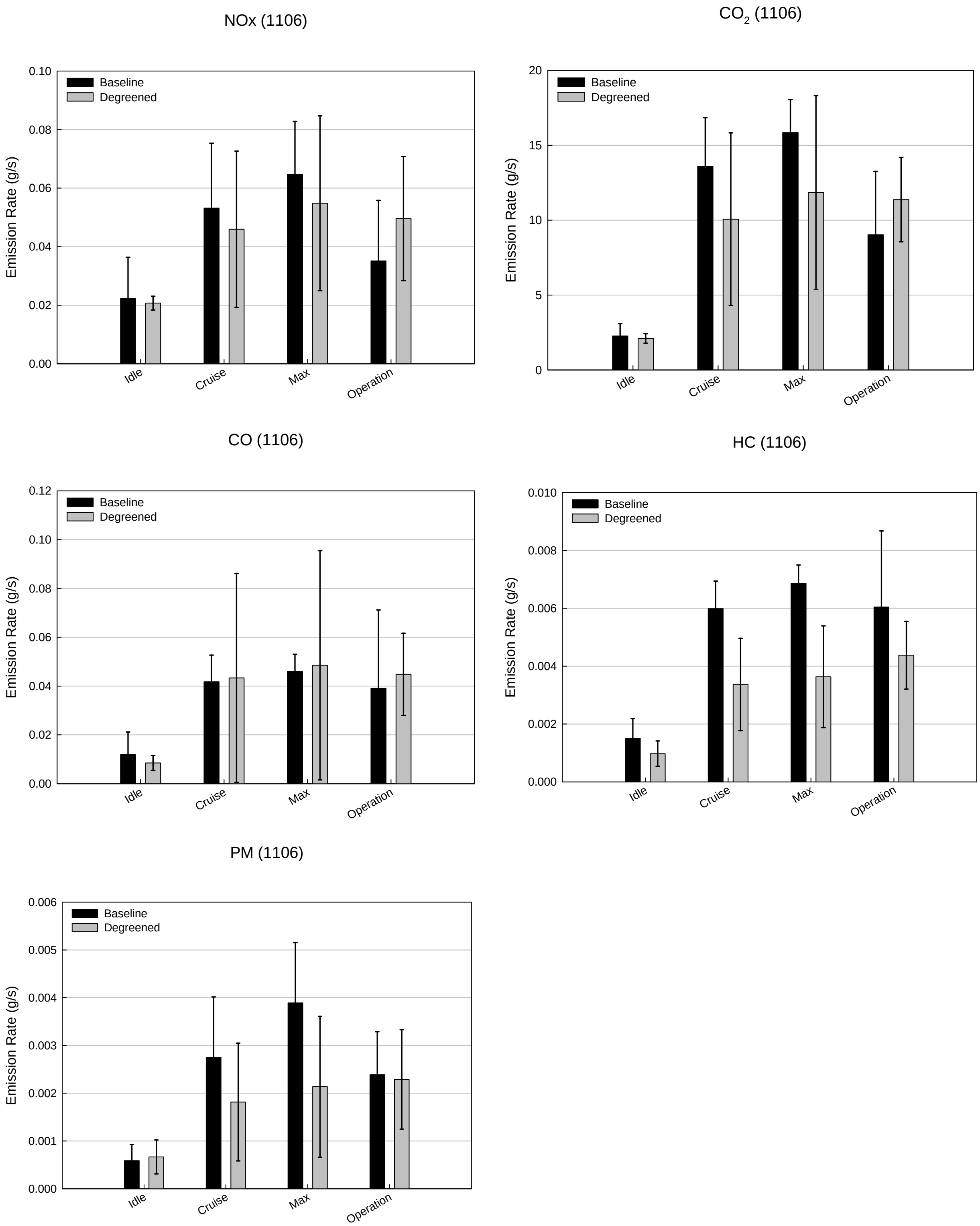


Figure G.2. Baseline Testing Results of Grader 1106G (Tier 2, Hydrogen Enrichment).

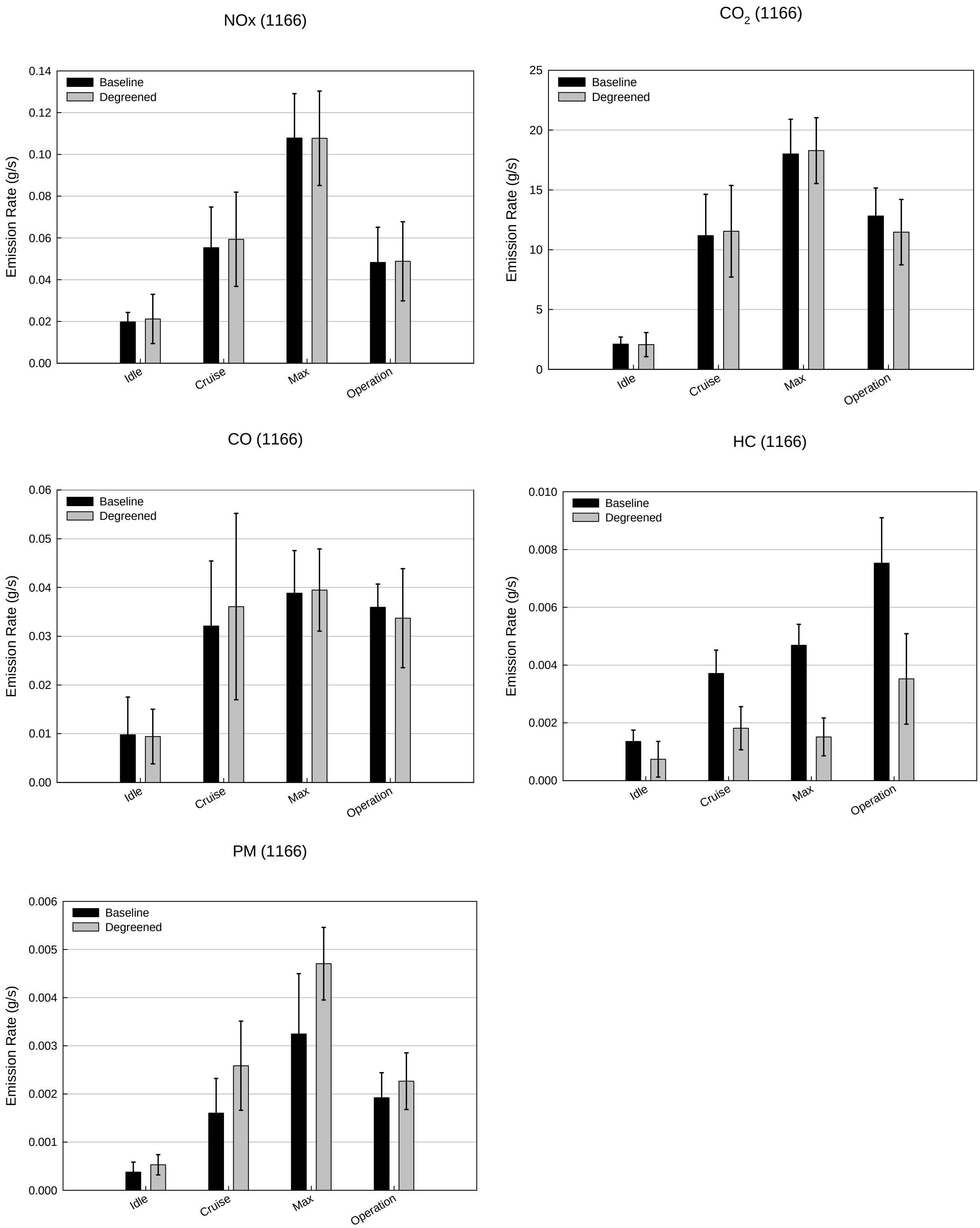


Figure G.3. Baseline Testing Results of Grader 1166G (Tier 2, Fuel Additive).

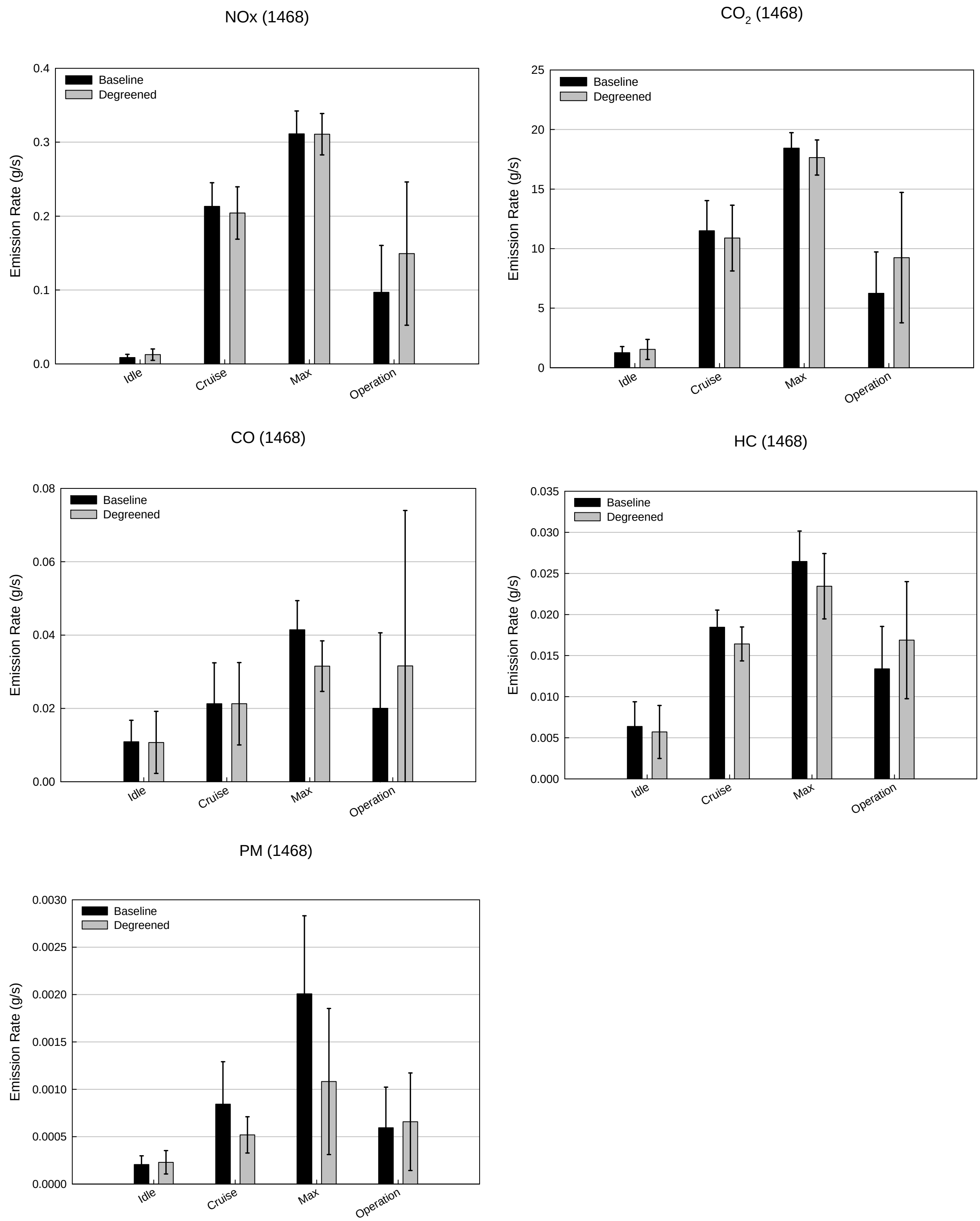
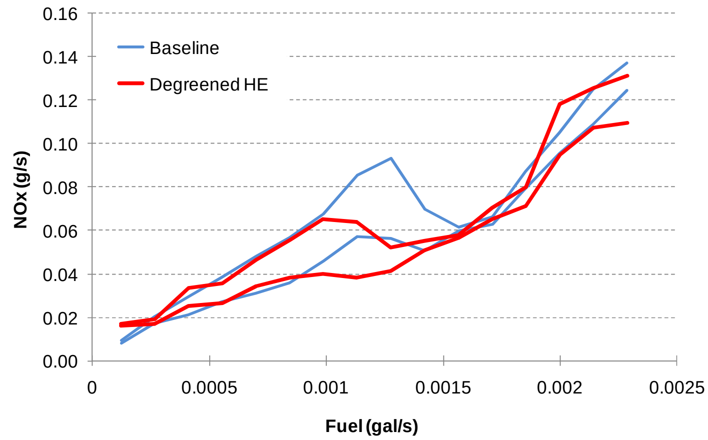


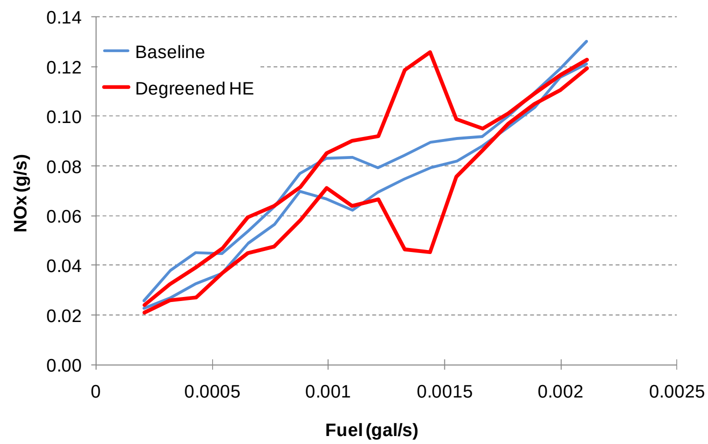
Figure G.4. Baseline Testing Results of Grader 1468 (Tier 0, Fuel Additive).

APPENDIX H:
PREDICTION INTERVAL RESULTS FOR HYDROGEN ENRICHMENT

Grader 1106 – Tier 2



Grader 1100 – Tier 1



Grader 1453 – Tier 0

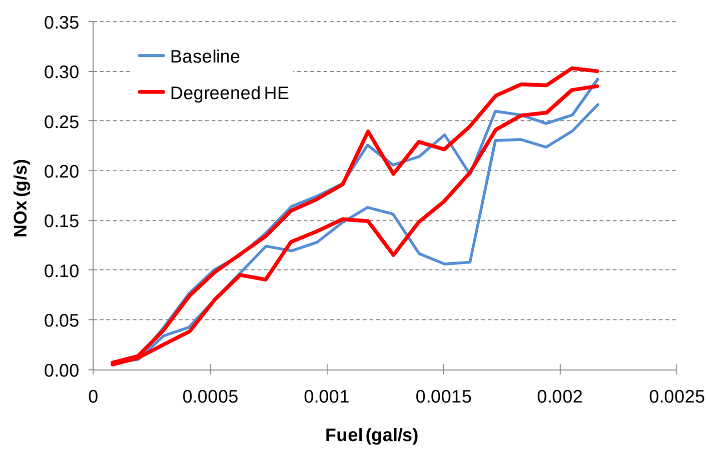


Figure H.1. NOx Results for Hydrogen Enrichment – Driving at the Maximum Speed.

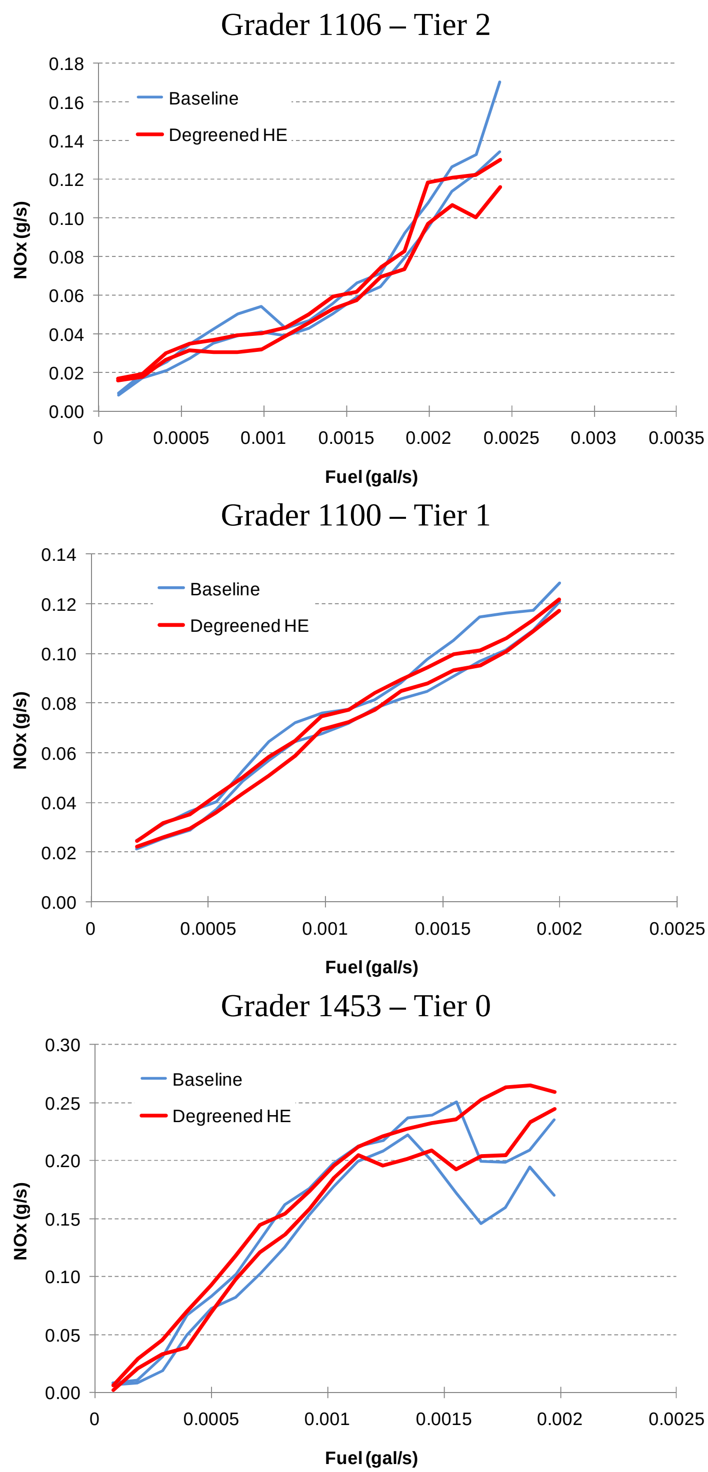


Figure H.2. NOx Results for Hydrogen Enrichment – Driving at 20 mph.

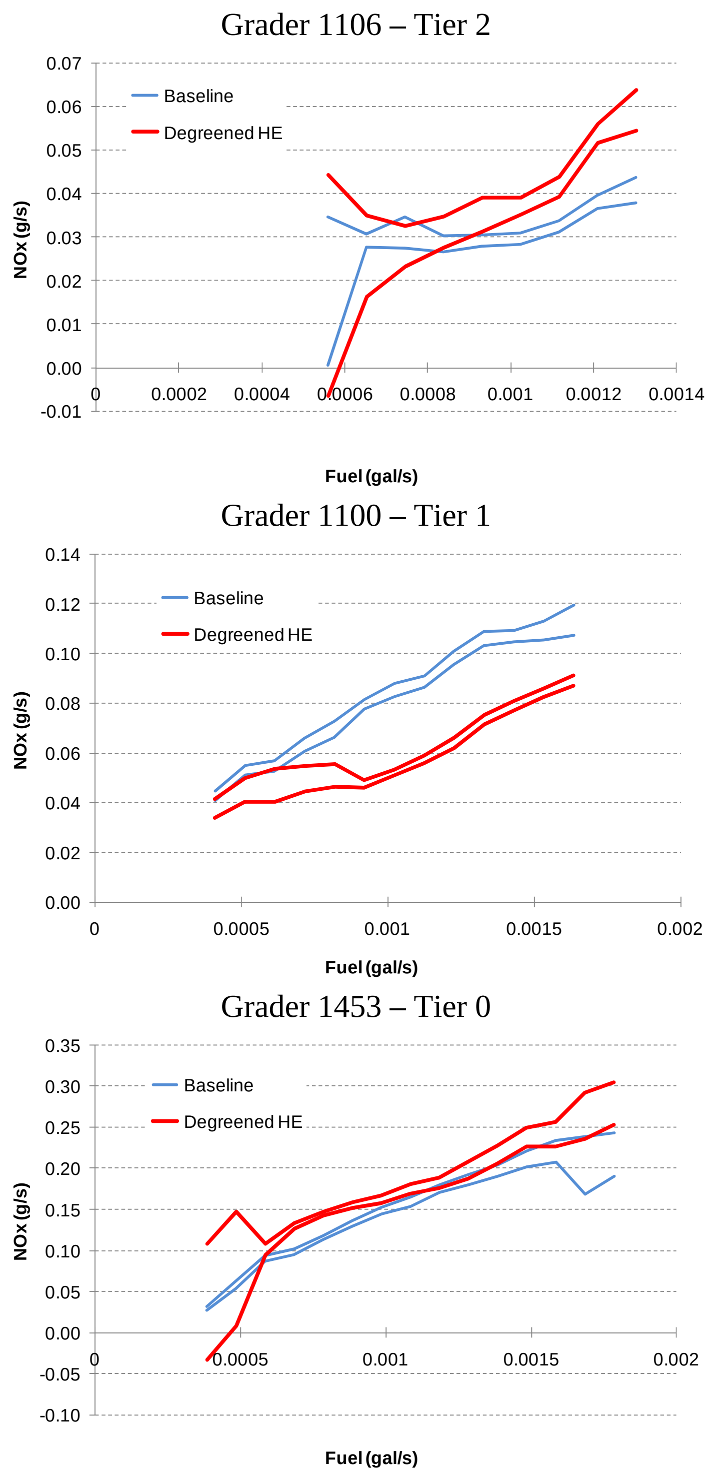
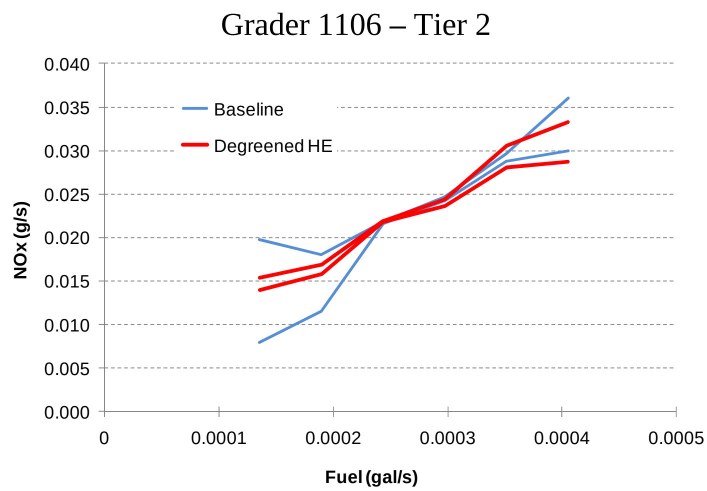
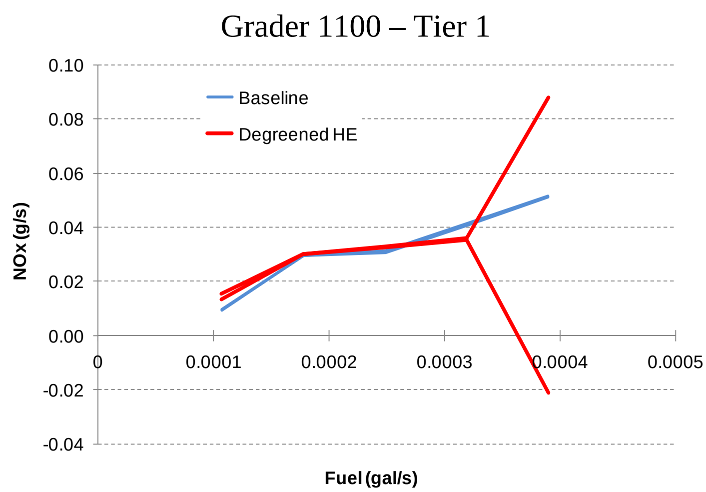


Figure H.3. NOx Results for Hydrogen Enrichment – Grading Operation.





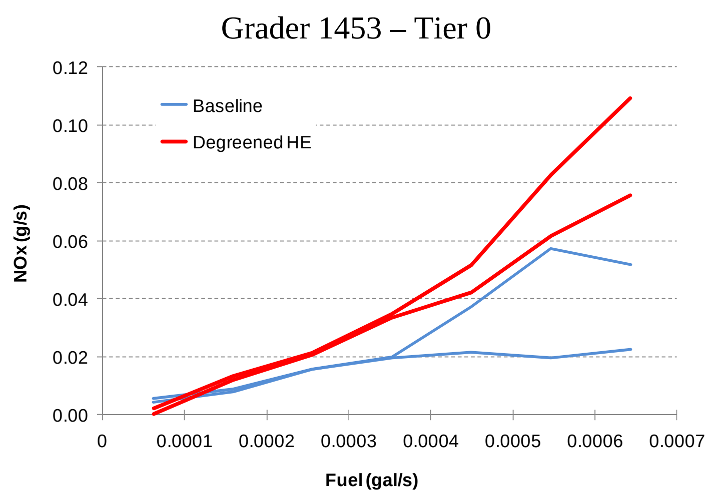


Figure H.4. NOx Results for Hydrogen Enrichment – Idling.

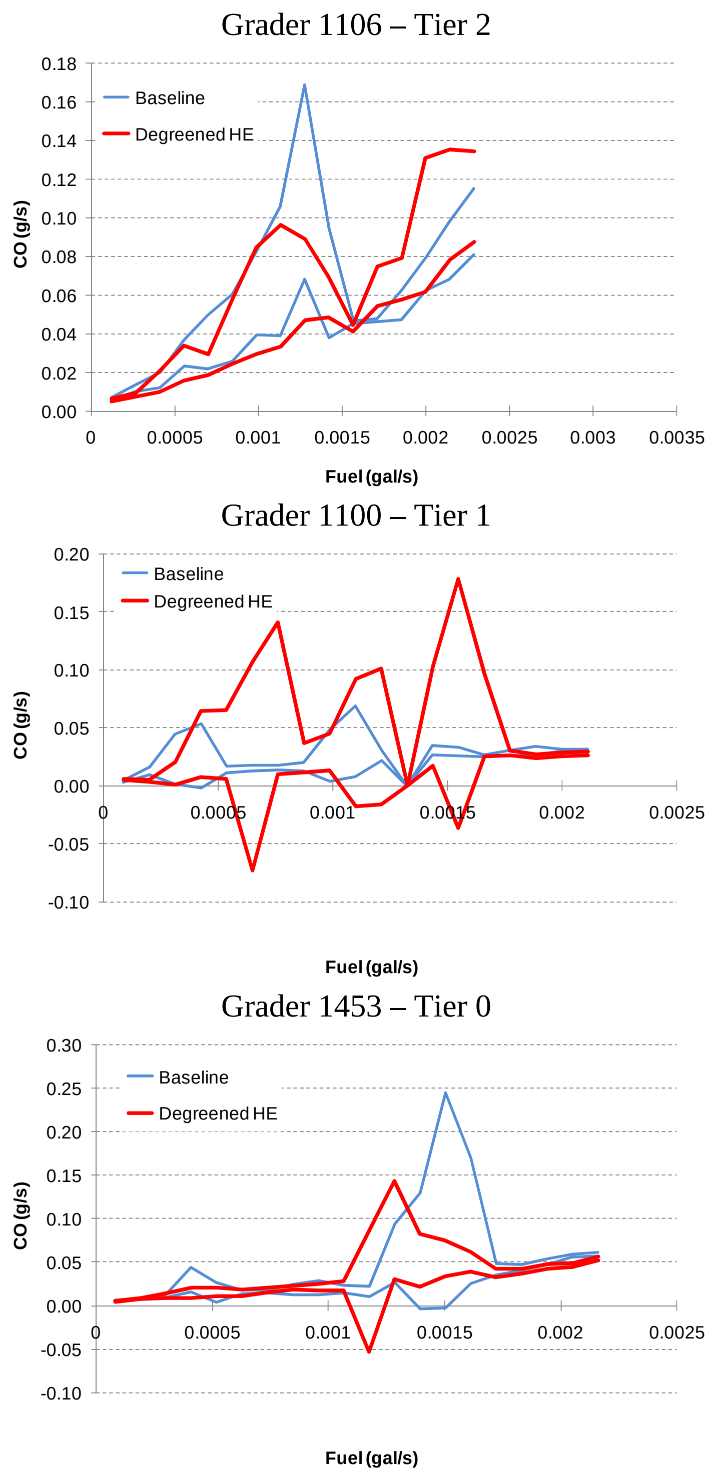


Figure H.5. CO Results for Hydrogen Enrichment – Driving at the Maximum Speed.

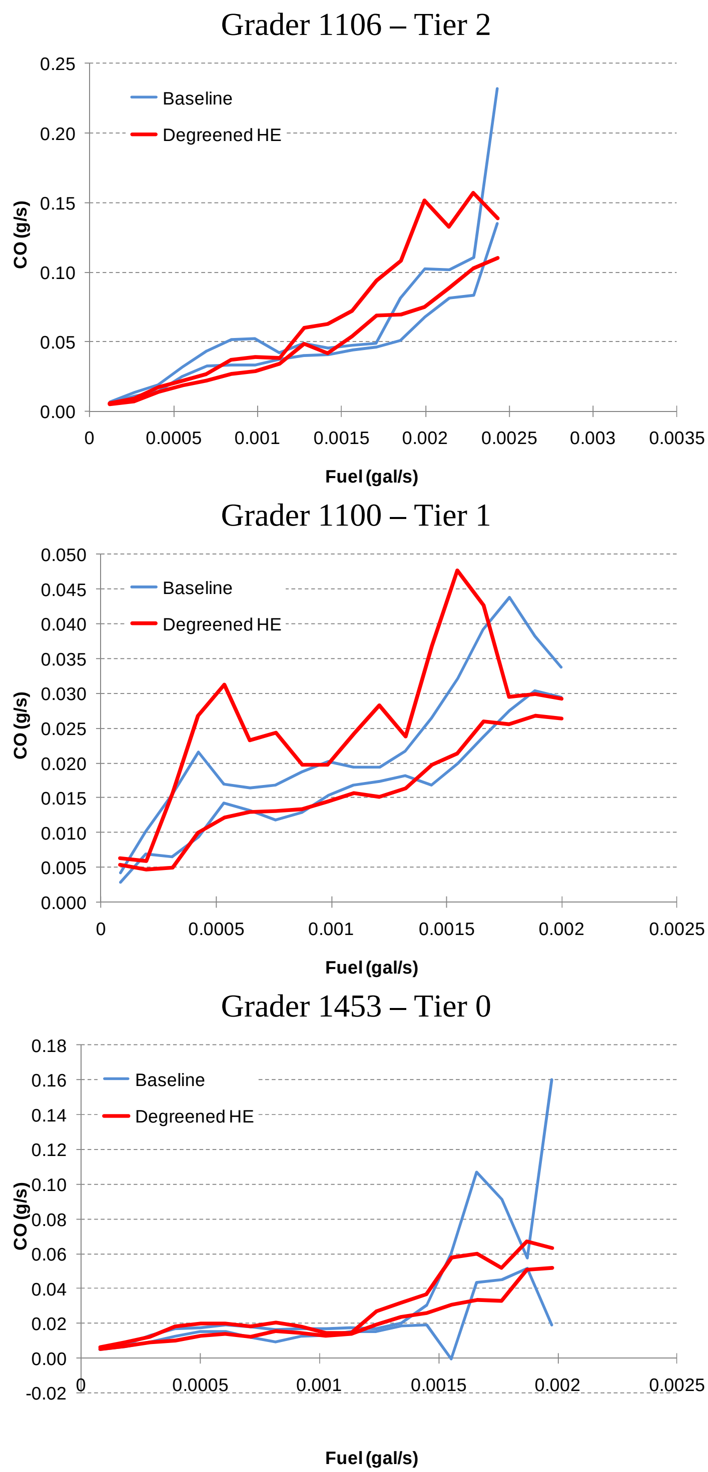


Figure H.6. CO Results for Hydrogen Enrichment – Driving at 20 mph.

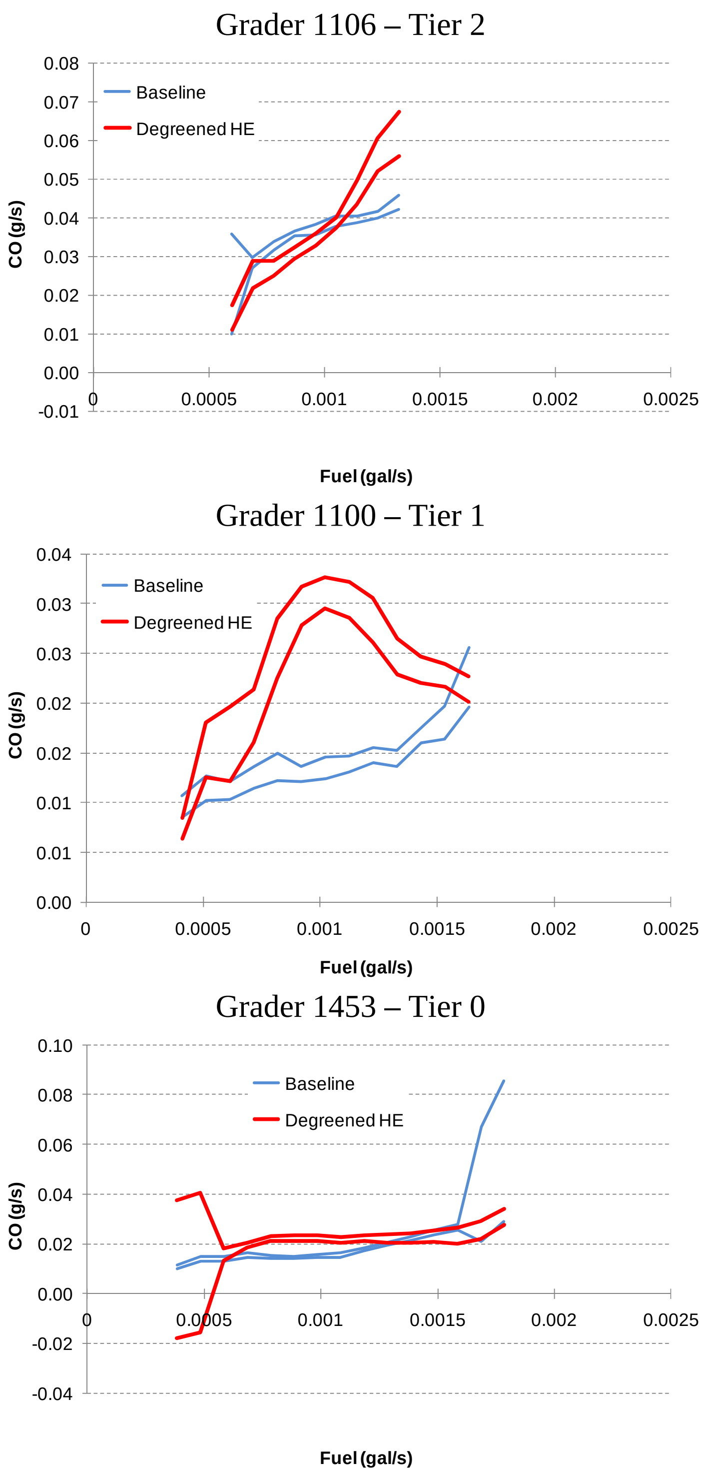


Figure H.7. CO Results for Hydrogen Enrichment – Grading Operation.

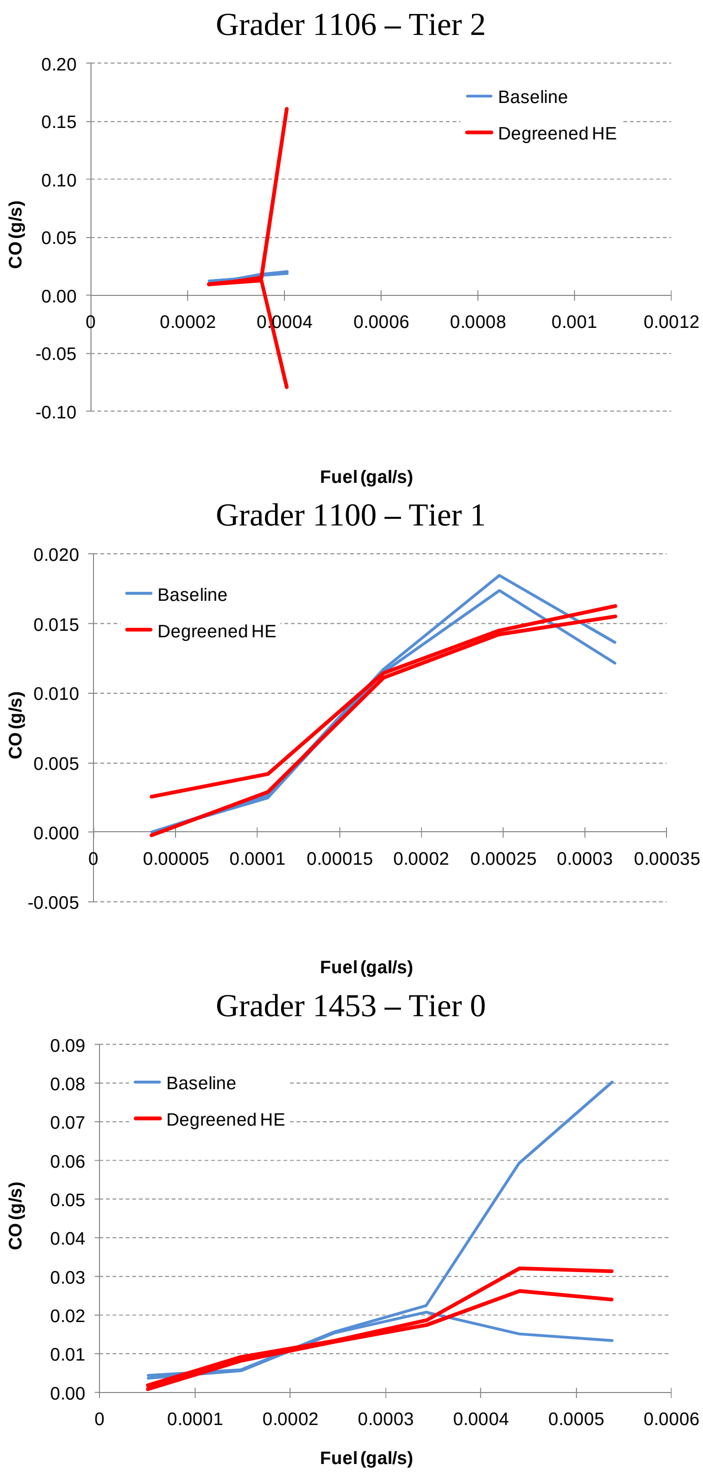


Figure H.8. CO Results for Hydrogen Enrichment – Idling.

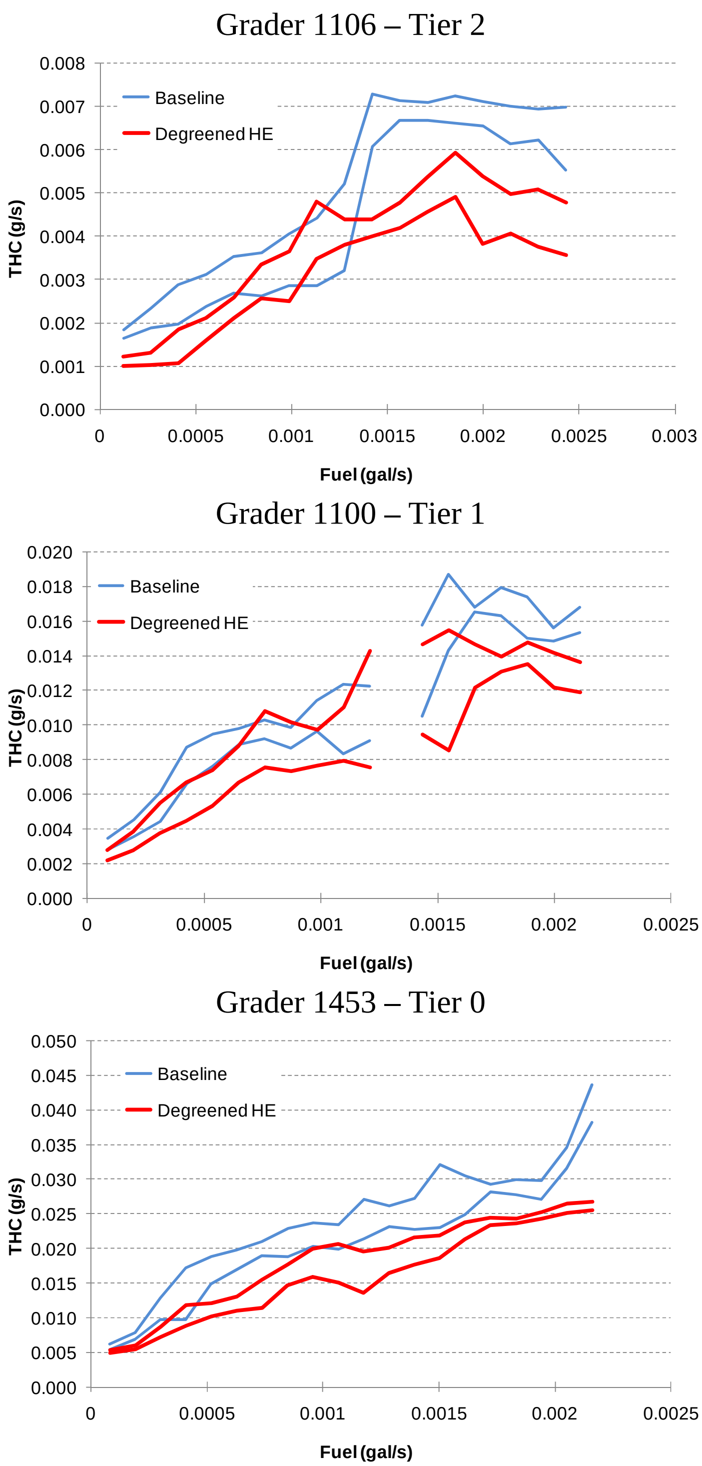


Figure H.9. THC Results for Hydrogen Enrichment – Driving at the Maximum Speed.

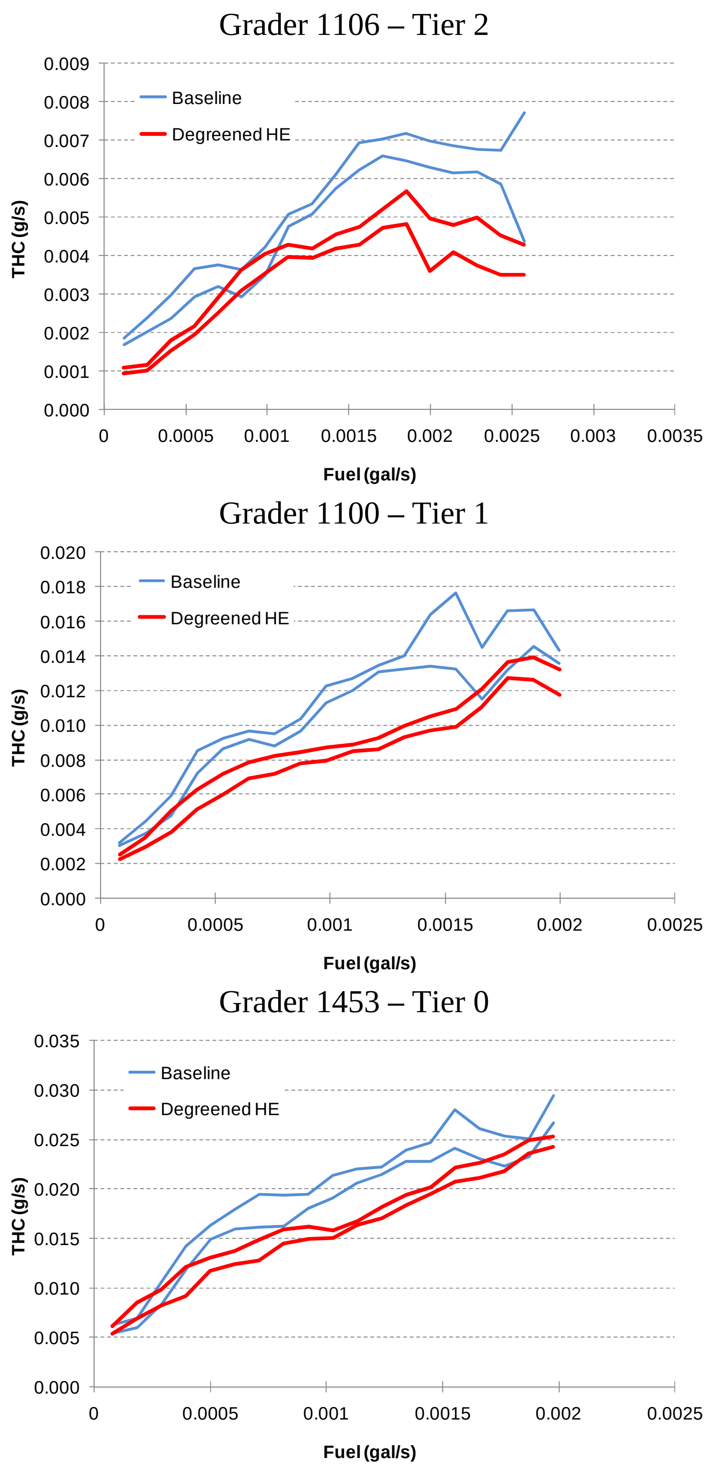


Figure H.10. THC Results for Hydrogen Enrichment – Driving at 20 mph.

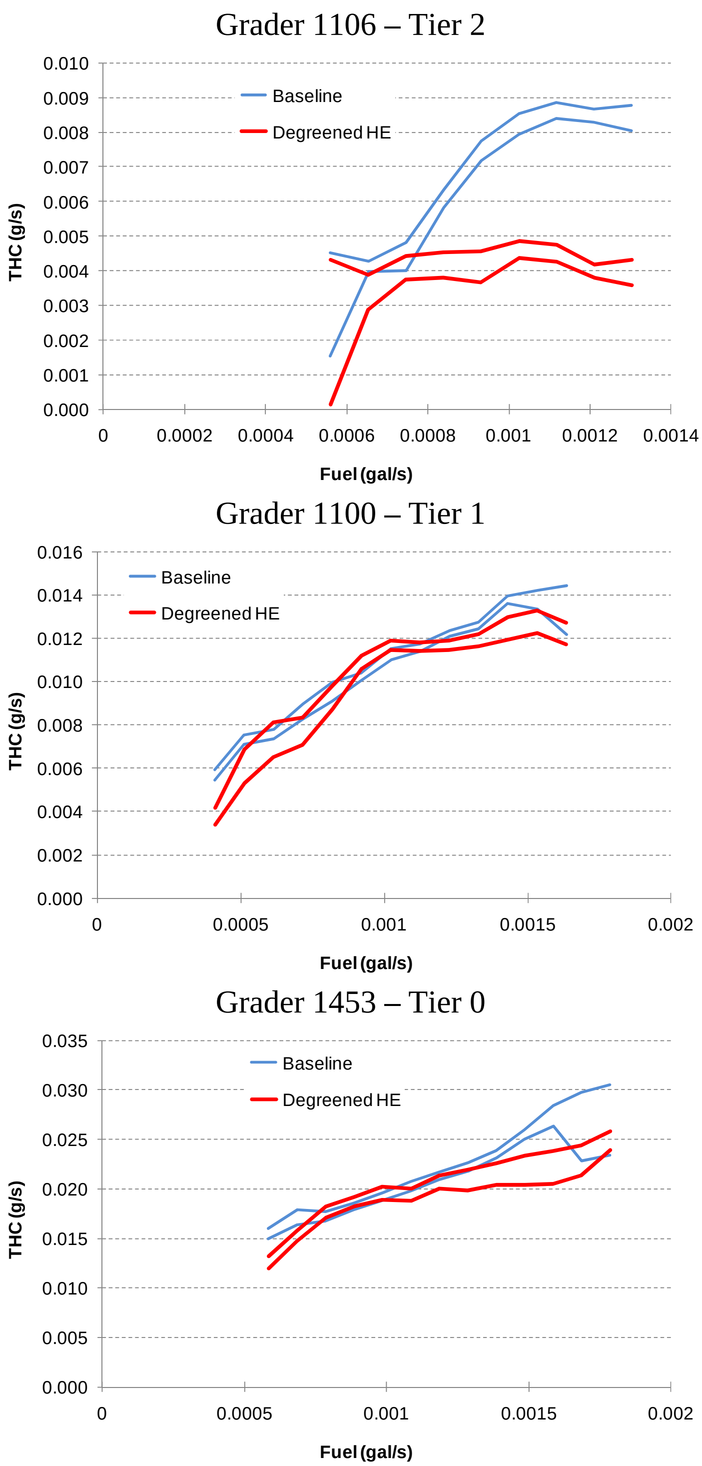


Figure H.11. THC Results for Hydrogen Enrichment – Grading Operation.

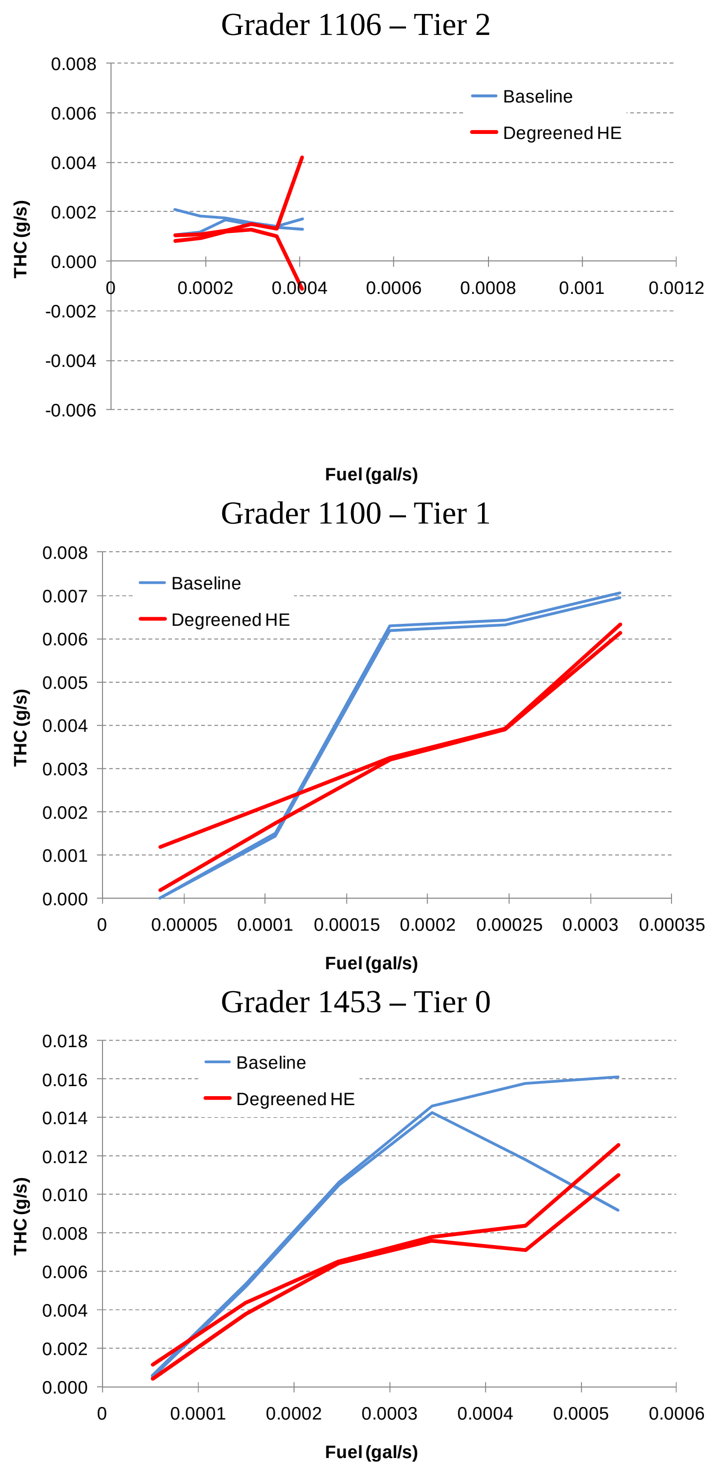
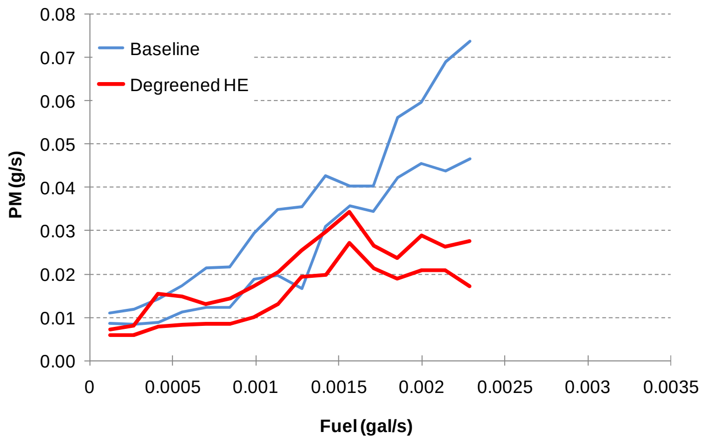


Figure H.12. THC Results for Hydrogen Enrichment – Idling.

Grader 1106 – Tier 2



Grader 1100 – Tier 1

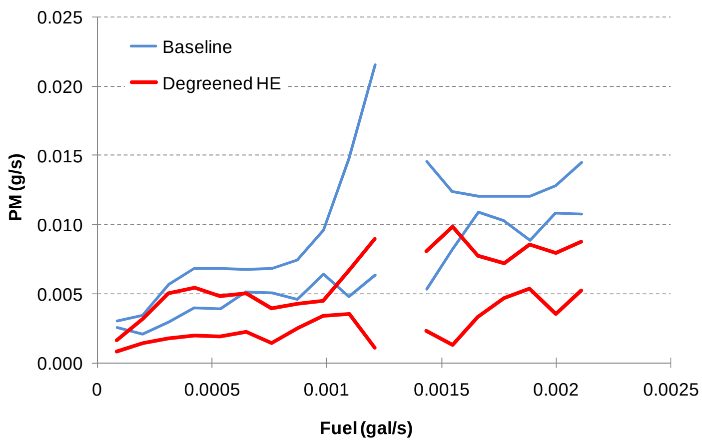
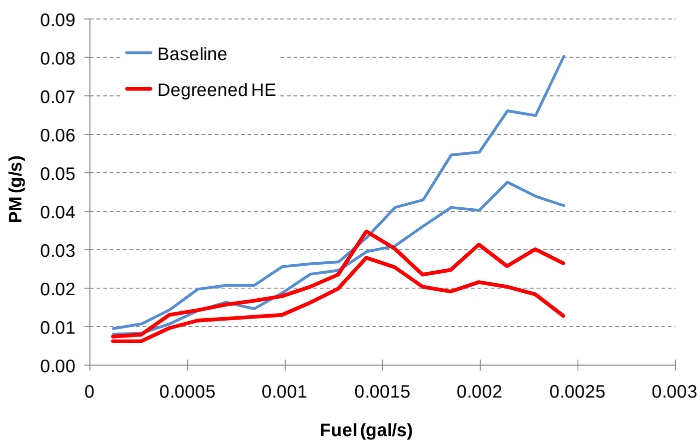


Figure H.13. PM Results for Hydrogen Enrichment – Driving at the Maximum Speed.

Grader 1106 – Tier 2



Grader 1100 – Tier 1

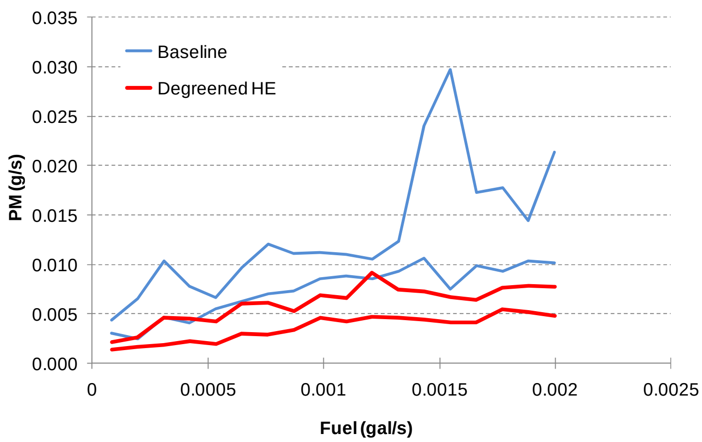
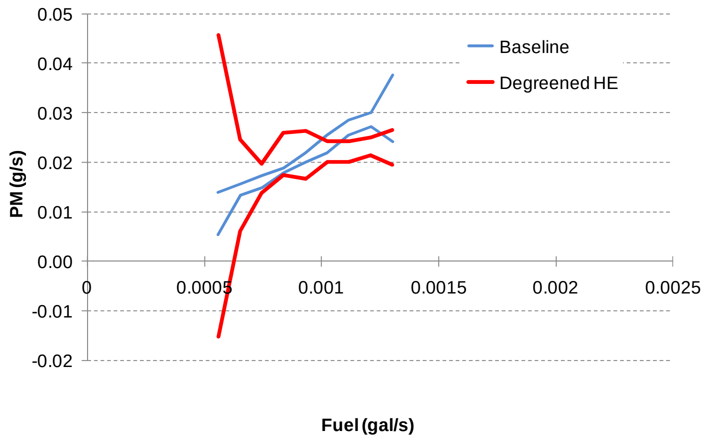


Figure H.14. PM Results for Hydrogen Enrichment – Driving at 20 mph.

Grader 1106 – Tier 2



Grader 1100 – Tier 1

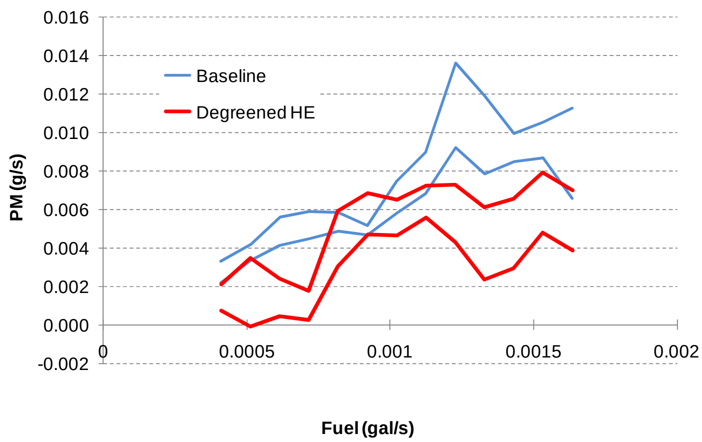


Figure H.15. PM Results for Hydrogen Enrichment – Grading Operation.

Grader 1100 – Tier 1

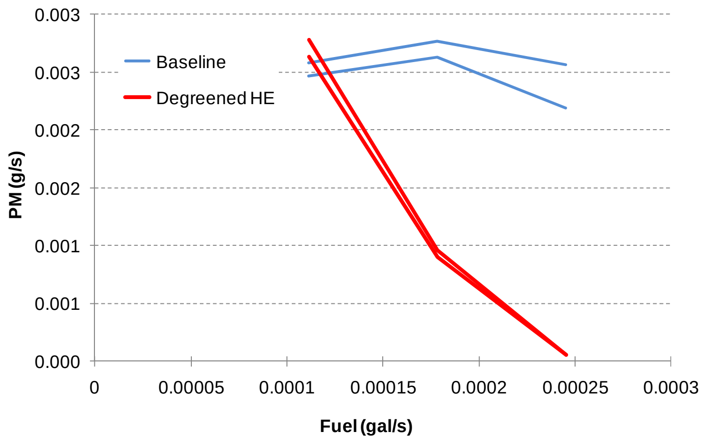
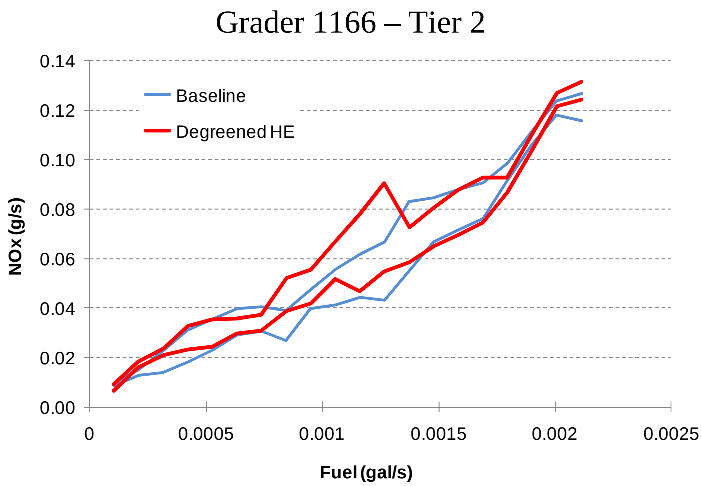
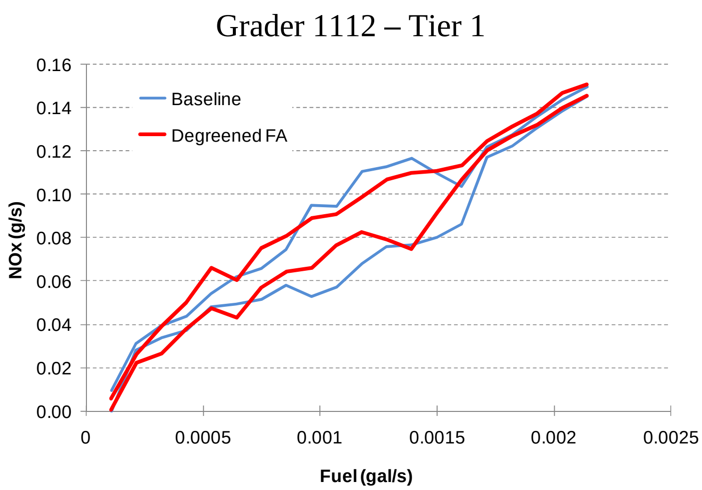


Figure H.16. PM Results for Hydrogen Enrichment – Idling.

APPENDIX I:
PREDICTION INTERVAL RESULTS FOR FUEL ADDITIVE





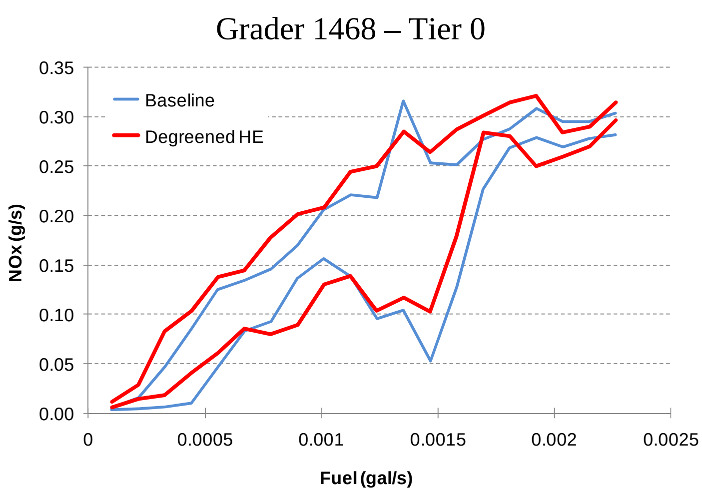
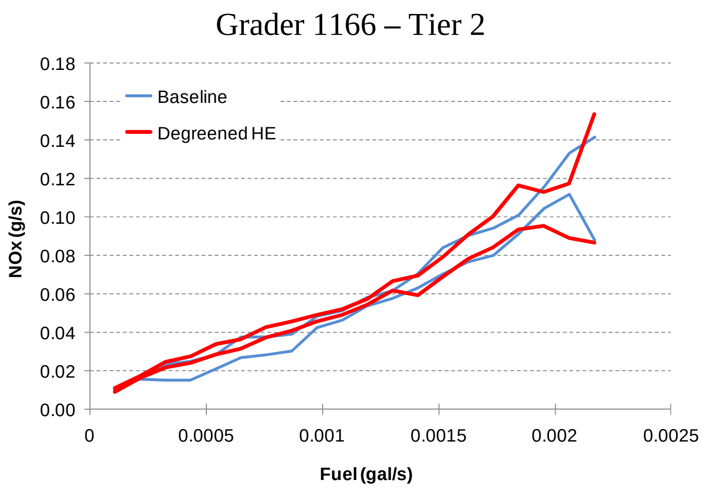
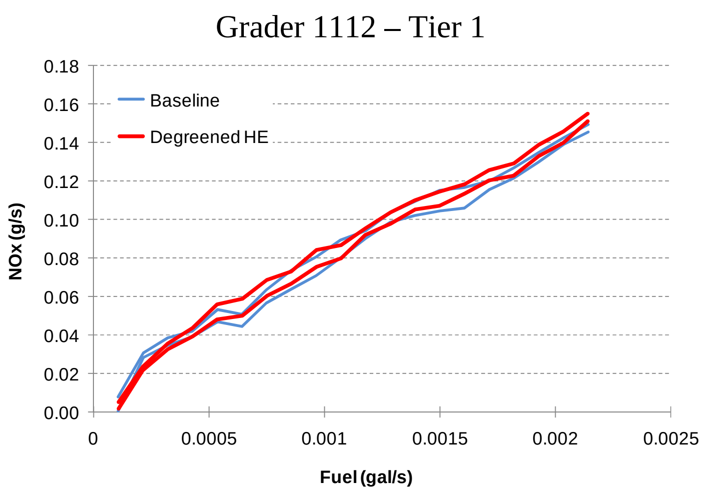


Figure I.1. NOx Results for Fuel Additive – Driving at the Maximum Speed.





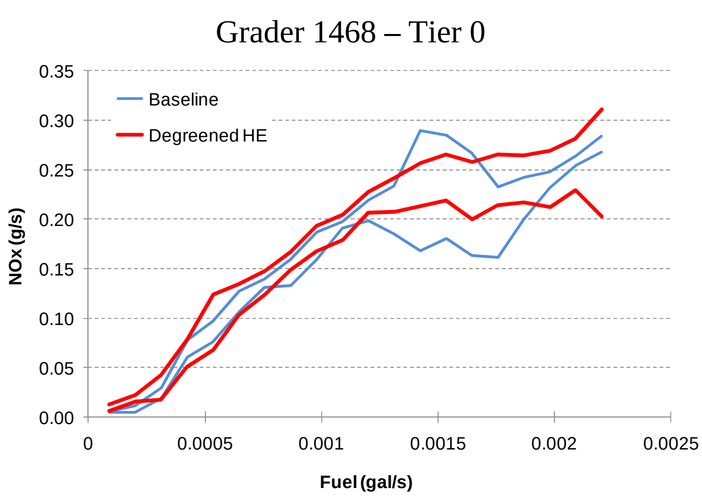


Figure I.2. NOx Results for Fuel Additive – Driving at 20 mph.

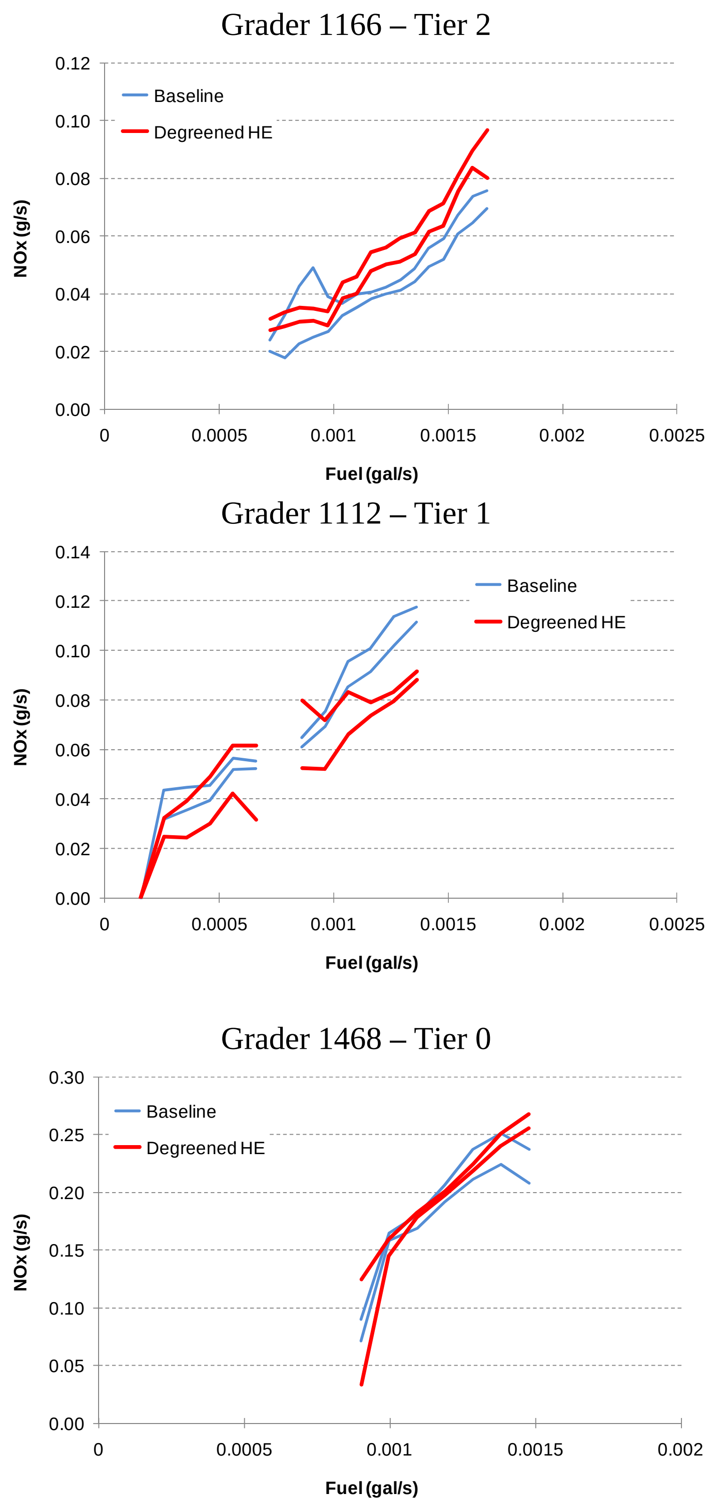


Figure I.3. NOx Results for Fuel Additive – Grading Operation.

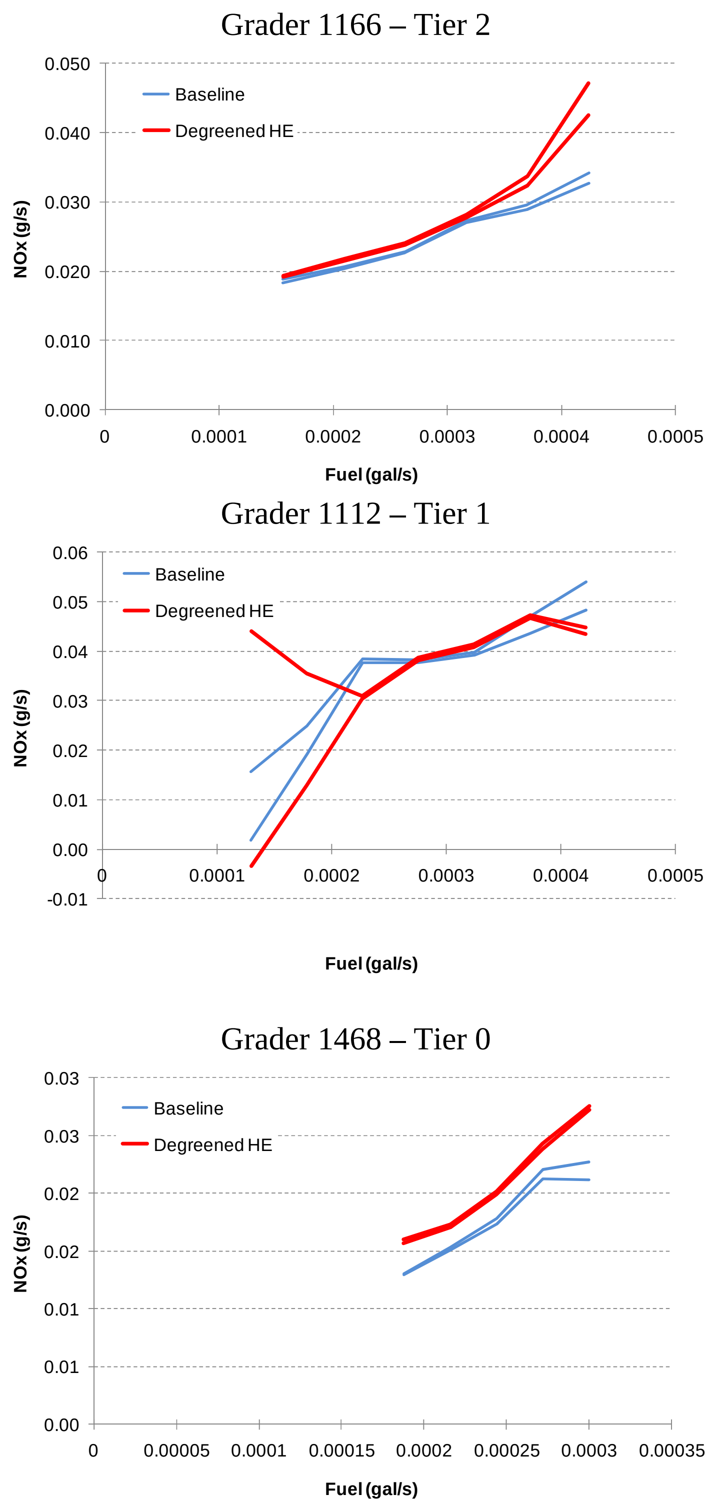


Figure I.4. NOx Results for Fuel Additive – Idling.

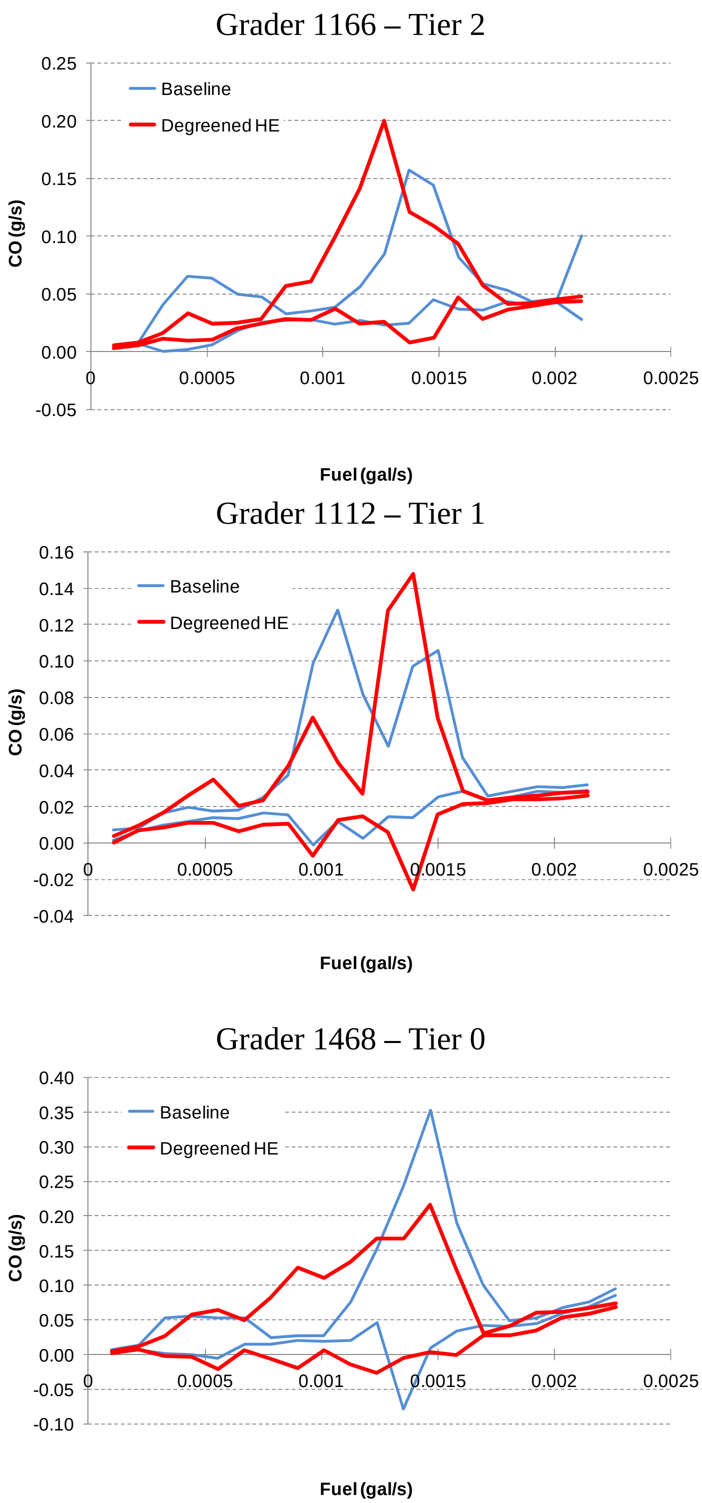


Figure I.5. CO Results for Fuel Additive – Driving at the Maximum Speed.

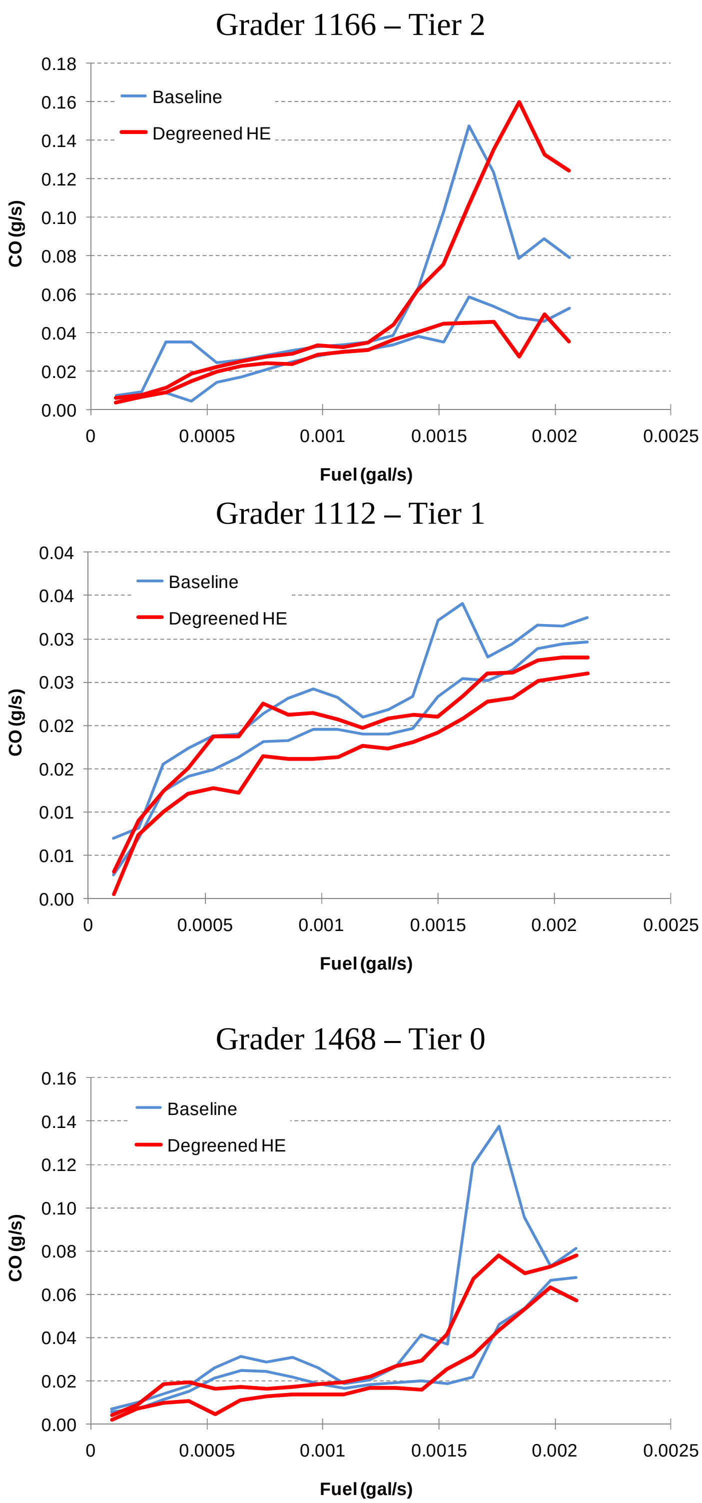
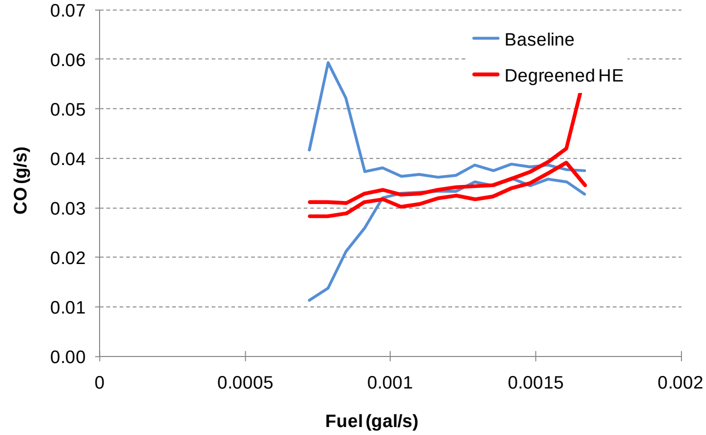
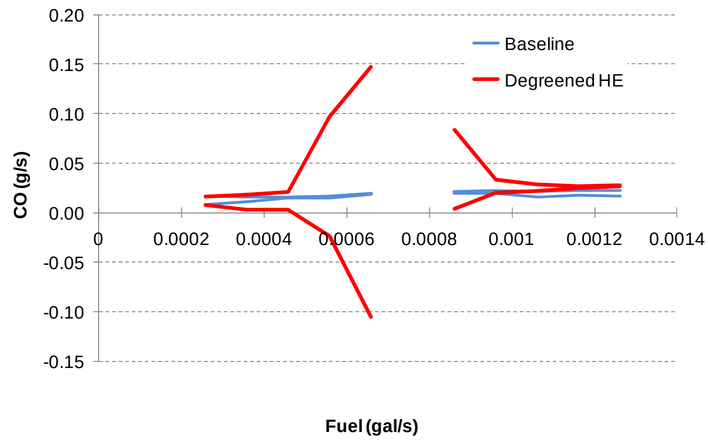


Figure I.6. CO Results for Fuel Additive – Driving at 20 mph.

Grader 1166 – Tier 2



Grader 1112 – Tier 1



Grader 1468 – Tier 0

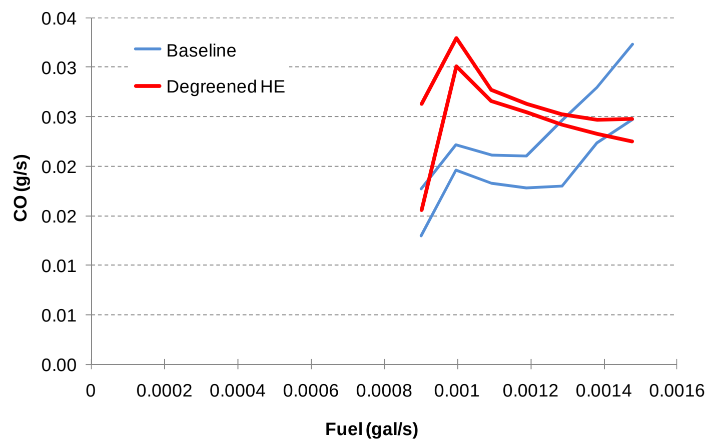


Figure I.7. CO Results for Fuel Additive – Grading Operation.

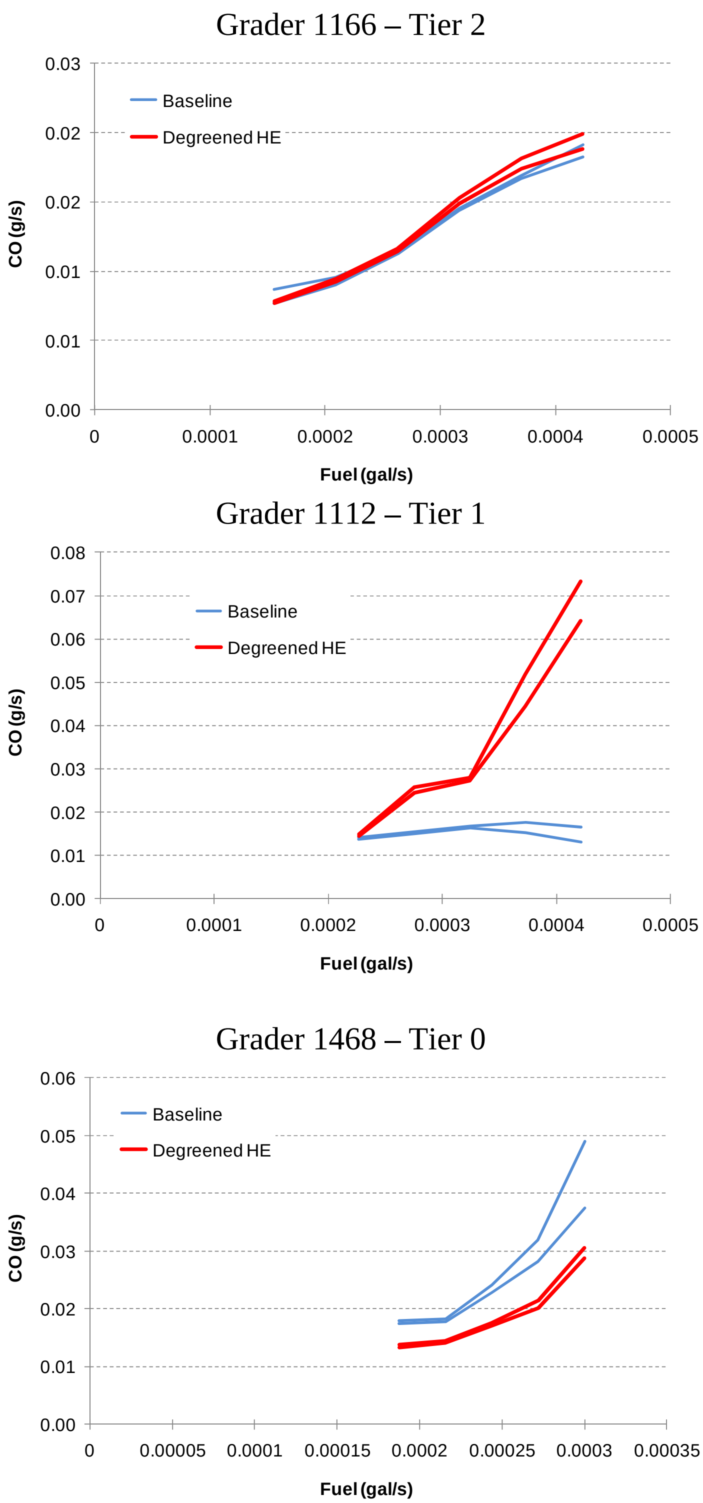


Figure I.8. CO Results for Fuel Additive – Idling.

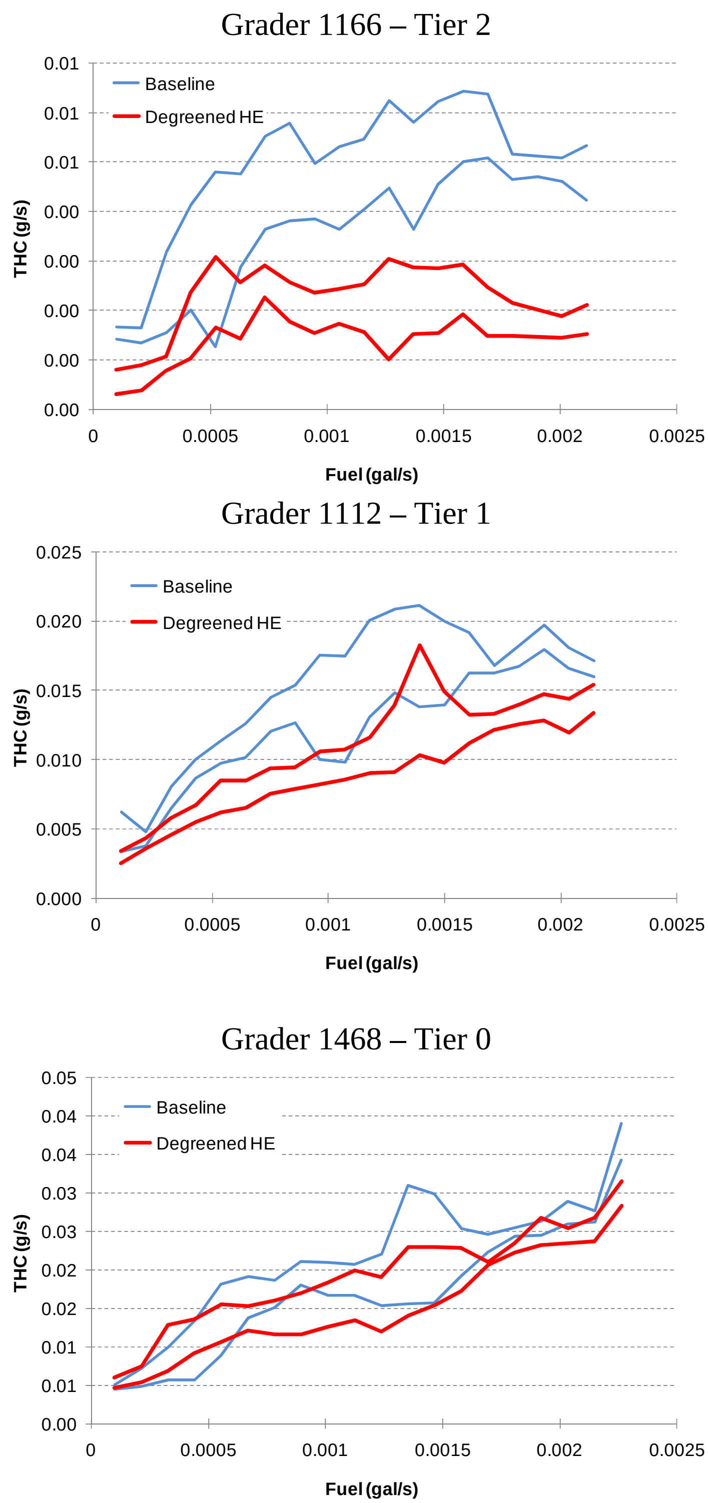
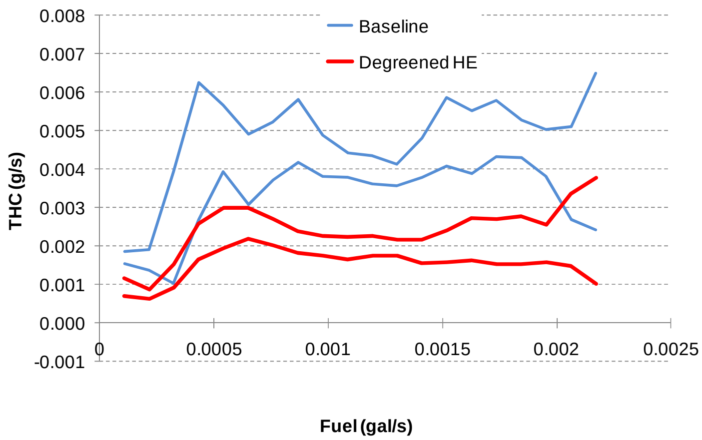
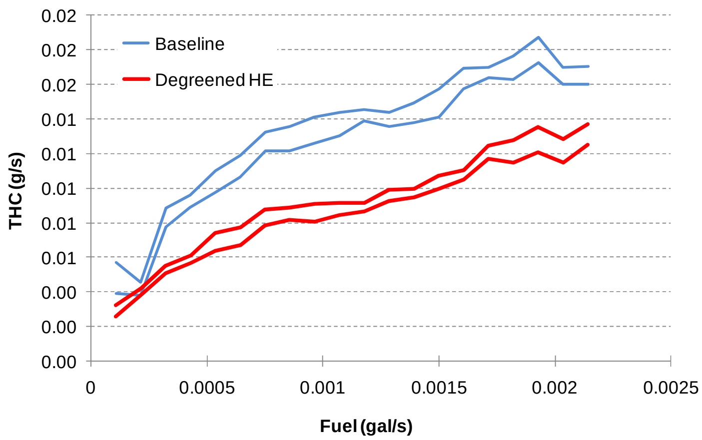


Figure I.9. THC Results for Fuel Additive – Driving at the Maximum Speed.

Grader 1166 – Tier 2



Grader 1112 – Tier 1



Grader 1468 – Tier 0

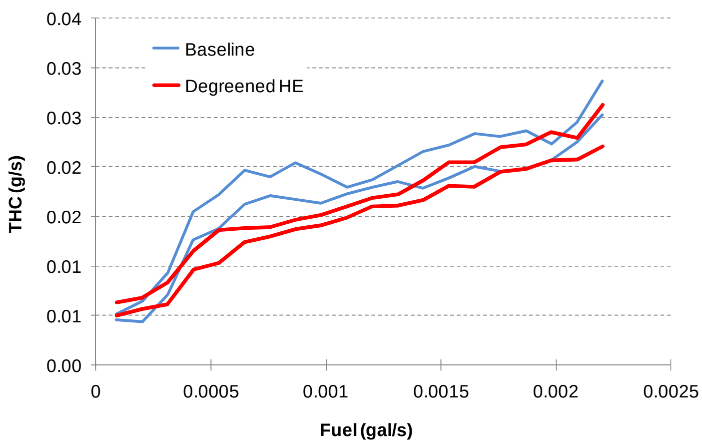


Figure I.10. THC Results for Fuel Additive – Driving at 20 mph.

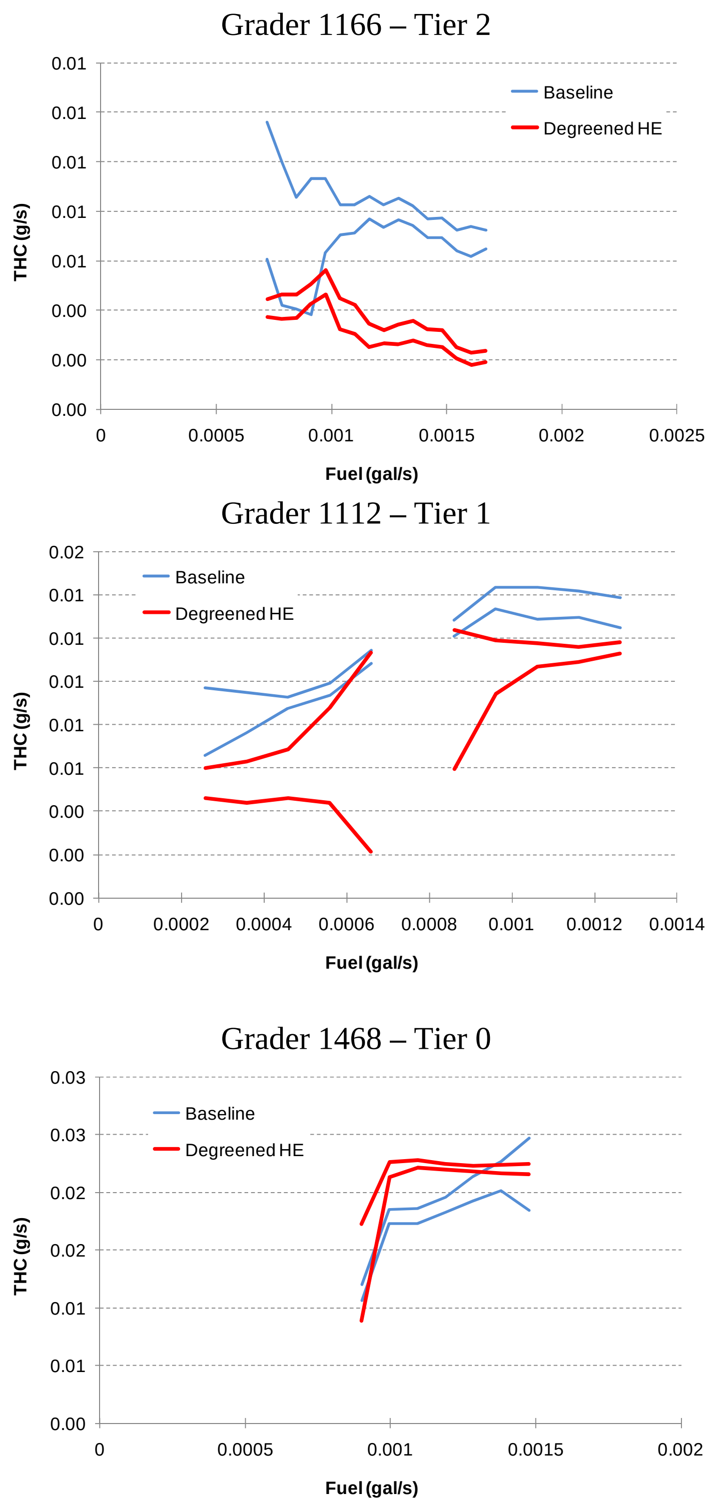
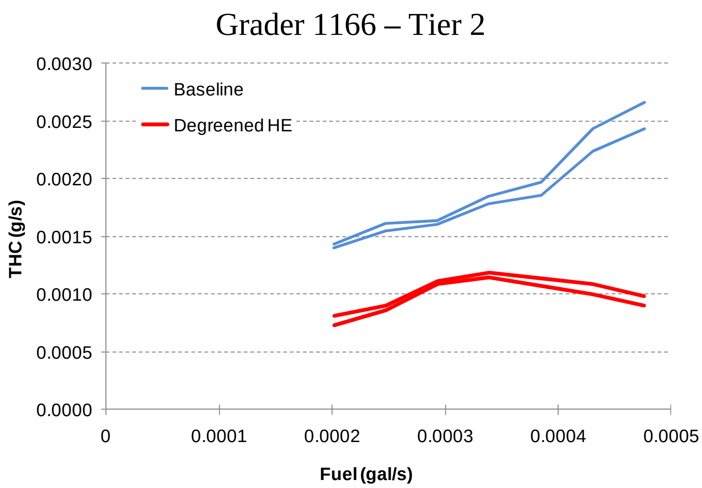
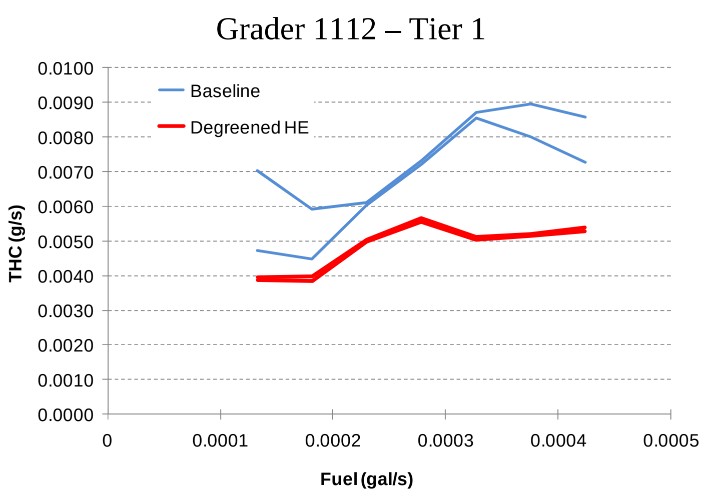


Figure I.11. THC Results for Fuel Additive – Grading Operation.





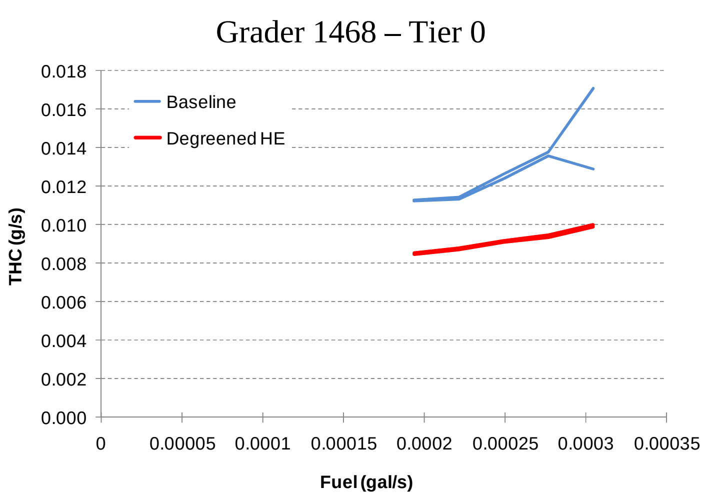


Figure I.12. THC Results for Fuel Additive – Idling.

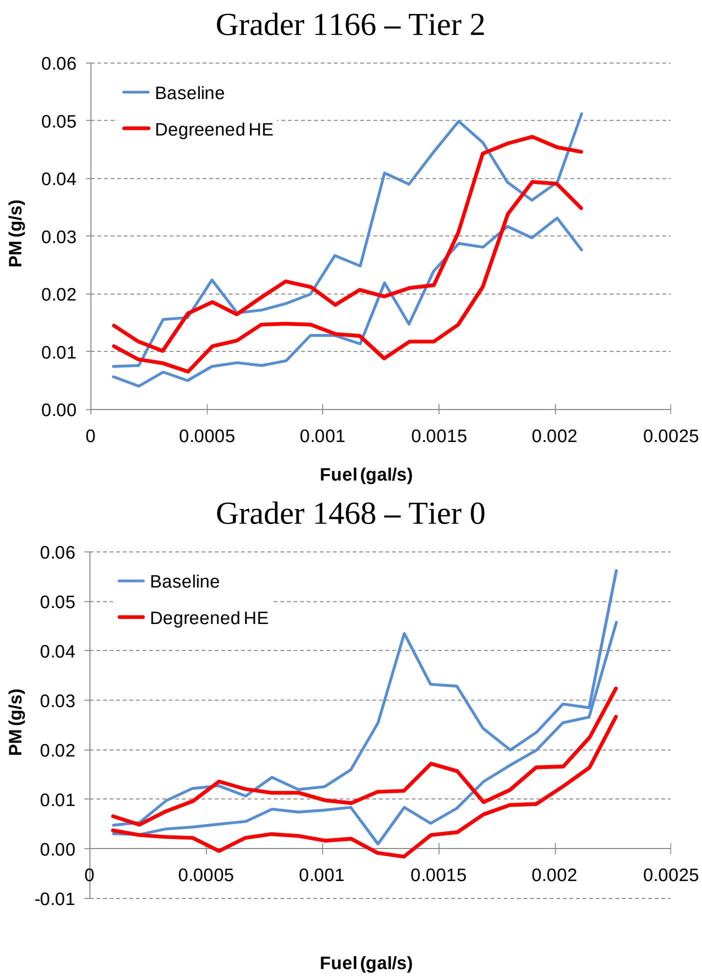


Figure I.13. PM Results for Fuel Additive – Driving at the Maximum Speed.

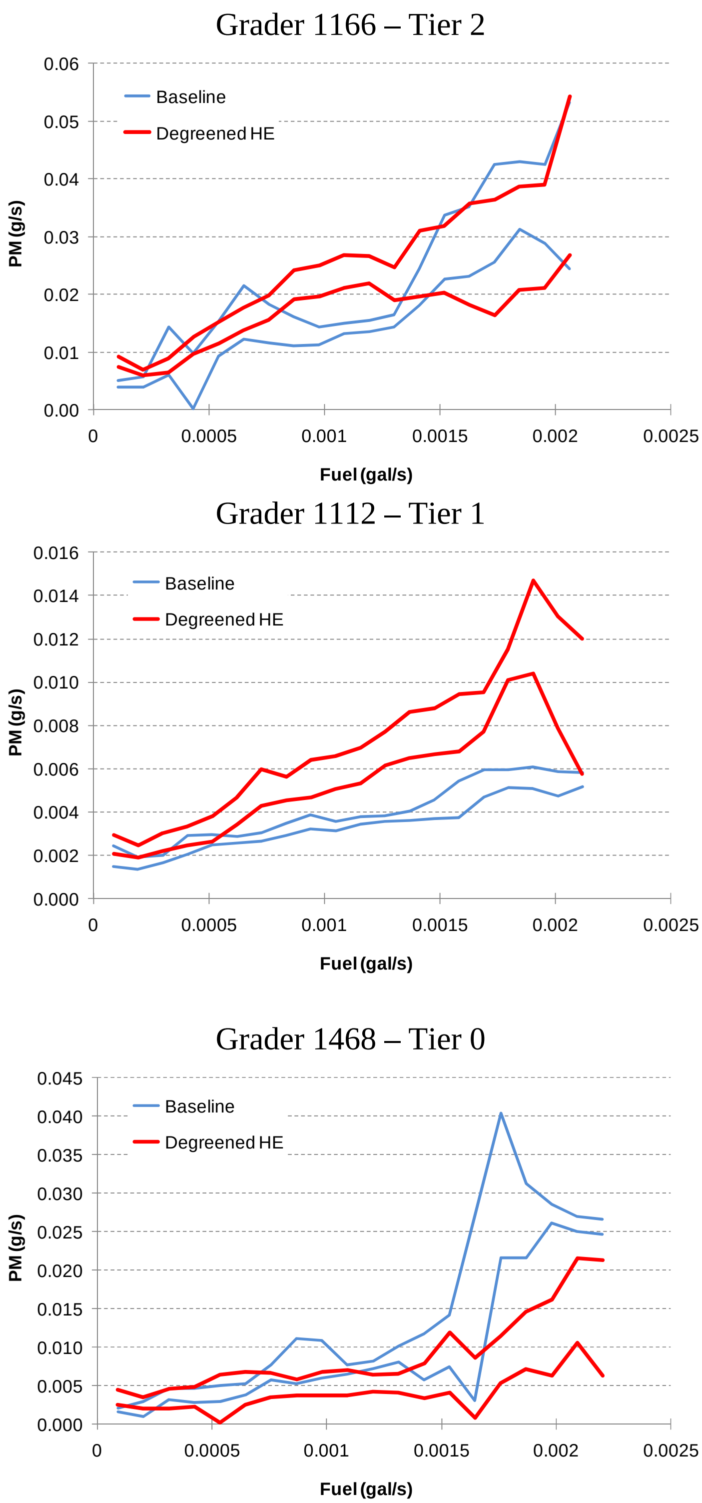
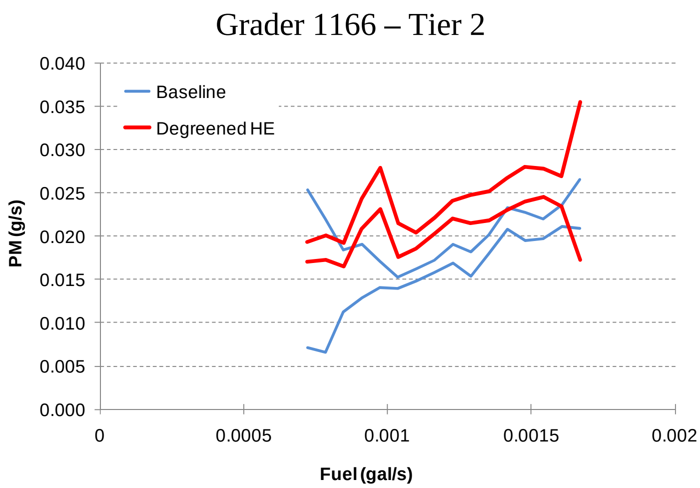
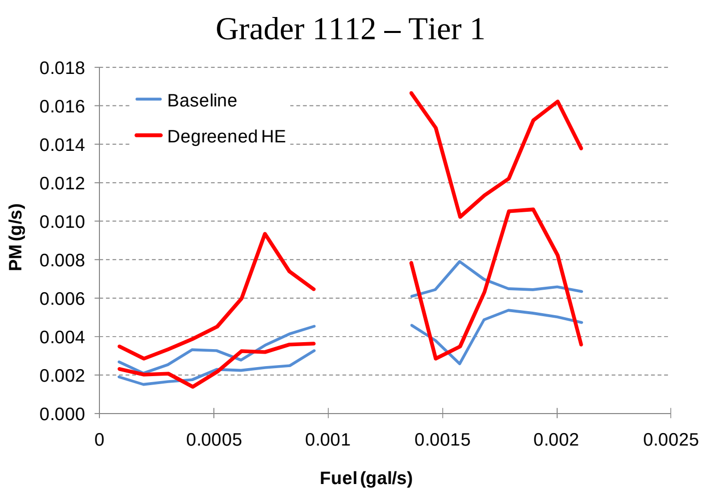


Figure I.14. PM Results for Fuel Additive – Driving at 20 mph.





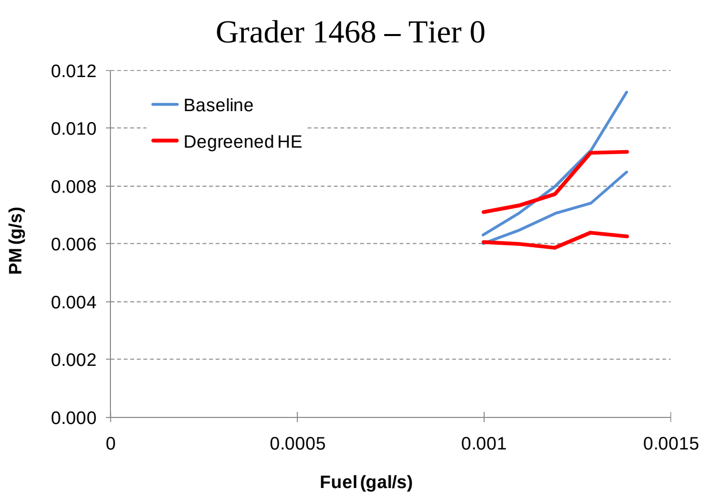
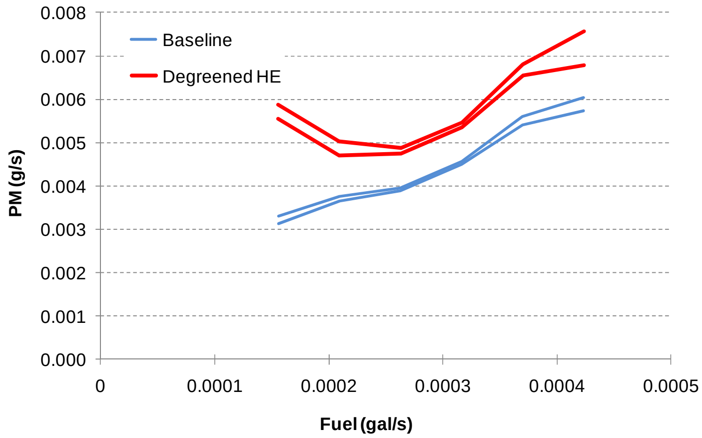


Figure I.15. PM Results for Fuel Additive – Grading Operation.

Grader 1166 – Tier 2



Grader 1468 – Tier 0

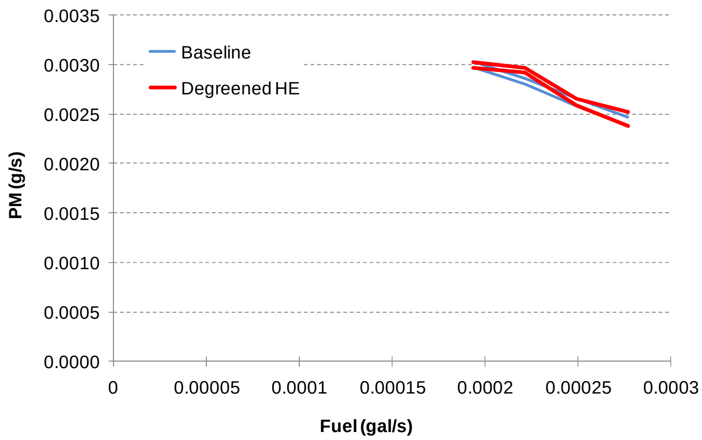


Figure I.16. PM Results for Fuel Additive – Idling.