ABSTRACT

PANG, SHIH-HAO. Life Cycle Inventory Incorporating Fuel Cycle and Real-World In-Use Measurement Data for Construction Equipment and Vehicles. (Under the direction of Dr. H. Christopher Frey.)

Biodiesel is an alternative fuel that can be made from vegetable oils or animal fat. This study focuses on whether substitution of soy-based biodiesel fuels for petroleum diesel would produce an overall reduction in emissions of selected pollutants. A life cycle inventory model was developed to estimate energy consumption and emissions of selected pollutants and greenhouse gases. Real-world measurements using portable emission measurement system (PEMS) were made for 15 construction vehicles, including five backhoes, four front-end loaders, and six motor graders on both petroleum diesel and soy-based B20 biodiesel. These data are used as the basis for vehicle tailpipe emission factors of CO_2, CO, HC, NO_x, and PM. The results imply that biodiesel is a promising alternative fuel for diesel, but that there are some environmental trade-offs. Analysis of empirical data reveals that intra-vehicle variability of energy use and emissions is strongly influenced by vehicle activity that leads to variations in engine load, as represented by manifold absolute pressure (MAP). Vehicle-specific models for fuel use and tailpipe emissions were developed for each of the 30 construction vehicle.

The time-based regression model has the highest explanatory ability among six models and is recommended in order to predict fuel use and emission rate for diesel-fueled nonroad construction equipment. Representative duty cycles for each type of vehicles were characterized by a frequency distribution of normalized manifold absolute pressure (MAP). In order to assess the variations of fuel use and emissions among different duty cycles, for a given engine, the inter-cycle variability is assessed. In order to assess the variations of fuel use and emissions among engines, for a given duty cycle, the inter-engine variability is assessed. The results indicated time-based inter-cycle and inter-engine variations of fuel use and emissions are significant. Fuel-based emission factors have less variability among cycles and engines than time-based emission factors. Fuel-based emission factors are more robust with respect to inter-engine and inter-cycle variations and are recommended in order to develop an emissions inventory for nonroad construction vehicles. Real-world in-use measurements should be a basis for developing duty cycle correction factors in models such as NONROAD.

Life Cycle Inventory Incorporating Fuel Cycle and Real-World In-Use Measurement Data for Construction Equipment and Vehicles

by

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A dissertation submitted to the Graduate Faculty of

North Carolina State University

In partial fulfillment of the

Requirements for the degree of

Doctor of Philosophy

Civil Engineering

Raleigh, NC

2007

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BIOGRAPHY

Shih-Hao Pang was born on the 11th of December, 1976 in Taipei, Taiwan. He got his Bachelor's Degree in Atmospheric Science from National Taiwan University, Taiwan, in 1999. After his graduation, he started his graduate studies in the Graduate Institute of Environmental Engineering in National Taiwan University. He worked on photochemical trajectory air quality modeling and got his Master's Degree in 2001. He came to North Carolina State University for his Doctoral Degree in Environmental Engineering in 2004. He was a research assistant in Dr. H. Christopher Frey's research group, and his research was focused on life cycle inventory for petroleum diesel and biodiesel fuels, assessment of on-board emissions measurements of nonroad construction equipment and vehicles, and emissions modeling. This dissertation completes the requirements for this degree.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0327731. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

I would like to express my appreciation to Dr. H. Christopher Frey for his continues guidance and valuable technical suggestions throughout the course of this work. Without Dr. Frey's suggestion and guidance, this work would not have been in its current form. I would like to thank Dr. W. Rasdorf and other committee members, Dr. E.D Brill and Dr. D. van der Vaart for their suggestions and assistances. I would like to thank Dr. Jon Van Gerpen, Dr. Carl J Bern, Dr. Dev Shrestha, Dr. Larry Johnson, Dr. Alex Hobbs, Mr. Jim Wilder, Mr. Andy Aden, Mr. Vince Vavpot, and Mr. Bev Thessen provided useful information and suggestions for the life cycle study. I would like also to thank my co-workers, Kaishan, Saeed, Kangwook, Phil, Haibo, Po-Yao, and Hyunk-Wook for helping me with any questions that I had and giving me company in the times of hard work.

Last, but certainly not least, I would like to thank my parents, my wife, my son, my sisters, and my mother-in-law for their sincere love, enormous support and enthusiasm for my education. Without their endless encouragement and support, this work could not have been possible.

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PART I INTRODUCTION

In 2002, annual emissions of nonroad diesel construction vehicles for carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NO_x), and particulate matter (PM_{10}) were 414, 85, 764 and 71 thousand short tons, respectively. These emissions are significant, yet they only include direct emissions from the vehicle and they do not include life cycle emissions from the fuel cycle. An improved quantitative understanding of life cycle emissions is needed in order to assess the role of these vehicles in air quality problems and to develop management strategies.

Nonroad diesel powered equipment is coming under increased scrutiny because it is a significant source of nonroad mobile source air pollutant emissions. Emissions from nonroad construction equipment are typically quantified based on steady-state engine dynamometer tests. However, such tests do not represent actual duty cycles. Emission inventory developed based on these steady-state engine dynamometer tests can not represent real-world emissions. Therefore, there is a need to quantify energy use and emissions from construction equipment based on in-use measurement methods. Compared with other types of vehicles, there has been relatively little real world measurement of in-use emissions of nonroad diesel powered vehicles. There is a need to develop a set of standard procedures for field data collection and analysis for this equipment.

In the United States, more than half of the biodiesel is made from soybean oil. The production of biodiesel accounted for 1.42% of total U.S. soybean oil consumption in 2004. Biodiesel can be used in a diesel engine without major modifications and has lower emissions of hydrocarbon (HC), carbon monoxide (CO), and particulate matters (PM) based on dynamometer testing of engines (EPA 2002). Based on engine dynamometer data from EPA and chassis dynamometer data from National Renewable Energy Laboratory (NREL), the percentage changes when comparing B20 biodiesel versus petroleum diesel of NO_x, PM, CO, and HC are +2%, -10%, -11%, and -21%, respectively, for the EPA data and +0.6%, -16%, -17%, and -12%, respectively, for the NREL data (EPA 2002, McCormick *et al.* 2006). The recent NREL study agrees on the Frey and Kim (2006) and other studies that show a decrease in NO_x for B20 if the blend stock meets the ASTM standard.

Biodiesel has several advantages, e.g., it is biodegradable, and non-toxic, and it has the potential of reducing U.S. dependence on foreign crude oil. Because of the Energy Policy Act of 2005, many government agencies are already using biodiesel in their heavy-duty trucks and construction vehicles.

Nonroad construction equipment is a significant source of nonroad mobile source air pollutant emissions. Three common types of construction vehicles are backhoes, front-end loaders, and motor graders. These vehicles contribute to 26.5% of NO_x, 29.1% of CO, 27.6% of HC and 28.3% of PM_{10} among all construction vehicles. In-use measurements on construction vehicles were described by Frey *et al.* (2007). Data collection procedures include: (1) pre-installation; (2) installation; (3) field data collection; and (4) decommissioning. Field data were reviewed by standard quality assurance procedures to determine whether any errors exist in the data, and corrected such errors if possible. Emission factors of HC, CO, NO_x, and PM were developed based on typical duty cycles performed by each vehicle.

Life cycle inventories are used for a more complete assessment of comparisons between fuels, taking into account energy consumption, and emissions for fuel production and fuel use. Life cycle inventory approaches, include process flow diagrams, matrix representation of product system, and input-output-based LCI. Process flow diagrams are the most common method for representing the energy use and emissions of processes in a product system (MacLean *et al.* 2003, Sheehan *et al.* 1998, Suh *et al.* 2005). An example is the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model. GREET has been used to estimate fuel cycle upstream energy use and air emissions in life cycle inventories of bio-based products and lubricants (Landis *et al.* 2007, Miller *et al.* 2007).

Sheehan *et al.* conducted a study of soy-based biodiesel and petroleum diesel life cycles in 1998. The study quantified environmental flows associated with soy-based biodiesel and petroleum diesel. The result indicated soy-based B20 biodiesel has lower life cycle emissions of carbon monoxide and particulate matters, but higher LCI emissions of nitrogen oxides (NO_x) and hydrocarbons (HC). However, this study was based on old soyoil plant, which is not subject to the new emission standards in 2004, and EPA engine dynamometer data. The EPA engine dynamometer data showed a 2% increase of vehicle tailpipe NO_x emissions when comparing B20 versus petroleum diesel. In recent study, the use of B20 biodiesel does not have significant change or perhaps a decrease in NO_x (McCormick *et al.* 2006).

Soy-based B100 biodiesel production includes three major processes: soybean farming, soybean oil extraction, and biodiesel production. In the United States, most soybean oil production plants use a solvent extraction process to remove the oil from the soybeans (Erickson 1995). Soybean oil extraction was found to be the most significant source of HC emissions in the biodiesel life cycle (Sheehan *et al.* 1998). In November 2004, EPA promulgated national emission standards for the solvent extraction process (EPA 2004). The standards require reduction of emissions of air toxics and volatile organic compounds from vegetable oil production facilities.

An improved quantification of the life cycle inventory (LCI) is developed here in order to evaluate the benefits of biodiesel and to assess the tailpipe emissions of selected types of construction vehicles. The key improvements include the use of PEMS data for real-world fuel use and emissions and comparisons based on 15 construction vehicles which cover different and vehicle type, engine tier, and horsepower.

1.1 Instrumentation

A portable emission measurement system (PEMS) was used for real world in-use data collection developed by Clean Air Technologies International, Inc. The PEMS is comprised of two identical gas analyzers, a particulate matter (PM) measurement system, an engine diagnostic scanner or sensor array, a global position system (GPS), and an on-board computer. This system is designed to measure mass emission rates under actual operating conditions of a vehicle using engine operating data and concentration of pollutants in the exhaust.

The engine data is obtained from either the engine scanner, which is used when an engine has an electronic diagnostic link, or a sensor array, which can be used as long as the engine has a port to which the manifold absolute pressure (MAP) sensor can be attached. The sensor array is composed of a MAP sensor, an engine speed sensor, and an intake air temperature sensor.

The concentrations for nitric oxide (NO), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) in the vehicle exhaust measured by the gas analyzer are expressed in parts per million or volume percentage. The PM measurement device includes a laser light scattering detector that is basically an opacity type of measurement, and a sample conditioning system. The results of the PM measurement have been correlated to a mass per volume basis by the instrument vendor. A global positioning system (GPS) is used to measure the vehicle position. The on-board computer synchronizes the incoming emissions, engine, and GPS data. Intake airflow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb (1997).

1.2 Research Objectives

The key research objectives are:

- Develop a life cycle inventory (LCI) model for energy consumption and emission of criteria pollutants and greenhouse gases. This LCI will support the future development of rigorous life cycle assessment and impact analyses for the purposes of air quality management
- Recommend a set of standard procedures for field data collection and analysis on nonroad construction vehicles and equipment

– Characterize the second-by-second in-use emissions and energy use of nonroad construction vehicles and equipment, including emissions of nitric oxide (NO), carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO_2), and particulate matters (PM)
– Develop a predictive micro-scale emission model to estimate energy use and emissions for a wide variety of activity patterns

1.3 Organization

Part I describes general information regarding nonroad construction vehicle emissions, production of biodiesel, life cycle inventory, and the needs for development of life cycle inventory for petroleum diesel and biodiesel fuels, the research objectives.

Part II explains the general procedures for portable on-board emissions data collection when collecting data on nonroad construction vehicle, including front-end loaders, backhoes, and motor graders. These procedures are good for all nonroad construction vehicles and equipment.

Part III describes data screening and quality assurance procedures for reviewing data collected in the field, determining whether any errors or problems exist in the data, correcting such errors or problems where possible, and removing invalid data if errors or problems cannot be corrected.

Part IV is a draft paper and applies recently collected in-use data to gain insight into real-world variability in fuel use and emissions for individual vehicles. Analysis of empirical data reveals that intra-vehicle variability of energy use and emissions is strongly influenced by vehicle activity that leads to variations in engine load, as represented by manifold absolute pressure (MAP). Vehicle-specific models for fuel use and tailpipe emissions were developed for each of the 32 construction vehicles.

Part V is a draft paper to characterize real-world variability in fuel use and emissions when comparing vehicles and duty cycles. Representative duty cycles for each type of vehicles were characterized by a frequency distribution of normalized manifold absolute pressure (MAP). Vehicle-specific models for fuel use and tailpipe emissions were developed for each of the construction vehicle based on physically-based regression model. In order to assess the variations of fuel use and emissions among different duty cycles, for a given engine, the inter-cycle variability is assessed. In order to assess the variations of fuel use and emissions among engines, for a given duty cycle, the inter-engine variability is assessed.

Part VI gives the reviews of previous life cycle studies and a comparison of each life cycle component for five major life cycle studies.

Part VII gives the methodology of life cycle inventory development, including the fuel life cycle and characterizing in-use emissions and energy use from nonroad construction vehicles and equipment.

Part VIII is a draft paper and focuses on whether substitution of soy-based biodiesel fuels for petroleum diesel would produce an overall reduction in emissions of selected pollutants. A life cycle inventory model was developed to estimate energy consumption and emissions of selected pollutants and greenhouse gases.

The main conclusions of this study and the recommendations for future are given in Part IX based on the analyses provided in Parts IV, V, and VIII.

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PART II FIELD DATA COLLECTION PROCEDURES ON NONROAD CONSTRUCTION EQUIPMENT

The objective of this section is to explain the general procedures for portable on-board emissions data collection when collecting data on nonroad construction vehicle, such as front-end loaders, backhoes, and motor graders. These procedures are for nonroad construction vehicles and equipment. These procedures include pre-installation, installation, field data collection, decommissioning, and cleanup. For each of these major steps of data collection, a checklist and explanation of procedures is given.

2.1 Pre-Installation

Construction workers usually start working in the early morning. In order to have sufficient time to install the Montana system and not to interfere with their work, the data collection crew installs some of the major components the day before a test. This is referred to as "pre-installation."

Pre-installation involves installing the sensors, sampling hoses, the safety cage, the cables, and the connections, except for the final installation of the main unit. The main unit is installed in the morning of data collection. It typically takes two people two to three hours to finish a pre-installation procedure. The pre-installation differs from installation because pre-installation is done the day before a test, typically in the afternoon.

Pre-installation includes the installation of the major test system components on the test vehicle, except for the instrument itself. The following sections explain these major components and installation procedures. Table 2.1 shows the checklist for pre-installation. Two people are needed to finish pre-installation. Even with two people working together pre-installation takes a minimum of two hours and forty minutes.

Figure 2.1 shows the timeline for pre-installation when performed by two people. Due to different engine models and ambient conditions, the time period for pre-installation may vary from two hours and forty minutes to three hours and forty minutes. Each of the items of equipment has a different engine model and engine compartment room shape. In some cases, pre-installation of engine sensors is very difficult due to the small engine compartment room. If the data collection crew cannot locate the port for the manifold absolute pressure sensor, the equipment cannot be tested.

When a new construction vehicle is to be tested (of a type not previously tested by the data collection crew) the data collection crew needs additional time to find the appropriate place to install engine sensors. When the same model of construction equipment is to be tested again, two hours and forty minutes is usually enough for pre-installation. Table 2.2 presents typical pre-installation time period and pre-installation time range for a backhoe, motor grader, and front-end loader.

The height of equipment presents also another difficulty for completing test equipment pre-installation. Working at 9 to 11 feet high from the ground and on the limited space of the roof of the construction equipment is not easy. These roofs were not initially designed for someone to be working on there. This area is very slippery and not safe. Extra care must be taken to ensure safety. For this reason, pre-installation may also need more time to be completed.

When pre-installation is completed, the main unit of the Montana system will be brought to the laboratory and calibrated. There is a gap in time between pre-installation completion and calibration, because of the traveling time from the construction site to the laboratory.

Table 2.1 Pre-installation Checklist Form

Pre-Installation Procedure Checklist	
Safety Cage – Installation on hood or roof of test vehicle	☐
Exhaust Gases Sampling Hoses – Fasten to tailpipe and secure hoses from tailpipe to safety cage	☐
Sensor Unit – Secure sensor unit on the test vehicle – Secure cables from sensor unit to safety cage	☐
Manifold Absolute Pressure Sensor – Find the port on the engine after turbocharger which is used for regular testing of engine pressure – Install manifold absolute pressure sensor and attached the sensor to the engine – Connect the cable from manifold absolute pressure sensor to sensor unit	☐
Engine Speed Sensor – Attach the engine speed sensor to test vehicle – Install optical tape on the pulley – Connect the cable from engine speed sensor to sensor unit	☐

(Continues on the next page)

Table 2.1 Continued.

Intake Air Temperature Sensor – Install intake air temperature sensor – Fix the intake air temperature sensor near the intake air flow using duct tape or plastic wire – Connect the cable from intake air temperature sensor to sensor unit	☐
External Power Source – Install external power source – Secure power cable to safety cage	☐
Measurement Instrument Pre-test – Install main unit of Montana system – Connect sensor unit to main unit – Read engine data to decide if it is necessary to re-install engine sensors	☐
Re-installation (if engine sensor is not installed properly) – Re-install sensors	☐
Re-test (after re-install sensors) – Read engine data to decide if it is necessary to re-install engine sensors again	☐
Wrap-up – Pick up tools and put into the toolbox	☐
Calibration of Montana System – Warm up the main unit for forty-five minutes – Perform calibration procedures according to "Operation Manual of OEM-2100 Montana System"	☐

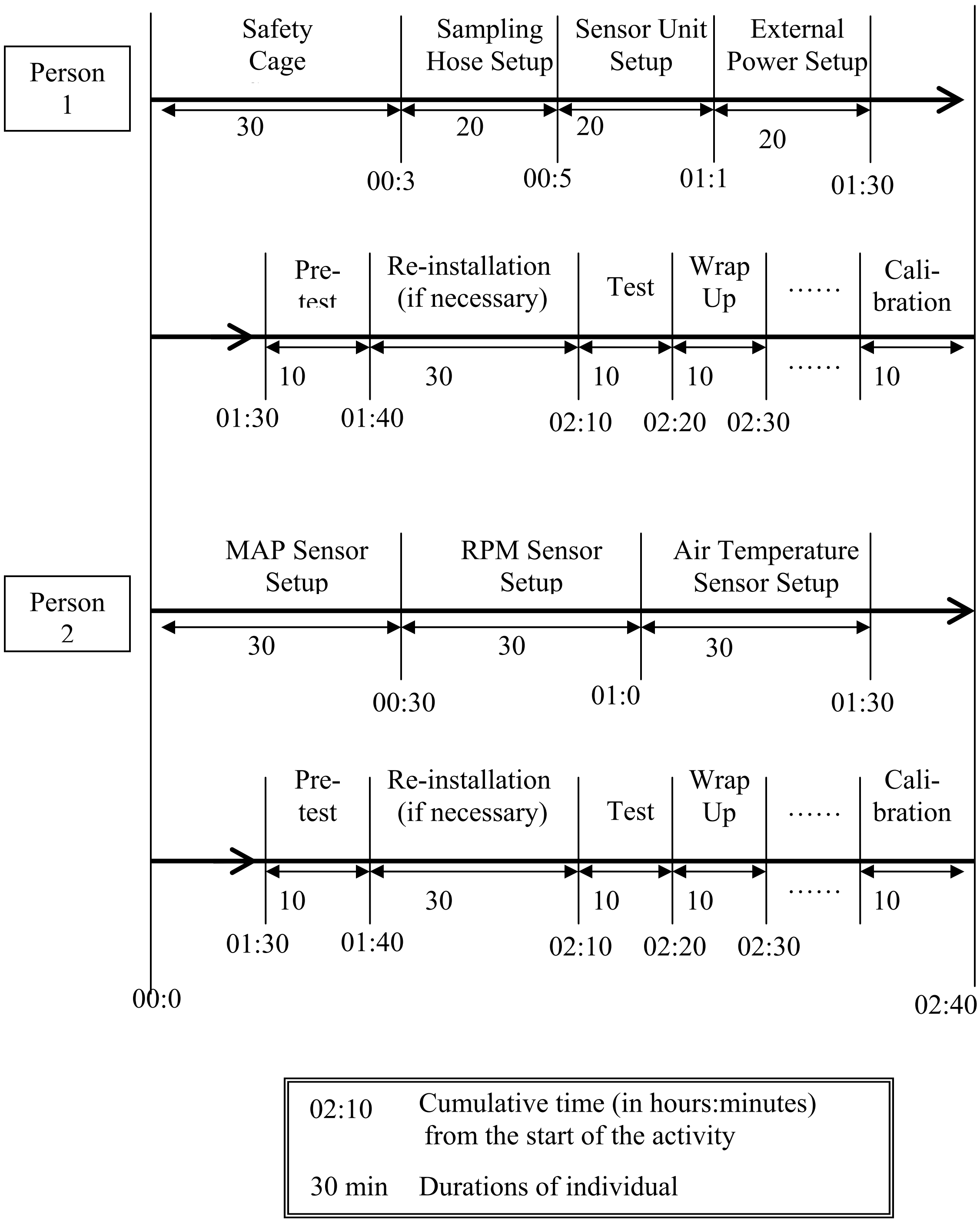

Figure 2.1 Timeline for Pre-installation Procedures Performed by Two People

Table 2.2 Typical Time Period and Range for Pre-installation

Equipment Type	Pre-Installation Time Period	
	Typical	Range
Backhoe	2 hr 40 min	2 hr 40 min to 3 hr 40 min
Motor Grader	2 hr 40 min	2 hr 40 min to 3 hr 40 min
Front-End Loader	2 hr 40 min	2 hr 40 min to 3 hr 40 min

2.1.1 Safety Cage

To protect the Montana system from damage, and to help control transmission of vibration from the vehicle to the Montana system, a hard metal safety cage has been developed. The cage is large enough to enclose the main unit of the Montana system. The cage is intended to protect the main unit from being impacted by tree branches or other potential obstacles that might be encountered at a construction site.

Vibration of the construction equipment might cause a short circuit and disconnection of cables in the Montana unit itself. To dampen vibrations, a flexible rubber pad is installed between the safety cage and the main unit. This cage is fastened to the hood or roof of the test vehicle using straps. The safety cage is covered to protect it from dust at the construction site. Figure 2.2 is a photograph that depicts the safety cage.

The Montana system should be located on a vehicle so that it does not block the driver or operator view of the task being performed, nor interfere with the task-oriented functions of the vehicle. For a backhoe, bulldozer, and front-end loader, the typical location for the safety cage is on the roof of test vehicle. For a motor grader, the typical location for the safety cage is on the hood. Figures 2.3 and 2.4 show the typical locations for a backhoe and a motor grader, respectively.

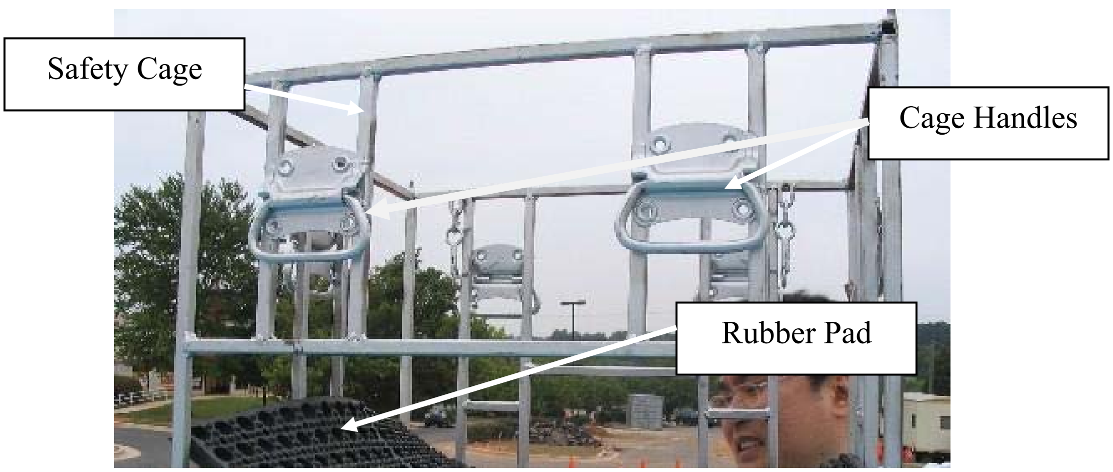

Figure 2.2. Safety Cage for Montana Installation

Figure 2.3. Safety Cage on a Backhoe

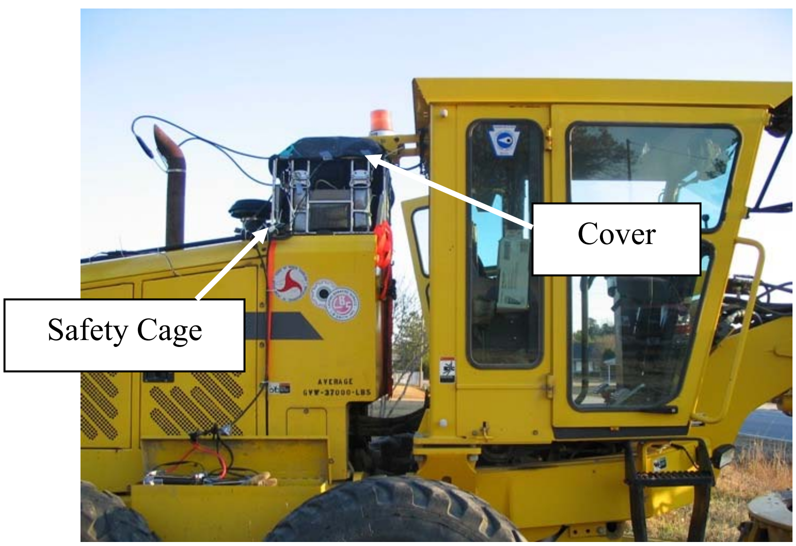

Figure 2.4. Safety Cage on a Motor Grader

2.1.2 Exhaust Gases Sampling Hoses

Two sampling hoses are used in order to take exhaust gas samples from the tailpipe. An exhaust gas sample for particulate matter is obtained from one sampling hose and for NO, HC, CO, CO_2, O_2 from the other. The sampling hoses include a probe that is inserted into the exhaust pipe. The probe assembly is secured to the tailpipe using an adjustable metal hose clamp shown in Figure 2.5.

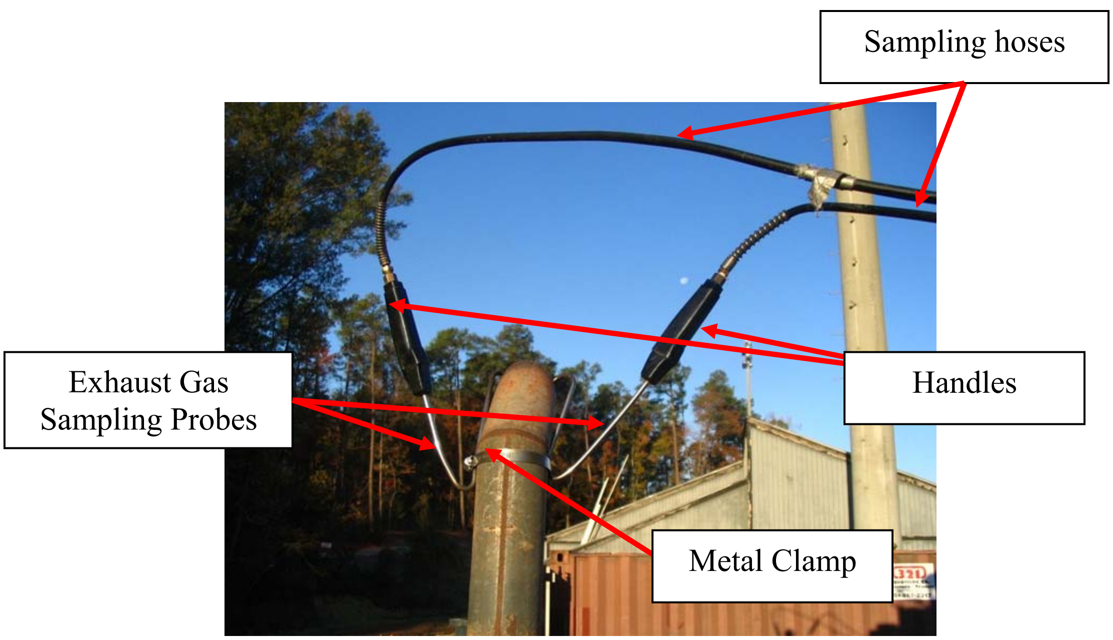

Figure 2.5. Attachment of Exhaust Gas Sampling Probes to the Tailpipe

The probe handles and the hoses should be located so that they are not in the path of hot gases and so that they are not likely to get caught on any obstacles. The sampling hoses should be secured to the equipment and there should be minimal slack in the line between the tailpipe and the main unit. Each sampling hose is attached to the main unit through a sample bowl. Figure 2.6 shows how a sampling hose connects to the main unit.

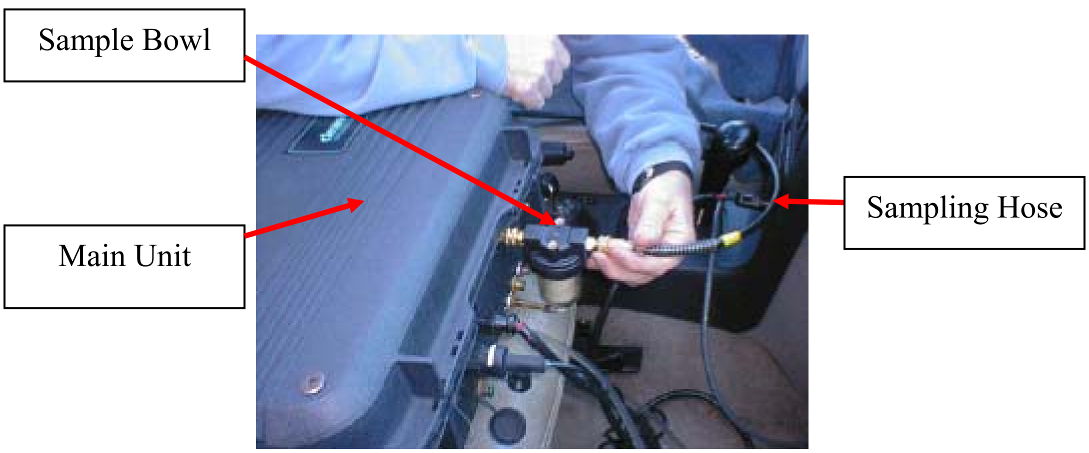

Figure 2.6. Attachment of the Sampling Hose to the Main Unit

The exhaust sampling probes should be inserted directly into the tailpipe in order to obtain accurate tailpipe emissions. However, some construction equipment has a gap between the muffler and tailpipe as shown in Figure 2.7. Fresh ambient air may enter the tailpipe from this gap and dilute the pollutant concentration. In order to get accurate emissions data, it is preferred not to have excess air enter the tailpipe and dilute the exhaust gas.

A method that has been tried in the field and that appears to work well is to use several layers of aluminum foil with two clamps for sealing the gap as shown in Figure 2.8. The area where aluminum foil is used for sealing the gap is hot and care must be taken when working with it.

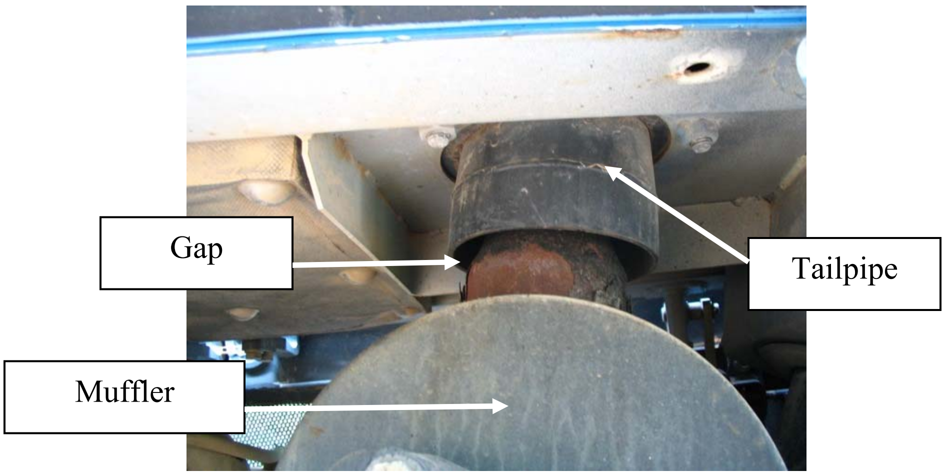

Figure 2.7. Illustration of a Typical Gap between Muffler and Tailpipe

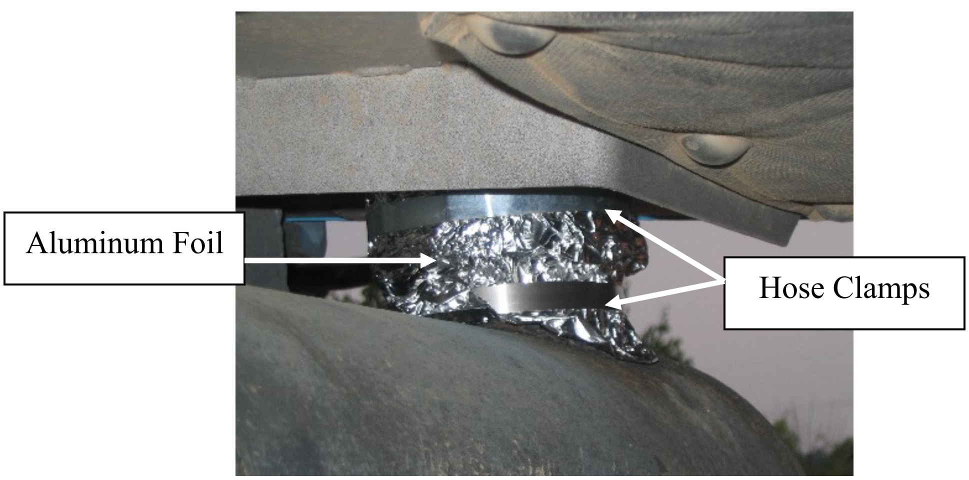

Figure 2.8. Sealing a Gap Using Aluminum Foil and Hose Clamps

2.1.3 Sensor Array

A sensor unit is connected to the main unit to provide engine data. The sensor array is composed of a manifold air boost pressure (MAP) sensor, engine speed sensor, intake air temperature sensor, and sensor unit.

2.1.3.1 Manifold Air Boost Pressure Sensor

In order to measure MAP, a pressure sensor is installed on the engine. There is a port on the engine after the turbocharger as shown in Figure 2.9. In a regular engine performance check, this port is used for performance testing of the turbocharger. The MAP sensor installation involves replacing Bolt "A", shown in Figure 2.9, with a barb fitting, shown in Figure 2.10. The data collection crew installs a barb fitting and connects it to the MAP sensor. Plastic ties are used to route and secure the MAP sensor cable between the engine and the main unit. Figure 2.11 shows the MAP sensor attached to a construction vehicle engine. The MAP sensor provides manifold air pressure data for the computer of the main unit through a cable that connects the sensor to the MAP port located in the back of the main unit. The MAP sensor should be secured to adjacent engine parts using plastic ties as shown in Figure 2.11.

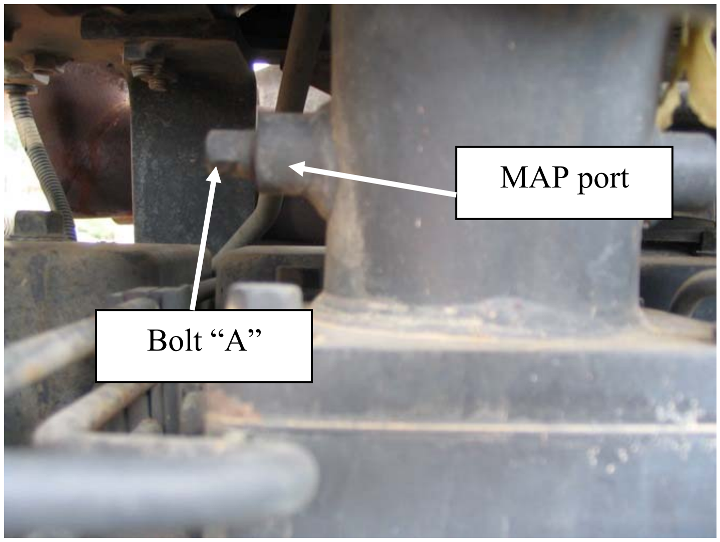

Figure 2.9. Illustration of MAP Port

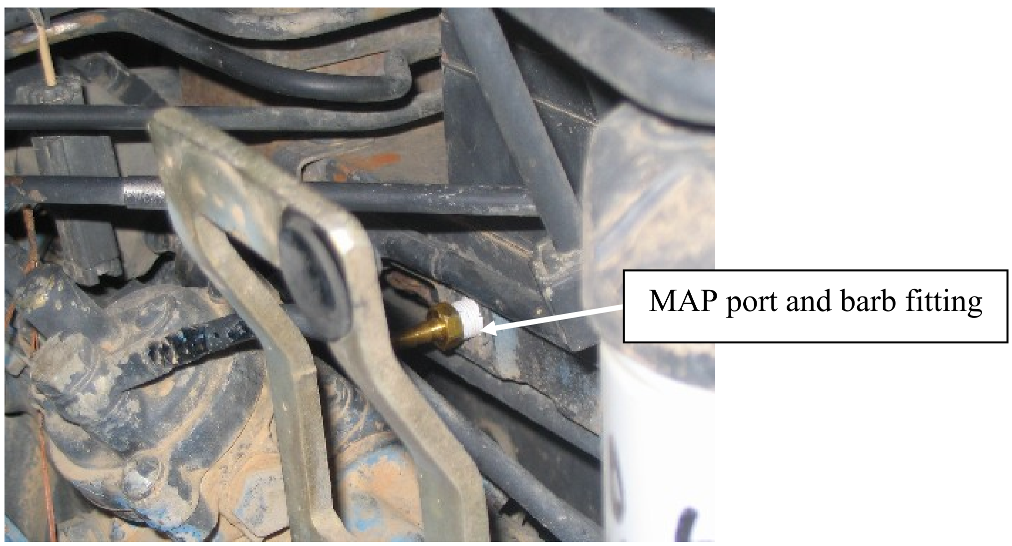

Figure 2.10. MAP Port on the Engine and a Barb Fitting Attached to the Port

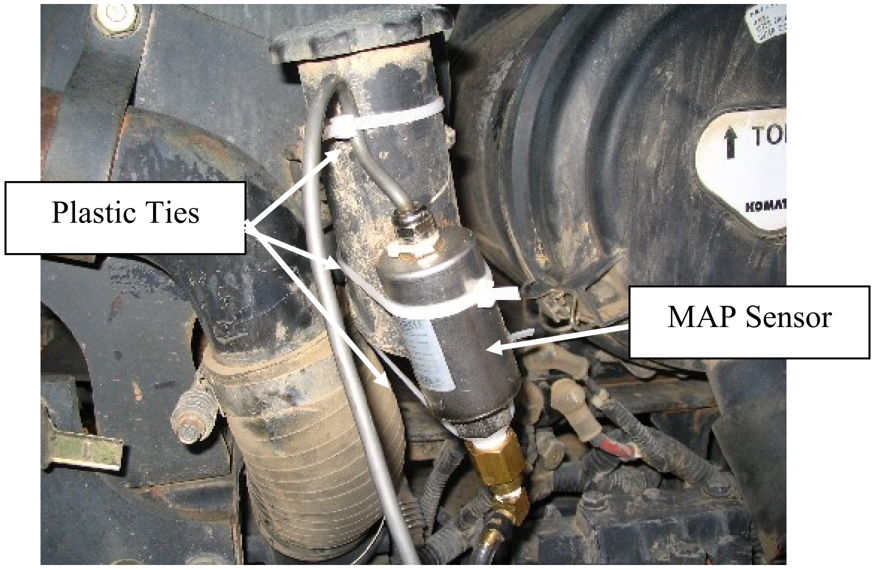

Figure 2.11. MAP Sensor after Installation

2.1.3.2 Engine Speed Sensor

The engine speed sensor must be installed at an adequate location in order to provide accurate data. The engine speed sensor has strong magnetization to enable it to be attached easily to metal materials as shown in Figure 2.12. Optical tape must be installed on the pulley which is connected to the crankshaft. Thus, the location of the engine speed sensor depends on the location of the optical tape. The optical tape reflects light from the engine speed sensor. Based on this reflection, the engine speed sensor estimates engine revolutions per minute. Thus, the correct placement of optical tape is essential to collect engine speed data.

Figure 2.13 shows the location of optical tape on a pulley. Here are some suggestions for the placement of the engine speed sensor:

1. Place in a position with no fans or other engine related obstacles
2. Place in a position with enough space to attach the sensor tightly
3. Place in a position within reachable length of the engine speed sensor cable

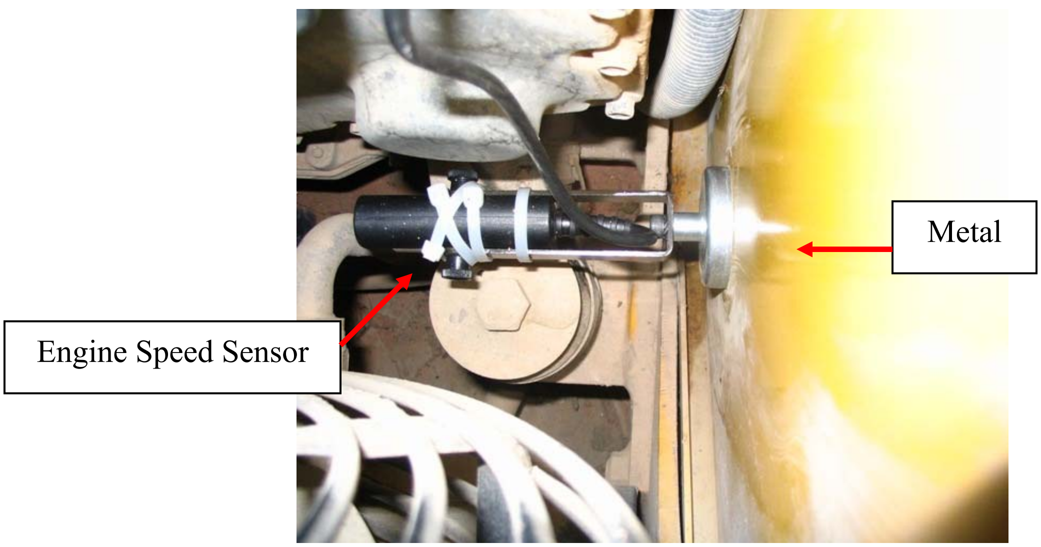

Figure 2.12. Magnetized Engine Speed Sensor Attached on the Metal

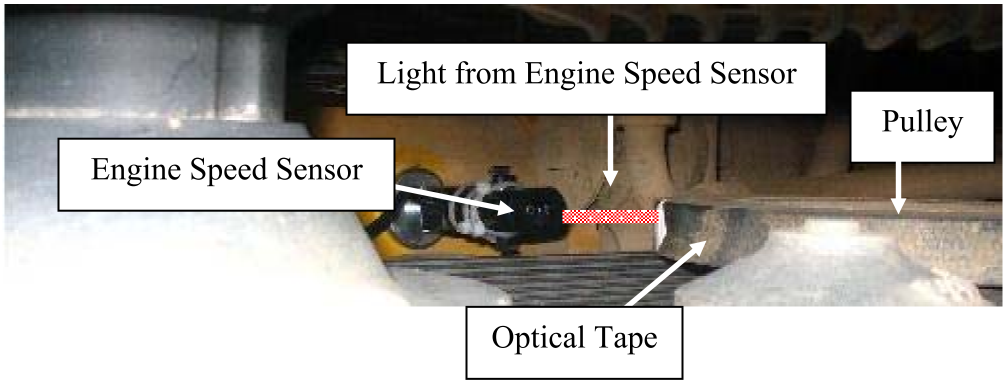

Figure 2.13. Engine Speed Sensor and Optical Tape

2.1.3.3 <u>Intake Air Temperature Sensor</u>

The engine intake air sensor needs to be installed in the intake air flow path. The sensor has a metal part that can detect temperature. Installation of the intake air temperature sensor is somewhat easy compared to the engine speed and MAP sensors. Using duct tape or a plastic tie, one can fix the intake air temperature sensor near the intake air flow where the MAP port is located. Figure 2.14 illustrates the location that the intake air temperature sensor is installed on the engine of a bulldozer. The temperature sensor and MAP port are close to each other, as shown in the figure.

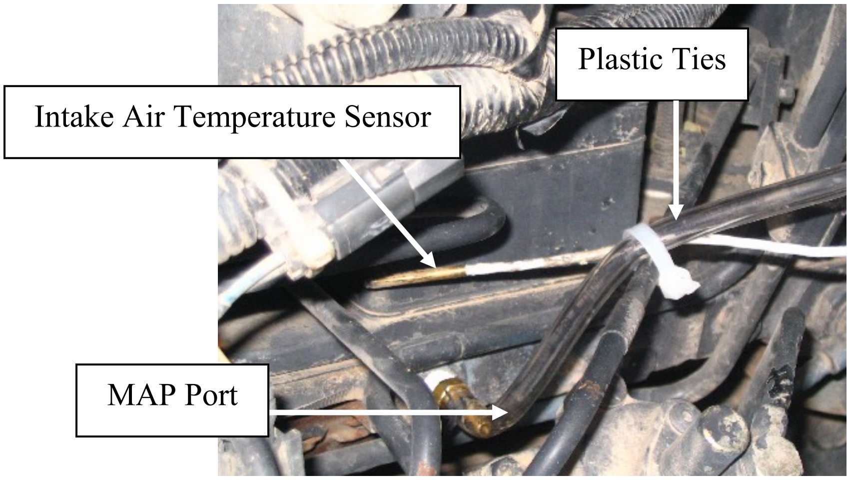

Figure 2.14. Installation of Intake Air Temperature Sensor

2.1.3.4 Sensor Unit

The sensor unit is the device which connects the intake air temperature and engine speed sensors to the main unit. The sensor unit is protected by the box shown in Figure 2.15. Plastic ties are used to secure the sensor unit to the construction vehicle. If the sensor unit cannot be affixed to the vehicle using plastic ties, duct tape can usually be used to secure the sensor unit.

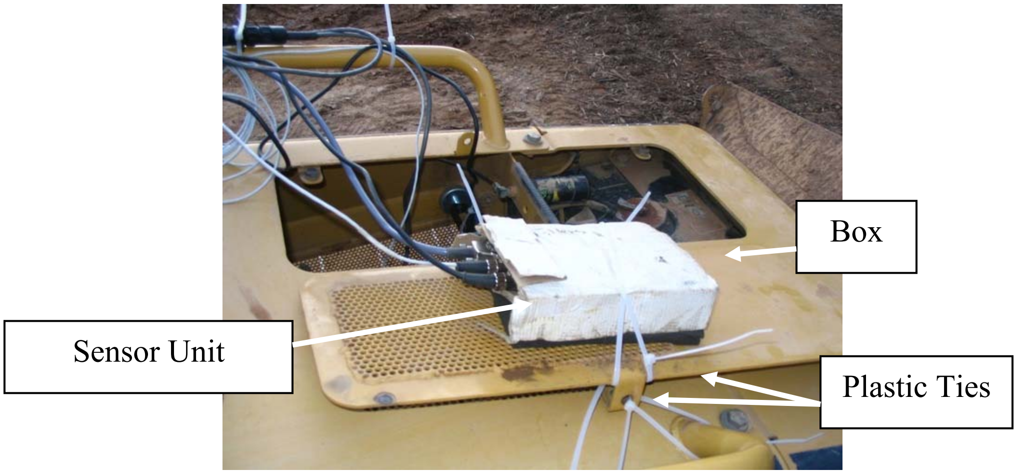

Figure 2.15. Sensor Unit on a Bulldozer

2.1.4 External Power Source

The main unit of the Montana system needs at least 12 volts and 4 to 6 amps of direct current electricity. Although it is often possible to obtain such power from the vehicle, the use of external batteries as a power source avoids putting additional load on the engine. Also, using batteries avoids an unintended shutdown of the Montana system if the vehicle operator inadvertently turns off the engine. When moving these batteries from the laboratory to the job site, it is important to tape all of the connectors using duct tape to avoid a short circuit. Also, the batteries should be placed into an appropriate container to protect them from being impacted. When installed, the batteries should be tied down to the body of the vehicle using a strap as shown in Figure 2.16. A rubber pad is used to reduce vibration from the vehicle. Each battery can operate the Montana system for 4 to 5 hours.

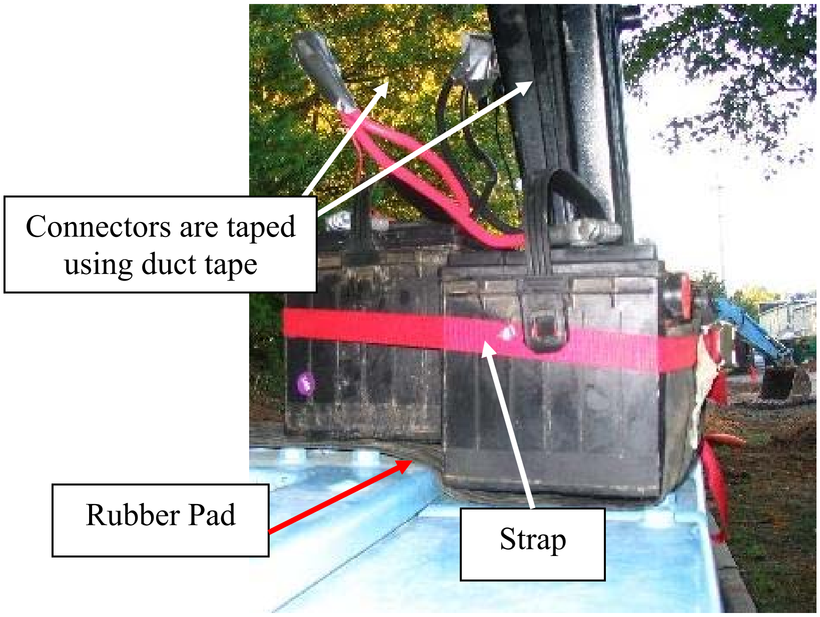

Figure 2.16. External Battery Setup for Montana System Power Source

2.1.5 Measurement Instrument Pre-test

After setup of the safety cage, exhaust gas sampling hoses, sensors, and batteries, the next step is to make sure that the main unit of the Montana system obtains valid data from the engine sensors. Generally, there is no problem with the MAP and intake air temperature sensors. However, the engine speed sensor often needs to be tested several times in order to find the best way to set up the sensor and the optical tape. If the Montana system cannot obtain engine speed data, or if the engine speed values fluctuate rapidly, there is a need to re-install the engine speed sensor. If the Montana system reads engine RPM data properly after the re-installation of the engine speed sensor, the pre-installation procedure is done. Otherwise, the pre-installation testing should be repeated until the Montana system can read RPM data properly.

2.1.6 Calibration of Montana System

Because the NO and O_2 sensors deteriorate with use, they have to be calibrated between once a week and once a month during data collection. To do so, after pre-installation, the main unit of the Montana system will be brought to the laboratory and calibrated. When performing calibration, the instrument has to be warmed up for forty-five minutes. The calibration procedures of the Montana system are detailed in the user's manual (Clean Air Technology Inc).

The calibration gas mixture recommended when data is to be collected from diesel engines is 200 ppm propane (C_3H_8), 0.5 *vol*-% carbon monoxide (CO), 6.0 *vol*-% carbon dioxide (CO_2) and 300 ppm nitric oxide (NO). There is no O_2 in the calibration mixture gas. During calibration, neither of the gas analyzer benches should detect O_2. If the O_2 concentration is higher than zero, then some leakage may have occurred inside the Montana system.

2.2 Installation

The difference between pre-installation and installation is that installation is done before the vehicle operator starts working on the test day, whereas pre-installation is done the day before the test. The data collection crew arrives at the job site one hour earlier than construction workers. When the installation is done, the Montana system is ready to collect data from the construction vehicle.

Some of the major components of the Montana system are already pre-installed on the construction vehicle as described previously in Section 4.1. On the test day, the installation procedures focus on set up of the main unit of the Montana system, the Geographical Positioning System (GPS), the video capture instrument (camcorder), and the laptop computer. Table 3.3 shows the checklist for installation.

The main unit has to warm up for forty-five minutes before collecting data. The data collection crew can install other instruments while the main unit is warming up. Two people are needed to operate the camcorder and the laptop computer separately during data collection. Figure 2.17 shows the timeline for installation procedures performed by two people. The installation procedures take one hour to finish. As mentioned before, the time period may vary due to the ambient condition and the height of construction equipment. Table 2.4 shows the typical installation time period and range for a backhoe, motor grader, and front-end loader.

Table 2.3 Installation Checklist Form

Installation Procedure Checklist	
Main Unit – Locate the main unit in the safety cage – Connect the engine sensors to the main unit – Warm up for forty-five minutes	☐
Geographical Positioning System – Affix the GPS receiver on the top of the construction vehicle – Connect the cable from GPS to the main unit – Secure the cable to the safety cage	☐
Camcorder – Connect the camcorder with the tripod – Slide the POWER switch to turn on the camcorder	☐
Laptop Computer – Turn on the laptop computer – Open Microsoft Excel – Run the Visual Basic Macro	☐
Synchronize – Synchronize the time of the main unit, camcorder, and laptop computer	☐

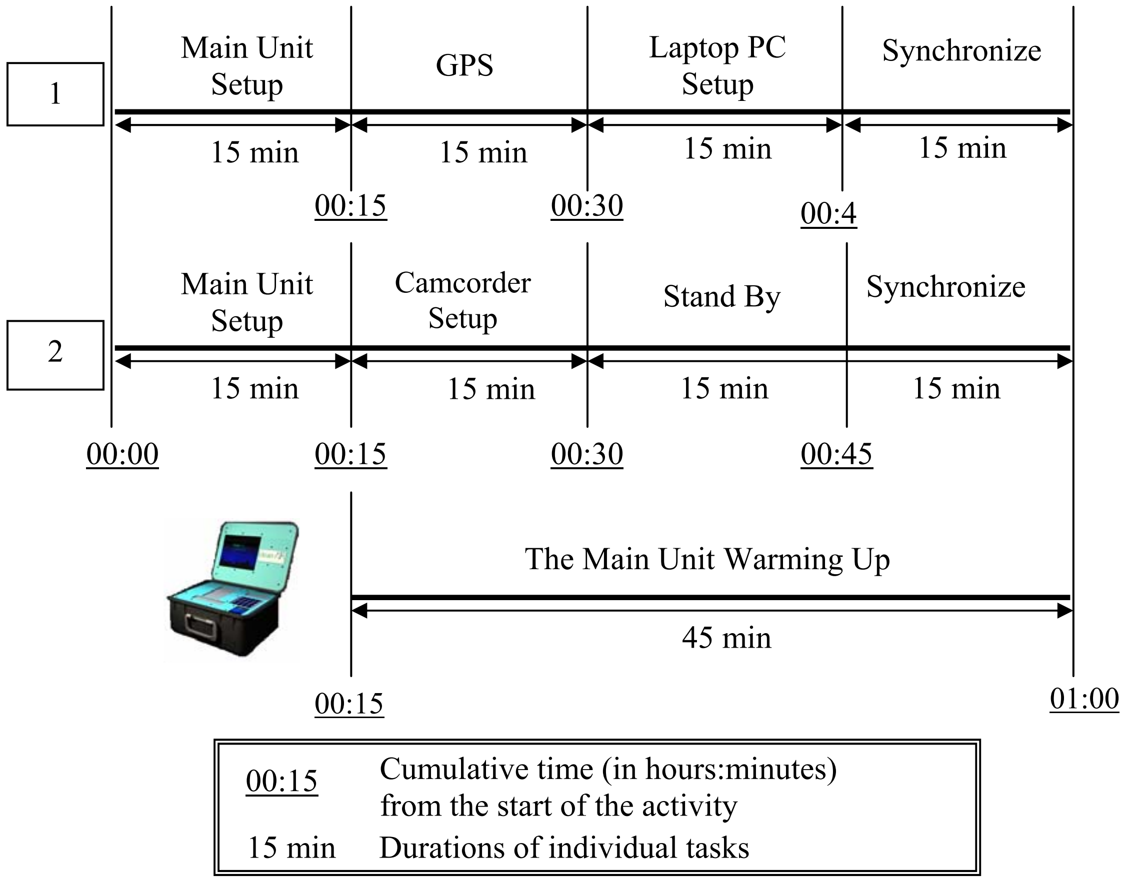

Figure 2.17 Timeline for Installation Procedures Performed by Two Persons

Table 2.4 Typical Time Period and Range for Installation Based on Equipment Type

Equipment Type	Installation Time Period	
	Typical	Range
Backhoe	1 hr 00 min	1 hr 00 min to 1 hr 50 min
Motor Grader	1 hr 00 min	1 hr 00 min to 1 hr 50 min
Front-End Loader	1 hr 00 min	1 hr 00 min to 1 hr 50 min

2.2.1 Main Unit

On the test day, when the data collection crew gets to the construction site, the first step is to install the main unit of the Montana system. Flexible rubber pads and foam rubber are placed underneath the main unit of the Montana system in order to reduce vibration from the construction vehicle as shown in Figure 2.2. Moreover, the main unit should be fastened with the safety cage using plastic ties. After the installation is done, the main unit should be warmed up for forty-five minutes. During this period, the data collection crew can set up the GPS, the camcorder, and the laptop computer.

2.2.2 Geographical Positioning System

The Global Positioning System (GPS) is a device to determine the construction vehicle's position by triangulating distances from satellites. This device has a strong magnetic tape under the receiver to hold it in place. Thus, the receiver can be affixed to a steel surface on the vehicle. The recommended location of the GPS receiver is on the roof of the vehicle so that it has the best signal from satellites. Figure 2.18 shows a picture of the GPS receiver of the Montana system.

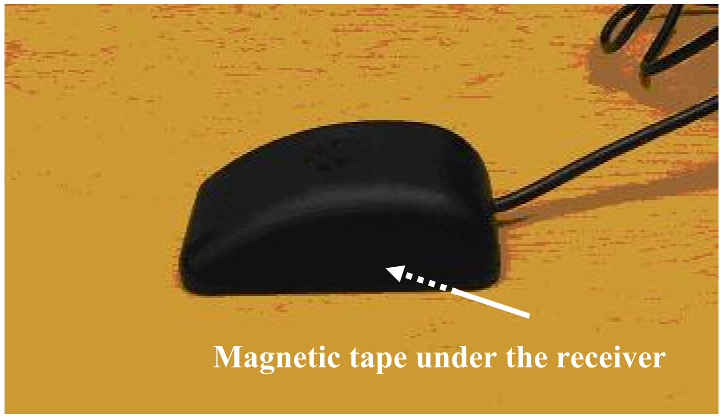

Figure 2.18 Trimble GPS Receiver

2.2.3 Camcorder

A camcorder with a tripod is used to record the activity pattern of the construction equipment. The camcorder should be installed in a safe place that is not too close to the work zone. A member of the data collection crew operates the camcorder and makes a video recording of the work activities. For example, as a motor grader often moves around a large area, the data collection crew should follow the motor grader and record the work activities. For other construction vehicles, such as backhoes and bulldozers, the data collection crew may stay in one place and record the video without moving the setup.

2.2.4 Laptop Computer

A laptop computer with Microsoft Excel is used to record data regarding the modal activity of the vehicle. A Visual Basic program has been prepared for recording modal activity. The program is running during data collection. A member of the data collection crew records modal activity using the keyboard. The laptop computer can be used for three hours. Its use is limited by battery capacity. It is recommended that the laptop computer be charged every two hours. The data collection crew uses the cigarette lighter in a passenger car to provide the power of laptop computer. Thus, data collection will not be interrupted when the laptop computer is recharging.

2.2.5 Synchronizing the Main Unit, Camcorder, and Laptop Computer

The data collection crew synchronizes the time of the camcorder and the laptop computer based on the main unit of the Montana system. Because data analysis is based on second-by-second data, if the time shown on the main unit, laptop computer, and camcorder are different, it would pose a challenge to data analysis. Thus, it is important to synchronize these instruments before data collection. Figure 2.19 shows the synchronization of camcorder and laptop computer.

Figure 2.19 Synchronization of the Camcorder and the Laptop Computer

2.3 Data Collection

On the day that data is to be collected, the researchers typically arrive at the construction site approximately two hours before data collection is to begin in order to prepare the equipment. There are six primary tasks to be completed in the data collection process. These are:

1. Install and use the Montana System
2. Prepare and use the laptop computer
3. Prepare and use the video camera
4. Assess and record the field conditions
5. Collect and record equipment data
6. Archive data

When the installation is completed and the Montana system has warmed up for forty-five minutes, the Montana system can be used to collect data from construction equipment. During data collection, the camcorder will make a video recording of the construction vehicle and the laptop computer is used to record the modal activity. This section describes the field procedures during data collection.

After the main unit has warmed up for forty-five minutes, it is ready for collecting data. One person uses the camcorder to record the work pattern of the construction vehicle. A second person records modal activities using the laptop computer. Approximately every thirty minutes, it is important to check the main unit of the Montana system to verify that it is working properly. Based on experience, there are various types of problems that can be encountered during field data collection. Many of these can be solved on site if they are detected or identified. These problems and their solutions are described in another appendix. The checklist for data collection is shown in Table 2.5. Figure 2.20 shows the timeline of the data collection procedures.

Table 2.5 Data Collection Checklist Form

Data Collection Checklist	
Montana System Measurement – Start a new file for data collection	☐
Camcorder – Make a video recording of the construction vehicle	☐
Laptop Computer – Record modal activities of the construction vehicle	☐
Periodic Checking of Montana System – Check the screen of the main unit – Perform corrective action as needed	☐

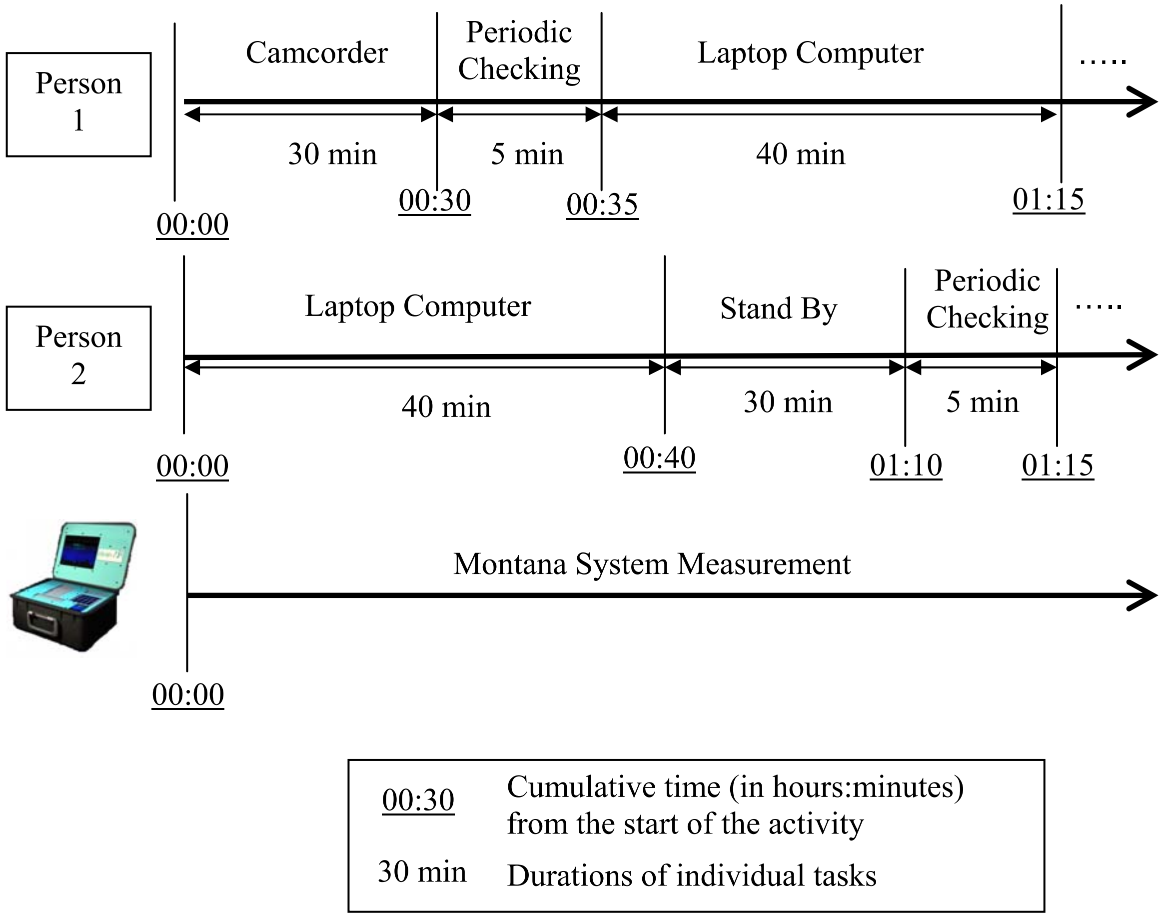

Figure 2.20 Timeline for Data Collection Procedures

2.4 Decommissioning

When data collection activity is finished, each instrument and sensor should be removed or disconnected from the construction equipment. It typically takes thirty minutes to finish the decommissioning. All equipment is brought to the laboratory for cleanup after decommissioning.

The decommissioning procedures can be completed by either one or two persons. Table 2.6 shows the checklist of decommissioning procedures. The timeline for decommissioning by one person is shown in Figure 2.21. Figure 2.22 depicts the timeline for two persons. Overall it takes one person about one hour and ten minutes to complete decommissioning and it takes 2 people about 35 minutes.

Table 2.6 Decommissioning Checklist Form

Decommissioning Checklist	
Main Unit – Disconnect the sampling hoses in the back of the main unit – Disconnect the sampling bowl – Disconnect the cables – Disconnect the GPS – Disconnect the keyboard – Bring the main unit to the laboratory	☐
Safety Cage – Dismantle the safety cage – Bring the safety cage to the laboratory	☐
Exhaust Gases Sampling Hoses – Disconnect the exhaust gases sampling hoses from the tailpipe – Put the exhaust gases sampling hoses into a plastic bag – Bring the sampling hoses to the laboratory	☐

(Continued on the next page)

Table 2.6. Continued.

Sensor Unit – Disconnect the cable from sensor unit to the engine sensors – Put the sensor unit into the box – Bring the sensor unit to the laboratory	☐
MAP Sensor – Disconnect the MAP sensor – Put the MAP sensor into the box – Bring the MAP sensor to the laboratory	☐
Engine Speed Sensor – Disconnect the engine speed sensor – Put the engine speed sensor into the box – Bring the engine speed sensor to the laboratory	☐
Intake Air Temperature Sensor – Disconnect the intake air temperature sensor – Put the intake air temperature sensor into the box – Bring the intake air temperature sensor to the laboratory	☐
External Power Sources – Disconnect external power sources – Tape all the connector using duct tape – Place the battery into a container – Bring the battery to the laboratory	☐
Geographical Positioning System – Disconnect geographical positioning system – Bring the GPS to the laboratory	☐

(Continued on the next page)

Table 2.6. Continued.

Video – Turn off the camcorder – Put the camcorder into the bag – Bring the camcorder to the laboratory	☐
Laptop Computer – Save the Excel file – Turn off the laptop computer – Put the laptop computer into the bag – Bring the laptop computer to the laboratory	☐
Wrap Up – Pick up tools and put into the toolbox	☐

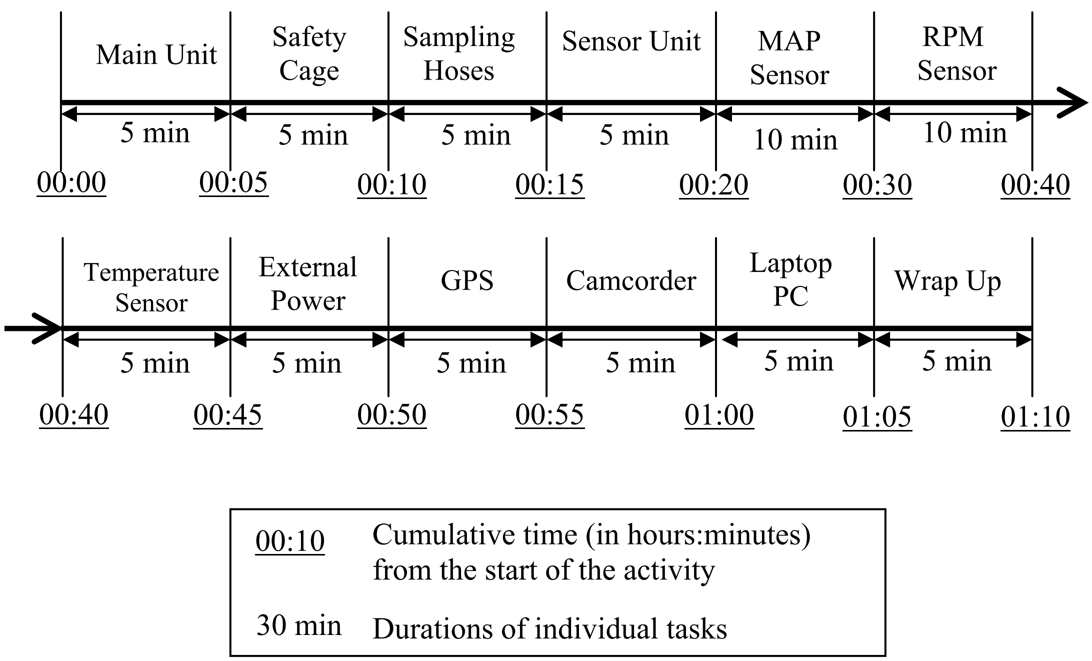

Figure 2.21 Timeline for Decommissioning Performed by One Person

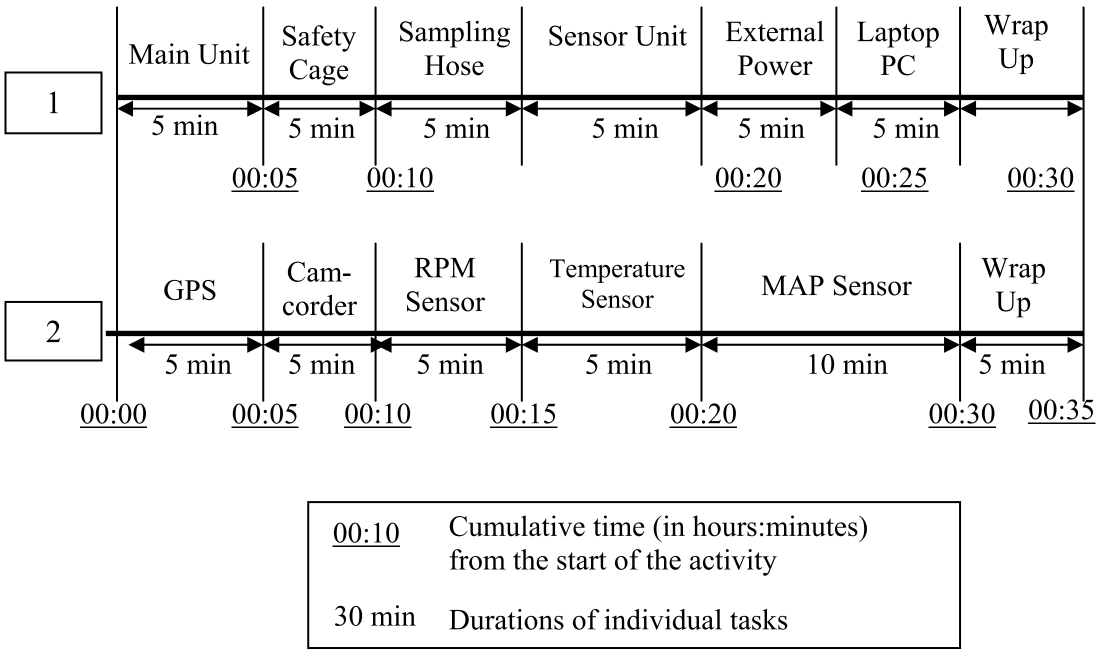

Figure 2.22 Timeline for Decommissioning Performed by Two Persons

2.4.1 Main Unit

The decommissioning of the main unit includes removing the safety cage and the main unit of the Montana system from the construction vehicle. First, the cables and the sampling hoses should be disconnected from the main unit. The main unit is usually installed on the roof of cab. The unit must be taken out of the safety cage and lower it to the ground. The best way to do this is if one person climbs to the roof and transfers the main unit to the other person.

2.4.2 Exhaust Gases Sampling Hoses

The decommissioning of sampling hoses is not difficult and takes only five minutes to finish. The plastic ties should be removed first. The sampling probes should be disconnected from the tailpipe. The sampling probes are very dirty after a full day of testing. Thus, the sampling hoses should be stored in a plastic bag for their return to the laboratory.

2.4.3 Engine Sensors

The decommissioning of engine sensors includes disconnection of the sensor unit, the MAP sensor, the intake air temperature sensor, and the engine speed sensor. Even after the engine of a construction vehicle has been shut off, the engine temperature can still be very high. For safety, the data collection crew usually starts decommissioning the sensors no sooner than ten minutes after the engine stops. Even then extreme care must be taken to prevent injuries.

2.4.4 External Power Source, Geographical Positioning System, Camcorder, and Laptop Computer

The decommissioning of the batteries, the GPS, the camcorder, and the laptop computer is the last step. The connectors of the batteries should be covered with duct tape. Then, the battery is placed into an appropriate container to protect the battery from being impacted. After the GPS is disconnected from the main unit, it should be put into the storage box. The camcorder should be shut down before decommissioning. The camcorder and tripod will be returned to the laboratory. Prior to decommissioning the laptop computer, the Excel file of modal activities should be saved first. The laptop computer will be shut down and returned to the laboratory. It is important to make sure that all instruments are brought to the laboratory.

2.5 Cleanup after Data Collection

Each of the main parts of the main unit should be cleaned up: outside the box, the gas analyzer, and the computer. Cleanup procedures for other instruments are also identified in this section. The checklist for cleanup procedure is shown in Table 2.7.

Table 2.7 Cleanup Checklist Form

Cleanup Checklist	
Main Unit – Clean up outside the box – Clean up the gas analyzers – Clean up the computer	☐
Safety Cage – Remove dust from the safety cage – Clean up the rubber pads	☐
Exhaust Gases Sampling Hoses – Remove dust from the hoses – Clean up the sampling probe – Clean up the sampling gas and PM bowl – Replace the filter for the gas sampling bowl as needed	☐
Engine Sensors – Remove dust from the MAP sensor – Remove dust from the engine speed sensor – Remove dust from the intake air temperature sensor – Remove dust from the sensor unit	☐
External Power Source – Remove dust from the batteries – Recharge the batteries	☐
Geographical Positioning System – Remove dust from the GPS	☐

(Continued on the next page)

Table 2.7 Continued.

Camcorder – Remove dust from the camcorder – Remove dust from the tripod – Download the video file	☐
Laptop Computer – Remove dust from the laptop computer – Remove dust from the keyboard – Download the Excel file of modal activities	☐

2.5.1 *Main Unit*

The following text explains the sequential steps that are necessary and critical for cleaning the Montana after data collection. These procedures are to be initiated after every field data collection operation is completed. Figure 2.23 shows the Montana system and identifies the different sections addressed in this cleaning procedure.

Figure 2.23 Parts of the Montana Addressed in the Cleaning Procedure

2.5.1.1 <u>Outside the Box</u>

The procedures for cleaning the box are listed below:

1. Close the top panel of the main unit
2. Ensure that all ports located on the back panel of the main unit are unplugged and that all caps are closed
3. Use a dust remover to clean the outside of case
4. Leave the main unit open for 3~5 minutes to allow air circulation to dry any accumulated moisture
5. Open the top panel of the main unit
6. Clean the power and computer panel using a dust remover
7. Leave the main unit open for 3~5 minutes to allow air circulation to dry any accumulated moisture

2.5.1.2 Gas Analyzers

The procedures for cleaning the gas analyzers are listed below:

1. Open the power panel to check the inside of the main unit
2. Find the location of the gas analyzers and sensors and check their status
3. Tilt the main unit about 30 to 45 degrees to the opposite side of where the electronic boards are located
4. Use a compressed clean air spray to remove dust
5. Check the gas sampling hoses to see if dust has collected inside of them and to determine if they need to be replaced
6. Check the PM and gas filters to see if they need to be replaced (turning to black color from yellow can be a good indicator of time for the replacement)
7. Check for any loose screws and connections before move to the next cleaning stage
8. Close the power panel after finishing step 1 to 7

2.5.1.3 Computer

The procedures for cleaning the computer are listed below:

1. Put a soft cover on the power panel to avoid damage of computer monitor
2. Clean dust on the computer panel using dust remover
3. Open the computer panel slowly not to damage the electronic connections
4. Use the compressed clean air spray to remove dust from board
5. Check any loosed screws and connections before move to the next cleaning stage
6. Close the computer panel after finishing step 1 to 5

2.5.3 Safety Cage

The procedures for cleaning the safety cage are listed below:

1. Remove dust from the safety cage
2. Clean the rubber pads

2.5.4 Exhaust Gases Sampling Hoses

The procedures for cleaning the sampling hoses are listed below:

1. Remove dust from the cables and sampling hoses
2. Clean the sampling gas and PM bowl
3. Replace the filter for the gas sampling bowl if needs to replace

2.5.5 Engine Sensors

The procedures for cleaning the engine sensors are listed below:

1. Remove dust from the intake air temperature, the manifold air pressure, and engine speed sensors
2. Keep the sensor connectors out of exposure to chemical cleaner due to the potential damage

2.5.6 External Power Source

The procedures for cleaning the engine sensors are listed below:

1. Remove dust from the batteries
2. Keep the batteries safely and well-organized
3. Recharge the batteries after cleanup

2.5.7 Geographical Positioning System

The procedures for cleaning the GPS are listed below:

1. Remove dust from the GPS
2. Keep the geographical positioning system in the box

2.5.8 Camcorder

The procedures for cleaning the camcorder are listed below:

1. Remove dust from camcorder
2. Remove dust from the tripod
3. Download the video file

2.5.9 Laptop Computer

The procedures for cleaning the laptop computer are listed below:

1. Remove dust from the laptop computer
2. Remove dust from the keyboard
3. Download the file of modal activity from laptop computer

2.6 Problems and Solutions for Field Measurement

In this section, problems that are expected to be encountered during field data collection are discussed. The general procedures for data collection include communication with equipment operators, installation of the portable emissions measurement system (PEMS), data collection, and removal of the PEMS. Typically, the removal step is straightforward. The most significant problems occur during the first three steps. The text that follows describes these problems. Table 2.8 provides an overview of each problem and its solution.

2.6.1 Communication with the Equipment Operator

Prior to data collection, cooperation must be obtained from the supervisor and the equipment operator to access the equipment for installation of the PEMS, and to interact with the operator during data collection. The latter is occasionally needed if a data collection problem occurs that requires intervention with the PEMS in order to correct it.

For construction vehicles, the "sensor array" of the PEMS must be used to obtain engine data. Thus, the installation of the PEMS is more complex for construction vehicles than for on-road vehicles. Based on preliminary data collection efforts on construction equipment, it was determined that it takes approximately two hours to install the engine sensor, sample line, and a protective cage for the PEMS device, and one hour to test the PEMS to make sure that it is capable of data collection (i.e. to make sure that data is available for all engine and emissions variables). Thus, in order to be ready for data collection at the start of a morning work shift, most of the system must be installed the afternoon before data collection is to occur. For security reasons, the PEMS itself is not left unattended overnight, but the cables, the hoses, and the safety cage can be installed and left overnight in most cases.

Some field data collection problems can be anticipated. It is found that the two main problem areas are the interactions with the equipment operator and the installation of the Montana system. These are individually identified and discussed.

EO-1. *<u>(Equipment Operator) The operator changes the work schedule and does not use the equipment that was to be monitored</u>*

It is important to communicate with the equipment operator regarding the availability of construction equipment for field data collection to allow sufficient time for installation the afternoon prior to the targeted day of data collection. On occasion, for various operational or weather-related reasons, the operator might alter their work schedule, or there may be unanticipated problems with the equipment itself. Some of these problems can be avoided by adequate communication and planning, while others are unavoidable and simply have to be dealt with on a real-time basis. For example, it may be necessary to remove the initial installation of cables, hoses, and protective cage prior to data collection if the targeted equipment is removed from service because it needs an unexpected repair.

EO-2. *<u>(Equipment Operator) The operator does not leave the key for the equipment</u>*

After pre-installation of the instruments, it is necessary to make sure the engine sensors are working. Engine sensors include an engine speed sensor, a MAP sensor, and a temperature sensor. One must have the key to start the engine and test the engine speed. Thus, if the equipment operator does not leave the key for the equipment, it is not possible to test engine speed when the pre-installation is completed. It would be very risky if engine speed was not tested before data collection. Thus, it is critical to explain the importance of the test and to communicate with the equipment operator effectively. They are then usually willing to leave the key for us.

EO-3. *<u>(Equipment Operator) The equipment operator may not have all information and specifications for the equipment</u>*

The engine specifications must be entered into the main unit before collecting data. The equipment operator may not know all the necessary information and specifications for the equipment. If not, a handbook must be consulted for that equipment make and model or a study must be made of the manufacturer's website. Usually, all information can ultimately be obtained from handbooks or the internet.

2.6.2 Installation and Data Collection

The data collection crews pre-install some of the major components the day before a test. Some problems occur when pre-installing instruments. During data collection, the data collection crews check the Montana system every thirty minutes. The following paragraphs describe some of the problems and solutions that occur during installation and data collection.

DC-1. *(Engine Characteristics) The pressure sensor will disconnect when the engine temperature increase.*

The pressure sensor is connected to the pressure valve using tubing. When the engine temperature increases, the tubing may disconnect from the pressure sensor. To correct this, two clamps are placed on the connection between the pressure sensor and the boost pressure port. In this manner the problem can be solved.

DC-2. *<u>(Engine Characteristics) The pressure sensor must be stabilized when it is installed</u>*

The pressure sensor must be stabilized in order to prevent damage. A plastic tie can be used to attach the pressure sensor to a support. Figure 2.24 provides an illustration of the use of a plastic tie to stabilize the pressure sensor.

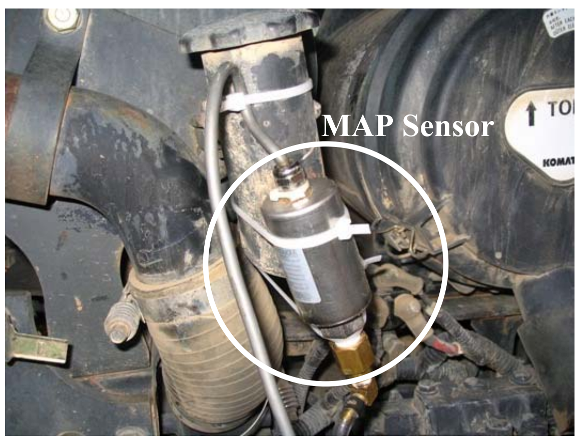

Figure 2.24. Illustration of a Stabilized Pressure Sensor

DC-3. <u>(Engine Characteristics) The engine speed sensor must have an adequate location in order to provide accurate measurements</u>

The engine speed sensor has exceedingly strong magnetization. It is easy to attach to metal materials. However, the location of the engine speed sensor depends on the location of the optical tape that it is sensing as shown in Figure 2.25. The following suggestions for the engine speed sensor installation should be followed:

- Locate the optical tape;
- Be sure that no fans or other engine related parts are near the engine speed sensor;
- Attach the sensor firmly but position it so that it clearly sees the optical tape; and
- Ensure that the cable is long enough to reach the sensor unit.

DC-4. <u>(Engine Characteristics) The optical tape used with the engine speed sensor must be well positioned in order to provide an accurate measurement</u>

The placement of the optical tape is essential to obtaining a reliable engine speed. Numerous locations can be considered. One excellent location is on the pulley as shown in Figure 2.25.

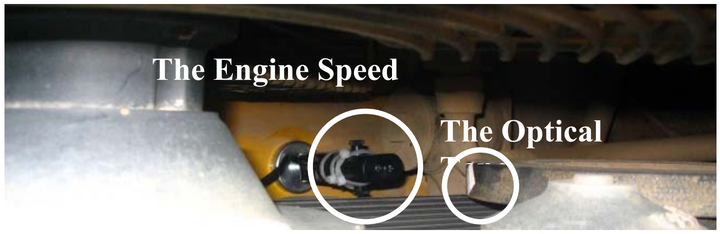

Figure 2.25 Illustration of an Engine Speed Sensor and Optical Tape

DC-5. *<u>(Montana system) The location of the main unit and cage can interfere with the operator</u>*

When the equipment cage is installed it must be placed so as not to interfere with the operator. For excavators, there is plenty of space to install the cage. But preliminary studies show that for dozes or other smaller equipment there is limited space to install the cage. If it is installed behind the operator it can interfere with his elbows. Careful and strategic placement is critical.

DC-6. *<u>(Montana system) The power supply for the Montana system was inadequate</u>*

Initially only a single battery was available to supply power to the Montana system. Unfortunately, a single battery has only a five hour life. Thus, an additional battery is necessary to collect data for ten hours. This then enables the field crew to maximize the data collection effort for each setup of equipment.

DC-7. *<u>(Montana system) Vibration must be controlled between the equipment body and the Montana system</u>*

Vibration may cause a short circuit or other damage to the Montana system. One way to control the vibration is by using a foam rubber pad between the equipment body and the Montana system. This method does decrease the vibration of Montana system, but doing so does not completely eliminate the vibration.

DC-8. *<u>(Montana system) Access to the site must be available early enough to warm up the Montana system</u>*

In order to acquire accurate data, the main unit of the Montana system needs to warm up for more than 45 minutes. Only if the data collection crew arrives at the site by 6:00AM and the construction workers start working at 7:00AM is there adequate time for installation preparations.

DC-9. (Montana system) The main unit gets very hot. If it overheats, the fuses burn out and it does not collect data

The Montana system is an electronic device. If the weather gets hot, the fuses will burn out and data cannot be obtained. To solve this problem requires the use of a cover for the Montana system to prevent direct sunlight from reaching it. Sunlight has been determined to be the main cause of the overheating problems. Still, after installing a cover, it is possible to have overheating problems with the Montana system in hot weather (32 degree Celsius or 90 degree Fahrenheit). The equipment itself usually does not impart overheating conditions.

DC-10. (Montana system) The main unit must be protected from dust

Dust may cause potential damage to the Montana system. Cotton is used as a filter to mitigate the intrusion of dust while still keeping the proper level of air flow inside the main unit for cooling. Still, there is a small amount of dust that accumulates inside the main unit. This is removed through the regular use of compressed air.

DC-11. *<u>(Montana system) The screen of Montana system was freezing</u>*

Sometimes, during data collection, the screen of Montana system would "freeze." The indicator of the screen freezing is that the time and pollutant concentration do not change for a long period of time. One possible reason might be short circuiting of the computer inside the main unit of Montana system. When this problem happened during data collection, the program was restarted and the screen freezing problem was solved.

DC-12. *<u>(Montana system) The PM value was abnormal</u>*

On December 20, the measured PM value was lower than it was on previous tests. It might be the problem of dirty pump inside the main unit of the Montana system. The applied solution was to clean the PM pump. On the next test, the measured PM value became normal and this problem was solved. The details of cleaning the pump are presented in the data collection procedures.

DC-13. <u>(Sample Line) The sample line entry into the tailpipe must be completely sealed in order to obtain accurate measurements</u>

For some construction vehicles, there is a gap between the muffler and tailpipe as shown in Figure 2.26. In such circumstances fresh air may enter the tailpipe and dilute the pollutant concentration. In order to acquire accurate data, we must either install the probe directly into the muffler or seal the gap. It has been found that aluminum foil can be used to seal the gap while firmly attached with two clamps as shown in Figure 2.27. The emission data show that there is little to no leakage after applying this solution method.

Figure 2.26 Gap Between Muffler and Tailpipe

Figure 2.27. Sealing the Gap between Muffler and Tailpipe

DC-14. *<u>(Sample Line) Water inside the sampling line was frozen</u>*

For two-day data collection, it is important to return the Montana system and batteries to the laboratory after the first day of data collection. Other instruments, such as the safety cage, sampling line, and engine sensors, can be left at the job site. One reason for this is that, in winter, sometimes the ambient temperature will drop below 0 degree Celsius (32 degree Fahrenheit). When this happens, the moisture inside the sampling line will be frozen. Data collection cannot then be undertaken. Thus, the main unit of the Montana system, its batteries, and its sampling hoses should be disconnected and returned to the laboratory after the first day of data collection and reinstalled the next day.

DC-15. *<u>(Laptop Computer) The laptop computer gets very hot which is potentially damaging</u>*

The laptop data collection computer is also an electronic device. When it gets very hot, circuits may be damaged. Thus, the laptop computer must be used in a shaded area. It too is highly susceptible to the heat of the sun.

DC-16. (Test Vehicle) The construction equipment malfunctions and no data can be collected

In addition to construction equipment schedule changes it is sometimes the case that the equipment malfunctions. The equipment operator may not use the equipment on the anticipated date thus making it impossible to collect data. There is no solution to this problem other than to patiently deal with it.

Table 2.8 Problems and Solutions during Data Collection

	Problem	Applied Solution	Date of Solving	Results of Applied Solution
EO1	**(Equipment Operator)** The equipment operator changes the work schedule and does not use the equipment that was for monitored	Keep in touch with the equipment operator frequently	**08/16/05**	This problem may occur in the further tests
EO2	**(Equipment Operator)** The equipment operator does not leave the key for the equipment	Communicate with the operator	**07/27/05**	The equipment operator may be willing to leave their key
EO3	**(Equipment Operator)** The equipment operator may not have all information and specifications for the equipment	Find information on internet and handbook	**07/27/05**	This problem has been solved
DC1	**(Engine Characteristics)** The pressure sensor will disconnect when engine temperature increases	Two clamps were used on the connection between pressure sensor and boost pressure port	**08/11/05**	This problem has been corrected using the clamps
DC2	**(Engine Characteristics)** The pressure sensor must be stabilized when it is installed	Using plastic tie	**08/11/05**	The pressure sensor was stable after using plastic tie
DC3	**(Engine Characteristics)** The engine speed sensor must have an adequate location in order to provide accurate measurements	Try different locations to find out the best way to measure the engine speed	**07/27/05**	The best location for the engine speed sensor depends on different equipment. Please see details in the chapter
DC4	**(Engine Characteristic)** The optical tape used with the engine speed sensor must have an adequate location in order to provide accurate measurement	Try different locations to find out the best way to measure the engine speed	**07/27/05**	Attaching the optical tape on pulley is the best way to detect the engine speed
DC5	**(Montana System)** The location of the main unit of the Montana system and cage sometimes interferes with the operator	Change the location of cage, which the Montana system won't interfere with the operator, please see chapter for detailed information	**08/16/05**	Operator did not complain about the cage after relocating it

(Continued on the next page)

Table 2.8 Continued.

	Problem	Applied Solution	Date of Solving	Results of Applied Solution
DC6	**(Montana System)** There is only one battery with a five hour life for the Montana system. An additional battery is required	Buy another battery	**08/16/05**	Two batteries can work for more than 10 hours, enabling data collection for an entire workday
DC7	**(Montana System)** Vibration must be controlled between the equipment body and the Montana system	Place a foam rubber pad between the equipment body and the Montana system		*Vibration is not completely eliminated by rubber pad. This problem requires continued assessment
DC8	**(Montana System)** Access to the site must be available early enough to warm up the Montana system	The data collection team arrives at the job site one hour before work starts	**08/11/05**	There is sufficient time to install and warm up the instrument at the job site
DC9	**(Montana System)** The main unit gets very hot. If it overheats, the fuses burn out and it does not collect data	Use a cover to block the Montana system from the sun		*After shading the Montana system there still is overheating problems on a hot day
DC10	**(Montana System)** The main unit must be protected from dust	Use cotton as a filter to protect the main unit from dust	**08/11/05**	Cotton can resist dust to some extent and still keep the air flow inside the main unit. But there is small amount of dust inside the main unit. Compressed air is used to clean the main unit regularly
DC11	**(Montana System)** The screen of main unit was freezing	Restart the program	**12/20/05**	Montana system operates normally after restarting the program
DC12	**(Montana System)** The PM value was abnormal	Clean the PM pump inside the main unit of Montana system	**12/30/05**	The problem was solved

(Continued on the next page)

Table 2.8 Continued.

	Problem	Applied Solution	Date of Solving	Results of Applied Solution
DC13	**(Sample Line)** The sample line entry into the tailpipe must be scaled completely in order to obtain accurate measurements	Seal the gap between the muffler and tailpipe	**08/16/05**	NO_x, HC, CO, CO_2 and PM concentrations go up after the sample line entry into the tailpipe is sealed
DC14	**(Sample Line)** Water inside the sampling line was frozen	Bring the sampling line to the laboratory for overnight storage after data collection	**12/12/05**	The problem was solved
DC15	**(Laptop Computer)** The laptop computer gets very hot which is potentially damaging	Choose a shaded area in which to use the laptop computer	**07/27/05**	Shading the laptop computer solves the overheating problem
DC16	**(Test Vehicle)** The construction test vehicle is not operating and no data can be collected	No solution applied		

*** Problem not solved**

PART III DATA SCREENING AND QUALITY ASSURANCE

Data screening and quality assurance are procedures for reviewing data collected in the field, determining whether any errors or problems exist in the data, correcting such errors or problems where possible, and removing invalid data if errors or problems cannot be corrected. The goal of data screening and quality assurance is to produce a database that contains valid data.

From previous work, a number of possible errors and problems have been identified (Frey *et al.*, 2001; 2005). In the previous work, engine data were collected via the electronic data link of the vehicle, such as the on-board diagnostic link of light duty gasoline vehicles and the engine control module link of heavy duty vehicles. However, in the current study, engine data are obtained using a sensor array. Thus, the data screening and quality assurance procedures required modification for this work to account for problems and errors that can occur in conjunction with the sensor array. One possible concern is the synchronization of the data streams from the sensor array and the gas analyzers. The others are the communication between sensor array and computer.

In addition to development of data screening and quality assurance procedures, a technique for evaluation of the data obtained from diesel engines was developed that involves comparison of the observed air-to-fuel ratio from the data with general expectations for the variability in air-to-fuel ratio for diesel engine as reported by others. This comparison can provide insight regarding whether air leakage might be a problem in the sampling line or gas analyzer of the Montana system. The standard quality assurance procedures include 10 steps. Only the QA procedures developed by Shih-Hao Pang are shown in the section. The complete data quality assurance procedures are provided in NCDOT report (Frey *et al.* 2007).

3.1 Montana System, Preliminary Data Validity Check

The Montana system performs a preliminary data validity check and reports indications of data quality problems in some situations. The purpose of this section is to describe how to deal with data that are flagged as invalid by the Montana system.

The Montana system detects exhaust concentration in units of parts per million (ppm) or volume percent (vol-%). In order to convert exhaust concentrations to mass emission rates (g/sec), engine data (engine speed, intake air temperature, and manifold absolute pressure) are needed. A reported value of "YES" means that the emission rate can be converted to a gram-per-second basis. On the other hand, a reported value of "NO" means that the emission rate can NOT be converted to a gram-per-second basis.

The reasons for not being able to make the conversion are numerous. The engine may not be running or the engine sensors may not be connected to the Montana system. In this case, the engine data are zero and there is no emission data that can be detected by the Montana system. If the communication between sensor array and the main unit of the Montana system is lost, the Montana system will flag the MAP data indicator as "-34." During the first few seconds of testing when the Montana system is initially turned on, both gas analyzers are zeroing. Thus, there is no exhaust emission that is detected by the Montana system. All of the indicators used by the Montana system are shown in Table 3.1.

Table 3.1 Indicators Flagged by the Montana System

Category of Data		Indicator	Description
Engine Data	Engine Speed, IAT[a],MAP[b]	Zero	The engine is off or engine sensors are not connected to the Montana system.
	MAP[b]	-34	Manifold absolute pressure is missing.
Gas Analyzer Data		Zero	Both gas analyzers are zeroing. There is no pollutant concentration detected by the Montana system.
Emission Data		YES	The reported emission rate is potentially valid.
		NO	The emission rate is not reported because of one or more data validity problems.

[a] IAT = intake air temperature
[b] MAP = manifold absolute pressure

In order to show all of the possible data validity problems, Table 3.2 presents four examples where the Montana system flagged data as valid or invalid. For Case 1, both the engine and emissions data are detected by the Montana system, thus emission rates can be converted to a gram-per-second basis. Thus, Case 1 is valid and the data are flagged as "YES."

For Case 2, the engine data are detected by the Montana system, but emission data are zero. This can happen during the first few seconds of testing when the Montana system is initially turned on. At this time, both gas analyzers are zeroing and there are no exhaust emissions that are detected by the Montana system. Therefore, the emission rates cannot be converted to a gram-per-second basis. Case 2 is invalid and is flagged as "NO." The second of data for this case will be excluded.

For Case 3, the exhaust emissions are detected by the Montana system, but the engine data are unavailable. This can happen when the engine is turned off or when the engine sensors are not connected to the Montana system. As a result, the emission rates cannot be correctly converted to a gram-per-second basis. Thus, Case 3 is also invalid and is flagged as "NO." The data for this case will be excluded.

For Case 4, the exhaust emissions, engine speed, and intake air temperature are detected and recorded by the Montana system. However, manifold absolute pressure is missing due to various reasons such as vibration. The reported value of "-34" is an indicator that MAP data is missing. In some cases, the missing MAP data can be estimated. For these cases, after estimating the missing MAP, the emission rate can be converted to a gram-per-second basis. Thus, in some cases, an emission rate can be estimated even if MAP data are partially missing. If this is done, the data for this case will be kept in the screening dataset.

Table 3.2 Examples of Data Flagged as Valid and Invalid

Category of Data	Case			
	1	2	3	4
Valid Data	YES[c]	NO[d]	NO[d]	NO[d]
Engine Speed (RPM)	799	798	**0**	797
IAT[a] (^oC)	30	25	**0**	25
MAP[b] (kPa)	100	100	**0**	**-34**
NO_x (ppm)	383	**0**	385	384
HC (ppm)	27	**0**	31	31
CO (vol-%)	0.016	**0**	0.016	0.016
CO_2 (vol-%)	1.93	**0**	1.95	1.95
O_2 (vol-%)	18	**0**	18	18

[a] IAT = intake air temperature
[b] MAP = manifold absolute pressure
[c] YES = emission rate can be converted to a gram-per-second basis
[d] NO = emission rate can NOT be converted to a gram-per-second basis
[e] "-34" = indication that MAP is missing

In summary, when one dataset is running the data validity check, Case 2 and Case 3 are two situations in which the data will be excluded from the dataset. Case 1 is the situation that the data will be retained in the dataset. If the missing MAP can be estimated in Case 4, the second of data can be still retained in the dataset. Otherwise, the second of data will be excluded from the dataset.

3.2 Data Quality Checks Associated With Intake Air Temperature

Intake air temperature (IAT) is measured after the turbocharger at the intake manifold of the engine. During initial startup of the engine, the IAT might be similar to the ambient air temperature. When the turbocharger is operating, the heating will be transferred from other components of the engine. It results in an increase of IAT. Generally, IAT typically changes only gradually over time. If the IAT value changes rapidly, there may be some problems with IAT sensor. Therefore, the purpose of this section is to describe the criteria for detecting IAT errors.

3.2.1 Criteria for Detecting Intake Air Temperature Errors

Intake air temperature should change gradually over time. Based on previous field data collection, the differences of IAT between two consecutive seconds are in the range of -1 to 1 ^{o}C. Figure 3.1 presents the cumulative frequency of IAT difference between two consecutive seconds of backhoe tested on December 30, 2005. More than 95% of the data does not change over two consecutive seconds.

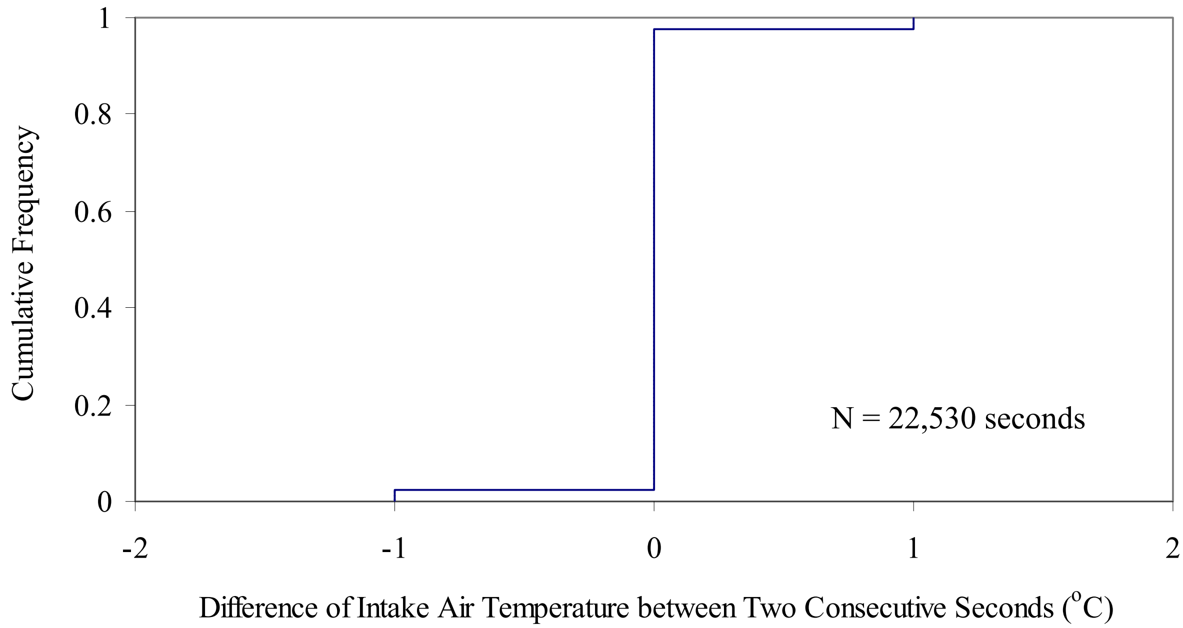

Figure 3.1 Cumulative Frequency of the Difference of Intake Air Temperature between Consecutive Seconds Based on a Backhoe Tested on December 30, 2005.

Based on the previous field data, the differences of IAT between two consecutive seconds never exceed 1 °C. Therefore, ±1 °C can be the lower and upper limit for the differences of IAT between two consecutive seconds. The following criterion was established at any given time *t*.

$$\mathbf{-1\ ^{o}C \leq IAT_{\mathit{t+1}} - IAT_{\mathit{t}} \leq 1\ ^{o}C}$$

where,

IAT_t	= Intake air temperature for time t (^oC)
1 ^oC	= Upper limit of IAT difference between two consecutive seconds (^oC)
-1 ^oC	= Lower limit of IAT difference between two consecutive seconds (^oC)

The verification procedures for IAT include:

1. Calculate the difference between two consecutive seconds
2. Check the difference if it is in the range of -1 to 1 ^oC
3. If yes, proceed to check the next data
4. If no, the second of data will be excluded from the dataset

3.2.2 Application of Intake Air Temperature Values to Real Data

To validate the criteria, an analysis was made using the field data of skid steer loader tested on January 20, 2006. Figure 3.2 shows the cumulative frequency of IAT differences between two consecutive seconds. If there is an error which the IAT difference between two consecutive seconds is NOT in the range of -1 to 1 ^{o}C, the data will be excluded. Fortunately, all of the IAT differences between two consecutive seconds are in the range of -1 to 1 ^{o}C. Therefore, there is no IAT error in this dataset.

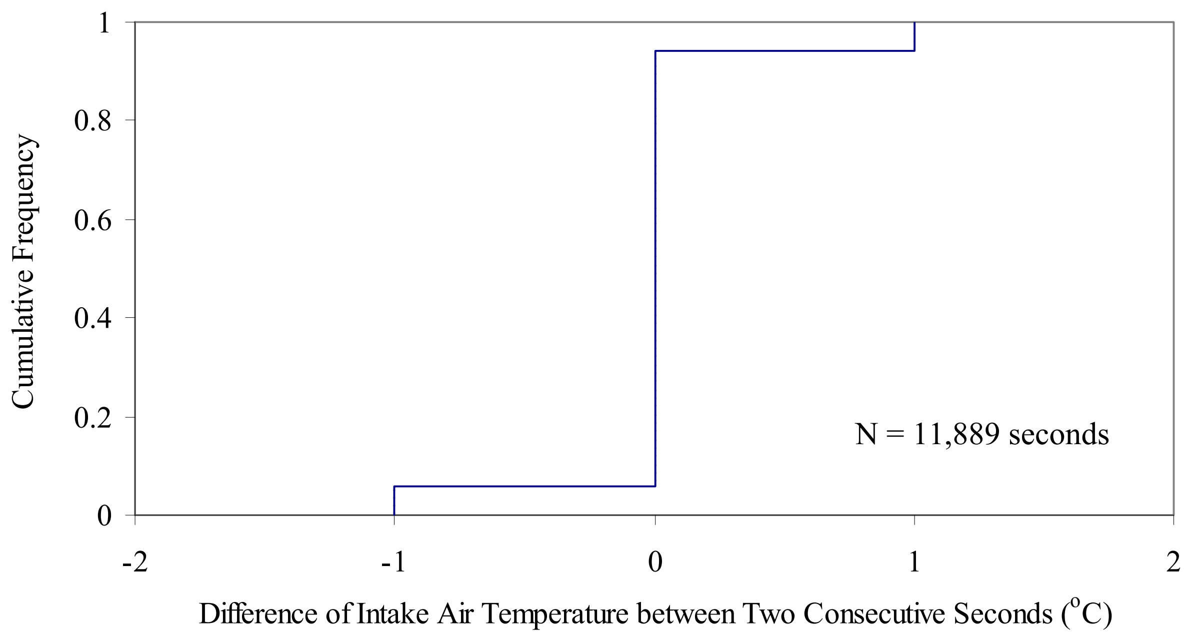

Figure 3.2 Cumulative Frequency of the Difference of Intake Air Temperature between Consecutive Seconds Based on a Skid Steer Loader Tested on January 20, 2006.

3.3 Identification and Evaluation of the Effects of Air Leakage on Data Quality

The purpose of this section is to develop a quality assurance procedure in order to determine whether an air leakage problem exists in the Montana system and how the leakage affects the mass emission rate (g/sec). Leakage might be observed either in the sampling hoses, or inside the main unit of the Montana system. When leakage occurs, air enters the sampling system upstream of the gas analyzers and, therefore, more excess air appears in the exhaust flow. To indicate the possibility of a leakage occurrence, the air-to-fuel ratio (AFR) is used as an indicator.

3.3.1 Air-to-Fuel Ratio

The mass-basis ratio of intake air to fuel consumption is known as the "Air-to-Fuel Ratio (*AFR*)". In order to estimate *AFR* for a diesel engine, the mass balance of diesel combustion should be considered. Generally, a diesel engine operates with a fuel lean mixture of fuel and air in which there is excess air. For general combustion, the chemical mass balance is:

$$CH_xO_z + u_t(0.21O_2 + 0.79N_2) \rightarrow b_tCO_2 + c_tCO + d_tC_6H_{14} + e_tNO + f_tH_2O + g_tO_2 + h_tN_2$$

where,

CH_xO_z = equivalent molecular formula of fuel

$u_t, b_t, c_t, d_t, e_t, f_t, g_t, h_t$ = stoichiometric coefficient of combustion for time t

The air-to-fuel ratio (AFR) is the ratio of mass of air to mass of fuel input into the engine:

$$AFR = \frac{M_{a,t}\left(\frac{mole}{s}\right) \times y_{O2,t,in} \times 32\left(\frac{g}{moleO_2}\right) + M_{a,t} \times y_{N2,t,in} \times 28\left(\frac{g}{moleN_2}\right)}{M_{f,t}\left(\frac{mole}{s}\right) \times (12 + x + 16z)\left(\frac{g}{moleCH_xO_z}\right)}$$

where

AFR = air-to-fuel ratio (gram Air/gram fuel)

$M_{a,t}$ = intake air molar flow rate (mole/sec) for time t assumed to be a mixture of 21 vol-% O_2 and 79 vol-% N_2

$M_{f,t}$ = fuel molar flow rate (mole/sec) for time t

$y_{O2,t,in}$ = mole fraction of O_2 (0.21) in the ambient air on a dry basis for time t

$y_{N2,t,in}$ = mole fraction of N_2 (0.79) in the ambient air on a dry basis for time t

The intake air molar flow rate (M_a) is estimated based on the engine data, including engine speed, intake air temperature, intake manifold air pressure, engine displacement, compression ratio, and engine volumetric efficiency. Thus, the intake air molar flow rate is calculated as:

$$M_a = \frac{P_M \quad \dfrac{P_B}{ER} \times EV \times \dfrac{ES}{30}}{R \times \left(T_{int} + 273.15\right)} \times \eta_{ev}$$

where,

ER = engine compression ratio

ES = engine speed (RPM)

EV = engine volume (liters)

M_a = intake air molar flow rate (mole/sec) assumed to be a mixture of 21 vol-% O_2 and 79 vol-% N_2

P_M = manifold absolute pressure (kPa)

P_B = barometric pressure (typically 101kPa)

R = ideal gas constant (8.314 kPa-l/mol-k)

T_{int} = intake air temperature (^oC)

η_{ev} = engine volumetric efficiency (typically 0.95)

In order to estimate fuel flow rate (M_f), dry exhaust flow rate (M_e), the following equations present the mass balance of element C, H and O based on intake air flow rate (M_a), fuel flow rate (M_f), dry exhaust flow rate (M_e), and exhaust water flow rate (M_w):

For C: $1 \times M_{f,t} = y_{CO2,t,dry} \times M_{e,t} + y_{CO,t,dry} \times M_{e,t} + 6 \times y_{C6H14,t,dry} \times M_{e,t}$

For H: $x \times M_{f,t} = 14 \times y_{C6H14,t,dry} \times M_{e,t} + 2 \times M_{w,t}$

For O: $z \times M_{f,t} + 2 \times 0.21 \times M_{a,t} = 2 \times y_{CO2,t,dry} \times M_{e,t} + y_{CO,t,dry} \times M_{e,t} + M_{w,t}$

$$+ 2 \times y_{O2,t,dry} \times M_{e,t} + y_{NO,t,dry} \times M_{e,t}$$

where

$M_{e,t}$ = dry exhaust molar flow rate (mole/sec) for time t

$M_{f,t}$ = molar flow rate of the fuel (mole/sec) for time t

$M_{w,t}$ = molar flow rate of water (mole/sec) for time t

$y_{i,t,dry}$ = mole fraction of species *i* on a dry basis (gmol/gmol dry exhaust gases) for time t

x, z = elemental composition of fuel CH_xO_z

The fuel molar flow rate (M_f) can be estimated based on the dry exhaust flow rate (M_e):

$$M_{f,t} = \left(y_{CO2,t,dry} + y_{CO,t,dry} + 6 \times y_{C6H14,t,dry}\right) \times M_{e,t}$$

The exhaust molar flow rate on a dry basis (M_e) is estimated based on the intake air molar flow rate (M_a). The relation between M_e and M_a can be derived as :

$$M_{e,t} = \frac{2 \times 0.21 \times M_{a,t}}{\left(2 + \frac{x}{2} - z\right) y_{CO2,t,dry} + \left(1 + \frac{x}{2} - z\right) y_{CO,t,dry} + 2 y_{O2,t,dry} + y_{NO,t,dry} + \left(\frac{x}{2} - 7 - 6z\right) y_{C6H14,t,dry}}$$

Therefore, air-to-fuel ratio (AFR) can be rewritten based on M_e and M_a:

$$AFR_t = \frac{M_{a,t}\left(\frac{mole}{s}\right) \times y_{O2,t,in} \times 32\left(\frac{g}{moleO_2}\right) + M_{a,t} \times y_{N2,t,in} \times 28\left(\frac{g}{moleN_2}\right)}{\left(y_{CO2,t,dry} + y_{CO,t,dry} + 6 \times y_{C6H14,t,dry}\right) M_{e,t}\left(\frac{mole}{s}\right) \times \left(12 + x + 16z\right)\left(\frac{g}{moleCH_xO_z}\right)}$$

McCormick *et al.* (2001) reported the elemental composition of diesel fuel is 86.6 wt-% of carbon and 13.4 wt-% of hydrogen. This corresponds to an equivalent molecular formula of $CH_{1.857}$. The default value of diesel fuel property in the Montana system is 86.4 wt-% of carbon and 13.6 wt-% of hydrogen which differs from McCormick *et al.* (2001) by 0.2%. Because there is no reference for the default value of the Montana system, $CH_{1.857}$ based on data reported by McCormick *et al.* (2001) was used to do the mass balance of diesel combustion.

For biodiesel B20, McCormick *et al.* (2001) reported the elemental composition of B20 is 84.6 wt-% of carbon, 13.4 wt-% of hydrogen, and 2.0 wt-% of oxygen. This corresponds to an equivalent molecular formula of $CH_{1.901}O_{0.284}$.

For biodiesel B100, the elemental composition of B100 is obtained from the average of three studies (Graboski et al., 2003, Schmaucher, 1993). The average elemental composition of B100 is 76.9 wt-% of carbon, 12.1 wt-% of hydrogen, and 11.0 wt-% of oxygen. This corresponds to an equivalent molecular formula of $CH_{1.888}O_{1.717}$. Table 3.3 shows the equivalent molecular formula for petroleum diesel, biodiesel B20, and biodiesel B100.

Table 3.3 Equivalent Molecular Formulas for Diesel, Biodiesel B20, and Biodiesel B100

Fuel	CH_xO_z	
	x	z
Diesel	1.857	0
B20	1.901	0.284
B100	1.888	1.717

3.3.2 Leakage Effect on Mass Emission Rate

The purpose of this section is to evaluate the effects of air leakage on the estimated emission rates. When there is leakage, mole fractions of CO_2, CO, HC and NO ($y_{CO2,t,dry}$, $y_{CO,t,dry}$, $y_{C6H14,t,dry}$, $y_{NO,t,dry}$) in the dry exhaust are decreased. However, mole fractions of O_2 and N_2 ($y_{O2,t,dry}$, $y_{N2,t,dry}$) will increase due to additional air into the system. When there is a leakage in the measurement system, the coefficient "u_t" will increase. Table 3.4 shows measured data from a generator tested on November 11, 2005 including the ppm or volume percent of exhaust gases and the calculated molar ratios per mole of carbon consumed. Table 3.5 shows the NO, HC, CO, CO_2 and O_2 concentrations of real data and the corresponding concentrations that would be observed for other values of the coefficient "u_t."

Table 3.4 An Example of One Second of Emission Data from a Generator Tested on November 11, 2005

	NO (ppm)	HC (ppm)	CO (%)	CO_2 (%)	O_2 (%)
Concentration on a dry basis	295	14	0.025	2.42	17.4
	$y_{NO,t,dry}$	$y_{C6H14,t,dry}$	$y_{CO,t,dry}$	$y_{CO2,t,dry}$	$y_{O2,t,dry}$
Mole fraction in the dry exhaust	2.95E-04	1.4E-05	2.5E-04	2.42E-02	0.174

Table 3.5 Example Case Study of the Predicted Effect of Air Leakage on Observed Concentrations of Pollutants from a Generator Tested on November 11, 2005

Ratio of Oxygen to Fuel (gmol Air/gmol C)[a]	AFR [b] (g air/g fuel)	NO (ppm)	HC (ppm)	CO (%)	CO_2 (%)	O_2 (%)
u_t = 16.2	84	295	14.0	0.025	2.42	17.4
u_t = 19.0	98	255	12.1	0.025	2.45	17.6
u_t = 29.0	150	169	8.04	0.022	2.09	18.1
u_t = 37.9	196	127	6.02	0.014	1.39	19.1
u_t = 56.9	295	84	4.01	0.011	1.04	19.6
u_t = 75.9	393	63	3.00	0.007	0.69	20.1
u_t = 94.8	491	51	2.40	0.005	0.52	20.3

[a] First row is based on an observed measurement. Subsequent rows are based on other scenarios for air leakage

[b] AFR = Air-to-Fuel ratio (g air/g fuel)

For each second, the Montana system estimates mass emissions rates (g/sec) based upon the mole fraction on a dry basis, dry exhaust molar flow rate and molar weight of exhaust gas:

$$E_{i,t} = y_{i,t,dry} \times M_{e,t} \times MW_i$$

where,

$y_{i,t,dry}$ = mole fraction of species *i* (gmol/gmol dry exhaust gases) on a dry basis for time t

$E_{i,t}$ = mass emission rate of pollutant *i* (g/sec), i = NO, HC, CO, CO_2, for time t

$M_{e,t}$ = exhaust molar flow rate (mole/sec) on a dry basis for time t

MW_i = molecular weight of species i (g/mol)

When there is leakage, the mole fractions of NO, HC, CO and CO_2 decrease as shown in Table 3.5. However, the corresponding dry exhaust molar flow rate (M_e) increases due to the excess air. The mass emission rates (g/sec) of each pollutant are calculated and an example based on data from a generator is shown in Table 3.6. Whether there is leakage, the mass emission rates are exactly the same. Therefore, even when there is leakage in the measurement system, the mass emission rate may still be valid.

Table 3.6 Mass Emission Rate of Each Pollutant at Different Ratio of Oxygen to Fuel from a Generator Tested on November 11, 2005

Ratio of Oxygen to Fuel (gmol Air/gmol C)[a,b]	AFR [c]	M_e (mole/sec)	NO (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)
u_t = 16.2	84	2.48	0.0341	0.0030	0.0176	2.673
u_t = 19.0	98	2.90	0.0341	0.0030	0.0176	2.673
u_t = 29.0	150	4.45	0.0341	0.0030	0.0176	2.673
u_t = 37.9	196	5.83	0.0341	0.0030	0.0176	2.673
u_t = 56.9	295	8.77	0.0341	0.0030	0.0176	2.673
u_t = 75.9	393	11.70	0.0341	0.0030	0.0176	2.673
u_t = 94.8	491	14.63	0.0341	0.0030	0.0176	2.673

[a] First row is based on an observed measurement. Subsequent rows are based on other scenarios for air leakage

[b] u_t refers to coefficient of Equation 16 for time t

[c] AFR = Air-to-Fuel ratio (g air/g fuel)

3.3.3 Criteria for Air-to-Fuel Ratio

The purpose of this section is to develop evaluation procedures based on air-to-fuel ratio (*AFR*) for data quality in the dataset. Taylor (1985) and Thiessen *et al.* (1996) reported that the normal range of air-fuel ratio for diesel engine is from 25 to over 100. Figure 3.3 shows the cumulative frequency of air-to-fuel ratio based on field measurement data for six examples of construction equipment. More than 99.9% of the second-by-second AFRs are within the range of 25 to 150. Based on this information, a judgment was made that AFR values between 25 and 150 are representative of normal operations. Conversely, values outside of this range are not expected and require additional evaluation. The typical expected ranges that correspond to the acceptable AFR range are 9.1 to 19.2 vol-% for O_2 and 1.4 to 8.7 vol-% for CO_2. The expected range may vary due to the different concentration of CO and HC in the dry exhaust.

As previously described, the mass emission rates are unchanged whether there is leakage. However, when the AFR is high, the mole fraction of each pollutant is low. In such a situation, random measurement error in the mole fraction may cause significant uncertainty in the mass emission rate (g/sec). Thus, there is a need to evaluate the data quality of the mass emission rate. Two examples are shown to represent two different scenarios. The first example is for a case in which all NO, CO, HC, and CO_2 concentrations are within the precision of the Montana system as shown in Table 3.7.

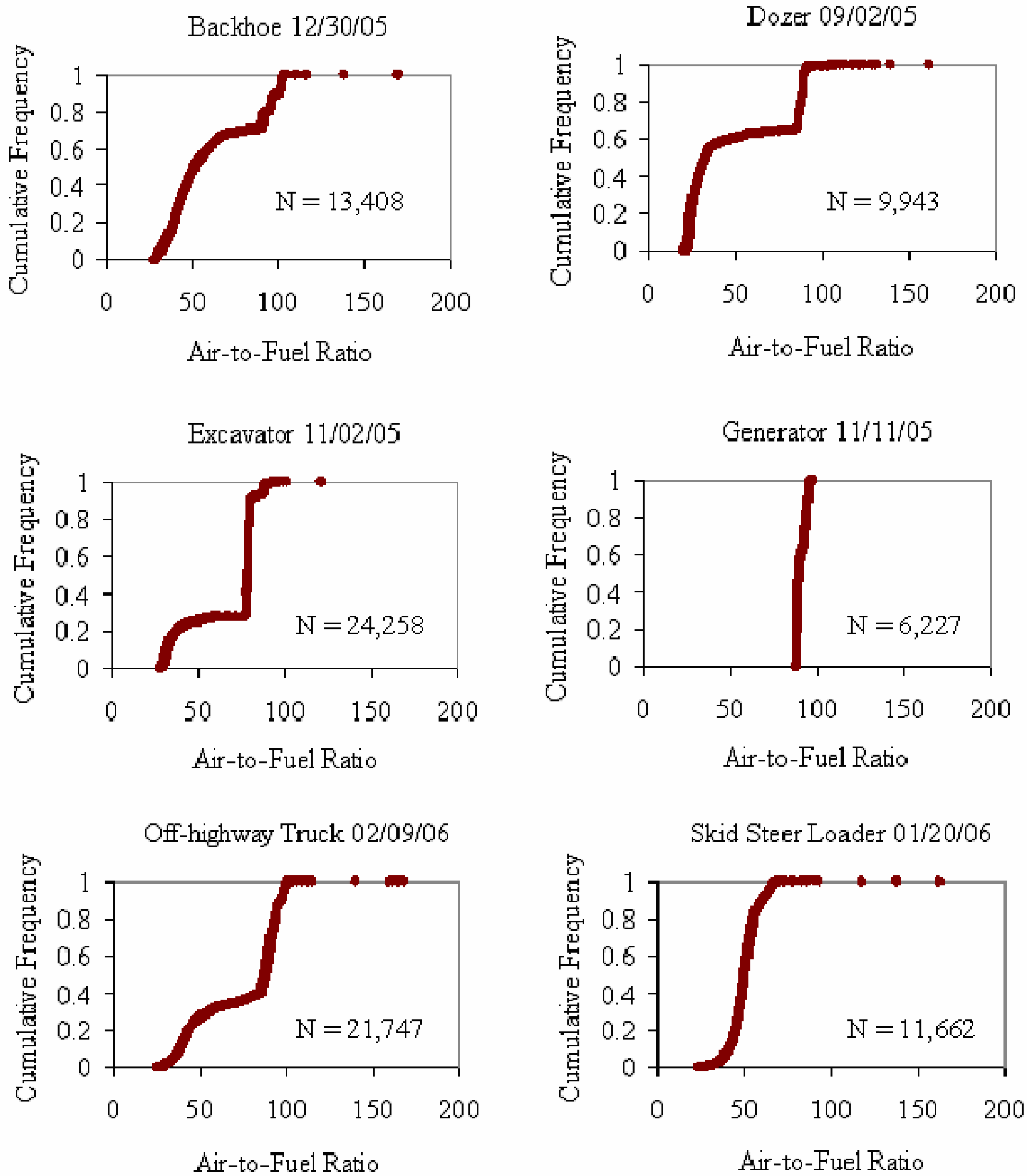

Figure 3.3 Cumulative Frequency of Air-to-Fuel Ratio for Different Construction Equipment, with Type of Equipment and Data of Field Measurement Indicated

Table 3.7 Case Study of One Second of Emission Data below the Precision of the Montana System

	Emission Data			
	NO (ppm)	CO (vol-%)	HC (ppm)	CO_2 (vol-%)
Concentration on a dry basis	20	0.007	3	0.20
Precision of the Montana System	±25	±0.02	±4	±0.30

The second example shows typical tailpipe emissions from an off-highway truck tested on February 09, 2006. The emission data are given in Table 3.8. All of the NO, CO, HC, and CO_2 concentrations are above the precision of the Montana system. In order to understand the leakage effect on the mass emission rate, the molar ratio of intake air to C (u_t) is varied from 2.23 to 41, which corresponds to AFR ranging from 25 to 459.

Theoretically, when the pollutant concentration is below the precision of the Montana system, the random measurement error may result in larger uncertainty in the mass emission rate. An uncertainty analysis is conducted for both scenarios to investigate the uncertainty range of mass emission rates due to the precision of the Montana system.

Table 3.8 Case Study of the Observed and Predicted Emission Data on a Dry Basis from an Off-Highway Truck Tested on February 09, 2006

Ratio of Oxygen to Fuel (gmol Air/gmol C)[a,b]	AFR [c] (g air/g fuel)	NO_{dry} (ppm)	HC_{dry} (ppm)	CO_{dry} (%)	$CO_{2,dry}$ (%)
$u_t = 2.23$	25	647	28	0.610	7.33
$u_t = 8.20$	92	172	7.6	0.163	1.95
$u_t = 13.4$	150	105	4.6	0.099	1.19
$u_t = 16.4$	184	86	3.8	0.081	0.97
$u_t = 24.6$	275	57	2.5	0.054	0.65
$u_t = 32.8$	367	43	1.9	0.041	0.48
$u_t = 41.0$	459	34	1.5	0.032	0.39

[a] First row is based on an observed measurement. Subsequent rows are predicted based on other scenarios for air leakage

[b] u_t refers to coefficient of Equation 16 for time t

[c] AFR = Air-to-Fuel ratio (g air/g fuel)

The mass emission rates are calculated based on the engine data and pollutant concentrations. Details of mass emission rates are discussed in Section 5.3.1. Pollutant concentrations are the inputs and mass emission rates are the outputs for the uncertainty analysis. The first step of uncertainty analysis is to define the probability distribution of all the inputs. Pollutant concentrations are assumed to be normal distributions with the indicated mean and standard deviation. The standard deviation of each pollutant concentration is one-half of the precision. Table 3.9 shows input assumptions for uncertainty analysis based on one second of data from Table 3.7 and one second of data from Table 3.8.

Table 3.9 Input Assumptions for Uncertainty Analysis

	Case Study					
	Emissions below the Precision			Off-Highway Truck		
	Point Estimate[a]	Dist	Parameter[b]	Point Estimate[a]	Dist	Parameter[b]
NO (ppm)	20	Normal	Mean=20 SD=12.5	600	Normal	Mean=600 SD=12.5
HC (ppm)	3.0	Normal	Mean=3 SD=2	27	Normal	Mean=27 SD=2
CO (vol-%)	0.007	Normal	Mean=0.007 SD=0.01	0.57	Normal	Mean=0.57 SD=0.01
CO_2 (vol-%)	0.20	Normal	Mean=0.20 SD=0.15	6.81	Normal	Mean=6.81 SD=0.15

[a] Point estimate is based on one second of the data shown in Tables 19 and 20
[b] SD = standard deviation

Monte Carlo simulation with 10,000 trials was used to quantify the uncertainty range in the mass emission rates. The simulation was done using the Crystal Ball™ for Microsoft Excel™. Table 3.9 and 5.10 show the uncertainty range of each pollutant emission rate based on one second of data from Table 3.8.

Table 3.10 shows the 95 percent probability range of the mass emission rate when there apparently was air leakage in the Montana system. Air leakage is suspected here because AFR is 867, in excess of expected values. Because the mole fractions of NO, HC, CO, and CO_2 concentrations are below the precision of the Montana system, the uncertainty in the emission rate is in a large range. With such a large range of uncertainty for concentrations and large air leakage, the estimated emission rates here are unreliable.

Table 3.10 95% Probability Range of Mass Emission Rates of One Second of Data below the Precision of the Montana System

Ratio of Oxygen to Fuel (gmol Air/gmol C)[a]	AFR[b]	NO (mg/sec)	HC (mg/sec)	CO (mg/sec)	CO_2 (g/sec)
		95% Range	95% Range	95% Range	95% Range
$u_t = 174$	867	2.22 ± 2.75	0.63 ± 0.81	4.78 ± 13.4	0.25 ± 0.32

[a] u_t refers to coefficient of Equation 16 for time t

[b] AFR = Air-to-Fuel ratio (g air/g fuel)

Table 3.11 95% Probability Range of Mass Emission Rates of One Second of Data from an Off-Highway Truck Tested on February 09, 2006

Ratio of Air to Fuel (gmol Air/gmol C)[a,b]	AFR[c]	NO (mg/sec)	HC (mg/sec)	CO (mg/sec)	CO_2 (g/sec)
		95% Range	95% Range	95% Range	95% Range
$u_t = 2.23$	25	66.9 ± 2.6	5.5 ± 0.8	387 ± 12	7.26 ± 0.29
$u_t = 8.20$	92	66.9 ± 9.7	5.5 ± 2.9	387 ± 48	7.26 ± 1.10
$u_t = 13.4$	150	66.9 ± 14.4	5.5 ± 4.3	387 ± 69	7.26 ± 1.60
$u_t = 16.4$	184	66.9 ± 19.4	5.5 ± 5.8	387 ± 93	7.26 ± 2.15
$u_t = 24.6$	275	66.9 ± 29.0	5.5 ± 8.7	387 ± 140	7.26 ± 3.35
$u_t = 32.8$	367	66.9 ± 40.0	5.5 ± 11.5	387 ± 188	7.26 ± 4.48
$u_t = 41.0$	459	66.9 ± 49.5	5.5 ± 14.5	387 ± 241	7.26 ± 5.48

[a] First row is based on an observed measurement. Subsequent rows are predicted based on other scenarios for air leakage

[b] u_t refers to coefficient of Equation 16 for time t

[c] AFR = Air-to-Fuel ratio (g air/g fuel)

The case study of an off-highway truck is shown in Table 3.11. When the AFR is greater than 150, the uncertainty range becomes larger. In this situation, the measurement error of the Montana system may cause larger uncertainty in the emission rates as described in the previous example. Thus, when the AFR is greater than 150, the spreadsheet cell containing the affected emission data will be automatically flagged as a different color by a Visual Basic Macro in Excel. If the pollutant concentration is below the precision of the Montana system, and if AFR exceeds 150, that second of data will be excluded from the dataset.

The following criteria and procedures were established to identify whether unusual values of AFR exist and regarding what actions, if any, to take if an unusual value occurs. The first step is to calculate the AFR_t. A choice regarding whether to retain or exclude data associated with large AFR values is made. The steps of the verification procedure are listed below. Figure 3.4 shows the flow diagram of the verification procedures for the mass emission rate.

The evaluation procedures of air-to-fuel ratio (AFR) include:

1. Calculate second-by-second AFR_t;
2. If the AFR_t is less than 150, the data will be kept in the dataset; and
3. If the AFR_t is greater than 150, the row in Excel that contains the data in question will be flagged with an indicator:
    - If all of the pollutant concentrations are above the precision of the Montana system (0.02 vol-% for CO, 4ppm for HC, 25ppm for NO and 0.3 vol-% for CO_2), the second of data will be kept in the dataset; and
    - If one or more pollutant concentration is less than the precision of the Montana system, the data will be excluded from the dataset.

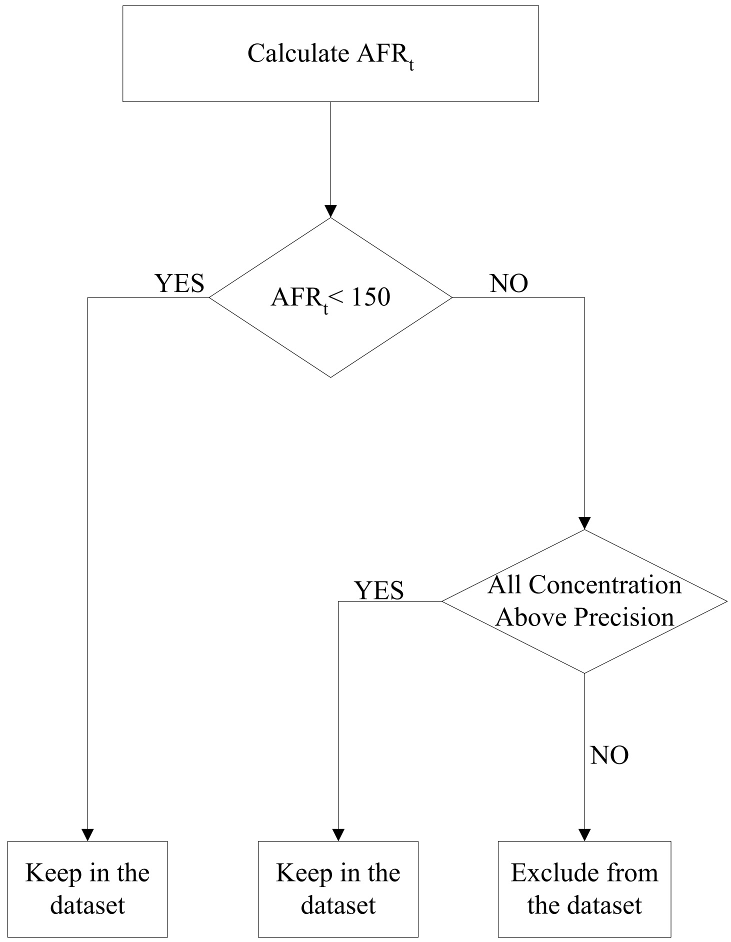

Figure 3.4 Flow Diagram of the Evaluation Procedures for Air-to-Fuel Ratio

Problems with unusual values of AFR appear to be rare. For example, 97,406 seconds of data from six construction vehicles were evaluated with respect to second-by-second AFR values. As shown in Table 3.12, only 1090 seconds of these data, or 1.12% of the total amount of data, had AFR>150. Of these unusual values, only 999 seconds had measured concentrations below the precision of the measurements for one or more pollutants. These 999 seconds of data were excluded. Thus, only 1.02 % of data from these six construction vehicles were lost due to unusual AFR values.

Table 3.12 Application of Criteria for Air-to-Fuel Ratio to Six Pieces of Construction Equipment

Equipment [a]	Field Time (No. of seconds)	AFR>150 (No. of seconds)	AFR>150 and One or More Pollutant Concentrations below the Instrument Precision (No. of seconds)
Backhoe	19,753	94	94
Dozer	10,113	22	20
Excavator	25,932	39	39
Generator	6,569	0	0
Off-Highway Truck	23,138	935	846
Skid Steer Loader	11,901	0	0
Total	97406	1090	999

[a] Based on a Backhoe Tested on December 30, 2005, a Dozer Tested on September 02, 2005, an Excavator Tested on August 26, 2005, a Generator Tested on November 11, 2005, an Off-Highway Truck Tested on February 09, 2006, and a Skid Steer Loader Tested on January 20, 2006

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PART IV VEHICLE-SPECIFIC EMISSIONS MODELING FOR NON-ROAD CONSTRUCTION EQUIPMENT BASED UPON REAL-WORLD MEASUREMENTS

Abstract

In 2002, estimated annual emissions of nitrogen oxides, carbon monoxide, hydrocarbon, and particulate matter from nonroad construction vehicles were 770, 1120, 135 and 73 thousand tons, respectively. An on-board measurement procedure for these vehicles using a portable emissions measurement system (PEMS) was developed to quantify second-by-second energy use and emissions based on real-world construction activities. The objective of this paper is to apply recently collected in-use data to develop vehicle-specific fuel use and emissions models.

Analysis of empirical data reveals that intra-vehicle variability of energy use and emissions is strongly influenced by vehicle activity that leads to variations in engine load, as represented by manifold absolute pressure (MAP). Based on data from in-use measurements of 32 construction vehicles, there is a consistent pattern of monotonic increase of average emission rate with respect to increasing MAP. Vehicle-specific models for fuel use and tailpipe emissions were developed for each of the 32 vehicles. For fuel use and emissions of CO_2, CO, HC, and PM (measured using an opacity surrogate), a linear model as a function of MAP was developed. For NO, a nonlinear model was developed in an effort to take into account the chemistry of NO formation. For each vehicle, four modal models and two physically-based regression models were developed and compared.

The average coefficient of determination (R^2), as an indicator of goodness-of-fit, of the time-based regression models is 0.97 for both fuel use and CO_2, 0.91 for NO, 0.81 for opacity, 0.63 for HC, and 0.51 for CO. The time-based regression model has the highest explanatory ability among the six models that were developed and is recommended in order to predict fuel use and emission rate for diesel-fueled nonroad construction equipment.

4.1 Introduction

According to the U.S. Environmental Protection Agency (EPA), most Americans living in urban areas breathe air that does not meet National Ambient Air Quality Standards (NAAQS) for either ozone or particulate matter. Heavy duty diesel vehicles, including both onroad and nonroad vehicles, emit significant amounts of nitrogen oxides (NO_x), which is a precursor to ozone formation, and particulate matter.

In 2005, nonroad diesel construction vehicles were estimated to emit annual U.S. national totals of 657,000 tons of NO_x, 1,100,000 tons of CO, 63,000 tons of PM_{10}, and 94,000 tons of SO_2 (EPA 2005). Over time, increasingly stringent regulations have been implemented to reduce tailpipe emissions of NO_x and particulate matter from diesel vehicles. Nonroad diesel equipment is now coming under increased scrutiny.

Emissions from nonroad construction equipment are typically quantified based on steady-state engine dynamometer tests. However, such tests do not represent actual duty cycles. Additionally engine dynamometer test procedures may not capture the real-world effects of actual duty cycles. The real-world emissions of diesel vehicles may be different than what is presumed in the regulatory framework. Thus, more accurately quantified emissions from diesel vehicles are needed to in order to identify opportunities to manage or to reduce emissions to improve air quality.

Compared to dynamometer-based measurement methods, on-board emissions measurement is widely recognized as a desirable approach for measuring emissions from vehicles (Tong *et al.* 2000). On-board Portable Emissions Measurement System (PEMS) is designed for measuring in-use emissions during real-world operations. The EPA, West Virginia University (WVU), and Clean Air Technologies International, Inc. (CATI), have separately conducted on-board in-use measurements to characterize emissions from construction vehicles (May *et al.* 2002, Gautam *et al.* 2002, Vojtisek-Lom 2003). However, not all of these data were quality assured or publicly available. WVU conducted real-world and engine dynamometer tests on one rubber-tire loader, one street sweeper, one excavator, and one bulldozer. The results show a significant difference between real-world tests and steady-state engine dynamometer tests.

The EPA's NONROAD emission inventory model produces fleet average emission estimates based on engine dynamometer data that are not representative of the real world duty cycles observed in the field data collection. This model includes pollutants of NO_x, HC, CO, and PM including the adjustments due to variations in fuel sulfur level. In addition, brake specific fuel consumption (BSFC) is given for fuel rate measurement (EPA 2004).

The purpose of this paper is to develop construction in-use vehicle and equipment emissions and energy use model (CIVEM) based on recent collected real-world data, in order to support accurate and robust approaches to emissions estimation. The modal-based approaches are presented here based on stratification of manifold absolute pressure (MAP) which is a direct indicator of engine load and vehicle activities.

The modal approaches are relatively easy to develop, but are based upon the averaging value of data of each mode, which may not be powerful to explain variations among vehicle activities. Therefore, physically-based regression approaches are developed in order to characterize the pollutant formation in the engine and also fitting a least-squares linear regression model to the data. Emission factor units of mass per time are useful if one can estimate the total amount of time that a vehicle is operating in the field. Alternatively, an emission factor in units of mass per gallon of fuel consumed is useful if one can estimate or measure the total fuel use for a vehicle or a fleet of similar vehicles.

Therefore, the modeling approaches used in this paper include:

1. Time-based engine-based modal model;
2. Fuel-based engine-based modal model;
3. Time-based task-based modal model;
4. Fuel-based task-based modal model;
5. Time-based regression model; and
6. Fuel-based regression model.

The objectives of this study are to: (1) develop vehicle-specific models of fuel use and emissions; (2) assess the goodness-of-fits of each model; (3) determine the best model for estimating nonroad construction vehicles emissions; and (4) benchmark predicted emission rates with EPA's NONROAD model.

4.2 Methodology

This section describes (1) instrumentation used in the field measurement; (2) data collection and data screening procedures; (3) exploratory analysis; (4) development of modal models; (5) development of physically based-regression model; and (6) benchmarking of predicted emissions.

4.2.1 *Instrumentation*

The PEMS used here is the OEM-2100 "Montana" system manufactured by Clean Air Technologies International, Inc. (Vojtisek-Lom and Cobb 1997), which is comprised of two parallel five-gas analyzers, a PM measurement system, an engine sensor array, a global position system (GPS), and an on-board computer. The sensor array includes sensors for measuring manifold absolute pressure (MAP), engine RPM, and intake air temperature. HC, CO and CO_2 are measured using non-dispersive infrared (NDIR). The PM measurements are semi-quantitative are used for relative comparisons. Because they are based on a light scattering method, they are analogous to opacity.

The gas analyzers are calibrated once a week based on a cylinder gas and also self-calibrate periodically using ambient air as a reference every ten minutes during data collection (Vojtisek-Lom 2003, Vojtisek-Lom and Allsop 2001). Two gas analyzer modules are used in parallel in order to have continuous data even when one goes off-line for periodic calibration.

4.2.2 Data

There are two key aspects with respect to data: data collection and quality assurance. Data collection procedures include four steps: (1) pre-installation; (2) installation; (3) field data collection; and (4) decommissioning. Data screening and quality assurance are procedures for reviewing data collected in the field, determining whether any errors exist in the data. The details of the instrumentation, data collection and data quality assurance procedure are given in Frey *et al.* (2007, 2008). The vehicle characteristics are given in Table 4.1.

4.2.3 Exploratory Analysis

The raw data were analyzed in terms of the effect of engine activity on fuel use and emissions. There was a need to develop standard procedures to estimate modal emission rates based upon engine variables, such as manifold absolute pressure (MAP), engine RPM, intake air temperature (IAT), and air-to-fuel ratio (AFR). A rank correlation analysis was performed to identify which engine variable is highly correlated with variations in fuel use and emission rates. Time series plots were used to represent the variation of fuel use and emission rates in terms of different real-world activities. The results of the rank correlation analysis as well as the time series plots are presented in Section 4.3.1.

Table 4.1 Characteristics of Tested Vehicles

Vehicle ID	Chassis Characteristics			Engine Characteristics			
	Manufacturer	Year	Model *	Tier	Disp.	Cyl.	HP
Dozer 1	CATERPILLAR	1988	D4H	0	5.0	6	89
Dozer 2	KOMATSU	2002	D39EX	2	3.9	4	95
Dozer 3	CATERPILLAR	2003	D5G	1	5.0	6	90
Dozer 4	CATERPILLAR	1998	D6H XL	1	8.8	6	175
Dozer 5	CATERPILLAR	1995	D8H	0	14.2	6	285
Excavator 1	KOMATSU	2001	PC300-7	1	8.3	6	254
Excavator 2	CATERPILLAR	2003	320CL	2	6.4	6	138
Excavator 3	KOBELCO	2002	SK130LC	1	3.9	6	93
Off-Highway Truck 1	VOLVO	2005	A25D	2	9.6	6	306
Off-Highway Truck 2	CATERPILLAR	1998	D300E	1	10.3	6	285
Off-Highway Truck 3	CATERPILLAR	1998	D300E	1	10.3	6	285
Backhoe 1	CATERPILLAR	2001	420D	1	4.0	4	88
Backhoe 2	JOHN DEERE	1999	310SE	1	4.5	4	88
Backhoe 3	JOHN DEERE	2000	310SG	1	4.5	4	89
Backhoe 4	CATERPILLAR	2004	420D	2	4.0	4	97
Backhoe 5	JCB	1997	215	0	4.2	4	90
Backhoe 6	JCB	2001	2.15E-01	1	4.2	4	90
Backhoe 7	CASE	1999	590SL	1	3.9	4	99
Backhoe 8	CATERPILLAR	2004	420D	2	4.0	4	97
Rubber Tire Loader 1	CATERPILLAR	2004	930G	2	6.0	6	149
Rubber Tire Loader 2	HYUNDAI	2002	HL740-TM3	1	5.9	6	130
Rubber Tire Loader 3	HYUNDAI	2002	HL740-TM3	1	5.9	6	130
Rubber Tire Loader 4	CASE	2002	621B XT	1	5.9	6	126
Rubber Tire Loader 5	HYUNDAI	2005	HL740-TM7	2	5.9	6	133
Skid Steer Loader	BOBCAT	2003	S160	1	2.0	4	44
Motor Grader 1	VOLVO	2001	G720VHP	1	8.27	6	195
Motor Grader 2	VOLVO	2004	G720B	2	7.1	6	195
Motor Grader 3	VOLVO	2001	G720VHP	1	8.27	6	195
Motor Grader 4	DRESSER	1990	850	0	8.27	6	167
Motor Grader 5	CHAMPION	1993	G720	0	8.27	6	160
Motor Grader 6	VOLVO	2007	G930	3	7.2	6	198
Track Loader	CATERPILLAR	2007	953C	3	7.2	6	127

* All tested vehicles are turbocharged.

4.2.4 Modal Model

Based on the results of the exploratory analysis, a key factor associated with fuel use and emissions was found to be manifold absolute pressure (MAP) of the turbo-charged diesel engines. Nonroad vehicle activity was quantified with respect to time or fuel consumption. Emission factors were developed for each of several modes based either on an "engine-based" or a "task-based" approach.

In order to develop *engine-based models*, the second-by-second data from the PEMS regarding MAP, fuel use rate, and emissions rate were sorted by MAP. The data were divided into 10 strata so that each stratum represents 10 percent of normalized MAP.

Task-based models were identified by characterizing real-world vehicle operations in terms of idling, use of a bucket or blade, and movement of the vehicle. For example, for a bulldozer, the task-based modes include idling, use of the blade (blade in contact with the ground), or movement without applying the blade to the ground. These modes of activity were recorded in the field using a separate laptop computer and by recording time stamps when transitioning from one mode to another. The average fuel use and emission rates for each of these task oriented modes were estimated.

Engine-Based Modal Models

Based on the exploratory analysis of data as reported in Results section, manifold absolute pressure (MAP) has been consistently identified as the most highly correlated engine variable associated with variations in fuel use and emission rates. Therefore, a procedure for estimating modal emission rates based on ranges of normalized MAP has been developed. The normalized MAP was defined as:

$$MAP_{nor} = \frac{MAP - MAP_{\min}}{MAP_{\max} - MAP_{\min}}$$

Where,

MAP_{nor} = Normalized MAP for a measured MAP for a specific vehicle;

MAP_{max} = Maximum MAP for a specific vehicle;

MAP_{min} = Minimum MAP for a specific vehicle;

MAP = Measured MAP for a specific vehicle.

The normalized MAP bins are defined as 0 to 0.1, 0.1 to 0.2, ets. to 0.9 to 1.0. The emission rates in mass per time and mass per gallon of fuel consumed were estimated for each normalized MAP bin. For the fuel based approach, results are not shown for fuel use since the mass of fuel consumed per gallon of fuel is a constant, regardless of engine activity. Similarly, since CO_2 emissions are highly correlated with fuel consumption, the CO_2 emissions on a per gallon basis are approximately constant and, therefore, are not shown.

Task-Based Modal Models

As an alternative to the "engine-based" modal analysis described above, a "*task-based*" modal analysis was also performed. During field data collection, a notation regarding the mode of activity was made using a laptop computer. The average fuel use and emission rates by task-based mode are estimated both on a mass per time and mass per gallon basis. The task-based modes were monitored for each type of vehicle and those modes that the vehicle routinely performs to accomplish a specific task.

4.2.5 Physically-Based Regression Model

Combustion temperature is the key factor affecting diesel exhaust emissions. When diesel fuel is oxidized, the heating value of the diesel fuel is released to the engine. The combustion temperature is actually influenced by engine load. When the engine load is increased, more fuel is injected into the engine which results in more diesel fuel combusted in the engine. This results in higher temperatures in the diesel engine. When the throttle is opened, the air flow into the manifold is increased. Results for the intake air flow rate and manifold pressure are in response to the opening of the throttle (increase in throttle angle) (Heywood 1988). The intake manifold pressure is approximately linearly-proportional to the throttle angle which is defined as engine load. Manifold absolute pressure is a strong indicator of the engine load. Consecutive averaging times of 12 seconds are used to reduce the influence of instrument response time and autocorrelation in vehicle activity.

The functional form of the regression equation for fuel use, CO_2, HC, CO, and PM is shown:

$$m_i = a_i \times MAP \tag{1}$$

where,

m_i = Average mass emission rate for i (fuel use, CO_2, HC, CO, PM) for consecutive averaging time of 12 seconds; (g/sec)

MAP = Manifold absolute pressure; (kPa)

a_i = Regression coefficient for i (fuel use, CO_2, HC, CO, PM)

The formation of NO is a function of gas temperature in the cylinder and equilibrium concentrations of O_2 and N_2. The theoretical equation of NO formation is estimated based on the Zeldovich mechanism (*0*).

$$\frac{d[NO]}{dt} = \frac{6 \times 10^{16}}{T^{0.5}} \exp\left(\frac{-69{,}090}{T}\right)[O_2]_e^{0.5}[N_2]_e \tag{2}$$

where,

$d[NO]/dt$= NO formation rate (mol/cm^3-s)

T = gas temperature in the cylinder (K)

$[O_2]_e$ = equilibrium concentration of O_2 in the engine (mol/cm^3)

$[N_2]_e$ = equilibrium concentration of N_2 in the engine (mol/cm^3)

The combustion temperature can be represented by manifold absolute pressure. The equilibrium concentrations of O_2 and N_2 vary due to the intake air flow and combustion process. Based on previous study (*0*), the exhaust concentrations of O_2 and N_2 did not affect emission rates significantly. Thus, an assumption was made that the concentrations of O_2 and N_2 are constant at equilibrium. The functional form of the regression equation for NO canthen be simplified as:

$$Y_{t,NO} = \frac{C_1}{(MAP_t)^{0.5}} \exp\left(\frac{C_2}{MAP_t}\right) \tag{3}$$

where,

$Y_{t,NO}$ = Average mass emission rate for NO for consecutive averaging time of 12 seconds (g/sec)

C_1, C_2 = Regression coefficients

For NO, a model with a physically-based interpretation was developed in the form of a non-linear equation, but it can be simplified to a linear combination of basis functions. The simplified linear equation for NO is presented as:

$$\ln\left(Y_{t,NO}\right) = \alpha - \beta_1 \times 0.5\ln\left(MAP_t\right) + \beta_2\left(MAP_t\right)^{-1} + \varepsilon_t \tag{4}$$

where,

β_1 , β_2 = regression coefficient;

4.2.6 Modal Validation

Least square regression models describe how the mean of the dependent variable (i.e. fuel use rate, emissions rate) varies with respect to changes in the corresponding explanatory variables (i.e. MAP). In order to illustrate the prediction capability of the regression model, the data were divided into calibration and validation datasets. Regression models were developed based on a "calibration" dataset and were verified based on a "validation" dataset.

The procedures are listed here:

- STEP 1: Identify time series “segments.” Each segment represents one complete duty cycle.
- STEP 2: Randomly assign the time series segments to the calibration dataset (75% of total data) or validation dataset (25% of total data).
- STEP 3: Compare the mean and standard deviation of MAP and emissions for the calibration and validation datasets.
- STEP 4: If the distributions of these two datasets are similar, the calibration and validation datasets are ready. If not, go back to STEP 2 and re-assign the segments.
- STEP 5: Using the calibration data, develop physically-based regression models for each vehicle or equipment.
- STEP 6: Predict emissions for validation dataset based on model coefficients developed by calibration dataset.
- STEP 7: Draw a parity plot of predicted versus observed fuel use and emission rates for validation dataset.
- STEP 8: Verify the slope and goodness-of-fit (R^2) with calibration dataset.

The goodness-of-fit is evaluated based on the slope and R^2 of a parity plot of predicted versus observed emission rates. The slope can be an indicator of model accuracy, whereas the R^2 is an indicator of model precision. In addition, the models were applied to the validation data sets to make independent predictions of fuel use and emission rates. Basically, the goodness-of-fit for the validation data set should be similar to that of the calibration dataset.

4.2.7 Benchmarking of Predicted Emissions

In order to determine whether the magnitudes of the emission factors estimated in this paper are similar to other study, fuel based emission factors from PEMS data were compared with fuel-based emission factors estimated in EPA's NONROAD model for the same model year, chassis type, and engine Tier.

The EPA's NONROAD model produces fleet average emission estimates based on engine dynamometer data. The NONROAD model reports zero-hour steady state emission factors of NO_x, HC, CO, and PM, including the adjustment factors due to variations in chassis type, model year and engine Tier. In addition, brake specific fuel consumption (BSFC) is given for fuel rate measurement (EPA 2004).

The emission factors reported in the NONROAD model were in the units of grams per brake horsepower-hour. However, in real-world PEMS measurements, the emission factors are obtained in the units of grams per second or grams per gallon of fuel consumed (Vojtisek-Lom 2003). Thus, in order to enable comparisons with the PEMS data, the emission factors in the NONROAD model were converted to the units of grams per gallon of fuel using the reported brake-specific fuel consumption rate in NONROAD model:

$$EF_{conv}\left(\frac{g}{gal}\right) = EF\left(\frac{g}{bhp-hr}\right) \times \frac{1}{BSFC}\left(\frac{bhp-hr}{lb}\right) \times TAF \times DF \times CF\left(\frac{lb}{gal}\right)$$

where:

EF_{conv} = Converted emission factor (*g/gal*)

EF = Zero-hour steady-state emission factor reported in EPA's NONROAD model (*g/hp-hr*)

TAF = Transient adjustment factor (*unitless*)

DF = Deterioration factor (*unitless*)

CF = Conversion factor (*lb/gal*)

4.3 Results

The results of construction in-use vehicle and equipment emissions and energy use model (CIVEM) are presented in this section. An exploratory analysis of empirical data was performed to identify the correlation between engine variable and emission rates. Based on the exploratory analysis, engine-based, task-oriented modal models and physically-based regression models were developed to predict fuel use and emission rates from different construction equipment and vehicles.

4.3.1 Exploratory analysis

The raw data were analyzed in terms of the effect of engine activity on fuel use and emissions. A rank correlation analysis was performed to identify which engine variable is highly correlated with variations in fuel use and emission rates. Table 4.2 is an exploratory analysis of data from a selected front-end loader. Based on an example of this as well as other vehicles, manifold absolute pressure (MAP) has been consistently identified as the engine variable most highly correlated with variations in fuel use and emission rates. The rank correlation of MAP with each of these rates often exceeded 0.95, except for NO and opacity for which the rank correlation was typically approximately 0.8. While engine RPM is also highly correlated with these rates, the correlations were slightly weaker than those for MAP. Thus, MAP was used as the basis for defining engine-based modes.

Table 4.2 Rank Correlation of Fuel Use and Emissions With Respect to Engine Data Based on Front-End Loader 1

	MAP [a]	RPM [b]	IAT [c]	AFR [d]
Fuel Use	0.99	0.93	0.48	-0.94
CO_2	0.98	0.93	0.48	-0.93
NO	0.77	0.73	0.44	-0.73
Opacity	0.85	0.81	0.44	-0.82
HC	0.99	0.93	0.48	-0.94
CO	0.96	0.90	0.48	-0.92

[a] MAP = Manifold absolute pressure [b] RPM = Engine RPM
[c] IAT = Intake air temperature [d] AFR = Air-to-fuel ratio

The data were also analyzed in terms of the fuel use and average emission rate for activity modes. A task-based mode can include idling, movement of the equipment for repositioning purposes, use of a blade or bucket, etc. These modes vary depending on the type of vehicle. In Figure 4.1, an example is shown (based on a front-end loader) to represent time-series fuel use and emissions in terms of different activity modes. As expected, the lowest MAP, fuel use, and NO emission rates are associated with the idling mode. The peak in MAP corresponds to the peak in fuel use and NO emission rates during moving and bucket modes. Task-based modes are useful to explain the variations of fuel use and emissions among different equipment use tasks. Time series plots of engine data, fuel use rate, and emission rates were used to visualize the association between these rates and engine data. Typically, a peak in MAP is associated with a corresponding peak in both fuel use and emission rates.

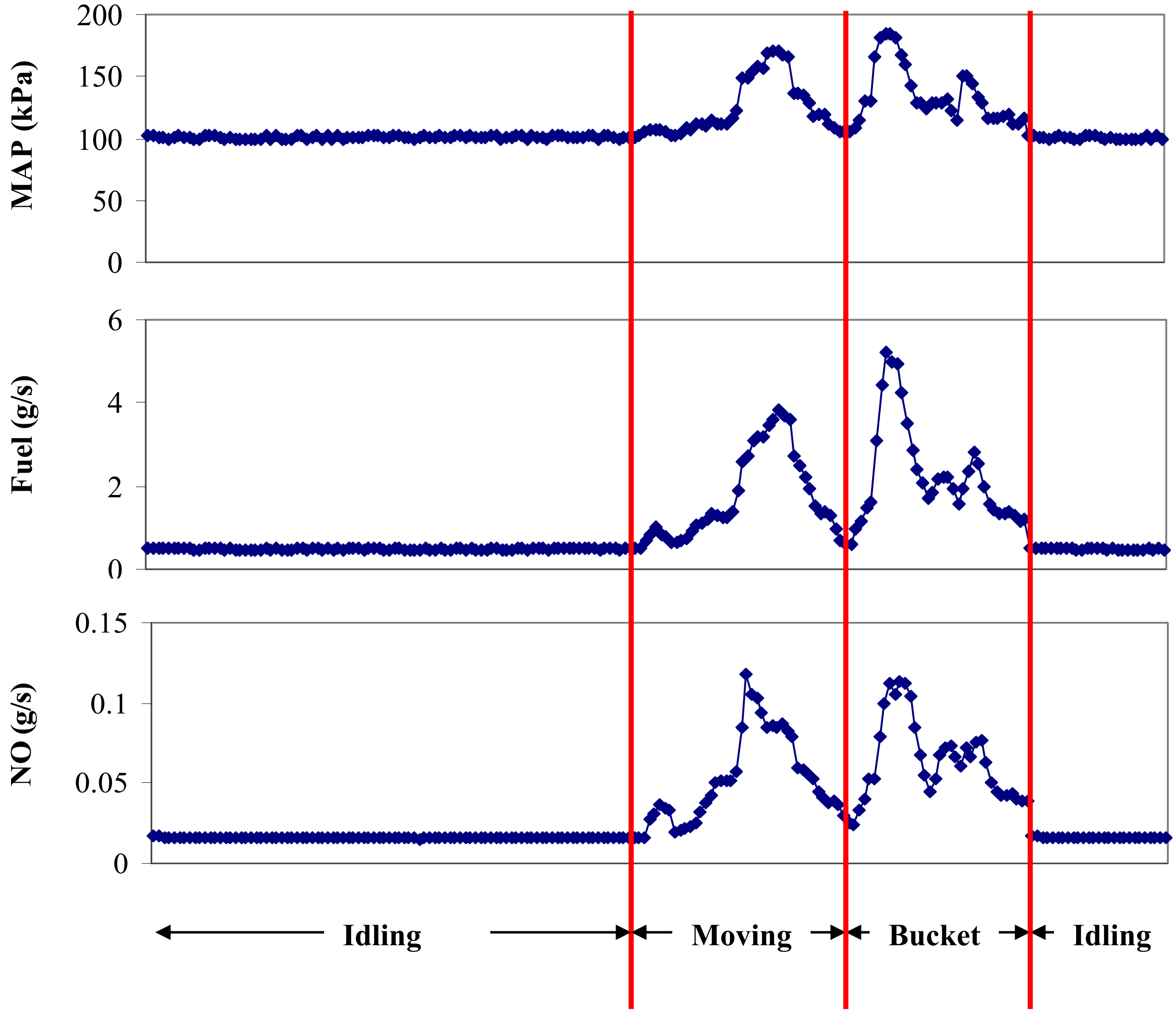
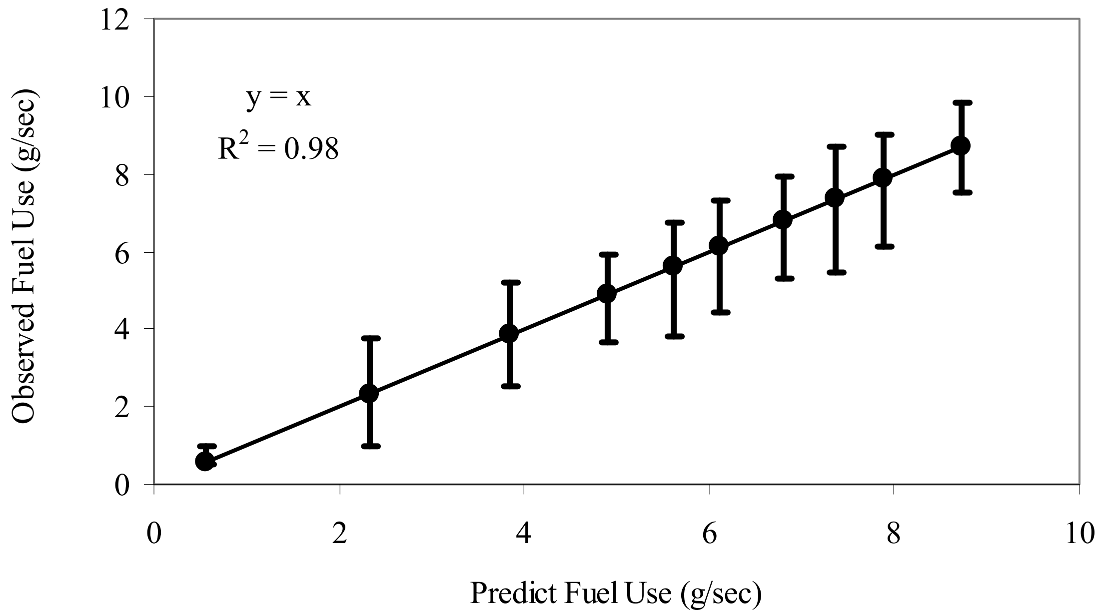


Figure 4.1. Example of a Time Series Plot of Manifold Absolute Pressure, Fuel Use, and NO Emission Rate for a Front-End Loader

4.3.2 Modal Model

The raw data were carefully reviewed by the data screening and quality assurance procedures. After determining whether any errors exist in the data, correcting such errors, and removing invalid data, the data were analyzed in terms of the fuel use and average emission rates for engine-based and task-based modes.

For each engine-based and task-based mode, the average fuel use and emission rates are calculated for each mode using the calibration dataset. Therefore, the second-by-second fuel use and emission rates of the validation dataset can be predicted based on the modal average emission rates. The modal emission rates for each vehicle are provided in Appendix A. A parity plot was used to compare the observed and predicted fuel use and emission rates. Figures 4.2 and 4.3 show an example of the parity plots based on Excavator 1 data. For each mode, the vertical bar represents the range in which 95% of the data will fall. The slope for all parity plots is 1. Coefficients of Determination (R^2) for these four models are presented in Tables 4.3, 4.4, 4.5, and 4.6.



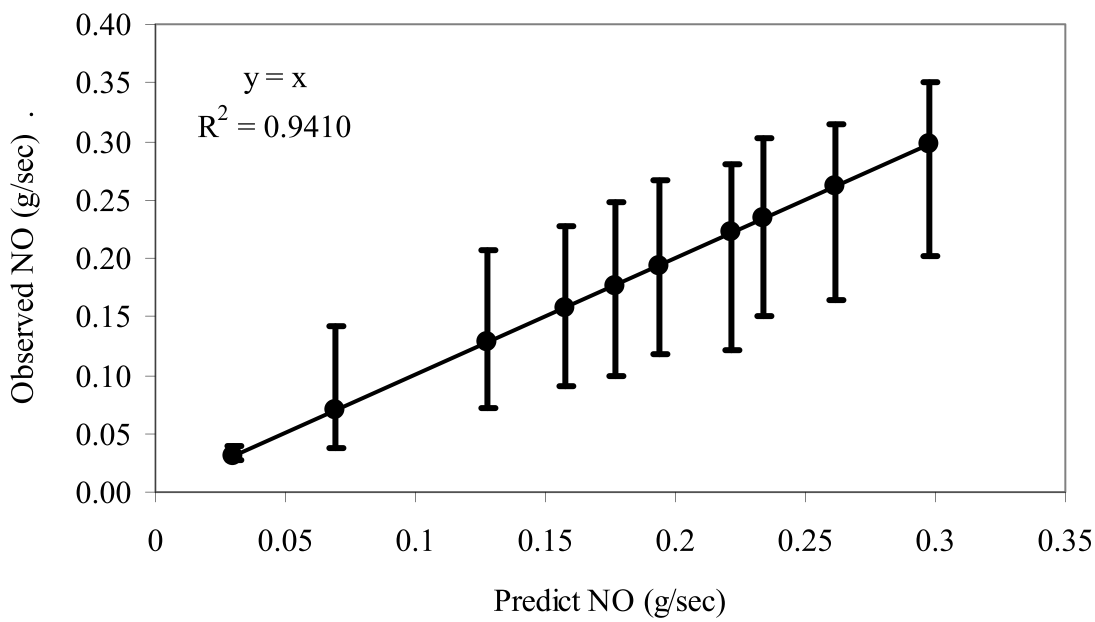


Figure 4.2 Observed Fuel Use and Emissions versus Predicted Fuel Use and Emissions Based on Time-Based Engine-Based Modal Models for Excavator 1

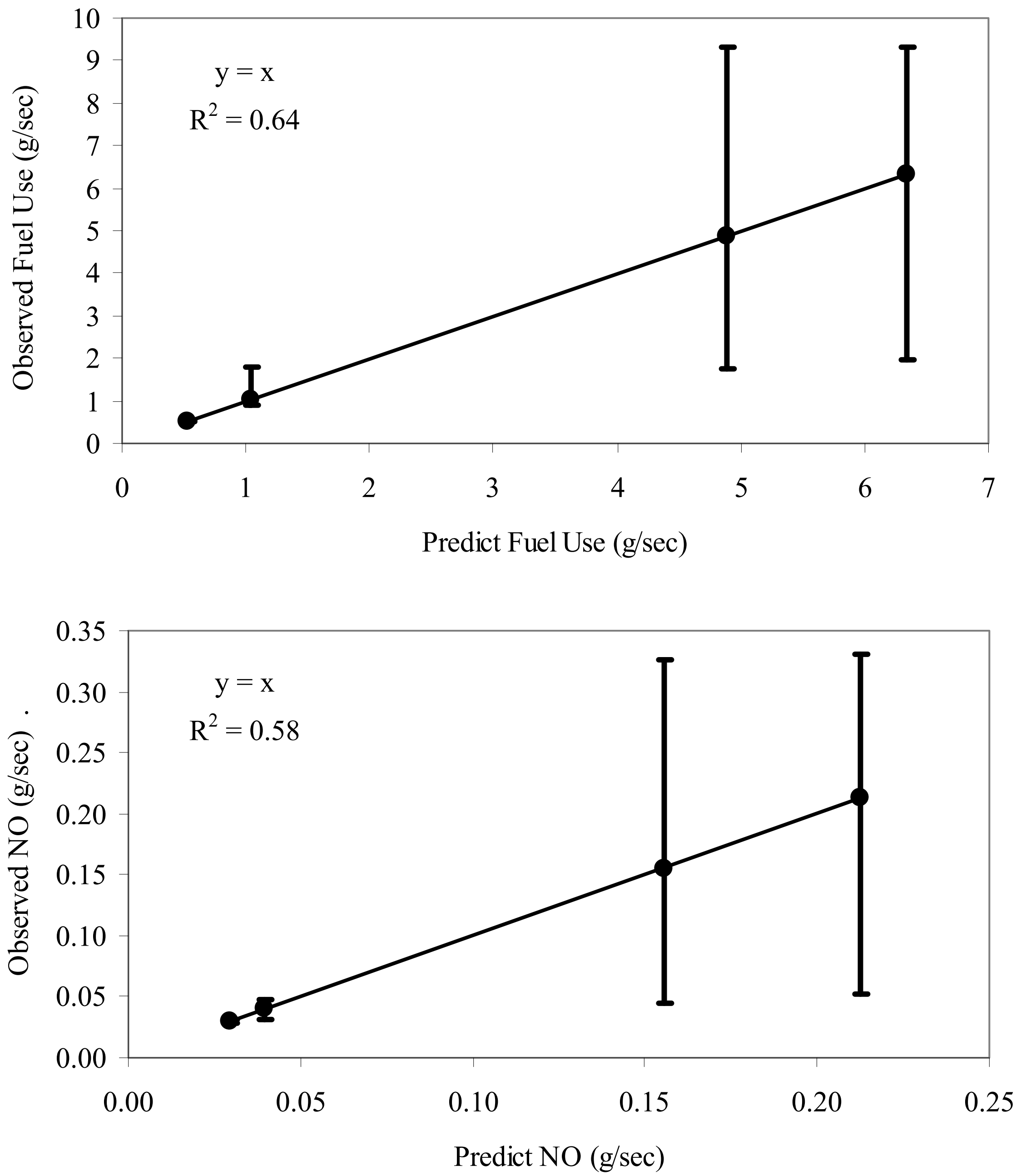


Figure 4.3 Observed Fuel Use and Emissions versus Predicted Fuel Use and Emissions Based on Time-Based Task-Based Modal Models for Excavator 1

Table 4.3 Coefficient of Determination (R^2) of Time-Based Engine-Based Modal Models for Fuel Use and Emissions

	Fuel	CO_2	NO_x	HC	CO	Opacity
Dozer 1	0.98	0.98	0.96	0.61	0.73	0.92
Dozer 2	0.95	0.95	0.91	0.68	0.23	0.81
Dozer 3	0.94	0.94	0.87	0.56	0.04	0.54
Dozer 4	0.98	0.98	0.91	0.72	0.20	0.80
Dozer 5	0.98	0.98	0.93	0.31	0.20	N/A
Excavator 1	0.98	0.98	0.97	0.58	0.73	0.84
Excavator 2	0.96	0.96	0.92	0.71	0.47	0.94
Excavator 3	0.91	0.91	0.87	0.34	0.04	0.89
Off-Highway Truck 1	0.87	0.87	0.76	0.78	0.30	0.81
Off-Highway Truck 2	0.94	0.94	0.74	0.42	0.43	0.82
Off-Highway Truck 3	0.97	0.97	0.90	0.74	0.71	0.70
Backhoe 1	0.86	0.86	0.70	0.38	0.18	0.65
Backhoe 2	0.78	0.78	0.74	0.21	0.19	0.21
Backhoe 3	0.96	0.96	0.89	0.67	0.25	0.43
Backhoe 4	0.94	0.94	0.92	0.75	0.71	0.90
Backhoe 5	0.96	0.96	0.91	0.30	0.62	0.76
Backhoe 6	0.92	0.92	0.71	0.60	0.50	0.83
Backhoe 7	0.84	0.84	0.75	0.48	0.12	0.46
Backhoe 8	0.89	0.89	0.87	0.57	0.62	0.88
Front-End Loader 1	0.88	0.88	0.79	0.77	0.56	0.85
Front-End Loader 2	0.94	0.94	0.91	0.72	0.32	0.84
Front-End Loader 3	0.93	0.93	0.90	0.55	0.25	0.81
Front-End Loader 4	0.87	0.87	0.83	0.42	0.25	0.76
Front-End Loader 5	0.95	0.95	0.87	0.47	0.71	0.88
Skid Steer Loader	0.94	0.94	0.91	0.80	0.77	0.78
Motor Grader 1	0.74	0.74	0.57	0.25	0.24	0.77
Motor Grader 2	0.94	0.94	0.79	0.38	0.07	0.66
Motor Grader 3	0.92	0.92	0.82	0.53	0.28	0.92
Motor Grader 4	0.83	0.83	0.72	0.19	0.13	0.64
Motor Grader 5	0.97	0.97	0.89	0.51	0.09	0.82
Motor Grader 6	0.93	0.93	0.48	0.21	0.14	0.87
Track Loader	0.98	0.98	0.90	0.07	0.78	0.74
Average R^2	**0.92**	**0.92**	**0.83**	**0.51**	**0.37**	**0.76**

Table 4.4 Coefficient of Determination (R^2) of Fuel-Based Engine-Based Modal Models for Fuel Use and Emissions

	NO_x	HC	CO	Opacity
Dozer 1	0.95	0.57	0.71	0.91
Dozer 2	0.95	0.68	0.38	0.84
Dozer 3	0.90	0.58	0.07	0.55
Dozer 4	0.93	0.72	0.16	0.78
Dozer 5	0.94	0.26	0.18	N/A
Excavator 1	0.95	0.59	0.74	0.84
Excavator 2	0.94	0.70	0.48	0.92
Excavator 3	0.93	0.32	0.05	0.86
Off-Highway Truck 1	0.88	0.72	0.37	0.80
Off-Highway Truck 2	0.88	0.71	0.41	0.81
Off-Highway Truck 3	0.94	0.77	0.77	0.73
Backhoe 1	0.83	0.39	0.19	0.68
Backhoe 2	0.89	0.24	0.31	0.38
Backhoe 3	0.87	0.59	0.23	0.42
Backhoe 4	0.93	0.74	0.73	0.91
Backhoe 5	0.87	0.18	0.67	0.72
Backhoe 6	0.84	0.58	0.57	0.84
Backhoe 7	0.88	0.12	0.18	0.56
Backhoe 8	0.89	0.61	0.70	0.89
Front-End Loader 1	0.90	0.78	0.67	0.87
Front-End Loader 2	0.97	0.69	0.36	0.86
Front-End Loader 3	0.92	0.62	0.25	0.81
Front-End Loader 4	0.92	0.29	0.34	0.81
Front-End Loader 5	0.96	0.31	0.70	0.89
Skid Steer Loader	0.97	0.76	0.79	0.87
Motor Grader 1	0.90	0.30	0.34	0.65
Motor Grader 2	0.85	0.48	0.11	0.69
Motor Grader 3	0.94	0.49	0.22	0.87
Motor Grader 4	0.89	0.23	0.06	0.61
Motor Grader 5	0.94	0.51	0.02	0.80
Motor Grader 6	0.58	0.19	0.15	0.84
Track Loader	0.90	0.08	0.68	0.70
Average R^2	**0.90**	**0.49**	**0.39**	**0.76**

Table 4.5 Coefficient of Determination (R^2) of Time-Based Task-Based Modal Models for Fuel Use and Emissions

	Fuel	CO_2	NO_x	HC	CO	Opacity
Dozer 1	0.86	0.86	0.88	0.57	0.69	0.84
Dozer 2	0.69	0.69	0.76	0.50	0.05	0.55
Dozer 3	0.62	0.62	0.61	0.47	0.15	0.33
Dozer 4	0.77	0.77	0.74	0.62	0.20	0.69
Dozer 5	0.82	0.82	0.74	0.19	0.14	N/A
Excavator 1	0.64	0.64	0.58	0.47	0.52	0.51
Excavator 2	0.43	0.43	0.39	0.27	0.13	0.34
Excavator 3	0.76	0.76	0.77	0.30	0.06	0.67
Off-Highway Truck 1	0.46	0.46	0.38	0.36	0.22	0.43
Off-Highway Truck 2	0.51	0.51	0.34	0.38	0.34	0.57
Off-Highway Truck 3	0.74	0.74	0.71	0.62	0.66	0.56
Backhoe 1	0.36	0.36	0.50	0.27	0.18	0.32
Backhoe 2	0.30	0.30	0.42	0.20	0.11	0.06
Backhoe 3	0.50	0.50	0.59	0.38	0.17	0.13
Backhoe 4	0.67	0.67	0.67	0.55	0.46	0.58
Backhoe 5	0.68	0.68	0.62	0.30	0.44	0.42
Backhoe 6	0.35	0.35	0.32	0.14	0.16	0.33
Backhoe 7	0.54	0.54	0.69	0.47	0.30	0.25
Backhoe 8	0.70	0.70	0.72	0.43	0.46	0.63
Front-End Loader 1	0.35	0.35	0.31	0.12	0.25	0.34
Front-End Loader 2	0.64	0.64	0.72	0.41	0.22	0.56
Front-End Loader 3	0.27	0.27	0.33	0.22	0.27	0.40
Front-End Loader 4	0.41	0.41	0.47	0.11	0.38	0.25
Front-End Loader 5	0.40	0.40	0.51	0.17	0.27	0.36
Skid Steer Loader	0.61	0.61	0.65	0.68	0.55	0.54
Motor Grader 1	0.20	0.20	0.16	0.10	0.10	0.25
Motor Grader 2	0.61	0.61	0.57	0.31	0.11	0.47
Motor Grader 3	0.33	0.33	0.26	0.37	0.12	0.36
Motor Grader 4	0.24	0.24	0.19	0.07	0.04	0.21
Motor Grader 5	0.58	0.58	0.59	0.38	0.06	0.50
Motor Grader 6	0.25	0.25	0.19	0.27	0.05	0.30
Track Loader	0.76	0.76	0.65	0.04	0.59	0.67
Average R^2	**0.53**	**0.53**	**0.53**	**0.34**	**0.26**	**0.43**

Table 4.6 Coefficient of Determination (R^2) of Fuel-Based Task-Based Modal Models for Fuel Use and Emissions

	NO_x	HC	CO	Opacity
Dozer 1	0.92	0.59	0.64	0.90
Dozer 2	0.93	0.68	0.22	0.81
Dozer 3	0.91	0.49	0.14	0.54
Dozer 4	0.92	0.61	0.14	0.77
Dozer 5	0.92	0.21	0.05	N/A
Excavator 1	0.88	0.47	0.68	0.82
Excavator 2	0.86	0.48	0.15	0.84
Excavator 3	0.93	0.33	0.04	0.85
Off-Highway Truck 1	0.88	0.74	0.41	0.80
Off-Highway Truck 2	0.84	0.21	0.37	0.74
Off-Highway Truck 3	0.95	0.75	0.70	0.72
Backhoe 1	0.77	0.42	0.24	0.65
Backhoe 2	0.89	0.26	0.30	0.20
Backhoe 3	0.88	0.50	0.20	0.36
Backhoe 4	0.90	0.71	0.72	0.88
Backhoe 5	0.86	0.21	0.60	0.69
Backhoe 6	0.86	0.47	0.58	0.82
Backhoe 7	0.69	0.46	0.25	0.56
Backhoe 8	0.87	0.69	0.70	0.89
Front-End Loader 1	0.90	0.65	0.66	0.74
Front-End Loader 2	0.94	0.51	0.27	0.85
Front-End Loader 3	0.87	0.41	0.28	0.72
Front-End Loader 4	0.89	0.42	0.42	0.80
Front-End Loader 5	0.92	0.39	0.68	0.86
Skid Steer Loader	0.95	0.63	0.56	0.81
Motor Grader 1	0.90	0.23	0.33	0.66
Motor Grader 2	0.81	0.37	0.01	0.68
Motor Grader 3	0.92	0.53	0.18	0.87
Motor Grader 4	0.85	0.21	0.11	0.61
Motor Grader 5	0.93	0.39	0.03	0.80
Motor Grader 6	0.47	0.31	0.14	0.82
Track Loader	0.89	0.02	0.70	0.64
Average R^2	**0.87**	**0.45**	**0.36**	**0.73**

The results shown in Figure 4.2 indicate that fuel use and NO emissions increase monotonically with an increase in MAP. An increase in MAP generally indicates an increase in engine load. The lowest normalized MAP range included idling of the engine. In Table 4.3, the time-based engine-based modal model was used for predicting fuel use and emission rates. The goodness-of-fit is good for fuel use, CO_2 (with an average R^2 of 0.92) and NO_x (with an average R^2 of 0.83). In most cases, the R^2 for the opacity is higher than 0.78. For diesel engines, it is expected to be low for the HC and CO emission rates. In some cases, vibration can affect the precision and accuracy of the analyzer for HC and CO measurement during data collection. When the HC and CO measurements are below the detection limit of the instrument, the HC and CO concentrations have a random pattern, which results in low R^2.

In Table 4.4, the fuel-based engine-based modal model was used for predicting fuel use and emission rates. Results are not shown for fuel use since the mass of fuel consumed per gallon of fuel is a constant, regardless of engine activity. Similarly, since CO_2 emissions are highly correlated with fuel consumption, the CO_2 emissions on a per gallon basis are approximately constant and, therefore, are not shown. The goodness-of-fit is good for NO_x (with an average R^2 of 0.90) when the fuel-based engine-based modal model applied. The results for HC, CO, and opacity are similar to time-based engine-based models.

In Table 4.5, the time-based task-based modal model was used for predicting fuel use and emission rates. Task-based modes can include idling, movement of the equipment for repositioning purpose, or use of a bucket, etc. These modes can vary depending on the type of vehicle. Generally, one type of construction equipment has 2 to 4 different task oriented modes. Thus, task-based modal models have less explanatory ability compared to engine-based modal models (10 modes). As expected, the R^2 shown in Table 4.5 are lower than engine-based modal model for fuel use, CO_2, NO_x, HC, CO, and opacity. A similar trend is shown for the fuel-based task-based modal models in Table 4.6.

The average (over all 32 tested vehicles) goodness-of-fits (R^2) for fuel use, CO_2, NO, HC, CO, and opacity rates is 0.92, 0.92, 0.83, 0.51, 0.37, 0.76, respectively, based on time-based engine-based modal models. The average goodness-of-fits (R^2) for NO, HC, CO, and opacity rates are 0.90, 0.49, 0.39, 0.76, respectively, based on fuel-based engine-based modal models. The results indicate that manifold absolute pressure (MAP) is a good explanatory variable for energy use and emission rates for both time-based and fuel-based engine-based modal models. Time-based and fuel-based engine-based modal models have similar explanatory capability for NO, Opacity HC, and CO. Due to the low emissions of CO and HC from diesel exhaust, sometimes the concentrations of CO and HC are below the detection limit, resulting in lower R^2 than for the other pollutants.

For task-based modal modes, the average (over all 32 tested vehicles) goodness-of-fits (R^2) for fuel use, CO_2, NO, HC, CO, and opacity rates are 0.53, 0.53, 0.53, 0.34, 0.26, 0.43, respectively, based on time-based task-based modal models. The average goodness-of-fits (R^2) for NO, HC, CO, and opacity rates are 0.87, 0.45, 0.36, 0.73, respectively, based on fuel-based task-based modal models. Generally, the R^2 for task-based modal models is lower than for the engine-based modal models. The results indicated that engine-based modal models perform better than task-based modal models. Because fuel-based emission rates have less variability, the R^2 for fuel-based modal models are higher than time-based modal models.

4.3.3 Regression Model

Linear regression models describe how the mean of a dependent variable varies with respect to changes in the corresponding explanatory variables. Thus, for example, they explain the relationship between fuel use and MAP. That is, MAP can be used as an indicator of fuel use. Emission rates in units of mass per time and in units of mass per gallon of fuel consumed are both estimated for the physically-based regression model. As expected, the slope in each regression model is 1 for all vehicles. The regression model coefficients for fuel use, CO_2, HC, CO, opacity, and NO for each vehicle are provided in Appendix B. Coefficients of Determination (R^2) for time-based and fuel-based regression models are shown in Tables 4.7 and 4.8 and are discussed below.

Table 4.7 Coefficient of Determination (R^2) of Time-Based Regression Models for Fuel Use and Emission Rates

	Fuel	CO_2	NO_x	HC	CO	Opacity
Dozer 1	0.99	0.99	0.99	0.63	0.91	0.95
Dozer 2	0.97	0.97	0.92	0.89	0.21	0.76
Dozer 3	0.97	0.97	0.92	0.56	0.07	0.62
Dozer 4	1.00	1.00	0.98	0.67	0.46	0.88
Dozer 5	1.00	1.00	0.98	0.73	0.17	N/A
Excavator 1	0.99	0.99	0.99	0.72	0.66	0.92
Excavator 2	0.99	0.99	0.96	0.80	0.45	0.92
Excavator 3	0.97	0.97	0.94	0.42	0.13	0.75
Off-Highway Truck 1	0.95	0.95	0.82	0.78	0.44	0.90
Off-Highway Truck 2	0.99	0.99	0.96	0.33	0.23	0.95
Off-Highway Truck 3	0.99	0.99	0.99	0.77	0.78	0.74
Backhoe 1	0.91	0.91	0.86	0.27	0.01	0.84
Backhoe 2	0.95	0.95	0.77	0.08	0.25	0.33
Backhoe 3	0.99	0.99	0.82	0.91	0.73	0.70
Backhoe 4	0.95	0.95	0.88	0.77	0.85	0.91
Backhoe 5	0.98	0.98	0.90	0.54	0.74	0.81
Backhoe 6	0.97	0.97	0.89	0.75	0.81	0.86
Backhoe 7	0.94	0.94	0.85	0.50	0.59	0.67
Backhoe 8	0.95	0.95	0.91	0.71	0.79	0.64
Front-End Loader 1	0.90	0.90	0.79	0.79	0.60	0.85
Front-End Loader 2	0.99	0.99	0.94	0.94	0.06	0.89
Front-End Loader 3	0.99	0.99	0.96	0.89	0.72	0.57
Front-End Loader 4	0.98	0.98	0.95	0.66	0.50	0.95
Front-End Loader 5	0.99	0.99	0.90	0.65	0.92	0.80
Skid Steer Loader	0.95	0.95	0.91	0.80	0.80	0.76
Motor Grader 1	0.95	0.95	0.90	0.66	0.73	0.96
Motor Grader 2	0.99	0.99	0.96	0.56	0.13	0.89
Motor Grader 3	0.97	0.97	0.86	0.84	0.62	0.96
Motor Grader 4	0.97	0.97	0.90	0.31	0.33	0.85
Motor Grader 5	1.00	1.00	0.95	0.81	0.21	0.95
Motor Grader 6	0.98	0.98	0.83	0.27	0.62	0.90
Track Loader	0.99	0.99	0.98	0.07	0.81	0.67
Average R^2	**0.97**	**0.97**	**0.91**	**0.63**	**0.51**	**0.81**

Table 4.8 Coefficient of Determination (R^2) of Fuel-Based Regression Models for Fuel Use and Emissions

	NOx	HC	CO	Opacity
Dozer 1	0.99	0.44	0.84	0.95
Dozer 2	0.93	0.82	0.23	0.73
Dozer 3	0.93	0.34	0.01	0.56
Dozer 4	0.89	0.25	0.28	0.85
Dozer 5	0.98	0.50	0.17	N/A
Excavator 1	0.98	0.64	0.72	0.92
Excavator 2	0.95	0.71	0.54	0.95
Excavator 3	0.93	0.34	0.12	0.94
Off-Highway Truck 1	0.82	0.77	0.37	0.86
Off-Highway Truck 2	0.89	0.25	0.38	0.85
Off-Highway Truck 3	0.89	0.25	0.28	0.85
Backhoe 1	0.76	0.12	0.01	0.71
Backhoe 2	0.80	0.04	0.24	0.33
Backhoe 3	0.92	0.92	0.67	0.59
Backhoe 4	0.94	0.82	0.86	0.95
Backhoe 5	0.96	0.08	0.82	0.08
Backhoe 6	0.89	0.72	0.81	0.43
Backhoe 7	0.87	0.10	0.40	0.65
Backhoe 8	0.91	0.63	0.76	0.95
Front-End Loader 1	0.76	0.59	0.62	0.84
Front-End Loader 2	0.96	0.58	0.41	0.92
Front-End Loader 3	0.97	0.72	0.17	0.91
Front-End Loader 4	0.97	0.02	0.01	0.97
Front-End Loader 5	0.94	0.20	0.88	0.90
Skid Steer Loader	0.94	0.83	0.45	0.76
Motor Grader 1	0.90	0.61	0.23	0.95
Motor Grader 2	0.97	0.76	0.29	0.93
Motor Grader 3	0.93	0.81	0.42	0.98
Motor Grader 4	0.91	0.17	0.01	0.86
Motor Grader 5	0.97	0.78	0.10	0.95
Motor Grader 6	0.84	0.42	0.48	0.93
Track Loader	0.98	0.05	0.87	0.77
Average R^2	**0.91**	**0.48**	**0.42**	**0.80**

For the time-based regression model, the average (over all 32 tested vehicles) goodness-of-fits (R^2) for fuel use, CO_2, NO, HC, CO, and opacity rates are 0.97, 0.97, 0.91, 0.63, 0.51, and 0.81, respectively. The average goodness-of-fits (R^2) for NO, HC, CO, and opacity rates are 0.91, 0.48, 0.42, 0.80, respectively, based on fuel-based regression models. Physically-based regression models for these vehicles perform well and MAP is a good explanatory variable for fuel use and emission rates. The R^2 for fuel use, CO_2, and NO is high for all engines based on time-based or fuel-based regression models. Similar to the other modeling approaches, the low emissions of CO and HC from diesel exhaust result in lower R^2 compared to the other pollutants for the physically-based regression models. Time-based regression models have the best explanatory capability among all models, i.e. they have the highest R^2.

4.3.4 Benchmarks of Predicted Emission Rates

For benchmarks of predicted emission rates based on EPA's NONROAD Model, The fuel based emission factors from the PEMS data were of comparable magnitude to fuel-based emission factors estimated from the NONROAD model for NO, HC, and CO shown in Table 4.9.

Table 4.9 Benchmarks of Weighted Average Emission Rates Based on NONROAD Model

	NO_x (g/gal)		HC (g/gal)		CO (g/gal)	
	PEMS	NONROAD Model	PEMS	NONROAD Model	PEMS	NONROAD Model
Dozer 1	149	114	7.1	18.6	27.5	109
Dozer 2	100	76	17	6.6	18.2	64.1
Dozer 3	152	91	9	9.4	37.6	63.9
Dozer 4	178	103	11.4	6.4	38.0	24.2
Dozer 5	187	156	3.0	14.5	21.3	100.3
Excavator 1	99	102	5.2	6.3	11.5	23.7
Excavator 2	76	74	9.3	6.9	27.9	26.8
Excavator 3	104	92	8.8	9.6	13.6	66.6
Off-Highway Truck 1	117	78	9	3.3	53	24.9
Off-Highway Truck 2	121	106	8.8	6.6	53.8	26.6
Off-Highway Truck 3	134	106	8.5	6.6	29.2	26.6
Backhoe 1	127	90	16.3	17.5	27.8	90.1
Backhoe 2	100	90	5.4	17.5	31.8	90.5
Backhoe 3	88	91	7.9	17.7	18.4	92.6
Backhoe 4	98	75	11	12	8.9	90
Backhoe 5	105	112	15	34	88	144
Backhoe 6	101	90	13	18	37	92
Backhoe 7	107	91	7	18	51	93
Backhoe 8	102	75	10	12	17	90
Front End Loader 1	92	74	11.3	6.8	38.9	26.0
Front End Loader 2	110	103	18	6.9	16	27
Front End Loader 3	129	103	17	6.9	13	27
Front End Loader 4	127	104	13	7.0	16	28
Front End Loader 5	95	74	5.6	6.8	11	26
Skid Steer Loader	80	76	12.7	9.4	15.9	59.3
Motor Grader 1	109	102	15	6.3	14	23
Motor Grader 2	98	75	12	6.2	12	23
Motor Grader 3	110	102	18	6.3	16	23
Motor Grader 4	130	159	19	15	31	110
Motor Grader 5	138	157	15	15	36	105
Motor Grader 6	68	45	6.2	3.7	9	22
Track Loader	59	45	1.0	3.7	14	26

Typically, there is substantial overlap in the ranges from both types of data for these three pollutants, with only a few exceptions. For example, the excavator NO_x emission rates based on PEMS data ranged from 76 to 104 g/gallon, whereas the estimates for similar model years and engine sizes from the NONROAD model ranged from 74 to 102 g/gallon. The PEMS and NONROAD data are not expected to agree because the PEMS data are for individual vehicles, whereas NONROAD is intended to predict average emissions for a fleet of vehicles. Also, the real-world duty cycles and ambient conditions of the PEMS data differ from the standardized engine dynamometer test conditions that are the basis of the NONROAD model. In general, the average emission rates from the PEMS field measurement data are of similar magnitude to those based on the NONROAD model for NO, HC, and CO.

4.4 Discussion

An on-board measurement procedure for nonroad construction vehicles using a portable emissions measurement system (PEMS) was developed to quantify second-by-second energy use and emissions based on real-world activities. This paper applied recently collected in-use data to gain insight into real-world variability in fuel use and emissions for individual vehicles, and when comparing vehicles, as well as to develop vehicle-specific models. Analysis of empirical data reveals that intra-vehicle variability of energy use and emissions is strongly influenced by vehicle activity that leads to variations in engine load, as represented by manifold absolute pressure (MAP). Based on data from in-use measurements of 32 construction vehicles, there is a consistent pattern of monotonic increase of average emission rate with respect to increasing MAP.

Vehicle-specific models for fuel use and tailpipe emissions were developed for each of the construction vehicle. For each vehicle, four modal models and two physically-based regression models were developed based on a twelve consecutive averaging time. Manifold absolute pressure (MAP) was a good explanatory variable for fuel use and emission rates for both time-based and fuel-based models.

For modal models, engine-based modal models perform better than task-based modal models. Time-based emission rates are found to be highly correlated with fuel flow. The physically-based regression model provides provide greater explanatory power of intra-engine variability than modal models. Time-based regression models have the best explanatory capability among all models. The R^2 for fuel use, CO_2, and NO_x are high for all vehicles. Because diesel engines have low emissions of CO and HC, sometimes the concentrations of CO and HC are below detection limit, resulting in low R^2 in the models. The time-based regression model is recommended in order to predict fuel use and emission rate for construction equipment.

The PEMS data are comparable to the NONROAD estimates with respect to magnitude for NO, HC, and CO; however they are much lower in magnitude for PM. The PEMS uses a light scattering technique for measuring PM concentration, which is similar to an opacity measurement. Thus, the PEMS data are generally consistent with the benchmark data.

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PART V CHARACTERIZATION OF INTER-CYCLE AND INTER-ENGINE VARIABILITY FROM DIESEL POWERED NON-ROAD CONSTRUCTION VEHICLES

Abstract

Heavy duty diesel construction vehicles emit significant amounts of nitrogen oxides (NO_x) and particulate matters. Currently, there is a lack of representative test cycle for construction vehicles. The on-board portable emissions measurement systems (PEMS) are now developed to collect exhaust emissions and engine data during real-world operation of the equipment. The objective of this study is to apply recently collected in-use data to gain insight into real-world variability in fuel use and emissions when comparing vehicles and duty cycles. Variability in vehicle emissions as a result of variation in vehicle operation or other factors can be represented and analyzed. Representative duty cycles for each type of vehicles were characterized by a frequency distribution of normalized manifold absolute pressure (MAP). Vehicle-specific models for fuel use and tailpipe emissions were developed for each of the construction vehicle based on physically-based regression model.

In order to assess the variations of fuel use and emissions among different duty cycles, for a given engine, the inter-cycle variability is assessed. In order to assess the variations of fuel use and emissions among engines, for a given duty cycle, the inter-engine variability is assessed. The results indicated time-based inter-cycle and inter-engine variations of fuel use and emissions are significant. Fuel-based emission factors have less variability among cycles and engines than time-based emission factors. Fuel-based emission factors are more robust with respect to inter-engine and inter-cycle variations and are recommended in order to develop an emissions inventory for nonroad construction vehicles. Real-world in-use measurements should be a basis for developing duty cycle correction factors in models such as NONROAD.

5.1 Introduction

Most Americans living in urban areas breathe air that does not meet National Ambient Air Quality Standards (NAAQS) for either ozone or particulate matter. Heavy duty diesel vehicles, including both onroad and nonroad vehicles, emit significant amounts of nitrogen oxides (NO_x) which is a precursor to ozone formation and particulate matters. Long term exposure to ozone and particulate matters may cause respiratory problems and air toxics from diesel exhausts may pose carcinogen risk for human health.

In 2002, nonroad equipment and vehicles contributed 35.7% of NO_x, 60.4% of PM, 28.2% of CO, 37.2% of HC to total transportation emissions (EPA 2007). Among these nonroad emissions, construction equipment contributed 15.9% of NO_x, 19.0% of PM, 4.4% of CO, 4.8% of HC. In the past few years, the regulations for exhaust emissions are mainly focused on onroad diesel engines. Over time, increasingly stringent regulations have been implemented to reduce tailpipe emissions from nonroad diesel engines.

Emission testing for nonroad diesel engine has been performed by engine dynamometer, chassis dynamometer and on-board portable emission measurement system. Engine dynamometer testing requires removing the engine from the equipment and putting on a test bed. The data collection procedures are time-consuming. Moreover, these tests are based on standard test cycle, which may not represent real-world activities. The chassis dynamometer testing requires placing the vehicle on a chassis dynamometer. Currently, there is a lack of representative test cycle for nonroad engines. Besides, accurately loading the engine is another problem when hydraulic system is being used. Because the operation style of the driver also has a significant impact on the engine load and emissions, the human errors during testing may pose challenges for the repeatability. The on-board portable emissions measurement systems (PEMS) are now developed to collect exhaust emissions and engine data during real-world operation of the equipment. On-board measurements are capable to represent the variability and uncertainty of real-world in-use emissions.

Variability in vehicle emissions as a result of variation in vehicle operation or other factors can be represented and analyzed. However, compared to engine dynamometer tests, there is relatively little real world measurement of in-use emissions using PEMS (Gautam *et al.* 2002, May *et al.* 2002, Vojtisek-Lom 2003). Huai *et al.* (2005) collected real-world operational data, including intake manifold air pressure, exhaust temperature, engine speed, and throttle position, for eighteen pieces of nonroad equipment. However, there is no linkage between engine data and emissions shown in the paper.

Recently, a methodology for collecting and analyzing real-world in-use data from non-road construction equipment is presented (Frey *et al.*). The methodology was being used to measure the in-use activity and emissions of construction vehicles such as bulldozers, excavators, front-end loaders, off-highway trucks, backhoes, skid steer loaders, and motor graders. More accurately quantified emissions from diesel vehicles were obtained to manage or to reduce emissions to improve air quality.

EPA NONROAD model estimate emission inventory for nonroad vehicles (EPA 2005). These estimates are measured in the laboratory based on a limited number of standard operating cycles, which are not representative of real-world activities. There is a need to develop new emission inventory for construction equipment based on in-use measurement. The application of the methodology presented in Frey *et al.* improved the characterization of in-use activity and emissions of these vehicles, which can further support development of improved emission models and approaches to emission inventories.

Recently developed vehicle-specific emission models for 30 construction vehicles applied collected in-use data to gain insight into real-world variability in fuel use and emissions for individual vehicles (Frey and Pang). The results indicate the physically-based regression model is recommended in order to predict fuel use and emission rate for nonroad construction equipment. In this paper, an average emission rate for a duty cycle was estimated based on the coefficients of physically-based regression model. The variability in average fuel use and emission rates from one duty cycle to another was assessed for each type of vehicle. Furthermore, comparisons were made for weighted averages of fuel use and emissions among different duty cycles for all of the tested engines.

The key research objectives are:

- To characterize typical duty cycles for each type of construction vehicles;
- To quantify duty cycles based on the cumulative frequency distribution (CDF) of manifold absolute pressure;
- To assess the variability in weighted average fuel use and emissions rates among different vehicles; and
- To assess the variability in weighted average fuel use and emission rates among different duty cycles.

5.2 Methodology

This section describes methodologies for including: (1) development of physically-based regression models; (2) development of representative duty cycles for construction vehicles and quantifying duty cycles based on the cumulative frequency distribution (CDF) of normalized manifold absolute pressure; and (3) prediction of fuel use and emission rates using regression models.

5.2.1 Development of Physically-Based Regression Models

Physically-based regression models were developed for each vehicles tested to date. Least square regression models describe how the mean of the dependent variable (i.e. fuel use rate, emissions rate) varies with respect to changes in the corresponding explanatory variables (i.e. MAP). The data used in emission models were reviewed and corrected based on standard quality assurance procedures (Frey *et al.* 2001, 2005, 2007). For fuel use, HC, CO, CO_2, and opacity, the equation is:

$$Y_t = \alpha + \beta \times MAP_t + \varepsilon_t$$

Where,

Y_t = pollutant emission at time t (g/sec);

α = intercept;

MAP_t = explanatory variable X_i at time t;

β_i = regression coefficient;

ε_t = error term;

For NO, a model with a physically-based interpretation was developed in the form of a non-linear equation, but it can be simplified to a linear combination of basis functions. The NO model is based on the simplified Zeldovich mechanism for thermal NO formation. The functional form of the regression equation for NO can be simplified as:

$$Y_{t,NO} = \frac{C_1}{\left(MAP_t\right)^{0.5}} \exp\left(\frac{C_2}{MAP_t}\right)$$

Where,

$Y_{t,NO}$ = NO emission at time t (g/sec);

C_1, C_2 = Model coefficients;

The linear equation for NO is presented as:

$$\ln\left(Y_{t,NO}\right) = \alpha - \beta_1 \times 0.5 \ln\left(MAP_t\right) + \beta_2 \left(MAP_t\right)^{-1} + \varepsilon_t$$

Where,

β_1 , β_2 = regression coefficient;

5.2.2 Development of Representative Duty Cycles for Construction Vehicles

A duty cycle may be defined as the sum of the task-related components that one specific vehicle can perform on a job site to complete a task such as mass excavation or material handling. In order to determine representative duty cycles for front-end loaders, dozers, excavators, off-highway trucks, backhoes, skid steer loaders, and motor graders, the data collection team went to the job site and observed the tasks for these vehicles prior to data collection. The following sections explain the typical duty cycles performed by each vehicle.

5.2.2.1 Front-End Loaders

The observed duty cycles for a front-end loader included "rock handling," "soil handling," and "load truck." The duty cycles for a front-end loader are similar to those for a backhoe; however, the front-end loader uses only a front bucket to perform tasks. The duty cycle components for "rock handling" and "soil handling" are load bucket, carry loaded, dump, and return empty; the primary difference in these two duty cycles is the type of the material that is being handled. The duty cycle components for "load truck" are load bucket, maneuver loaded, dump, and maneuver empty.

5.2.2.2 Dozers

There were three observed duty cycles for dozers. These duty cycles were defined as "clearing land," "spreading material (I)," and "spreading material (II)." "Clearing land" is the typical duty cycle for a dozer. The duty cycle components for "clearing land" typically include pushing and maneuver empty. In addition to clearing land, a dozer also performs the duty cycles of "spreading material." "Spreading material" is when the dozer uses the bucket to move material, such as soil, sand, or stone, from one location to another. The duty cycle components for "spreading material" typically include pushing and return empty. Compared to soil and sand, spreading rocks needs higher engine load to perform this duty. Thus, there are two separate duty cycles for spreading material. "Spreading material (I)" is for stone, and "spreading material (II)" is for soil and sand.

5.2.2.3 Excavators

There were three observed duty cycles for excavators. These duty cycles were defined as "mass excavation," "moving objects," and "tree/stump removal." "Mass excavation" is the typical duty cycle for an excavator. The duty cycle components for "mass excavation" include digging, swing loaded, dumping, and swing empty. In addition to mass excavation, an excavator also performs the duty cycles of "moving object" and "tree/stump removal." "Moving object" is when the excavator uses the bucket to move material, such as soil, sand, or stone, from one location to another. The duty cycle components for "moving object" include lifting, carrying loaded, setting, and return empty. "Tree/stump removal" is a timed activity and not a typical duty cycle for excavators. The data collection team observed this special duty cycle for one excavator.

5.2.2.4 Off-Highway Trucks

There was one observed duty cycle for off-highway truck. The duty cycle was defined as "material hauling." The duty cycle components for "material hauling" include receiving load, hauling loaded, dumping, and return empty.

5.2.2.5 Backhoes

There were three observed duty cycles for backhoes. These duty cycles were defined as "load truck," "material handling," and "mass excavation." "Load truck" is the typical duty cycle for a backhoe to load material with the front bucket in a dump truck. The duty cycle components for "load truck" typically include load bucket, maneuver loaded, dump, and maneuver empty. In addition to loading trucks, a backhoe also performs the duty cycles of "material handling" and "mass excavation." "Material handling" is when the backhoe uses the front bucket to move material, such as soil, sand, or stone, from one location to another. The duty cycle components for "material handling" typically include load bucket, carry loaded, dump, return empty. "Mass excavation" is when the backhoe uses the rear bucket to dig in earth. The duty cycle components for "mass excavation" typically include dig, swing loaded, dump, and swing empty.

5.2.2.6 Skid Steer Loaders

There was one observed duty cycle for skid steer loader. The duty cycle was defined as "material handling." The duty cycle components for "material hauling" include load bucket, carry loaded, dump, and return empty.

5.2.2.7 Motor Graders

There were two observed duty cycles for a motor grader. These two observed duty cycles were defined as "resurfacing" and "shouldering." The typical components for each of these duty cycles include pass and maneuver. A "pass" is when the motor grader uses the blade for a long segment of road or shoulder. After a "pass" is completed, the motor grader lifts the blade and maneuvers to another location to perform another "pass."

"Resurfacing" refers to a common dirt road maintenance activity that involves the motor grader using most or all of the blade length to re-shape and repair ruts in the surface of an unpaved road. "Shouldering" is when the motor grader uses a portion of the blade length to scrape and grade the shoulders and ditches beside a paved road. Thus, "resurfacing" has a higher engine load compared to "shouldering" because of more resistance of the motor grade blade on the surface of the ground while performing work.

5.2.2.8 Summary of Duty Cycles

The representative duty cycles for construction vehicles are summarized below.

Duty Cycle 1: Rock handling using a front-end loader;

Duty Cycle 2: Soil handling using a front-end loader;

Duty Cycle 3: Load a truck using a front-end loader;

Duty Cycle 4: Clearing land using a bulldozer;

Duty Cycle 5: Spreading rocks using a bulldozer;

Duty Cycle 6: Spreading soil using a bulldozer;

Duty Cycle 7: Tree/Stump removal using an excavator;

Duty Cycle 8: Moving objects using an excavator;

Duty Cycle 9: Mass excavation using an excavator;

Duty Cycle 10: Material hauling using an off-highway truck;

Duty Cycle 11: Load a truck using a backhoe;

Duty Cycle 12: Material handling using a backhoe;

Duty Cycle 13: Mass excavation using a backhoe;

Duty Cycle 14: Material handling using a skid steer loader;

Duty Cycle 15: Resurfacing; and

Duty Cycle 16: Shouldering.

5.2.3 Prediction of Fuel Use and Emission Rates Using Regression Models

Depending on the physically-based regression models presented in Section 8.2.1, intercept and coefficients were obtained for each vehicle. Cycle-average fuel use and emission rates were estimated based on the cumulative frequency of normalized MAP for each duty cycle for each duty cycle. The fuel-based weighted average emission rates were estimated based on the following equation:

$$EF_{fuel,predicted} = \frac{E_{total,predicted}}{Fuel_{total,predicted}} \times \rho$$

Where,

$EF_{fuel,predicted}$ = Predicted fuel-based emission rate for NO, HC, CO, and Opacity based on a given duty cycle (g/gallon);

$E_{total,predicted}$ = Predicted total emissions for NO, HC, CO and Opacity based on a given duty cycle (g);

$Fuel_{total,predicted}$ = Predicted total fuel use for a given duty cycle (g); and

ρ = density of diesel fuels (g/gallon).

5.3 Results

Each duty cycle observed during real-world activities is characterized by a frequency distribution of normalized manifold absolute pressure (MAP). For purposes of general and somewhat stylized comparisons, average emission rates were estimated for each engine for each of the 11 duty cycles. In some cases, an engine that is used in one type of vehicle could potentially be used in a different type of vehicle. Thus, it is possible for one type of engine to be subject to a variety of duty cycles.

5.3.1 Representative Duty Cycles for Construction Vehicles

In order to estimate average emission rates, representative duty cycles were developed for each type of construction vehicles.

For front end loaders, three cycles were identified, including rock handling, soil handling, and loading a truck. There was less difference in average engine load among these three cycles. For dozers, three cycles were identified, including clearing land, spreading material (I), and spreading material (II). Because spreading material (I) is pushing the rocks, the engine load is significant higher than spreading soil and sand. For excavators, three cycles were observed, including mass excavation, moving objects, and tree/stump removal. Mass excavation has the highest engine load compared to the other two observed duty cycles. For off-highway truck, there is only one duty cycle observed in the field. The vehicle has a lot of idling during receiving load. For backhoes, three cycles were identified that represent mass excavation, material handling, and loading a truck with dirt. These cycles have significant differences in engine load. Compared to the other two observed duty cycles, "load truck" typically had higher engine loads because of the weight of the material in the bucket. For skid steer loader, one duty cycle was observed. Approximate sixty percent of time, the vehicle operated at higher engine load. For motor graders, two cycles were observed, including resurfacing an unpaved road and the shoulders of a road. These two cycles have significant differences in average engine load. The "resurfacing" cycle has a higher average engine load compared to the "shouldering" cycle because of the resistance of the blade on the ground surface while a motor grader works. The distributions of normalized MAP for each duty cycle are shown in Figure 5.1.

5.3.2 Inter-Cycle and Inter-Engine Variability

The average fuel use and emission rates for each duty cycle are predicted based on the distributions of normalized MAP using physically-based regression model. These results enable a consistent comparison of fuel use and emission rates among different engines. There are inter-cycle variations among cycle-average emission rates when comparing different duty cycles. Also, there are inter-engine variations when applying the same duty cycle. The predicted fuel use and NO_x, emission rates are shown in Tables 5.1, and 5.2, respectively.

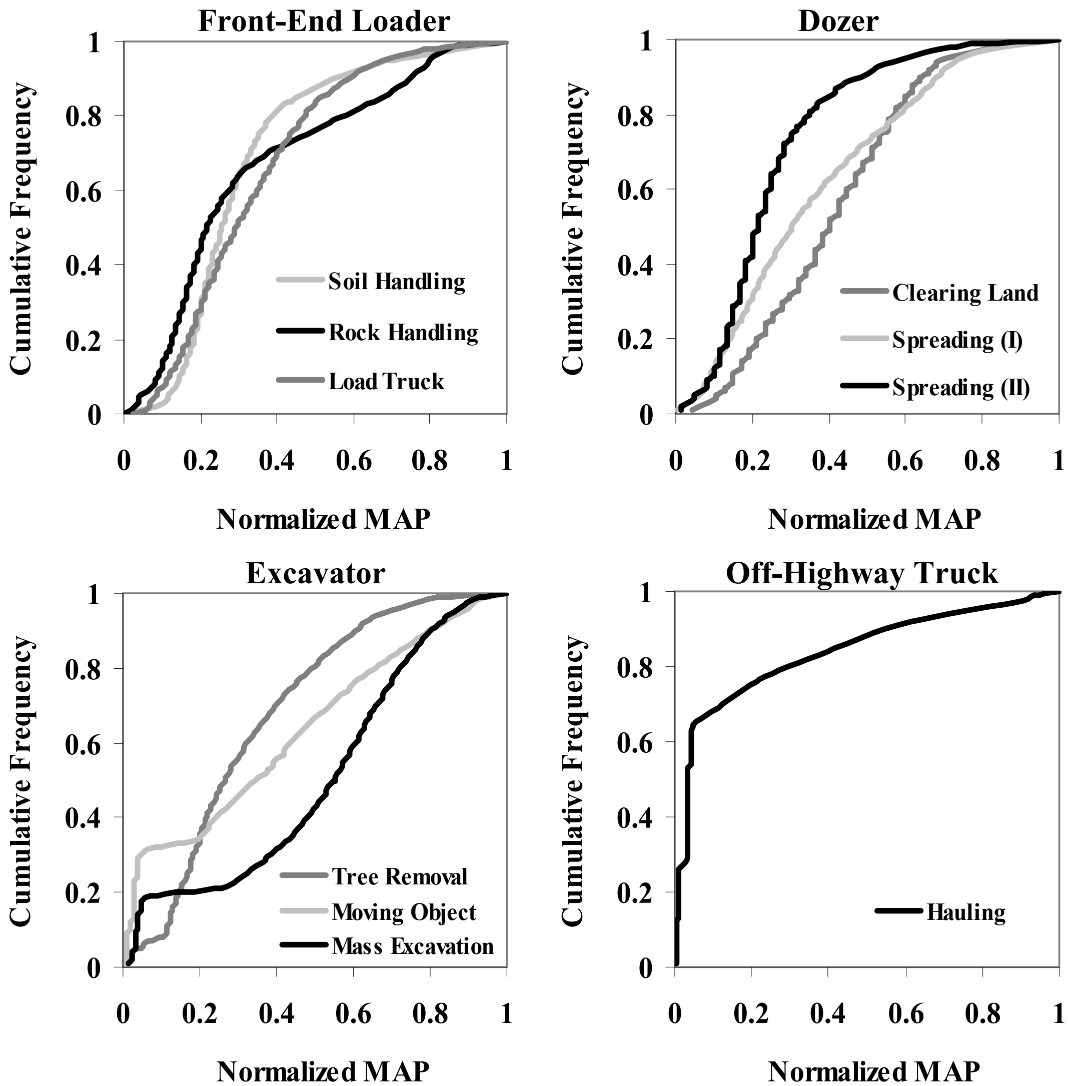

Figure 5.1 Cumulative Frequency Distribution of MAP for All Duty Cycles

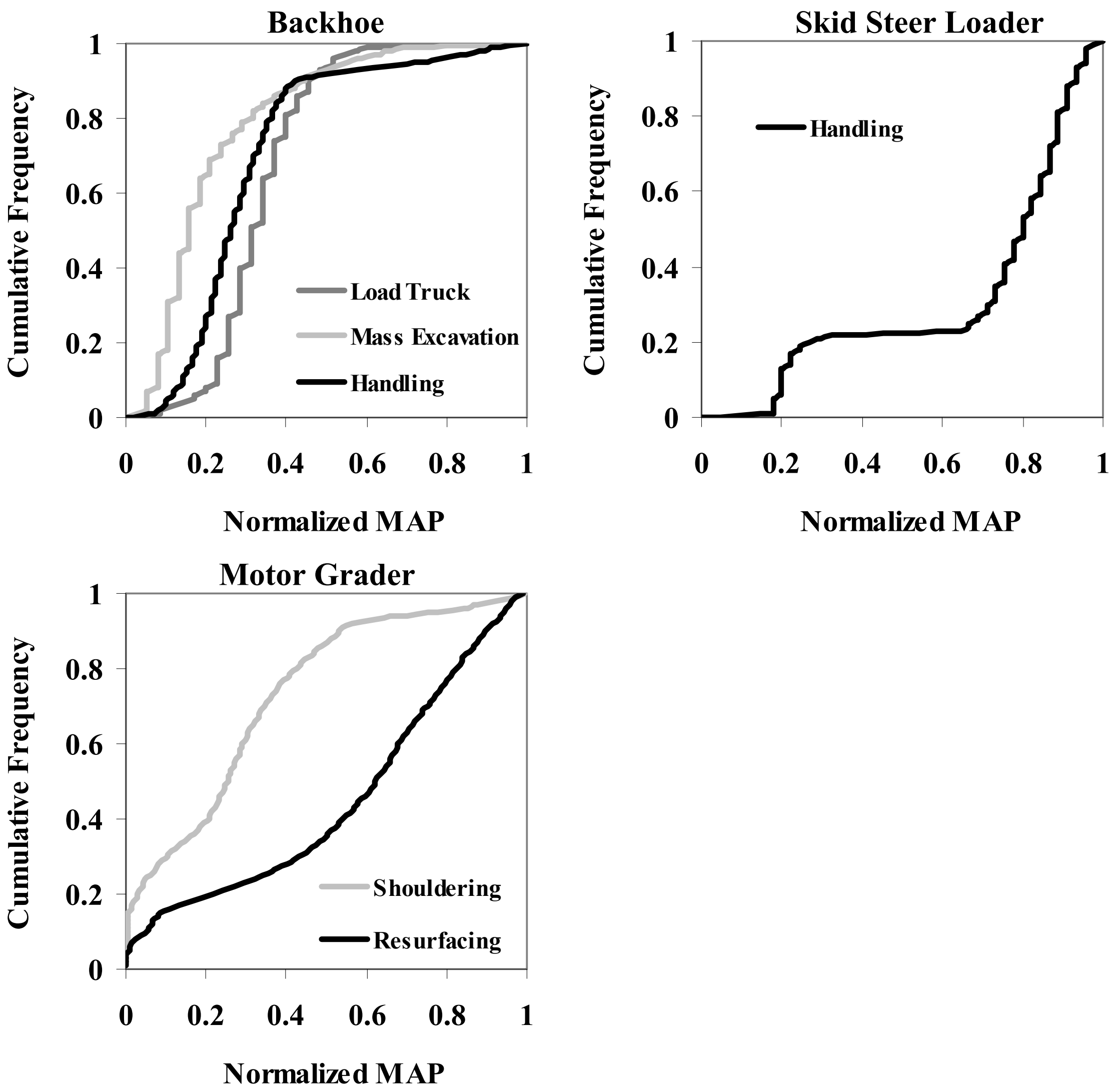

Figure 5.1 Continued.

In Table 5.1, for one specific vehicle, fuel use rates are estimated for each duty cycle. Duty cycles 4, 5, and 6 are estimated based on bulldozer activities. In order to show the inter-cycle and inter-engine variations among the same type of equipment, Engines 6, 7, 8, and 9 are grouped together (Engine 6, 7, 8, and 9 represent Dozer 1, 2, 3, and 4, respectively). Similarly, Engines 7, 8, and 9 are grouped together to show the inter-cycle and inter-engine variations for excavators. Table 5.1 shows the time-base emission factors which have significant inter-cycle and inter-engine variations among duty cycles. For example, the fuel use rates for Engine #1 (Front-End Loader 1) range from 1.4 g/sec to 4.2 g/sec among 16 duty cycles. This is a 200% difference between the high versus low values. In Table 5.2, the inter-cycle and inter-engine variations of time-based NO emission rates are shown.

In Table 5.2, generally, time-based NO emission factors have significant inter-cycle and inter-engine variations for all vehicles. For example, the time-based NO emission rates for Engine #10 (Excavator 1) range from 74 to 248 mg/sec. This is a 235% difference between the high versus low values. Among same type of equipment, the inter-cycle and inter-engine variations are also significant. For backhoes, the time-based NO emission rates for Engines #16 to 23 and Duty Cycles 11, 12, and 13 range from 22 mg/sec to 78 mg/sec. This is a 255% difference between the high versus low values.

Table 5.1 Inter-Engine and Inter-Cycle Variations of Time-Based Fuel Use Rates (g/sec)

DC	Engine																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DC1	2.3	2.1	1.9	2.4	1.9	1.7	1.3	2.6	3.6	3.7	3.0	1.4	4.0	5.3	5.0	1.4	1.7	1.1	0.9	1.6	1.6	1.4	0.9	0.5
DC2	2.2	2.0	1.9	2.3	1.8	1.7	1.3	2.5	3.5	3.6	2.9	1.3	3.8	5.1	4.8	1.3	1.7	1.1	0.9	1.5	1.6	1.4	0.8	0.5
DC3	2.3	2.2	2.0	2.4	1.9	1.8	1.4	2.7	3.7	3.8	3.0	1.4	4.0	5.4	5.1	1.4	1.8	1.2	1.0	1.6	1.7	1.5	0.9	0.5
DC4	2.7	2.6	2.3	2.9	2.3	2.2	1.6	3.2	4.4	4.6	3.6	1.7	4.8	6.5	6.2	1.6	2.2	1.4	1.1	2.0	2.0	1.8	1.1	0.6
DC5	2.4	2.3	2.1	2.6	2.0	1.9	1.4	2.8	3.9	4.1	3.2	1.5	4.3	5.8	5.5	1.5	1.9	1.2	1.0	1.7	1.8	1.6	1.0	0.6
DC6	1.9	1.8	1.6	1.9	1.5	1.4	1.1	2.1	3.0	3.0	2.5	1.1	3.3	4.4	4.1	1.1	1.4	0.9	0.8	1.3	1.3	1.2	0.7	0.4
DC7	2.2	2.1	1.9	2.3	1.9	1.7	1.3	2.6	3.5	3.7	2.9	1.4	3.9	5.2	4.9	1.3	1.7	1.1	0.9	1.6	1.6	1.4	0.9	0.5
DC8	2.5	2.3	2.1	2.7	2.1	2.0	1.5	2.9	4.0	4.1	3.3	1.5	4.4	5.9	5.6	1.5	1.9	1.3	1.0	1.8	1.8	1.6	1.0	0.6
DC9	3.1	3.0	2.8	3.5	2.7	2.6	1.9	3.8	5.2	5.4	4.2	2.0	5.6	7.7	7.3	1.9	2.6	1.6	1.3	2.3	2.3	2.2	1.3	0.7
DC10	1.4	1.3	1.1	1.4	1.1	0.9	0.8	1.5	2.1	2.1	1.8	0.8	2.4	3.1	2.8	0.8	1.0	0.7	0.5	1.0	0.9	0.7	0.5	0.3
DC11	2.3	2.2	2.0	2.5	1.9	1.8	1.4	2.7	3.7	3.8	3.1	1.4	4.1	5.5	5.2	1.4	1.8	1.2	1.0	1.7	1.7	1.5	0.9	0.5
DC12	2.1	2.0	1.8	2.2	1.8	1.6	1.3	2.4	3.4	3.5	2.8	1.3	3.7	5.0	4.7	1.3	1.6	1.1	0.9	1.5	1.5	1.3	0.8	0.5
DC13	1.7	1.5	1.4	1.7	1.3	1.2	1.0	1.8	2.6	2.6	2.2	1.0	2.9	3.8	3.5	1.0	1.2	0.8	0.7	1.2	1.1	1.0	0.6	0.4
DC14	4.2	4.1	3.8	4.8	3.7	3.7	2.6	5.3	7.2	7.5	5.7	2.8	7.7	11	10	2.6	3.6	2.2	1.9	3.1	3.2	3.1	1.8	1.0
DC15	3.4	3.3	3.1	3.9	3.0	2.9	2.1	4.2	5.8	6.0	4.7	2.3	6.2	8.6	8.2	2.1	2.9	1.8	1.5	2.6	2.6	2.5	1.5	0.8
DC16	2.0	1.8	1.7	2.0	1.6	1.5	1.2	2.2	3.1	3.2	2.6	1.2	3.4	4.6	4.3	1.2	1.5	1.0	0.8	1.4	1.4	1.2	0.8	0.5

(Continued on the next page)

Table 5.1 Continued.

DC	Engine					
	25	26	27	28	29	30
DC1	3.3	3.4	3.3	4.0	3.5	2.3
DC2	3.2	3.2	3.2	3.8	3.4	2.2
DC3	3.4	3.4	3.4	4.1	3.6	2.4
DC4	4.0	4.1	4.1	4.8	4.3	2.9
DC5	3.6	3.6	3.6	4.3	3.8	2.6
DC6	2.7	2.8	2.7	3.3	2.9	1.9
DC7	3.3	3.3	3.3	3.9	3.5	2.3
DC8	3.7	3.7	3.7	4.4	3.9	2.6
DC9	4.7	4.8	4.8	5.6	5.1	3.5
DC10	2.0	2.0	1.8	2.4	2.0	1.2
DC11	3.4	3.5	3.4	4.1	3.6	2.4
DC12	3.1	3.2	3.1	3.7	3.3	2.2
DC13	2.4	2.4	2.3	2.9	2.5	1.6
DC14	6.4	6.5	6.7	7.7	7.1	5.0
DC15	5.2	5.3	5.4	6.2	5.7	4.0
DC16	2.9	2.9	2.8	3.5	3.0	2.0

Engine 1 = Front-End Loader 1;
Engine 2 = Front-End Loader 2;
Engine 3 = Front-End Loader 3;
Engine 4 = Front-End Loader 4;
Engine 5 = Front-End Loader 5;
Engine 6 = Dozer 1;
Engine 7 = Dozer 2;
Engine 8 = Dozer 3;
Engine 9 = Dozer 4;
Engine 10 = Excavator 1;
Engine 11 = Excavator 2;
Engine 12 = Excavator 3;
Engine 13 = Off-Highway Truck 1;
Engine 14 = Off-Highway Truck 2;
Engine 15 = Off-Highway Truck 3;
Engine 16 = Backhoe 1;
Engine 17 = Backhoe 2;
Engine 18 = Backhoe 3;
Engine 19 = Backhoe 4;
Engine 20 = Backhoe 5;
Engine 21 = Backhoe 6;
Engine 22 = Backhoe 7;
Engine 23 = Backhoe 8;
Engine 24 = Skid Steer Loader;
Engine 25 = Motor Grader 1;
Engine 26 = Motor Grader 2;
Engine 27 = Motor Grader 3;
Engine 28 = Motor Grader 4;
Engine 29 = Motor Grader 5; and
Engine 30 = Motor Grader 6.

Table 5.2 Inter-Engine and Inter-Cycle Variations of Time-Based NO_x Emission Rates (mg/sec)

DC	Engine																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DC1	59	75	84	97	58	84	38	106	192	118	73	46	130	119	155	36	40	29	30	60	52	46	29	16
DC2	62	79	86	100	60	78	41	115	183	110	72	43	135	110	148	46	48	32	30	61	51	50	29	15
DC3	64	84	91	107	64	85	42	124	196	118	76	46	140	117	158	44	52	35	32	72	57	53	31	16
DC4	72	96	106	128	76	103	48	146	235	143	88	55	158	139	189	42	61	43	38	94	70	60	38	19
DC5	64	84	93	110	65	92	42	123	209	128	79	50	142	127	169	38	49	35	33	75	60	52	32	17
DC6	56	70	75	86	52	67	36	99	159	94	64	37	121	95	128	42	42	27	26	50	43	44	25	14
DC7	62	80	88	103	61	82	41	118	190	115	74	45	135	114	153	41	49	34	31	68	54	50	30	16
DC8	60	78	90	106	62	97	39	113	216	136	78	53	135	136	174	29	42	32	33	72	59	47	31	17
DC9	72	98	114	136	80	126	47	145	278	176	97	68	163	173	224	27	53	42	42	102	79	58	41	21
DC10	39	45	51	55	33	52	23	59	122	74	47	30	84	80	96	20	21	15	18	30	29	28	17	10
DC11	68	90	96	115	69	84	46	137	198	117	79	45	148	114	160	54	62	40	34	78	59	58	33	17
DC12	61	78	84	98	58	76	40	112	178	107	71	42	133	107	144	48	48	31	29	57	49	49	29	15
DC13	50	60	65	73	44	58	32	84	139	82	57	33	108	85	112	37	34	23	23	40	37	39	22	12
DC14	77	101	130	151	86	172	49	134	366	248	117	98	184	251	299	17	35	33	47	89	91	54	45	25
DC15	73	97	118	139	81	140	47	139	304	198	102	77	168	198	247	22	46	38	43	96	82	56	42	22
DC16	55	69	76	88	53	73	35	100	169	103	66	40	120	104	136	37	41	28	27	55	46	44	26	14

(Continued on the next page)

Table 5.2 Continued.

DC	Engine					
	25	26	27	28	29	30
DC1	128	119	108	158	150	49
DC2	123	122	103	152	153	48
DC3	129	128	110	162	165	50
DC4	150	146	130	192	198	57
DC5	136	130	117	172	170	52
DC6	109	109	90	132	132	43
DC7	126	124	107	157	158	49
DC8	140	126	121	176	165	52
DC9	174	155	153	225	214	63
DC10	87	77	70	101	85	34
DC11	130	134	110	164	176	51
DC12	120	120	101	148	149	47
DC13	98	97	80	117	112	39
DC14	228	178	205	290	238	78
DC15	190	160	169	244	219	67
DC16	114	109	96	140	136	44

Engine 1 = Front-End Loader 1;
Engine 2 = Front-End Loader 2;
Engine 3 = Front-End Loader 3;
Engine 4 = Front-End Loader 4;
Engine 5 = Front-End Loader 5;
Engine 6 = Dozer 1;
Engine 7 = Dozer 2;
Engine 8 = Dozer 3;
Engine 9 = Dozer 4;
Engine 10 = Excavator 1;
Engine 11 = Excavator 2;
Engine 12 = Excavator 3;
Engine 13 = Off-Highway Truck 1;
Engine 14 = Off-Highway Truck 2;
Engine 15 = Off-Highway Truck 3;
Engine 16 = Backhoe 1;
Engine 17 = Backhoe 2;
Engine 18 = Backhoe 3;
Engine 19 = Backhoe 4;
Engine 20 = Backhoe 5;
Engine 21 = Backhoe 6;
Engine 22 = Backhoe 7;
Engine 23 = Backhoe 8;
Engine 24 = Skid Steer Loader;
Engine 25 = Motor Grader 1;
Engine 26 = Motor Grader 2;
Engine 27 = Motor Grader 3;
Engine 28 = Motor Grader 4;
Engine 29 = Motor Grader 5; and
Engine 30 = Motor Grader 6.

In addition, there are inter-cycle and inter-engine variations when predicting fuel-based emission factors. The predicted fuel-based NO emission rates are shown in Table 5.3. In general, inter-cycle and inter-engine variations for fuel-based NO emission factors are not as significant as time-based emission rates. For example, the fuel-based NO emission rates for Engine #10 (Excavator 1) range from 97 to 112 g/gal. This is a 15% difference between the high versus low values, as compared to 235% for time-based NO emission rates. The inter-cycle variations among the 16 duty cycles are estimated for the engines of all vehicles and equipment. In Table 5.4, the ratios of the high versus low average fuel use and emissions rates are given based on comparison of the duty cycles. Similarly, Table 5.5 shows the ratios for high versus low fuel-based emission rates.

Table 5.3 Inter-Engine and Inter-Cycle Variations of Fuel-Based NO_x Emission Rates (g/gal)

DC	Engine																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DC1	82	114	141	129	97	157	93	130	170	101	77	104	103	71	99	82	75	84	106	119	103	104	102	102
DC2	90	126	144	138	106	146	100	146	166	97	79	105	113	69	98	113	90	93	106	129	101	114	115	95
DC3	88	121	145	142	107	150	95	146	168	99	81	104	111	69	99	100	92	93	102	143	107	112	110	102
DC4	85	117	147	140	105	149	95	145	170	99	78	103	105	68	97	83	88	98	110	149	111	106	110	101
DC5	85	116	141	135	103	154	95	140	170	99	79	106	105	70	98	81	82	93	105	140	106	103	102	90
DC6	94	124	149	144	110	152	104	150	169	100	81	107	117	69	99	121	95	95	103	122	105	117	114	111
DC7	90	121	147	142	102	153	100	144	173	99	81	102	110	70	99	100	92	98	110	135	107	114	106	102
DC8	76	108	136	125	94	154	83	124	172	105	75	112	98	73	99	61	70	78	105	127	104	93	99	90
DC9	74	104	129	124	94	154	79	121	170	104	73	108	93	71	98	45	65	83	103	141	109	84	100	95
DC10	89	110	147	125	95	184	91	125	185	112	83	119	111	82	109	80	67	68	114	95	102	127	108	106
DC11	94	130	153	146	115	148	104	161	170	98	81	102	115	66	98	123	110	106	108	146	110	123	117	108
DC12	92	124	148	142	102	151	98	148	166	97	81	103	114	68	97	117	95	90	102	121	104	120	115	95
DC13	94	127	148	137	108	154	102	148	170	100	82	105	118	71	102	118	90	91	104	106	107	124	117	95
DC14	58	78	109	100	74	148	60	80	162	105	65	111	76	75	94	21	31	48	79	91	90	55	80	80
DC15	68	93	121	113	86	154	71	105	167	105	69	106	86	73	96	33	50	67	91	117	100	71	89	87
DC16	87	122	142	140	105	155	93	145	173	102	81	106	112	72	101	98	87	89	107	125	104	117	103	89

(Continued on the next page)

Table 5.3 Continued.

DC	Engine					
	25	26	27	28	29	30
DC1	123	111	104	126	136	68
DC2	122	121	102	127	143	69
DC3	121	120	103	126	146	66
DC4	119	113	101	127	146	63
DC5	120	115	103	127	142	64
DC6	128	124	106	127	145	72
DC7	121	119	103	128	144	68
DC8	120	108	104	127	135	64
DC9	118	103	101	128	133	57
DC10	138	122	124	134	135	90
DC11	122	122	103	127	155	68
DC12	123	119	104	127	144	68
DC13	130	129	111	128	142	78
DC14	113	87	97	120	107	50
DC15	116	96	100	125	122	53
DC16	125	120	109	127	144	70

Engine 1 = Front-End Loader 1;
Engine 2 = Front-End Loader 2;
Engine 3 = Front-End Loader 3;
Engine 4 = Front-End Loader 4;
Engine 5 = Front-End Loader 5;
Engine 6 = Dozer 1;
Engine 7 = Dozer 2;
Engine 8 = Dozer 3;
Engine 9 = Dozer 4;
Engine 10 = Excavator 1;
Engine 11 = Excavator 2;
Engine 12 = Excavator 3;
Engine 13 = Off-Highway Truck 1;
Engine 14 = Off-Highway Truck 2;
Engine 15 = Off-Highway Truck 3;
Engine 16 = Backhoe 1;
Engine 17 = Backhoe 2;
Engine 18 = Backhoe 3;
Engine 19 = Backhoe 4;
Engine 20 = Backhoe 5;
Engine 21 = Backhoe 6;
Engine 22 = Backhoe 7;
Engine 23 = Backhoe 8;
Engine 24 = Skid Steer Loader;
Engine 25 = Motor Grader 1;
Engine 26 = Motor Grader 2;
Engine 27 = Motor Grader 3;
Engine 28 = Motor Grader 4;
Engine 29 = Motor Grader 5; and
Engine 30 = Motor Grader 6.

Table 5.4 Ratio of High versus Low Value for Cycle Average Time-Based Fuel Use and Emission Rates Based on Comparisons of 16 Duty Cycles for Engines of Each of 30 Tested Engines

Engines [a]	Fuel		CO_2		NO		Opacity		HC		CO	
	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient
Engine 1	11.0	5.0	11.0	5.0	7.0	3.9	20.6	7.8	4.6	4.1	9.0	4.2
Engine 2	9.9	4.8	9.9	4.8	7.0	3.2	17.4	6.0	3.1	2.8	2.2	2.1
Engine 3	10.2	4.7	10.2	4.7	6.2	3.5	5.8	3.1	3.8	2.6	2.5	2.1
Engine 4	10.4	4.1	10.4	4.1	7.7	3.2	11.6	5.6	3.1	2.3	2.4	2.1
Engine 5	12.1	5.6	12.1	5.6	9.0	3.9	17.9	6.3	3.8	3.5	8.7	3.2
Engine 6	13.4	3.9	13.4	3.9	8.1	2.8	16.9	2.7	2.5	1.5	4.0	1.5
Engine 7	9.2	6.4	9.2	6.4	6.3	4.5	29.3	13.2	4.3	3.9	1.9	1.8
Engine 8	11.5	9.9	11.5	9.9	10.4	8.9	16.6	16.7	2.7	2.5	1.0	1.1
Engine 9	10.8	5.4	10.8	5.4	7.8	4.5	8.4	3.8	3.9	2.5	5.7	2.7
Engine 10	16.1	5.6	16.1	5.6	9.8	6.3	22.0	7.0	3.3	1.7	3.8	1.4
Engine 11	10.3	3.2	10.3	3.2	5.7	2.3	21.5	5.9	3.2	1.7	3.1	1.4
Engine 12	9.0	2.1	9.0	2.1	6.1	2.0	11.5	2.7	3.2	1.4	1.8	1.3
Engine 13	10.6	5.3	10.6	5.3	5.9	4.0	16.6	6.9	6.0	4.1	32.4	7.0
Engine 14	12.6	4.3	12.6	4.3	6.2	4.1	16.1	3.9	4.1	1.8	10.0	2.2
Engine 15	12.6	4.3	12.6	4.3	6.2	4.1	13.0	3.9	4.0	2.1	3.9	1.9
Engine 16	9.2	5.7	9.2	5.7	6.4	2.8	5.2	3.5	2.6	3.5	1.9	4.2
Engine 17	9.7	3.2	9.7	3.2	11.1	2.6	12.4	6.4	2.3	1.5	6.9	2.5
Engine 18	9.0	6.0	9.0	6.0	12.7	5.5	4.4	3.6	3.2	2.8	3.7	3.2
Engine 19	13.8	4.1	13.8	4.1	7.6	2.8	14.6	4.5	8.0	2.6	15.9	4.0
Engine 20	14.4	4.0	14.4	4.0	53.1	6.7	4.4	4.1	2.6	1.9	35.3	15.9

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Table 5.4 Continued.

Engines [a]	Fuel		CO_2		NO		Opacity		HC		CO	
	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient
Engine 21	16.1	5.2	16.1	5.2	13.7	4.6	8.4	5.2	9.9	6.0	11.1	4.9
Engine 22	10.3	5.6	10.3	5.6	3.9	2.2	33.1	12.3	1.7	1.8	8.6	5.5
Engine 23	13.2	4.1	13.2	4.1	7.6	2.9	13.7	4.9	4.6	2.9	8.5	3.4
Engine 24	10.2	3.2	10.2	3.2	5.9	2.4	9.0	2.9	3.8	1.5	2.1	1.4
Engine 25	9.3	4.2	9.3	4.2	6.0	3.2	7.8	3.4	4.2	2.7	3.9	2.7
Engine 26	11.4	4.0	11.4	4.0	6.4	2.7	12.1	3.5	3.9	1.3	3.7	2.7
Engine 27	18.6	6.0	18.6	6.0	11.0	4.9	20.3	5.0	7.7	3.4	7.4	4.0
Engine 28	10.1	4.9	10.1	4.9	9.4	4.5	22.3	7.6	2.7	2.3	2.6	2.2
Engine 29	13.4	4.5	13.4	4.5	11.9	4.0	11.3	3.7	3.7	1.9	1.5	1.4
Engine 30	15.4	5.9	15.4	5.9	5.8	3.1	16.4	5.4	7.1	2.9	12.3	6.8
Average	**11.8**	**4.8**	**11.8**	**4.8**	**9.4**	**3.9**	**14.7**	**5.7**	**4.1**	**2.6**	**7.3**	**3.4**

[a] Engine 1 = Front-End Loader 1; Engine 2 = Front-End Loader 2;
Engine 3 = Front-End Loader 3; Engine 4 = Front-End Loader 4;
Engine 5 = Front-End Loader 5; Engine 6 = Dozer 1;
Engine 7 = Dozer 2; Engine 8 = Dozer 3;
Engine 9 = Dozer 4; Engine 10 = Excavator 1;
Engine 11 = Excavator 2; Engine 12 = Excavator 3;
Engine 13 = Off-Highway Truck 1; Engine 14 = Off-Highway Truck 2;
Engine 15 = Off-Highway Truck 3; Engine 16 = Backhoe 1;
Engine 17 = Backhoe 2; Engine 18 = Backhoe 3;
Engine 19 = Backhoe 4; Engine 20 = Backhoe 5;
Engine 21 = Backhoe 6; Engine 22 = Backhoe 7;
Engine 23 = Backhoe 8; Engine 24 = Skid Steer Loader;
Engine 25 = Motor Grader 1; Engine 26 = Motor Grader 2;
Engine 27 = Motor Grader 3; Engine 28 = Motor Grader 4;
Engine 29 = Motor Grader 5; Engine 30 = Motor Grader 6.

Table 5.5 Ratio of High versus Low Value for Cycle Average Fuel-Based Emission Rates Based on Comparisons of 16 Duty Cycles for Engines of Each of 30 Tested Engines

Engines [a]	NO		Opacity		HC		CO	
	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient
Engine 1	1.0	1.3	1.9	1.5	1.0	1.3	1.0	1.3
Engine 2	1.1	1.5	1.0	1.3	1.0	1.7	1.8	2.2
Engine 3	1.0	1.4	1.0	1.5	1.0	1.9	1.0	2.3
Engine 4	1.0	1.3	1.1	1.4	1.0	1.8	1.0	1.9
Engine 5	1.1	1.5	1.5	1.5	1.0	1.8	1.3	1.8
Engine 6	1.0	1.7	2.2	1.8	1.0	5.8	1.0	3.6
Engine 7	1.0	1.5	2.3	3.1	1.0	1.7	1.0	4.0
Engine 8	1.0	1.1	1.4	1.7	1.0	4.1	1.0	10.3
Engine 9	1.0	1.3	1.0	1.7	1.0	2.3	1.0	2.4
Engine 10	1.0	1.1	1.4	1.3	1.0	3.8	1.0	4.5
Engine 11	1.0	1.5	2.1	2.0	1.0	2.3	1.1	4.9
Engine 12	1.0	1.1	1.2	1.7	1.0	1.4	1.0	2.2
Engine 13	1.0	1.3	1.9	1.6	1.0	1.3	1.7	3.8
Engine 14	1.0	1.2	1.0	1.4	1.0	3.5	1.0	1.6
Engine 15	1.0	1.1	1.0	1.3	1.0	2.2	1.0	2.8
Engine 16	1.4	2.1	1.0	1.8	1.0	1.7	1.0	1.4
Engine 17	1.4	1.3	1.5	2.8	1.0	2.5	1.0	1.4
Engine 18	1.0	1.5	1.0	1.6	1.0	2.4	1.0	2.0
Engine 19	1.0	1.4	1.1	1.3	1.0	1.6	1.2	1.3
Engine 20	1.7	3.7	1.0	1.4	1.0	2.3	1.5	3.7

(Continued on the next page)

Table 5.5 Continued

Engines [a]	NO		Opacity		HC		CO	
	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient	Max vs Idle	Transient
Engine 21	1.0	1.2	1.0	1.7	1.0	2.9	1.1	1.7
Engine 22	1.0	2.7	1.4	2.3	1.0	6.6	1.0	1.5
Engine 23	1.0	1.5	1.0	1.4	1.0	1.8	1.0	1.5
Engine 24	1.0	1.3	1.0	1.5	1.0	2.1	1.0	2.2
Engine 25	1.0	1.3	1.0	1.2	1.0	2.0	1.0	1.6
Engine 26	1.0	1.6	1.2	1.3	1.0	3.6	1.3	10.6
Engine 27	1.0	1.5	1.3	1.3	1.0	2.4	1.0	2.2
Engine 28	1.0	1.4	2.2	1.5	1.0	2.2	1.0	2.1
Engine 29	1.0	1.3	1.1	1.3	1.0	2.8	1.0	5.3
Engine 30	1.0	2.3	1.5	1.6	1.2	5.4	1.3	3.9
Average	**1.1**	**1.5**	**1.3**	**1.6**	**1.0**	**2.6**	**1.1**	**3.1**

[a]

Engine 1 = Front-End Loader 1; Engine 2= Front-End Loader 2;
Engine 3 = Front-End Loader 3; Engine 4= Front-End Loader 4;
Engine 5 = Front-End Loader 5; Engine 6= Dozer 1;
Engine 7 = Dozer 2; Engine 8= Dozer 3;
Engine 9 = Dozer 4; Engine 10 = Excavator 1;
Engine 11 = Excavator 2; Engine 12 = Excavator 3;
Engine 13 = Off-Highway Truck 1; Engine 14 = Off-Highway Truck 2;
Engine 15 = Off-Highway Truck 3; Engine 16 = Backhoe 1;
Engine 17 = Backhoe 2; Engine 18 = Backhoe 3;
Engine 19 = Backhoe 4; Engine 20 = Backhoe 5;
Engine 21 = Backhoe 6; Engine 22 = Backhoe 7;
Engine 23 = Backhoe 8; Engine 24 = Skid Steer Loader;
Engine 25 = Motor Grader 1; Engine 26 = Motor Grader 2;
Engine 27 = Motor Grader 3; Engine 28 = Motor Grader 4;
Engine 29 = Motor Grader 5; Engine 30 = Motor Grader 6.

In Table 5.4, for each variable (fuel, CO_2, NO, Opacity, HC, and CO), one ratio, labeled as “Max vs. Idle,” is with respect to maximum versus idling value. The other ratio, labeled as “Transient,” is with respect to duty cycles that are not 100% idling and comparing the high versus low value of 16 cycles that represent variations in engine load.

For “Max vs. Idle,” the average ratios of high versus low value for time-based fuel use, CO_2, NO, Opacity, HC, and CO emission rates are 11.8, 11.8, 9.4, 14.7, 4.1, and 7.3, respectively. The highest average ratio is for opacity, because opacity rate is more sensitive to engine load.

For “Transient Cycle,” the average ratios of high versus low value for fuel use, CO_2, NO, Opacity, HC, and CO are 4.8, 4.8, 3.9, 5.7, 2.6, and 3.4, respectively. Similarly, the highest average ratio is for opacity and the lowest ratios are for HC and CO. The ratios indicated that inter-cycle variations of fuel use and emission rates are significant for all engines. Opacity is the most sensitive variable to different engine load.

The ratio of high versus low value for cycle average fuel-based emission rates based on comparisons of 16 duty cycles for engines of each of 30 tested engines are shown in Table 5.5. For "Max vs. Idle," the average ratios for high versus low value for NO, Opacity, HC, and CO emission rates are 1.1, 1.3, 1.0, and 1.1, respectively. Some of these ratios are 1.0 because the fuel-based emission rate in some cases is highest for idling when comparing to transient cycles. For NO, there are some exceptions for Engines 2, 5, 16, 17 and 20, because NO formation is a nonlinear function with respect to manifold absolute pressure (MAP). For CO, there are some exceptions, because a substantial proportion of the measured exhaust gas concentrations of CO are below the detection limit. There is less confidence in the fuel-based emission rates when a large proportion of the measured CO concentrations are below the detection limits. Thus, due to the low exhaust CO concentration of diesel engine; this ratio of high versus low value for CO may not be robust. The highest average ratio is for opacity, which is similar to the results shown in Table 5.4. The ratios are much lower than those for time-based emission rates. For example, the average ratios of high versus low value for NO are 9.4 for time-based emission rates and 1.1 for fuel-based emission rates.

For “Transient Cycle,” the average ratios of high versus low value for NO, Opacity, HC, and CO are 1.5, 1.6, 2.6, and 3.1, respectively. The average ratios for fuel-based emission rates are substantially lower than those for time-based emission rates. For example, the average ratios of high versus low value for NO are 3.9 for time-based emission rates and 1.5 for fuel-based emission rates. The results indicated that fuel-based emission rates are less sensitive to differences in duty cycles. In order to assess the correlation between emission rates and fuel flow, a rank correlation was done for Engine 6 data as an example. Based on an example of Engine 6, the rank correlation of fuel use with each of emission rates are 1.00 for CO_2, 0.96 for NO, 0.96 for Opacity, 0.94 for HC, and 0.73 for CO. The results indicate that CO_2, NO, Opacity, HC, and CO emission rates are highly correlated with fuel use. Because of the high correlation between emission rate and fuel use, there is less variability in the fuel-based versus time-based approach.

The inter-engine variations among the 30 engines are estimated for the engines of all duty cycles. In Table 5.6, the ratios of the high versus low average fuel use and emissions rates are given based on comparison of the duty cycles. Similarly, Table 5.7 shows the ratios for high versus low fuel-based emission rates.

For time-based emission rates shown in Table 5.6, the average ratios for fuel use, CO_2, NO, Opacity, HC, and CO are 10.4, 10.3, 12.8, 25.9, 9.8, and 27.3, respectively. The highest average ratios are for CO and opacity, which means that CO and opacity are sensitive to not only different duty cycle, but also sensitive to different engines.

For fuel-based emission rates shown in Table 5.7, the average ratios for NO, Opacity, HC, and CO are 3.1, 11.7, 4.3, and 15.0, respectively. The highest average ratios are for CO and opacity, which means fuel-based CO and opacity rates are also sensitive to different engines. For NO, Opacity, HC, and CO, the fuel-based emission rates are less sensitive to different engine than time-based emission rates. An example of scatter plot for time-based and fuel-based NO emission rate versus engine displacement is shown in Figure 5.2 for 30 engines based on Duty Cycle 11. The R^2 is 0.66 for time-based emission rate and 0.014 for fuel-based emission rates. The results indicate that average fuel based emission rates are less sensitive to variations among engines than time-based rates.

Table 5.6 Ratio of High versus Low Value for Cycle Average Time-Based Fuel Use and Emission Rates Based on Comparisons of 30 Engines for Each of 16 Duty Cycle [a]

Duty Cycle [b]	Fuel	CO_2	NO	Opacity	HC	CO
Duty Cycle 1	10.6	10.4	12.0	25.0	9.6	27.0
Duty Cycle 2	10.2	10.1	12.2	23.3	9.9	26.8
Duty Cycle 3	10.8	10.1	12.3	25.0	9.7	27.7
Duty Cycle 4	10.8	10.8	12.4	25.7	9.4	27.6
Duty Cycle 5	9.7	10.7	12.3	26.7	9.6	27.6
Duty Cycle 6	11.0	9.9	11.4	24.0	10.2	26.6
Duty Cycle 7	10.4	10.3	11.9	25.0	9.6	27.6
Duty Cycle 8	9.8	10.3	12.7	28.3	9.7	27.3
Duty Cycle 9	11.0	10.5	13.2	24.4	9.5	27.9
Duty Cycle 10	10.3	9.7	12.2	30.0	11.1	25.9
Duty Cycle 11	11.0	10.2	11.6	26.7	9.4	27.0
Duty Cycle 12	10.0	10.5	11.9	28.0	9.8	27.1
Duty Cycle 13	9.5	9.9	11.6	27.5	10.7	26.1
Duty Cycle 14	10.6	11.1	21.5	25.0	9.5	30.0
Duty Cycle 15	10.8	10.8	13.8	24.0	9.4	28.4
Duty Cycle 16	9.2	10.3	12.1	26.0	9.9	26.8
Average	**10.4**	**10.3**	**12.8**	**25.9**	**9.8**	**27.3**

[a] 30 engines were compared, including Front-End Loader 1, Front-End Loader 2, Front-End Loader 3, Front-End Loader 4, Front-End Loader 5, Dozer 1, Dozer 2, Dozer 3, Dozer 4, Excavator 1, Excavator 2, Excavator 3, Off-Highway Truck 1, Off-Highway Truck 2, Off-Highway Truck 3, Backhoe 1, Backhoe 2, Backhoe 3, Backhoe 4, Backhoe 5, Backhoe 6, Backhoe 7, Backhoe 8, Skid Steer Loader, Motor Grader 1, Motor Grader 2, Motor Grader 3, Motor Grader 4, Motor Grader 5, and Motor Grader 6.

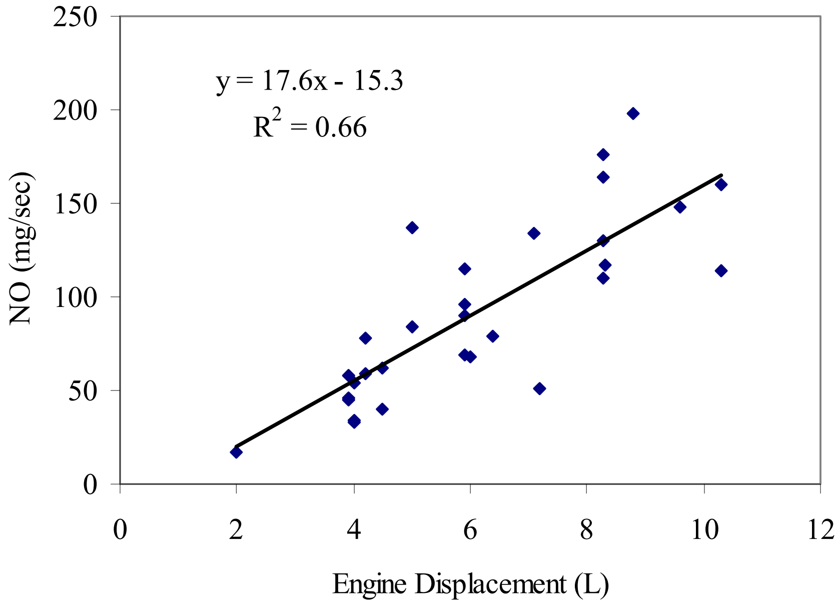
[b] Duty Cycles 1, 2, and 3 are associated with the test on a Front-End Loader;
Duty Cycles 4, 5, and 6 are associated with the test on a Dozer;
Duty Cycles 7, 8, and 9 are associated with the test on an Excavator;
Duty Cycle 10 is associated with the test on an Off-Highway Truck;
Duty Cycles 11, 12, and 13 are associated with the test on a Backhoe;
Duty Cycle 14 is associated with the test on Skid Steer Loader; and
Duty Cycles 15 and 16 are associated with the test on a Motor Grader.

Table 5.7 Ratio of High versus Low Value for Cycle Average Fuel-Based Emission Rates Based on Comparisons of 30 Engines for Each of 16 Duty Cycle [a]

Duty Cycle [b]	NO	Opacity	HC	CO
Duty Cycle 1	2.5	11.8	4.1	14.9
Duty Cycle 2	2.4	10.4	4.2	15.1
Duty Cycle 3	2.5	11.4	4.3	15.5
Duty Cycle 4	2.7	11.7	4.4	15.4
Duty Cycle 5	2.7	12.5	4.2	16.1
Duty Cycle 6	2.5	10.5	4.1	14.7
Duty Cycle 7	2.5	10.7	4.2	14.8
Duty Cycle 8	2.8	12.9	4.2	15.1
Duty Cycle 9	3.8	11.0	4.7	16.4
Duty Cycle 10	2.8	12.6	3.9	10.7
Duty Cycle 11	2.6	11.5	4.1	14.5
Duty Cycle 12	2.5	13.0	4.1	14.9
Duty Cycle 13	2.4	11.6	4.0	13.0
Duty Cycle 14	7.8	12.0	5.1	17.6
Duty Cycle 15	5.0	11.2	4.8	16.6
Duty Cycle 16	2.5	12.0	4.1	14.4
Average	**3.1**	**11.7**	**4.3**	**15.0**

[a] 30 engines were compared, including Front-End Loader 1, Front-End Loader 2, Front-End Loader 3, Front-End Loader 4, Front-End Loader 5, Dozer 1, Dozer 2, Dozer 3, Dozer 4, Excavator 1, Excavator 2, Excavator 3, Off-Highway Truck 1, Off-Highway Truck 2, Off-Highway Truck 3, Backhoe 1, Backhoe 2, Backhoe 3, Backhoe 4, Backhoe 5, Backhoe 6, Backhoe 7, Backhoe 8, Skid Steer Loader, Motor Grader 1, Motor Grader 2, Motor Grader 3, Motor Grader 4, Motor Grader 5, and Motor Grader 6.

[b] Duty Cycles 1, 2, and 3 are associated with the test on a Front-End Loader;
Duty Cycles 4, 5, and 6 are associated with the test on a Dozer;
Duty Cycles 7, 8, and 9 are associated with the test on an Excavator;
Duty Cycle 10 is associated with the test on an Off-Highway Truck;
Duty Cycles 11, 12, and 13 are associated with the test on a Backhoe;
Duty Cycle 14 is associated with the test on Skid Steer Loader; and
Duty Cycles 15 and 16 are associated with the test on a Motor Grader.



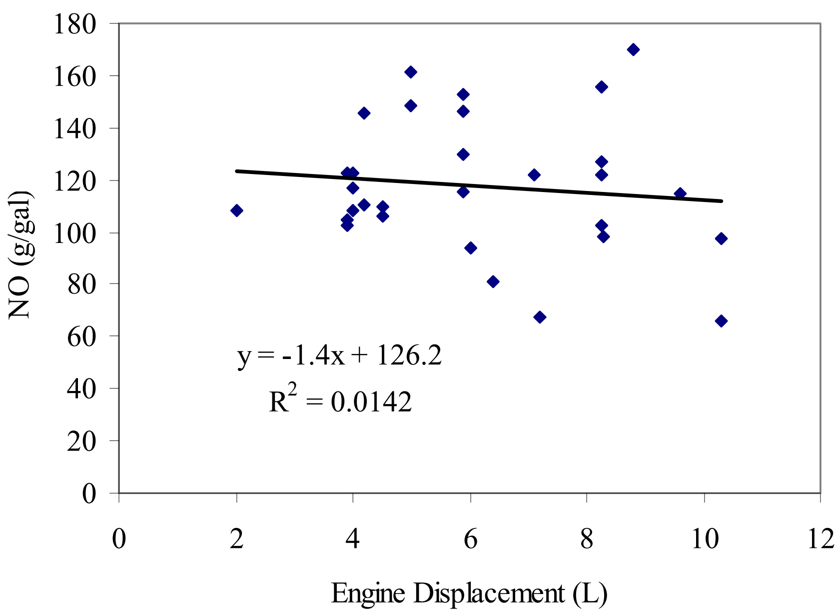


Figure 5.2 Scatter Plot of Time-Based and Fuel-Based NO Emission Rate versus Engine Displacement Based on Duty Cycle 11

5.4 Discussion

Data from nonroad construction vehicles were obtained using a portable emissions measurement system (PEMS) to quantify second-by-second fuel use and emissions based on real-world activities. This paper applied recently collected in-use data to gain insight into real-world variability in fuel use and emissions when comparing different duty cycle and vehicles.

Representative duty cycles for each type of vehicles were characterized by a frequency distribution of normalized manifold absolute pressure (MAP). Vehicle-specific models for fuel use and tailpipe emissions were developed for each of the construction vehicle based on physically-based regression model.

In order to assess the variations of fuel use and emissions among different duty cycles, for a given engine, the inter-cycle variability is assessed. In order to assess the variations of fuel use and emissions among engines, for a given duty cycle, the inter-engine variability is assessed. An engine that is used in one type of vehicle could potentially be used in a different type of vehicle Thus, cycle-average emission rates were estimated for each engine for each of the 16 duty cycles.

The results indicated time-based inter-cycle and inter-engine variations of fuel use and emissions are significant. Fuel-based emission factors have less variability among cycles and engines than time-based emission factors. Fuel-based emission factors are more robust with respect to inter-engine and inter-cycle variations. The fuel-based emission rates are recommended in order to develop an emissions inventory for nonroad construction vehicles because of less inter-cycle and inter-vehicle variations. Real-world in-use measurements should be a basis for developing duty cycle correction factors in models such as NONROAD.

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PART VI REVIEW OF PREVIOUS LIFE CYCLE STUDIES

The purpose of this section is to review previous life cycle studies. There are eleven life cycle studies discussed in this section. However, sufficient information is available for only five of these for purpose of conducting comparisons of life cycle components. A comparison of these five life cycle studies is provided in Table 6.1. Discussions will be provided in Section 6.6.

6.1 The Greenhouse Gases, Regulated Emissions, and Energy consumption in Transportation (GREET) Model

The Greenhouse Gases, Regulated Emissions, and Energy consumption in Transportation model (GREET) was developed by the Argonne National Laboratory (ANL) in the mid-1990s for the United States Department of Energy (Wang, M. 1999a, 1999b). The GREET model was developed to calculate per-mile energy consumption and emission rates of various combinations of vehicle technologies.

The GREET separates energy cycles into fuel and vehicle cycles. The fuel cycle includes the feedstock production, transportation, and storage; fuel production, transportation, storage, and distribution. The vehicle cycle includes primary material recovery, vehicle production, vehicle operation, and vehicle disposal/recycling.

The GREET model aggregates energy consumption and emissions from all stages of the life cycle and takes into account loss of fuel during the fuel cycle. Combustion emissions are estimated based on the amount of fuel burned and combustion emission factors. Emission factors of HC, CO, NO_x, and PM_{10} were primarily derived by ANL from the fifth edition of EPA's AP-42 document (EPA 1995).

6.2 Lifecycle Emissions Model (LEM)

DeLucchi (2003) developed a comprehensive life cycle model, known as Life cycle Emissions Model (LEM), in 2003. The LEM was developed in order to evaluate different strategies for reducing emissions of urban air pollutants and greenhouse gases. LEM estimates energy consumption, criteria pollutant emissions, and CO_2-equivalent GHG emissions from a variety of transportation and energy life cycles. LEM includes a wide range of vehicles and input data for 30 countries, for the years 1970 to 2050. The system boundaries of LEM fuel cycle included feedstock production, feedstock transport, fuel production, fuel distribution, and storage, and the end use of a finished fuel product. Feedstock is the materials to produce fuel product, such as coal, petroleum, or natural gas etc.

For the vehicle life cycle, the system boundaries include materials use, and operation/maintenance. The LEM estimates emissions of carbon dioxide (CO_2), total particulate matter (PM), methane (CH_4), particulate matter (PM_{10}), nitrous oxide (N_2O), hydrogen (H_2), carbon monoxide (CO), chlorofluorocarbons (CFC-12), nitrogen oxides (NO_x), hydrofluorocarbons (HFC-134a), non-methane organic compounds ($NMOC_s$), sulfur dioxide (SO_2) and the CO_2-equivalent of all of these pollutants.

6.3 GM Well-to-Wheel North American Study

The purpose of the GM Well-to-Wheel North American study is to evaluate the energy and greenhouse gases (GHG) emission impacts associated with producing different transportation fuels (GM 2001). The GM Well-to-Wheel North American study focused on the U.S. light-duty vehicle market in 2005 and beyond. The study included different fuels and vehicles for which best estimates of life cycle emissions as well as comparisons between fuel/vehicle propulsion systems. A Hybrid Powertrain Simulation Program (HPSP) was developed by General Motors, which is a proprietary tool to predict vehicle fuel economy. The GREET model was used to estimate fuel cycle energy consumption and emission impacts of alternative transportation fuels.

GM European study was intended to provide advice to decision makers from different sectors of society and economy (GM 2002). For the given target year of 2010, the study evaluated the key elements of fuel production, supply, distribution and ultimate consumption within the vehicle life cycle.

6.4 Economic Input-Output Life-Cycle Analysis Model

MacLean *et al.* developed an Economic Input-Output Life-Cycle Analysis model (EIO-LCA). This model includes arrays of indicators which quantify the affect of a product or service on the economy and the environment (Maclean *et al.* 1998). The purpose of the EIO-LCA model is to quantify the economic impact, resource use, and environmental discharges from the life cycle. The model has been applied to quantify the overall life cycle of an automobile from manufacture to end disposal.

Lave *et al.* studied life cycle analysis of alternative automobile fuel and propulsion technologies by examining the economic and environmental implications of the fuels and propulsion technologies (Lave *et al.* 2000). The purpose was to find out the desirable fuel/propulsion options for light duty vehicle (LDV) in the next decades. EIO-LCA was used to investigate the entire supply chain, from the extraction of materials and fuels, for 485 sectors of the U.S. economy. MacLean *et al.* also evaluated fuel/vehicle options with the potential to create greener cars (Maclean *et al.* 2003).

6.5 National Renewable Energy Laboratory Study

Sheehan *et al.* conducted a study of biodiesel and petroleum diesel life cycles in 1998 (Sheehan *et al.* 1998). The study quantified and compared a comprehensive set of environmental flows associated with biodiesel and petroleum diesel. The system boundary of petroleum diesel included crude oil extraction, crude oil transportation, diesel refining, diesel fuel transportation and fuel use. The geographical boundary was limited to the use of petroleum diesel and biodiesel in the United States.

The study included overall energy requirements, CO_2 emissions, other pollutant emissions (PM_{10}, NMHC, NO_x, CH_4, HC, and TPM), water emissions and solid wastes. Total primary energy, feedstock energy and process energy were included in an estimate of total energy requirements. Feedstock energy and process energy are the subsets of primary energy. The energy contained in raw materials is called feedstock energy. The process energy is needed to produce final fuel product. Energy efficiency was used to determine the amount of process energy consumption.

The LCI result of NREL study estimated that 1.2007MJ primary energy is used to produce 1 MJ of petroleum diesel fuel. The corresponding total life cycle energy efficiency was estimated 83.28%. Process energy in refining was estimated to account for 60% of total process energy consumption and crude oil extraction accounted for 29%.

6.6 Other Life Cycle Studies

Furuholt quantified energy consumption and emission of three different fuel products, regular gasoline, gasoline with MTBE and diesel (Furuholt 1995). The study compared energy consumption and emissions of CO_2, CO, NO, SO_x, HC. Gasoline with MTBE was estimated to have larger potential environmental effects than regular gasoline due to emissions from the production of MTBE. Production of gasoline with MTBE had potentially larger environmental impacts than production of regular gasoline, due to the extra facilities for production of MTBE. The study indicated that production of diesel had lower potential environmental effects than production of gasoline.

Hackney described a life cycle model comparing the emissions, energy efficiency and cost performance of different fuel and vehicle technologies (Hackney 2001). This model included the fuel and vehicle life cycles, excluding consideration of taxes or differential incentives. The model reported pollutant emission including particulate matter (PM), hydrocarbons, nitrogen oxides (NO_x), carbon dioxide (CO_2) and methane (CH_4). The model analyzed 23 fuel chains of alternative motor fuels, and 17 types of vehicles. The study indicated that reformulated gasoline (RFG) had the best overall performance.

Daniel *et al.* examined pollutant emissions for thirteen fuel life cycles for automobiles (Daniel and Rosen, 2002). The results suggested that compressed natural gas use in motor vehicles produced the most emissions relative to other fuel cycles. Hybrid electric vehicles using diesel were estimated to use the lowest amount of fuel use and life cycle emissions among all thirteen fuel/vehicle combinations.

Tan *et al.* developed a life-cycle model (POLCAGE 1.0) of 10 different fuels, which was based on the GREET 1.5a fuel cycle inventory model of the Argonne National Laboratory and upon the Danish Environmental Design of Industrial Products (EDIP) method (*0*). POLCAGE 1.0 was developed to provide a decision framework for alternative motor vehicle fuels. Emissions of CO_2, N_2O, CH_4, HC_s, CO, NO_x, PM_{10} and SO_x were considered in POLCAGE 1.0. Alternative fuel cycles in POLCAGE 1.0 include electricity, liquid (LH2) and gaseous hydrogen (GH2), bioethanol (BioEtOH), biodiesel (BD), liquid natural gas (LNG), compressed natural gas (CNG) and methanol (MeOH). Conventional diesel and gasoline were also considered in POLCAGE 1.0 as baseline study.

Among previous life cycle studies, only five of them provided sufficient information for comparisons of life cycle components. In general, life cycle studies include the following components: (1) region; (2) time frame; (3) vehicle type; (4) vehicle drivetrain type; (5) system boundaries; (6) fuels; (7) feedstock; (8) vehicle energy-use and emission modeling; (9) fuel life cycle; (10) vehicle life cycle; and (11) pollutant emissions. Each of these attributes is briefly described. The comparison of life cycle studies is shown in Table 6.1.

(1) Region means the countries or regions covered by the study. Most of the studies focus on the United States. Some studies also consider data from other countries. In our study, we focus on the United States.

(2) Time frame refers to the target year of the study. Only LEM and GREET include both near term and long term period. Other studies only cover near term period. In our LCI, we focus on near term period.

(3) Transport modes (vehicle types) refers to the types of passenger transport modes included light-duty vehicles, heavy-duty vehicles and other vehicle types. In our study, we consider nonroad construction vehicles and equipment.

(4) Vehicle drivetrain types generally include internal combustion-engine vehicles (ICEVs), hybrid-electric vehicles (HEVs), battery-powered electric vehicles (BPEVs) and fuel-cell powered electric vehicles (FCEVs). Our study focuses on internal compression engine vehicles (ICEVs).

(5) System boundaries in previous studies generally include crude oil recovery, crude oil transportation, refining, fuel transportation and storage, fuel distribution and vehicle operation. Some models consider life cycle of the vehicle, such as vehicle design, vehicle manufacture and maintenance. In our study, we include five stage of life cycle inventory for petroleum diesel: crude oil recovery, crude oil transportation, diesel refining, diesel transportation, and vehicle operation. For biodiesel, the system boundaries include soybean farming, soybean transportation, soybean oil plant, soybean oil transportation, biodiesel plant, biodiesel transportation and vehicle operation.

(6) Fuels carried and used by motor vehicles include gasoline, diesel, liquefied petroleum gases (LPG), Fischer-Tropsch diesel (FTD), compressed natural gas (CNG), liquefied natural gas (LNG), compressed hydrogen (CH2), liquefied hydrogen (LH2), and dimethyl ether (DME). Because we focus on nonroad construction vehicles and equipment, we consider diesel and biodiesel fuels only.

(7) Feedstocks are the raw materials to produce and transport the fuel. In previous life cycle studies, feedstocks include crude oil, natural gas, coal, crops, lingo-cellulostic, biomass, renewable and nuclear power. In our study, we consider crude oil, gasoline, diesel, natural gas, electricity, residual oil, coal and biodiesel.

(8) Vehicle energy use and emission modeling are used to estimate vehicle energy consumption. GM North America and GM European studies estimate vehicle energy consumption and emission by their own simulator. Other studies develop their own models for vehicle energy consumption and emission. Our study used real-world measurement data using portable emissions measurement system (PEMS) on backhoes, front-end loaders, and motor graders. Each vehicle was tested for both petroleum diesel and biodiesel fuels.

(9) The fuel life cycle includes the fuel production and emissions from different stages. There are lots of assumptions regarding energy efficiency, emission rate, process fuel use for each fuel LCI stages. Some studies refer to LEM and GREET model and make their own calculation for the fuel LCI. In our study, the fuel cycle energy use and emission factors are estimated based on GREET 1.6 and updated for the following inputs:

- Update of combustion source emission factors, such as for coal-fired utility and industrial boilers based on 2006 US national average emission rates;
- Vehicle tailpipe emission rates based on real-world measurement data for petroleum diesel and B20 biodiesel;
- Inclusion of Pre-NSPS and NSPS soyoil plants;
- Inclusion of soyoil transport; and
- Inclusion of biogenic HC emissions during soybean farming, which is estimated based on measurements of air-surface exchange rates of HC compounds.

(10) Vehicle life cycle refers to the life cycle of materials and vehicle including raw material production and transport, manufacture of finished materials, assembly of parts and vehicles, maintenance and repair, and disposal. Only LEM and EIO-LCA include vehicle life cycle in their model. Because we tested the same vehicles for both petroleum diesel and biodiesel, the energy use and emissions during vehicle production are approximately the same. Thus, our LCI model does not include vehicle life cycle.

(11) Pollutants considered in previous lifecycle studies include greenhouse gases (CO_2, CH_4, N_2O) and criteria pollutants (NO_x, HC, SO_x, PM, CO). The U.S. EPA has estimated that, in 2002, diesel-fueled construction vehicles emitted 764,000 tons of NO_x, 414,000 tons of CO, 85,000 tons of hydrocarbons (HC), and 71,000 tons of PM_{10}. These emissions are significant, thus, life cycle CO_2, NO_x, HC, PM and CO emissions are estimated in our study. Because the PEMS do not collect N_2O and CH_4 emissions, these two greenhouse gases are excluded from our study.

Table 6.1 A Comparison of Previous Life Cycle Models

	GM-ANL GREET	DeLucchi LEM	GM-LBST	CMU EIO-LCA	NREL
Region	North America	Multi-country (primary data for U.S.; other data for up to 30 countries)	Europe	United States	United States
Time frame	Near term, long term	Any year from 1970 to 2050	2010	Near term	Near term
Transport modes (vehicle types)	LDVs	LDVs, HDVs, buses, light-rail transit, heavy-rail transit, minicars, scooters, offroad vehicles	LDV	LDVs	Bus
Vehicle drivetrain type	- Conventional spark-ignition (SI) engine - spark-ignition, direct-injection (SIDI) engines - compression-ignition, direct-injection (CIDI) engines - ICEVs - grid-independent hybrid electric vehicles (HEVs) powered by SI engines - grid-independent HEVs powered by CIDI engines - BPEVs - FCEVs	Internal- combustion-engine vehicle (ICEVs), battery-powered electric vehicles (BPEVs), fuel-cell electric vehicles (FCEVs)	ICEVs, HEVs, FCEVs	ICEVs	ICEVs

(Continued on next page)

Table 6.1 Continued.

	GM-ANL GREET	DeLucchi LEM	GM-LBST	CMU EIO-LCA	NREL
System boundaries	- Feedstock production, transportation and storage - Fuel production, transportation, distribution and storage - Vehicle operation (including vehicle refueling, fuel combustion / conversion, fuel evaporation and tire/brake wear)	- Lifecycle of fuels and electricity - End use - dispensing of fuels - fuel distribution and storage - fuel production - feedstock, transport - feedstock production - Lifecycle of materials - Crude oil recovery - Transport of finished materials to end uses - Lifecycle of vehicles - Materials use - Vehicle assembly - Operation and maintenance - Second fuel cycle - Lifecycle of infrastructure - Energy consumption and materials production	- Crude oil recovery - Crude oil transportation - Refinery - Fuel transportation - Fuel storage - Fuel distribution - Fuel refilling - Vehicle operation	- Vehicle design and develop - Material extraction - Vehicle manufacture - Vehicle use - Fuel cycle (including fuel production, fuel distribution) - Vehicle operation - End of life	- Petroleum Diesel Life Cycle - Extract crude oil from the ground - Transport crude oil to an oil refinery - Refine crude oil to diesel fuel - Transport diesel fuel to its point of use - Use the fuel in a diesel bus engine - Biodiesel Life Cycle - Produce soybeans - Transport soybeans to a soy crushing facility - Recover soybean oil at the crusher - Transport soybean oil to a biodiesel manufacturing facility - Convert soybean oil to biodiesel - Transport biodiesel fuel to the point of use - Use the fuel in a diesel bus engine

(Continued on next page)

Table 6.1 Continued.

	GM-ANL GREET	DeLucchi LEM	GM-LBST	CMU EIO-LCA	NREL
Fuels	Gasoline, Diesel, naptha, LPG, FTD, CNG, LNG, methanol, ethanol, methanol dimethyl ether (DME) , CH2, LH2,biodiesel, electricity	Gasoline, diesel, liquefied petroleum gases (LPG), Fischer-Tropsch diesel (FTD), compressed natural gases (CNG), liquefied natural gases (LNG), methanol, ethanol, compressed hydrogen (CH2), liquefied hydrogen (LH2), electricity	Gasoline, diesel, naptha, FTD, CNG, LNG, methanol, ethanol, CH2, LH2, Bioester from plant oil, ETBE as blending agent for gasoline, MTBE as blending agent for gasoline	Gasoline, diesel, biodiesel, CNG, methanol, ethanol	Diesel, biodiesel
Feedstocks	Crude oil, natural gas, coal, crops, lingo-cellulosic biomass, renewable and nuclear power	Crude oil, natural gas, coal, crops, lingo-cellulosic biomass, renewable and nuclear power	Crude oil, natural gas, coal, crops, lingo-cellulosic biomass, waste, renewable and nuclear power	Crude oil, natural gas, crops, lingo-cellulosic biomass	Crude oil, Soybean Oil, Methanol, Electricity, Sodium Methoxide, natural gas, coal, crops
Vehicle energy-use and emission modeling	GM simulator, U.S. combined city/ highway driving	Simple model based on SIMPLEV-like simulator, U.S. combined city/highway driving	GM simulator, European Drive Cycle	Gasoline fuel economy assumed	TEAM model
Fuel Life Cycle	GREET model	Detailed model	LBST E2 database	Own calculations based on other models (LEM, GREET….etc)	Own calculations
Vehicle lifecycle	Not included	Literature review and analysis	Not included	Environmental Input-Output Life Cycle Analysis software (developed by CMU)	Not included
Pollutant emissions	CO_2, CH_4, N_2O, VOC, CO, NO_x, PM_{10},SOx	CO_2, CH_4, N2O, NO_x, VOC, SO_x, PM, CO, NMHC, CFC-12, HFC-134a	CO_2, CH_4, N_2O, NO_x, SO_2, CO, VOC	CO_2, CH_4, N_2O, SO_x, CO, NO_x, VOC, PM	CO_2, CH_4, N_2O, SO_x, CO, NO_x, VOC, PM, NH_3, benzene, HCl,HF

(Continued on next page)

Table 6.1 Continued.

	GM-ANL GREET	DeLucchi LEM	GM-LBST	CMU EIO-LCA	NREL
Reference	General Motors, Argonne National Lab, et al., *Well-to-Wheel Energy consumption and Greenhouse Gas Emissions of Advanced Fuel/Vehicle System*s, in three volumes, published by Argonne National Laboratory, June (2001).	Mark A. Delucchi, A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels and Materials, Institute of Transportation Studies, University of California, UCD-ITS-RR-03-17, December 2003	GM, LBST, bp, ExxonMobil, Shell, TotalFinaElf, GM Well-to-Wheel Analysis of Energy consumption and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study, September 2002	Lester Lave, Heather Maclean, Chris Hendrickson, Rebecca Lankey, Life-Cycle Analysis of Alternative Automobile Fuel/Propulsion Technologies, Environ. Sci. Technol. 2000, 34, 3598-3605	Sheehan J., V. Camobreco, J. Duffield, M. Graboski, H. Shapouri (1998), “Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus”, National Renewable Energy Laboratory, sponsored by U.S. Department of Agriculture and U.S. Department of Energy, NREL/SR-580-24089

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PART VII DEVELOPMENT OF LIFE CYCLE INVENTORY FOR PETROLEUM DIESEL AND BIODIESEL FUELS

The section discusses the methodology of this study, including the life cycle inventory and characterizing in-use emissions and energy use of nonroad construction vehicles and equipment.

Life cycle inventory is a tool to quantify energy use, raw material requirements, and air pollutant emissions throughout the life cycle of a fuel product. There are different types of life cycle studies, e.g., process flow diagram, matrix representation of product system, and input-output-based LCI. The LCI in this study was characterized using a process flow diagram to show the typical processes associated with the production of petroleum diesel and biodiesel. The fuel cycle energy use and emissions were estimated based on the greenhouse gases, regulated emissions, and energy use in the transportation model developed by the Argonne National Laboratory. Emission factors were updated as appropriate and incorporated into our LCI framework.

7.1 Definition of LCI System Boundaries

The life cycle inventory of nonroad construction vehicle for petroleum diesel involves five stages:

Stage 1: Crude oil recovery

Stage 2: Crude oil transportation and storage

Stage 3: Refining

Stage 4: Diesel transportation and distribution

Stage 5: Vehicle operation

The first four stages are called Well-to-Pump stages and vehicle operation is called Pump-to-Wheel stage. Figure 7.1 is the diagram of overall life cycle inventory of nonroad construction vehicles and equipments. The overall lifecycle from stage 1 to stage 5 is so called Well-to-Wheel stages. The detail diagrams of Stage 4 and Stage 5 are in Figures 7.2 and 7.3, respectively. The stage 4 (diesel transportation and distribution) includes four types of transportation, which are pipeline, tanker car, rail and barge. Most of diesel fuels are transported by pipeline. Most of emissions and energy use are from the stage 5 (vehicle operation). The detail diagram is shown in Figure 7.3.

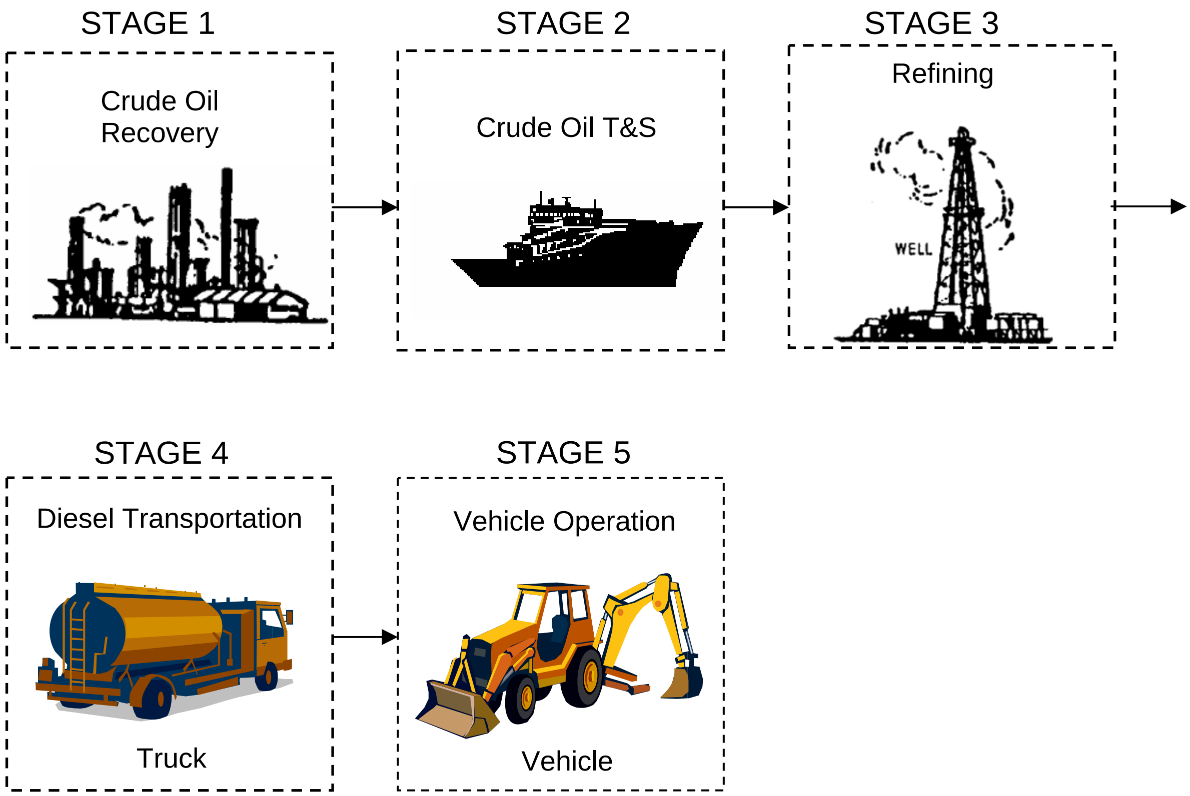

Figure 7.1. Diagram of Life Cycle Inventory for Petroleum Diesel

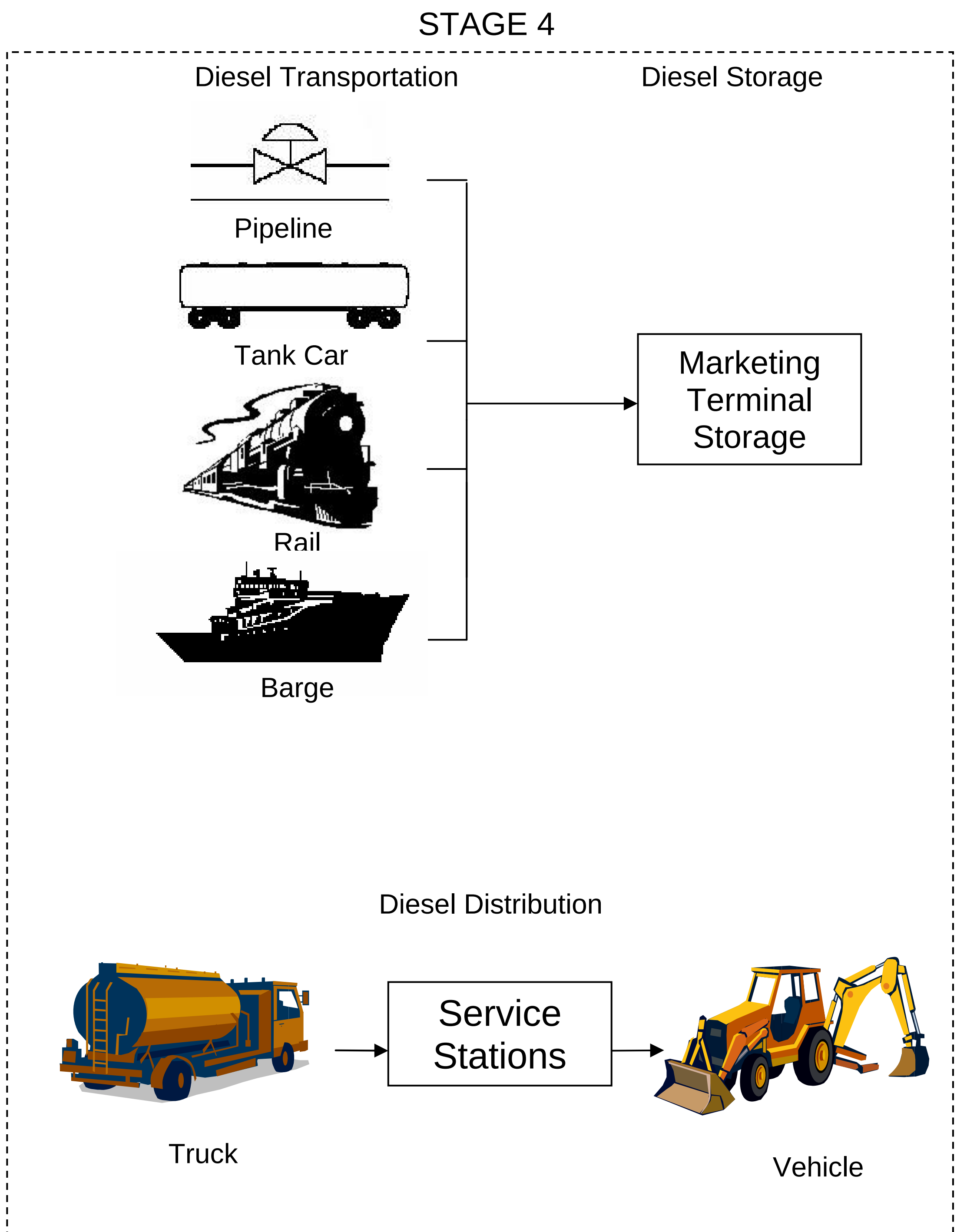

Figure 7.2 Detailed Diagram of Stage 4 of Petroleum Diesel Life Cycle

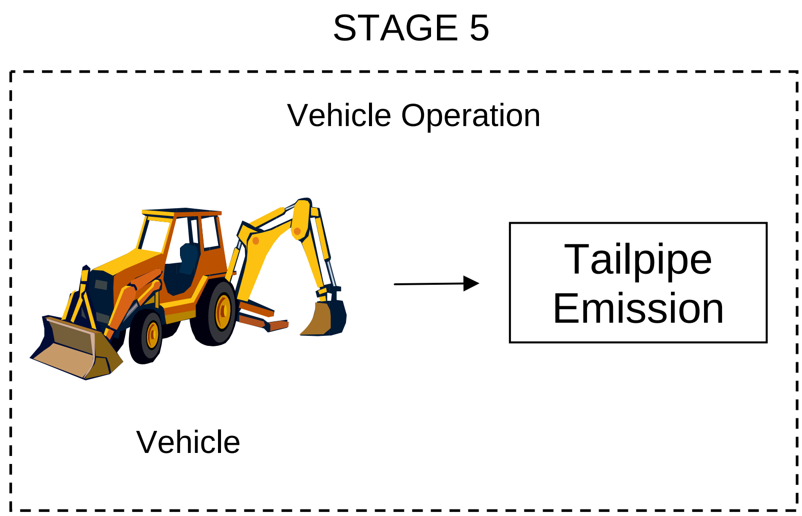

Figure 7.3 Detailed Diagram of Stage 5 of Petroleum Diesel Life Cycle

System boundaries for biodiesel life cycle include six stages:

Stage 1: Soybean agriculture

Stage 2: Soybean transportation

Stage 3: Soyoil extraction

Stage 4: Soyoil transport

Stage 5: Soyoil conversion (transesterification)

Stage 6: Biodiesel transport

Figure 7.4 shows system boundaries for biodiesel life cycle. Soybean agriculture includes soybean farming, fertilizer, herbicide and pesticide use. Soybean transport is by heavy-duty trucks. Soybean agriculture, soyoil extraction and soyoil conversion contribute to most of energy consumption.

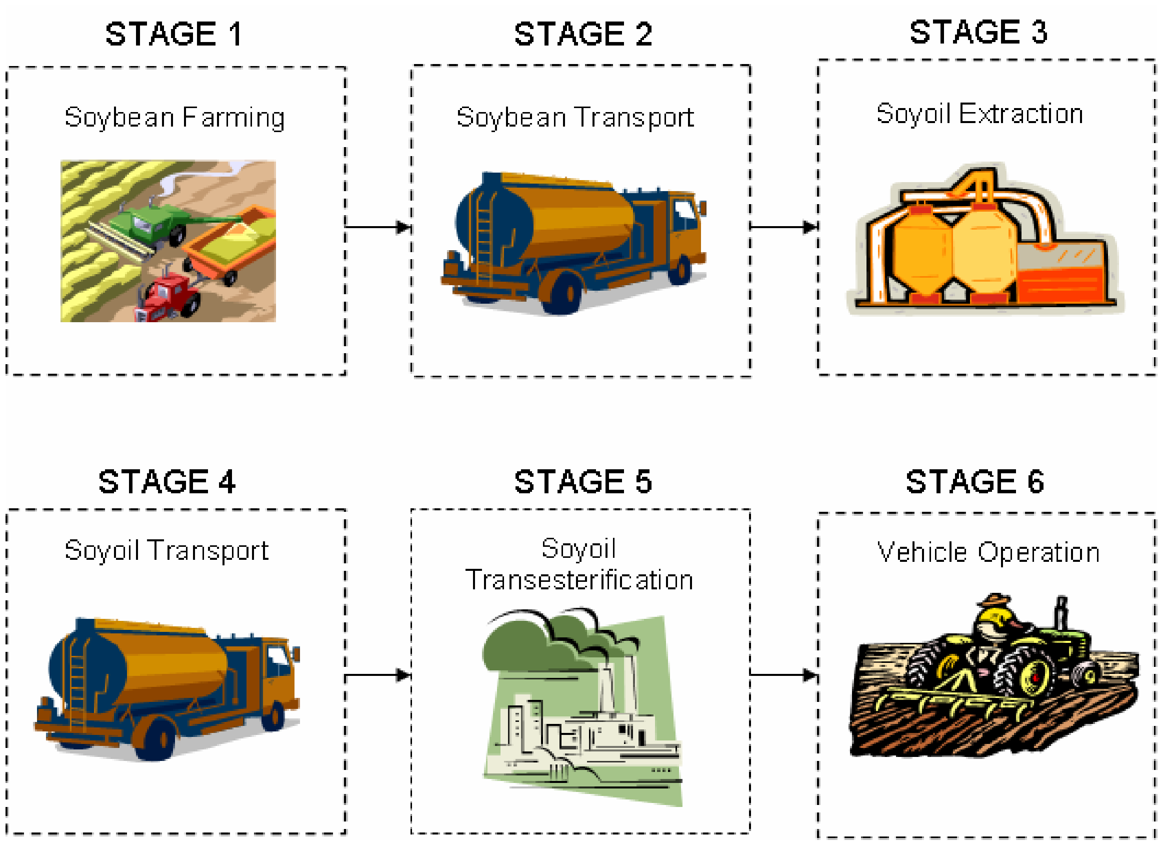

Figure 7.4 Diagram of Life Cycle Inventory for Biodiesel

7.2 Estimations of Energy Use and Emissions for Well-to-Pump Stages

In the fuel life cycle, energy efficiency (η) is used to estimate the energy consumption for crude oil recovery and crude oil refining. The energy consumption is referred to an process energy consumption. The energy efficiency is defined as the energy output divided by the energy input for a process stage. The energy inputs include process energy ($E_{PF,m}$) and feedstock energy ($E_{F,m}$).

$$\eta_m = \frac{E_{out,m}}{E_{in,m}} \tag{7-1}$$

<u>where</u>

η_m = energy efficiency (%) for stage m

$E_{in,m}$ = energy input (BTU) for stage m

$E_{out,m}$ = energy output (BTU) for stage m

An example of a process stage is crude oil recovery. The process energy consumption, feedstock energy, and energy output are 24,500Btu, 10^6 Btu, and 10^6 Btu, respectively. The energy efficiency for crude oil recovery stage is 97.7%. Energy input ($E_{in,m}$) can also be rewritten from Equation 3-1 as:

$$E_{in,m} = \frac{E_{out,m}}{\eta_m} \tag{7-2}$$

Energy input ($E_{in,m}$) can be separated into process energy ($E_{PF,m}$) and feedstock energy ($E_{F,m}$):

$$\begin{aligned} E_{in,m} &= \frac{E_{out,m}}{\eta_m} = E_{F,m} + E_{PF,m} \\ E_{PF,m} &= \frac{E_{out,m}}{\eta_m} - E_{F,m} \end{aligned} \tag{7-3}$$

where

η_m	= energy efficiency (%) of a given stage m
$E_{in,m}$	= energy input (BTU) of a given stage m
$E_{out,m}$	= energy output (BTU) for a given stage m
$E_{F,m}$	= feedstock energy (BTU) for a given stage m
$E_{PF,m}$	= process energy (BTU) required for a given stage m

If there is a fuel loss (leakage, spillage and evaporation), energy consumption must be corrected by fuel loss factor (*L*).

$$\eta_m = \frac{E_{out,m}}{E_{in,m}} = \frac{E_{out,m}}{E_{F,m} + E_{PF,m}} = \frac{E_{out,m}}{E_{out,m}\left(1 \big/ 1 - L_m\right) + E_{PF,m}} \tag{7-4}$$

where

η_m = energy efficiency (%) for a given stage m

$E_{in,m}$ = energy input (BTU) for a given stage m

$E_{out,m}$ = energy output (BTU) for a given stage m

$E_{F,m}$ = feedstock energy (BTU)for a given stage m

$E_{PF,m}$ = process energy (BTU) required for a given stage m

L_m = fuel loss factor (%) for a given stage m

After the process energy consumption is estimated, the process energy is allocated to different process fuels. The diagram of process fuel allocation is shown in Figure 7.5.

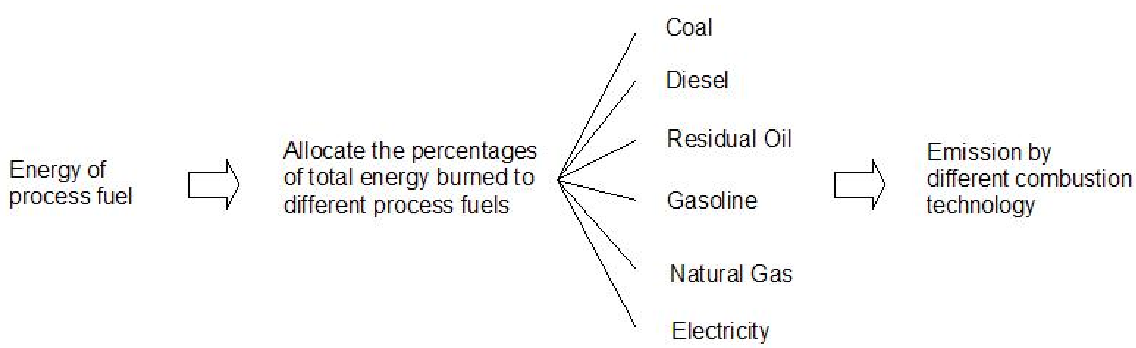

Figure 7.5 Example of Allocation of Process Fuel Among Life Cycle Inventory

The emissions are calculated from process fuel combustion by different combustion technologies as:

$$EM_{m,i} = \left(\sum_j \sum_k EF_{i,j,k} \times E_{PF,m,j,k} \right) \tag{7-5}$$

where

$EM_{m,i}$ = Emissions of pollutant *i* for stage m (g/gallon fuel throughput)

$EF_{m,i,j,k}$ = Emission factor of pollutant *i* for process fuel *j* with combustion technology *k* (g/Btu)

$E_{PF,m,j,k}$ = Process energy consumption of fuel *j* with combustion technology *k* in stage m (Btu/gallon fuel throughput)

To examine emission factors used in our life cycle inventory of nonroad construction vehicle and equipment model, the national average emission factors were compared with emission factors in the GREET model. The national average emission factors are estimated from national total emission divided by national total energy consumption. The data for national total emission and energy consumption are from the U.S. Environmental Protection Agency EPA and Energy Information Administration (EIA) of the U.S. department of energy.

National emission data were based on the *1970 - 2002 Average annual* emissions, which provides average emissions of criteria pollutants, such as particulate matters, NO_x, SO_2, CO and HC (EPA 2006). Besides, each pollutant emission is separated into different fuel combustion and facilities. In the following comparison, we choose four types of combustion technologies, which are coal-fired utility boiler, natural-gas-fired utility boiler, coal-fired industrial boiler and natural-gas-fired industrial boiler. These four types of combustion technologies are widely used in the life cycle inventory.

National energy consumption data are published in *Annual Energy Review 2003* (EIA 2005). The *Annual Energy Review* provides energy consumption of different fuels. The units of energy consumption for solid and gaseous fuel are short tons and cubic feet, respectively. The *Annual Energy Review* also provides heat content of fuel in Appendices A. Thus energy consumption in unit of 10^6 Btu was obtained.

Emission factor is equal to national total emission divided by national total energy consumption. The estimated national average emission factors of utility boiler and industrial boiler are shown in Tables 7.1 and 7.2. The first column is emission type of five criteria pollutants, PM_{10}, NO_x, SO_x, CO and VOC_s. The second column is national total emission from EPA, *1970 - 2002 Average annual emissions*, which include two sub-categories.

The left-hand subcategory is data directly derived from the EPA report with original units (thousand short tons). The right-hand subcategory is emission data with unit of pounds. The third column is national total energy consumption data from EIA, *Annual Energy Review 2003*. Similarly, the left-hand subcategory of energy consumption data is directly derived from EIA report with unit of short tons for coal and cubic feet for natural gas. The right-hand category of energy consumption is transferred to unit of million Btu, which is easy for calculating national average emission factors. The fourth column is national average emission factors, which is calculated by national total emission divided by national total energy consumption.

Table 7.3 shows the difference of emission factors between GREET 1.6 model and national average in utility boilers. Table 7.3 shows the difference of emission factors between GREET 1.6 model and national average in industrial boilers. VOC and CO emission factors for natural-gas-fired utility boiler are much lower in national average than in GREET 1.6.

Table 7.1 Estimate of 2002 U.S. National Average Emission Factors of Utility Boiler

Estimate of US National Average Emission Factors of Utility Boiler					
Emission Type	National Total Emission EPA[1]		National Total Energy Consumption, EIA		National Average Emission Factors
Coal-fired Utility Boiler	Thousand short tons	lb (1)	Short tons [2]	10^6Btu [4] (2)	(1) / (2)
Particulate (PM_{10})	6.41×10^{2}	1.28×10^{9}	9.78×10^{8}	1.98×10^{10}	6.48×10^{-2}
Nitrogen Oxides	4.09×10^{3}	8.19×10^{9}	9.78×10^{8}	1.98×10^{10}	4.14×10^{-1}
Sulfur Oxides	9.73×10^{3}	1.95×10^{10}	9.78×10^{8}	1.98×10^{10}	9.84×10^{-1}
Carbon Monoxide	2.56×10^{2}	5.12×10^{8}	9.78×10^{8}	1.98×10^{10}	2.59×10^{-2}
Volatile Organic Compounds (VOCs)	3.10×10^{1}	6.20×10^{7}	9.78×10^{8}	1.98×10^{10}	3.13×10^{-3}
Natural-Gas-fired Utility Boiler	Thousand Short tons	lb (3)	Thousand Cubic Feet [3]	10^6Btu [5] (4)	(3) / (4)
Particulate (PM_{10})	1.20×10^{1}	2.40×10^{7}	5.67×10^{9}	5.79×10^{9}	4.15×10^{-3}
Nitrogen Oxides	2.64×10^{2}	5.28×10^{8}	5.67×10^{9}	5.79×10^{9}	9.13×10^{-2}
Sulfur Oxides	NA	NA	5.67×10^{9}	5.79×10^{9}	NA
Carbon Monoxide	NA	NA	5.67×10^{9}	5.79×10^{9}	NA
Volatile Organic Compounds (VOC_s)	NA	NA	5.67×10^{9}	5.79×10^{9}	NA

1 U.S. EPA, 1970 - 2002 Average annual emissions, all criteria pollutants, January 2005
http://www.epa.gov/ttn/chief/trends/index.html
Year 2002 was selected.

2 Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003), U.S. Department of Energy, September 7, 2004
Table 4.3 Coal Consumption by Sector, Selected Years, 1949-2003
Year 2002 was selected.
http://www.eia.doe.gov/emeu/aer/pdf/pages/sec7_9.pdf

3 Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003), U.S. Department of Energy, September 7, 2004
Table 6.5 Natural Gas Consumption by Sector, Selected Years, 1949-2003
http://www.eia.doe.gov/emeu/aer/pdf/pages/sec6_13.pdf
Year 2002 was selected.

4 The heat content in coal is 20.238 (Million Btu per Short Ton).
Reference: Table A5. Approximate Heat Content of Coal and Coal Coke, Selected Years, 1949-2003.
Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003)

5 The heat content in natural gas is 1,020 (Btu per Cubic Foot).
Reference: Table A4. Approximate Heat Content of Natural Gas, Selected Years, 1949-2003
Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003)

Table 7.2 Estimate of 2002 U.S. National Average Emission Factors of Industrial Boiler

Estimate of US National Average Emission Factors of Industrial Boiler					
Emission Type	National Total Emission EPA[1]		National Total Energy Consumption, EIA		National Average Emission Factors
Coal-fired Industrial Boiler	Thousand short tons	lb (1)	Short tons [2]	10^6Btu [4] (2)	(1) / (2)
Particulate (PM_{10})	5.00×10^{1}	1.00×10^{8}	8.44×10^{7}	2.01×10^{9}	4.98×10^{-2}
Nitrogen Oxides	4.47×10^{2}	8.94×10^{8}	8.44×10^{7}	2.01×10^{9}	4.45×10^{-1}
Sulfur Oxides	1.14×10^{3}	2.29×10^{9}	8.44×10^{7}	2.01×10^{9}	1.14
Carbon Monoxide	1.25×10^{2}	2.50×10^{8}	8.44×10^{7}	2.01×10^{9}	1.24×10^{-1}
Volatile Organic Compounds (VOC_s)	1.00×10^{1}	2.00×10^{7}	8.44×10^{7}	2.01×10^{9}	9.96×10^{-3}
Natural-Gas-fired Industrial Boiler	Thousand Short tons	lb (3)	Cubic Feet [3]	10^6Btu [5] (4)	(3) / (4)
Particulate (PM_{10})	7.20×10^{1}	1.44×10^{8}	8.67×10^{12}	8.91×10^{9}	1.73×10^{-2}
Nitrogen Oxides	8.37×10^{2}	1.67×10^{9}	8.67×10^{12}	8.91×10^{9}	2.01×10^{-1}
Sulfur Oxides	NA	NA	8.67×10^{12}	8.91×10^{9}	NA
Carbon Monoxide	NA	NA	8.67×10^{12}	8.91×10^{9}	NA
Volatile Organic Compounds (VOCs)	NA	NA	8.67×10^{12}	8.91×10^{9}	NA

1 U.S. EPA, 1970 - 2002 Average annual emissions, all criteria pollutants, January 2005
http://www.epa.gov/ttn/chief/trends/index.html
Year 2002 was selected.

[2] Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003), U.S. Department of Energy, September 7, 2004
Table 4.3 Coal Consumption by Sector, Selected Years, 1949-2003
Year 2002 was selected.
http://www.eia.doe.gov/emeu/aer/pdf/pages/sec7_9.pdf

[3] Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003), U.S. Department of Energy, September 7, 2004
Table 6.5 Natural Gas Consumption by Sector, Selected Years, 1949-2003
http://www.eia.doe.gov/emeu/aer/pdf/pages/sec6_13.pdf
Year 2002 was selected.

[4] The heat content in coal is 23.793 (Million Btu per Short Ton).
Reference: Table A5. Approximate Heat Content of Coal and Coal Coke, Selected Years, 1949-2003.
Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003)

[5] The heat content in natural gas is 1,028 (Btu per Cubic Foot).
Reference: Table A4. Approximate Heat Content of Natural Gas, Selected Years, 1949-2003
Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003)

Table 7.3 Comparison of 2002 U.S. National Average Emission Factors with GREET 1.6 Model, Utility Boiler

Comparison of US National Average Emission Factors with GREET Model				
Emission Type	Estimate of National Average Emission Factors	GREET 1.6 Model Emission Factors[2]		Difference
Coal-fired Utility Boiler	lb / 10^6Btu (1)	g / 10^6Btu	lb / 10^6Btu (2)	lb / 10^6Btu (1)-(2)
Particulate (PM10)	0.065	12.7	0.028	0.037
Nitrogen Oxides	0.41	211	0.46	-0.05
Sulfur Oxides	0.98	600	1.32	-0.34
Carbon Monoxide	0.026	9.61	0.021	0.005
Volatile Organic Compounds (VOCs)	3.13×10^{-3}	1.14	2.51×10^{-3}	6.2×10^{-4}
Natural-Gas-fired Utility Boiler	lb / 10^6Btu (3)	g / 10^6Btu[1]	lb / 10^6Btu (4)	lb / 10^6Btu (3)-(4)
Particulate (PM10)	0.0041	3.7	0.0081	-4.01×10^{-3}
Nitrogen Oxides	0.091	48.9	0.11	-1.90×10^{-2}
Sulfur Oxides	NA	0.31	6.83×10^{-4}	NA
Carbon Monoxide	NA	41.1	0.09	NA
Volatile Organic Compounds (VOCs)	NA	2.7	5.95×10^{-3}	NA

Table 7.4 Comparison of 2002 U.S. National Average Emission Factors with GREET 1.6 Model, Industrial Boiler

Comparison of US National Average Emission Factors with GREET Model				
Emission Type	Estimate of National Average Emission Factors	GREET Model Emission Factors		Difference
Coal-fired Industrial Boiler	lb / 10^6Btu (1)	g / 10^6Btu[1]	lb / 10^6Btu (2)	lb / 10^6Btu (1)-(2)
Particulate (PM10)	6.48×10^{-2}	12.7	0.028	3.7×10^{-2}
Nitrogen Oxides	4.14×10^{-1}	211	0.46	-0.046
Sulfur Oxides	9.84×10^{-1}	600	1.32	-0.34
Carbon Monoxide	2.59×10^{-2}	96.1	0.21	-0.18
Volatile Organic Compounds (VOCs)	3.13×10^{-3}	0.96	2.1×10^{-3}	1.0×10^{-3}
Natural-Gas-fired Industrial Boiler	lb / 10^6Btu (3)	g / 10^6Btu[1]	lb / 10^6Btu (4)	lb / 10^6Btu (3)-(4)
Particulate (PM10)	4.15×10^{-3}	3.7	8.15×10^{-3}	-4.0×10^{-3}
Nitrogen Oxides	9.13×10^{-2}	48.9	1.08×10^{-1}	-0.016
Sulfur Oxides	NA	0.31	6.8×10^{-4}	NA
Carbon Monoxide	NA	41.1	9.06×10^{-2}	NA
Volatile Organic Compounds (VOCs)	NA	2.70	5.95×10^{-3}	NA

Aggregation of energy use and emissions for each stage together can be calculated when one gallon fuel was delivered at the vehicle pump. If there is no fuel loss during a stage, calculated energy use (in BTU) and emissions (in grams per gallon diesel throughput) for each stage can simply be added together to obtain total energy use and emissions.

7.3 Vehicle Tailpipe Emissions

The tailpipe emissions data were collected from five backhoes, four front-end loaders, and six motor graders using a portable emission measurement system (PEMS). Each vehicle was tested once on petroleum diesel and once on B20 biodiesel. The details of the instrumentation, data collection, data quality assurance, and results are given in Frey *et al.* (2007a, 2007b). The vehicles information includes model years, manufacturers, and horsepower shown in Table 7.5.

The PEMS used here is the OEM-2100 "Montana" system manufactured by Clean Air Technologies International, Inc. (Vojtisek-Lom and Cobb, 1997), which is comprised of two parallel five-gas analyzers, a PM measurement system, an engine sensor array, which collects engine RPM, manifold absolute pressure, and intake air temperature, a global position system (GPS), and an on-board computer. PM measurements are based on a light scattering method, which is analogous to opacity.

Table 7.5 Characteristics of Tested Vehicles

Vehicle ID [1]	Chassis Characteristics				Engine Characteristics				
	Manufacturer	Year	Model [2]	GVW (lbs)	Tier	Displacement	Cylinders	Horsepower	Cumulative Hours
BH1	CATERPILLAR	2004	420D	22,000	2	4.0	4	97	78
BH2	JCB	2001	215	16,540	0	4.2	4	90	11,528
BH3	JCB	2001	2.15E-01	16,540	1	4.2	4	90	2,792
BH4	CASE	1999	590SL	19,578	1	3.9	4	99	3,874
BH5	CATERPILLAR	2004	420D	22,000	2	4.0	4	97	740
FL1	HYUNDAI	2002	HL740-TM3	29,000	1	5.9	6	130	3,645
FL2	HYUNDAI	2002	HL740-TM3	29,000	1	5.9	6	130	9,345
FL3	CASE	2002	621B XT	28,000	1	5.9	6	126	3,569
FL4	HYUNDAI	2005	HL740-TM7	29,000	2	5.9	6	133	446
MG1	VOLVO	2001	G720VHP	37,000	1	8.27	6	195	4,367
MG2	VOLVO	2004	G720B	37,000	2	7.1	6	195	841
MG3	VOLVO	2001	G720VHP	37,000	1	8.27	6	195	3,044
MG4	DRESSER	1990	850	37,000	0	8.27	6	167	440
MG5	CHAMPION	1993	G720	37,000	0	8.27	6	160	4,554
MG6	VOLVO	2007	G930	37,000	3	7.2	6	198	3

[1] BH = Backhoe
FL = Front-End Loader
MG = Motor Grader

[2] All tested vehicles are turbocharged.

The field data of NO_x, HC, and CO were carefully reviewed and screened by standard quality checking procedures. The procedures include: (a) initial screening based on error flags generated automatically by the PEMS; (b) reviewing and correcting the synchronization of engine, GPS, and exhaust concentration data; (c) identifying and correcting problems associated with the sensor array; (d) identifying problems associated with the gas analyzers; and (e) identifying potential problems with air leakage into the sampling system based on assessment of the air-to-fuel ratio. A 19-step data screening and quality assurance process has been automated using Visual Basic macros in Excel.

For PM, the PEMS measures the opacity which is adequate for relative comparisons between petroleum diesel and B20 biodiesel. The NONROAD model provides PM emission factors based on petroleum diesel (EPA 2004). The PM emission factors for B20 biodiesel (EF_{B20}) are estimated based on the ratio of opacity rates when comparing B20 biodiesel versus petroleum diesel:

$$EF_{B20} = EF_{PD} \times \frac{Opacity_{B20}}{Opacity_{PD}}$$

where

EF_{B20} = PM emission rates (g/gallon) for B20 biodiesel;

EF_{PD} = PM emission rates (g/gallon) for petroleum diesel;

$Opacity_{B20}$ = Opacity rate for B20 biodiesel based on PEMS measurements; and

$Opacity_{PD}$ = Opacity rate for petroleum diesel based on PEMS measurements;

Based on engine dynamometer data from EPA and chassis dynamometer data from National Renewable Energy Laboratory (NREL), the percentage changes when comparing B20 biodiesel versus petroleum diesel of NO_x, PM, CO, and HC are +2%, -10%, -11%, and -21%, respectively, for the EPA data and +0.6%, -16%, -17%, and -12%, respectively, for the NREL data (EPA 2004, McCormick *et al.* 2006). These two studies are included here as different tailpipe emission scenarios for B20 biodesel.

7.4 Model Inputs and Parameters

This section described the input assumptions used in the life cycle inventory. Tables 7.6 and 7.7 present the types of inputs for the feedstock and the product through the life cycle stages, respectively. The type of process energy for each stage is shown in Figure 7.6. The energy efficiency is an important assumption to estimate process energy consumption for crude oil recovery and diesel refining and is shown in Table 7.8.

For transportation stages, the energy consumption is estimated based on the distance traveled by the vehicle and the type of vehicles. The travel distances for the petroleum diesel and biodiesel LCI are shown in Tables 7.9 and 7.10. The energy use for each fuel cycle stage for both petroleum diesel and biodiesel LCI are shown in Table 7.11.

Table 7.6 Petroleum Diesel LCI: Feedstock and Product

Stages	Feedstock	Product
Crude Oil Recovery	Crude Oil	Crude Oil
Crude Oil Transportation	Crude Oil	Crude Oil
Crude Oil Refining	Crude Oil	Diesel
Diesel Transportation	Diesel	Diesel
Vehicle Operation	Diesel	

Table 7.7 Biodiesel B100 LCI: Feedstock and Product

Stages	Feedstock	Product
Soybean Farming	Soybeans	Soybeans
Soybean Transportation	Soybeans	Soybeans
Soybean Oil Plant	Soybeans	Soybean Oil
Soybean Oil Transportation	Soybean Oil	Soybean Oil
Biodiesel Plant	Soybean Oil	Biodiesel
Biodiesel Transportation	Biodiesel	Biodiesel
Vehicle Operation	Biodiesel	

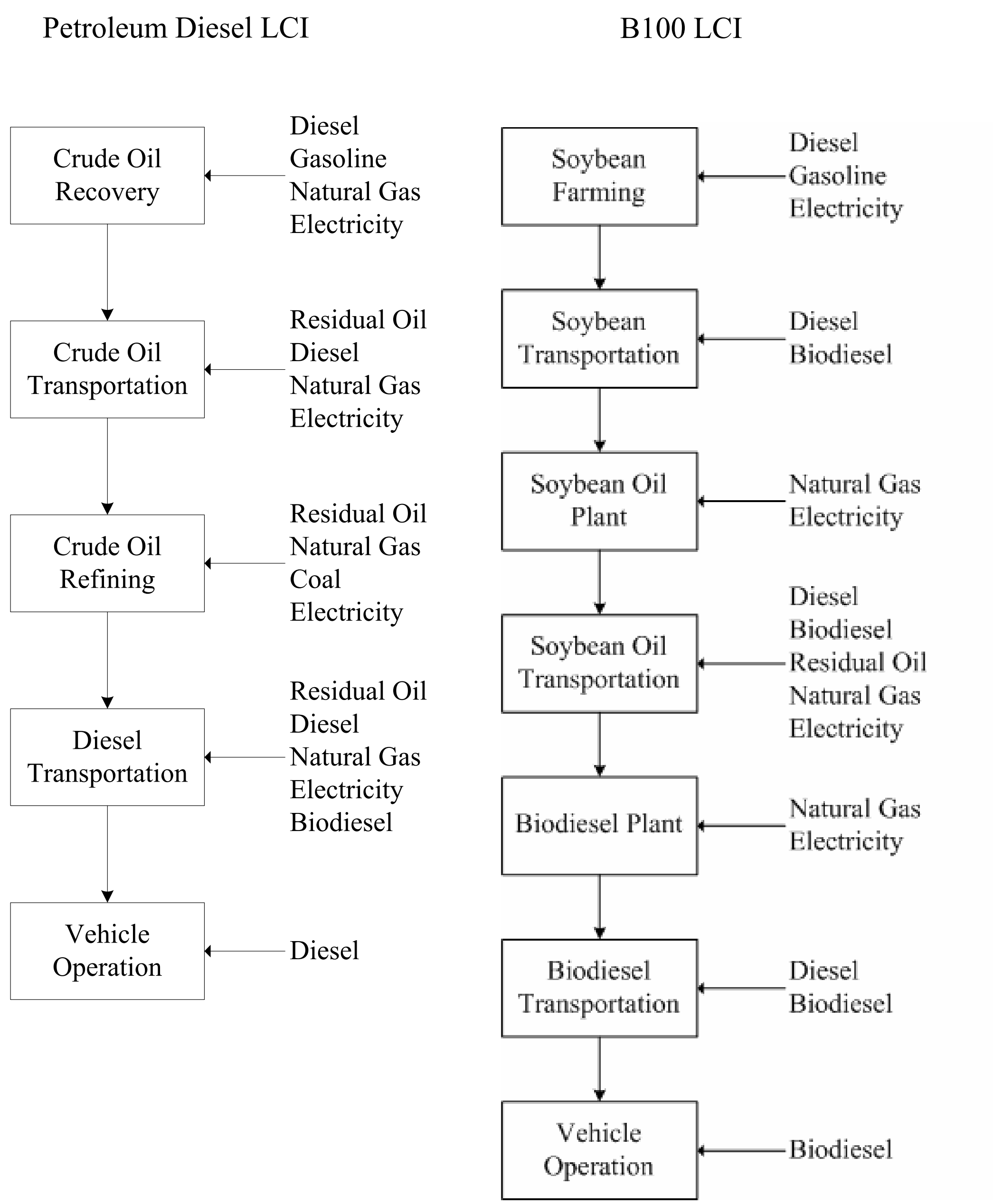

Figure 7.6 Process Energy for Petroleum Diesel and B100 LCI

Table 7.8 Energy Efficiencies for Petroleum Diesel Fuel Cycle

Fuel-Cycle Stages	Energy Efficiency (%)
Crude oil recovery	97.7
Diesel Refining	89.0

(Source: GREET 1.6 Model)

Table 7.9 Transportation Distance for Petroleum Diesel LCI

Stages	Transportation Type	One-way Distance (mile)
Crude Oil Transport	Ocean Tanker	5080
	Barge	500
	Pipeline	750
Diesel Transport	Ocean Tanker	1450
	Barge	520
	Pipeline	400
	Rail	800
	Truck	30

(Source: GREET 1.6 Model)

Table 7.10 Transportation Distance for Biodiesel B100 LCI

Stages	Transportation Type	One-way Distance (mile)
Soybean Transportation	Truck	75[a]
Soybean Oil Transportation	Truck	571[a]
Soybean Oil Transportation	Barge	520[b]
	Pipeline	400[b]
	Rail	800[b]
	Truck	30[b]

[a] Based on Sheehan *et al* (1998)
[b] Based on GREET 1.6 Model

Table 7.11 Energy Use for Petroleum Diesel and Biodiesel Fuel Cycle

Fuel	Life Cycle Stage	Energy Use per Gallon of Fuel Throughput
Petroleum Diesel	Crude Oil Recovery	4,187
	Crude Oil Transport	1,272
	Diesel Refining	17,589
	Diesel Transport	1,019
Biodiesel B100 with Existing Soyoil Plant	Soybean Farming	27,553
	Soybean Transport	953
	Soybean Oil Plant	32,411
	Soybean Oil Transport	2,506
	Biodiesel Plant	25,903
	Biodiesel Transport	1,104
Biodiesel B100 with New Soyoil Plant	Soybean Farming	27,553
	Soybean Transport	953
	Soybean Oil Plant	28,905
	Soybean Oil Transport	2,506
	Biodiesel Plant	25,903
	Biodiesel Transport	1,104

7.5 Probability Distribution of Inputs for Uncertainty Analysis

This section documents the input assumptions for uncertainty analysis. Tables 7.12, and 7.13 present the input assumptions used in the petroleum diesel and biodiesel LCI, respectively.

The uncertainty analysis was done according to the following steps:

(1) Define the probabilistic distribution for each inputs based on GREET model and professional judgment.

(2) Define the uncertainty outputs, such as life cycle emissions or energy consumption for petroleum diesel and biodiesel;

(3) Define the number of trials running Monte Carlo simulation (n=10,000);

(4) Run the Crystal Ball software in Microsoft Excel; and

(5) Extract results from Crystal Ball.

Table 7.12 Probability Distributions of Uncertain Inputs for Petroleum Diesel Life Cycle

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Crude Oil Recovery Efficiency	Triangular	97.7%	Min=96.0% Likeliest=98.0% Max=99.0%	GREET Model [a]
Gasoline Refining Efficiency	Normal	85.5%	20 percentile= 85.0% 80 percentile= 86.0%	GREET Model [a]
Petroleum Diesel Refining Efficiency	Normal	89.0%	20 percentile= 88.0% 80 percentile= 90.0%	GREET Model [a]
Near-Term Natural Gas Recovery Energy Efficiency: North American sources	Normal	97.5%	20 percentile= 96.0% 80 percentile= 99.0%	GREET Model [a]
Near-Term Natural Gas Recovery Energy Efficiency: Non-North American sources	Normal	97.5%	20 percentile= 96.0% 80 percentile= 99.0%	GREET Model [a]
Near-Term Natural Gas Processing Energy Efficiency: North American sources	Normal	97.5%	20 percentile= 96.0% 80 percentile= 99.0%	GREET Model [a]
Near-Term Natural Gas Processing Energy Efficiency: Non-North American sources	Normal	97.5%	20 percentile= 96.0% 80 percentile= 99.0%	GREET Model [a]
Long-Term Natural Gas Recovery Energy Efficiency: North American sources	Normal	97.5%	20 percentile= 96.0% 80 percentile= 99.0%	GREET Model [a]
Long-Term Natural Gas Recovery Energy Efficiency: Non-North American sources	Normal	97.5%	20 percentile= 96.0% 80 percentile= 99.0%	GREET Model [a]
Long-Term Natural Gas Processing Energy Efficiency: North American sources	Normal	97.5%	20 percentile= 96.0% 80 percentile= 99.0%	GREET Model [a]
Long-Term Natural Gas Processing Energy Efficiency: Non-North American sources	Normal	97.5%	20 percentile= 96.0% 80 percentile= 99.0%	GREET Model [a]
Near-Term Natural Gas Compression Energy Efficiency of Compressors	Normal	93.0%	20 percentile= 92.0% 80 percentile= 94.0%	GREET Model [a]

(Continued on next page)

Table 7.12 Continued

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Near-Term Natural Gas Compression Energy Efficiency of Electric Compressors	Triangular	97.0%	Min=96.0% Likeliest=97.0% Max=98.0%	GREET Model [a]
Near-Term Natural Gas Liquefaction Energy Efficiency: North American	Triangular	90.3%	Min=87.0% Likeliest=91.0% Max=93.0%	GREET Model [a]
Near-Term Natural Gas Compression Energy Efficiency: Non-North American	Triangular	90.3%	Min=87.0% Likeliest=91.0% Max=93.0%	GREET Model [a]
Long-Term Natural Gas Compression Energy Efficiency of natural gas Compressors	Normal	93.0%	20 percentile= 92.0% 80 percentile= 94.0%	GREET Model [a]
Long-Term Natural Gas Compression Energy Efficiency: Electric Compressors	Triangular	97.0%	Min=96.0% Likeliest=97.0% Max=98.0%	GREET Model [a]
Long-Term Natural Gas Liquefaction Energy Efficiency : North American	Triangular	90.3%	Min=87.0% Likeliest=91.0% Max=93.0%	GREET Model [a]
Long-Term Natural Gas Liquefaction Energy Efficiency: Non-North American	Triangular	90.3%	Min=87.0% Likeliest=91.0% Max=93.0%	GREET Model [a]
Cargo Payload By Ocean Tanker and by Gasoline	Triangular	150,000 Tons	Min=100,000; Likeliest=150,000; Max=200,000	GREET Model [a]
Cargo Payload By Ocean Tanker and by Diesel	Triangular	150,000 tons	Min=100,000; Likeliest=150,000; Max=200,000	GREET Model [a]
Current Residual Oil-Fired Power Plant Energy Conversion Efficiency	Normal	35.0%	20 percentile= 32.0% 80 percentile= 38.0%	GREET Model [a]
Future Residual Oil-Fired Power Plant Energy Conversion Efficiency	Normal	35.0%	20 percentile= 32.0% 80 percentile= 38.0%	GREET Model [a]
Natural Gas-Fired Power Plant Energy Conversion Efficiency	Normal	35.0%	20 percentile= 32.0% 80 percentile= 38.0%	GREET Model [a]

(Continued on next page)

Table 7.12 Continued

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Current Natural Gas-Fired Power Plant Energy Conversion Efficiency	Triangular	55.0%	Min=50% Likeliest=55%; Max=60%	GREET Model [a]
Future Coal-Fired Power Plant Energy Conversion Efficiency	Normal	35.5%	20 percentile= 33.0% 80 percentile= 38.0%	GREET Model [a]
Coal Mining Energy Efficiency	Normal	99.3%	20 percentile= 99.0% 80 percentile= 99.7%	GREET Model [a]
Current Natural Gas Utility/Industrial Boiler HC Emission Factor	Normal	1.1 g/MMBtu	2.5%= 0.77 97.5%= 1.43	Frey and Li (2003)[b]
Current Natural Gas Utility/Industrial Boiler CO Emission Factor	Normal	13.8 g/MMBtu	2.5%= 9.66 97.5%= 17.94	Frey and Li (2003)[b]
Current Natural Gas Utility/Industrial Boiler NO_x Emission Factor	Normal	41.4 g/MMBtu	2.5%= 31.05 97.5%= 51.75	Frey and Li (2003)[b]
Current Natural Gas Utility/Industrial Boiler PM Emission Factor	Normal	1.88 g/MMBtu	2.5%= 1.32 97.5%= 2.44	Frey and Li (2003)[b]
Future Natural Gas Utility/Industrial Boiler HC Emission Factor	Normal	1.1 g/MMBtu	2.5%= 0.77 97.5%= 1.43	Frey and Li (2003)[b]
Future Natural Gas Utility/Industrial Boiler CO Emission Factor	Normal	13.8 g/MMBtu	2.5%= 9.66 97.5%= 17.94	Frey and Li (2003)[b]
Future Natural Gas Utility/Industrial Boiler NOx Emission Factor	Normal	15.6 g/MMBtu	2.5%= 11.7 97.5%= 19.5	Frey and Li (2003)[b]
Future Natural Gas Utility/Industrial Boiler PM Emission Factor	Normal	1.88 g/MMBtu	2.5%= 1.32 97.5%= 2.44	Frey and Li (2003)[b]
Current Natural Gas Small Industrial Boiler HC Emission Factor	Normal	6.0 g/MMBtu	2.5%= 4.2 97.5%= 7.8	Frey and Li (2003)[b]
Current Natural Gas Small Industrial Boiler CO Emission Factor	Normal	54.8 g/MMBtu	2.5%= 38.36 97.5%= 71.24	Frey and Li (2003)[b]
Current Natural Gas Small Industrial Boiler NO_x Emission Factor	Normal	48.1 g/MMBtu	2.5%= 36.08 97.5%= 60.13	Frey and Li (2003)[b]
Current Natural Gas Small Industrial Boiler PM Emission Factor	Normal	7.33 g/MMBtu	2.5%= 5.13 97.5%= 9.53	Frey and Li (2003)[b]

(Continued on next page)

Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Future Natural Gas Small Industrial Boiler HC Emission Factor	Normal	2.7 g/MMBtu	2.5%= 1.89 97.5%= 3.51	Frey and Li (2003)[b]
Future Natural Gas Small Industrial Boiler CO Emission Factor	Normal	41.1 g/MMBtu	2.5%= 28.77 97.5%= 53.43	Frey and Li (2003)[b]
Future Natural Gas Small Industrial Boiler NO_x Emission Factor	Normal	15.6 g/MMBtu	2.5%= 11.7 97.5%= 19.5	Frey and Li (2003)[b]
Future Natural Gas Small Industrial Boiler PM Emission Factor	Normal	3.7 g/MMBtu	2.5%= 2.59 97.5%= 4.81	Frey and Li (2003)[b]
Current Natural Gas Large Gas Turbine HC Emission Factor	Normal	1.05 g/MMBtu	2.5%= 0.74 97.5%= 1.37	Frey and Li (2003)[b]
Current Natural Gas Large Gas Turbine CO Emission Factor	Normal	7.5 g/MMBtu	2.5%= 5.25 97.5%= 9.75	Frey and Li (2003)[b]
Current Natural Gas Large Gas Turbine NO_x Emission Factor	Normal	49.4 g/MMBtu	2.5%= 37.05 97.5%= 61.75	Frey and Li (2003)[b]
Current Natural Gas Large Gas Turbine PM Emission Factor	Normal	3.29 g/MMBtu	2.5%= 2.30 97.5%= 4.28	Frey and Li (2003)[b]
Future Natural Gas Large Gas Turbine HC Emission Factor	Normal	1.05 g/MMBtu	2.5%= 0.74 97.5%= 1.37	Frey and Li (2003)[b]
Future Natural Gas Large Gas Turbine CO Emission Factor	Normal	7.5 g/MMBtu	2.5%= 5.25 97.5%= 9.75	Frey and Li (2003)[b]
Future Natural Gas Large Gas Turbine NO_x Emission Factor	Normal	49.4 g/MMBtu	2.5%= 37.05 97.5%= 61.75	Frey and Li (2003)[b]
Future Natural Gas Large Gas Turbine PM Emission Factor	Normal	3.29 g/MMBtu	2.5%= 2.30 97.5%= 4.28	Frey and Li (2003)[b]
Current Natural Gas Small Turbine HC Emission Factor	Normal	0.91 g/MMBtu	2.5%= 0.64 97.5%= 1.18	Frey and Li (2003)[b]

(Continued on next page)

Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Current Natural Gas Small Turbine CO Emission Factor	Normal	77.2 g/MMBtu	2.5%= 54.04 97.5%= 100.4	Frey and Li (2003)[b]
Current Natural Gas Small Turbine NO_x Emission Factor	Normal	154 g/MMBtu	2.5%= 115.5 97.5%= 192.5	Frey and Li (2003)[b]
Current Natural Gas Small Turbine PM Emission Factor	Normal	11.6 g/MMBtu	2.5%= 8.12 97.5%= 15.08	Frey and Li (2003)[b]
Current Natural Gas Stationary Reciprocating Engine HC Emission Factor	Normal	37.3 g/MMBtu	2.5%= 26.1 97.5%= 48.5	Frey and Li (2003)[b]
Current Natural Gas Stationary Reciprocating Engine CO Emission Factor	Normal	1000 g/MMBtu	2.5%= 700 97.5%= 1300	Frey and Li (2003)[b]
Current Natural Gas Stationary Reciprocating Engine NO_x Emission Factor	Normal	1570 g/MMBtu	2.5%= 1178 97.5%= 1963	Frey and Li (2003)[b]
Current Natural Gas Stationary Reciprocating Engine PM Emission Factor	Normal	7.33 g/MMBtu	2.5%= 5.13 97.5%= 9.53	Frey and Li (2003)[b]
Future Natural Gas Stationary Reciprocating Engine HC Emission Factor	Normal	37.3 g/MMBtu	2.5%= 26.1 97.5%= 48.5	Frey and Li (2003)[b]
Future Natural Gas Stationary Reciprocating Engine CO Emission Factor	Normal	543 g/MMBtu	2.5%= 380 97.5%= 706	Frey and Li (2003)[b]
Future Natural Gas Stationary Reciprocating Engine NO_x Emission Factor	Normal	1060 g/MMBtu	2.5%= 795 97.5%= 1325	Frey and Li (2003)[b]
Future Natural Gas Stationary Reciprocating Engine PM Emission Factor	Normal	7.33 g/MMBtu	2.5%= 5.13 97.5%= 9.53	Frey and Li (2003)[b]

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Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Current Residual-Oil-fired Utility Boiler HC Emission Factor	Normal	2.46 g/MMBtu	2.5%= 1.722 97.5%= 3.2	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-fired Utility Boiler CO Emission Factor	Normal	16.2 g/MMBtu	2.5%= 11.34 97.5%= 21.1	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-fired Utility Boiler NO_x Emission Factor	Normal	104 g/MMBtu	2.5%= 78 97.5%= 135	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-fired Utility Boiler PM Emission Factor	Normal	6.15 g/MMBtu	2.5%= 4.31 97.5%= 8.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Residual-Oil-fired Utility Boiler HC Emission Factor	Normal	2.46 g/MMBtu	2.5%= 1.72 97.5%= 3.2	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Residual-Oil-fired Utility Boiler CO Emission Factor	Normal	16.2 g/MMBtu	2.5%= 11.34 97.5%= 21.1	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Residual-Oil-fired Utility Boiler NO_x Emission Factor	Normal	84.2 g/MMBtu	2.5%= 63.2 97.5%= 105.3	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Residual-Oil-fired Utility Boiler PM Emission Factor	Normal	6.15 g/MMBtu	2.5%= 4.31 97.5%= 8.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-Fired Industrial Boiler HC Emission Factor	Normal	0.91 g/MMBtu	2.5%= 0.64 97.5%= 1.18	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-Fired Industrial Boiler CO Emission Factor	Normal	16.2 g/MMBtu	2.5%= 11.34 97.5%= 21.1	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-Fired Industrial Boiler NO_x Emission Factor	Normal	178 g/MMBtu	2.5%= 133.5 97.5%= 222.5	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-Fired Industrial Boiler PM Emission Factor	Normal	6.15 g/MMBtu	2.5%= 4.3 97.5%= 8.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]

(Continued on next page)

Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Future Residual-Oil-Fired Industrial Boiler HC Emission Factor	Normal	0.91 g/MMBtu	2.5%= 0.64 97.5%= 1.18	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Residual-Oil-Fired Industrial Boiler CO Emission Factor	Normal	16.2 g/MMBtu	2.5%= 11.3 97.5%= 21.1	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Residual-Oil-Fired Industrial Boiler NO_x Emission Factor	Normal	145 g/MMBtu	2.5%= 108.8 97.5%= 188.5	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Residual-Oil-Fired Industrial Boiler PM Emission Factor	Normal	6.15 g/MMBtu	2.5%= 4.31 97.5%= 8.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-Fired Commercial Boiler HC Emission Factor	Normal	1.10 g/MMBtu	2.5%= 0.77 97.5%= 1.43	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-Fired Commercial Boiler CO Emission Factor	Normal	16.2 g/MMBtu	2.5%= 11.3 97.5%= 21.1	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-Fired Commercial Boiler NO_x Emission Factor	Normal	19.5 g/MMBtu	2.5%= 14.6 97.5%= 25.4	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Residual-Oil-Fired Commercial Boiler PM Emission Factor	Normal	14.1 g/MMBtu	2.5%= 9.87 97.5%= 18.3	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Industrial Boiler HC Emission Factor	Normal	0.71 g/MMBtu	2.5%= 0.50 97.5%= 0.92	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Industrial Boiler CO Emission Factor	Normal	17.7 g/MMBtu	2.5%= 12.4 97.5%= 23.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Industrial Boiler NO_x Emission Factor	Normal	84.7 g/MMBtu	2.5%= 63.5 97.5%= 105.9	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]

(Continued on next page)

Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Current Diesel Industrial Boiler PM Emission Factor	Normal	3.53 g/MMBtu	2.5%= 2.47 97.5%= 4.6	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Diesel Industrial Boiler HC Emission Factor	Normal	0.71 g/MMBtu	2.5%= 0.50 97.5%= 0.92	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Diesel Industrial Boiler CO Emission Factor	Normal	17.7 g/MMBtu	2.5%= 12.4 97.5%= 23.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Diesel Industrial Boiler NO_x Emission Factor	Normal	35.3 g/MMBtu	2.5%= 26.5 97.5%= 44.1	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Diesel Industrial Boiler PM Emission Factor	Normal	3.53 g/MMBtu	2.5%= 2.47 97.5%= 4.59	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Commercial Boiler HC Emission Factor	Normal	1.2 g/MMBtu	2.5%= 0.84 97.5%= 1.56	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Commercial Boiler CO Emission Factor	Normal	17.7 g/MMBtu	2.5%= 12.4 97.5%= 23.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Commercial Boiler NO_x Emission Factor	Normal	70.4 g/MMBtu	2.5%= 52.8 97.5%= 88.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Commercial Boiler PM Emission Factor	Normal	6.15 g/MMBtu	2.5%= 4.31 97.5%= 8.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Diesel Commercial Boiler HC Emission Factor	Normal	1.2 g/MMBtu	2.5%= 0.84 97.5%= 1.56	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Diesel Commercial Boiler CO Emission Factor	Normal	17.7 g/MMBtu	2.5%= 12.4 97.5%= 23.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Diesel Commercial Boiler NO_x Emission Factor	Normal	56.3 g/MMBtu	2.5%= 42.2 97.5%= 70.4	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Diesel Commercial Boiler PM Emission Factor	Normal	6.15 g/MMBtu	2.5%= 4.31 97.5%= 8.0	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]

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Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Current Diesel Engine HC Emission Factor	Normal	39.9 g/MMBtu	2.5%= 27.9 97.5%= 51.9	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Engine CO Emission Factor	Normal	414 g/MMBtu	2.5%= 290 97.5%= 538	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Engine NO_x Emission Factor	Normal	1560 g/MMBtu	2.5%= 1170 97.5%= 1950	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Diesel Engine PM Emission Factor	Normal	48.7 g/MMBtu	2.5%= 34.1 97.5%= 63.3	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Controlled Diesel Turbine HC Emission Factor	Normal	1.34 g/MMBtu	2.5%= 0.94 97.5%= 1.74	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Controlled Diesel Turbine CO Emission Factor	Normal	8.71 g/MMBtu	2.5%= 6.1 97.5%= 11.3	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Controlled Diesel Turbine NO_x Emission Factor	Normal	131 g/MMBtu	2.5%= 98.3 97.5%= 163.8	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Controlled Diesel Turbine PM Emission Factor	Normal	17.0 g/MMBtu	2.5%= 11.9 97.5%= 22.1	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Gasoline Engine HC Emission Factor	Normal	93 g/MMBtu	2.5%= 65.1 97.5%= 120.9	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Gasoline Engine CO Emission Factor	Normal	4440 g/MMBtu	2.5%= 3108 97.5%= 5772	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Gasoline Engine NO_x Emission Factor	Normal	1100 g/MMBtu	2.5%= 825 97.5%= 1375	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Gasoline Engine PM Emission Factor	Normal	8.7 g/MMBtu	2.5%= 6.1 97.5%= 11.3	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Coal-Fired Utility Boiler HC Emission Facto	Normal	1.42 g/MMBtu	2.5%= 0.99 97.5%= 1.85	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Coal-Fired Utility Boiler CO Emission Facto	Normal	11.8 g/MMBtu	2.5%= 8.3 97.5%= 15.3	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Coal-Fired Utility Boiler NO_x Emission Facto	Normal	188 g/MMBtu	2.5%= 141 97.5%= 235	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Coal-Fired Utility Boiler PM10 Emission Facto	Normal	29.4 g/MMBtu	2.5%= 20.6 97.5%= 38.2	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]

(Continued on next page)

Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Future Coal-Fired Utility Boiler HC Emission Facto	Normal	1.14 g/MMBtu	2.5%= 0.80 97.5%= 1.48	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Coal-Fired Utility Boiler CO Emission Facto	Normal	9.61 g/MMBtu	2.5%= 6.73 97.5%= 12.5	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Coal-Fired Utility Boiler NO_x Emission Facto	Normal	106 g/MMBtu	2.5%= 79.5 97.5%= 132.5	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Coal-Fired Utility Boiler PM Emission Facto	Normal	12.6 g/MMBtu	2.5%= 8.82 97.5%= 16.4	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Coal-Fired Industrial Boiler HC Emission Factor	Normal	4.52 g/MMBtu	2.5%= 3.2 97.5%= 5.9	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Coal-Fired Industrial Boiler CO Emission Factor	Normal	56.5 g/MMBtu	2.5%= 39.6 97.5%= 73.5	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Coal-Fired Industrial Boiler NO_x Emission Factor	Normal	202 g/MMBtu	2.5%= 152 97.5%= 253	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Current Coal-Fired Industrial Boiler PM Emission Factor	Normal	22.6 g/MMBtu	2.5%= 15.8 97.5%= 29.4	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Coal-Fired Industrial Boiler HC Emission Factor	Normal	0.96 g/MMBtu	2.5%= 0.67 97.5%= 1.25	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Coal-Fired Industrial Boiler CO Emission Factor	Normal	96.1 g/MMBtu	2.5%= 67.3 97.5%= 125	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Coal-Fired Industrial Boiler NO_x Emission Factor	Normal	169 g/MMBtu	2.5%= 127 97.5%= 211	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]
Future Coal-Fired Industrial Boiler PM Emission Factor	Normal	12.6 g/MMBtu	2.5%= 8.8 97.5%= 16.4	Frey and Li (2003) and Frey and Abdel-Aziz (2003) [b]

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Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Petroleum Diesel Tailpipe HC Emission for Backhoe 1	Normal	11.0 g/gallon	2.5%= 10.45 97.5%=11.55	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Backhoe 1	Normal	8.9 g/gallon	2.5%= 8.19 97.5%= 9.61	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Backhoe 1	Normal	97.7 g/gallon	2.5%= 94.77 97.5%= 100.6	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Backhoe 1	Normal	6.2 g/gallon	2.5%= 5.89 97.5%= 6.51	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Backhoe 1	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Backhoe 2	Normal	15.3 g/gallon	2.5%= 14.54 97.5%= 16.07	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Backhoe 2	Normal	88.3 g/gallon	2.5%= 81.24 97.5%= 95.36	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Backhoe 2	Normal	104.7 g/gallon	2.5%= 101.6 97.5%= 107.8	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Backhoe 2	Normal	25 g/gallon	2.5%= 23.75 97.5%= 26.25	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Backhoe 2	Normal	10478 g/gallon	2.5%= 10269 97.5%= 10688	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Backhoe 3	Normal	13.0 g/gallon	2.5%= 12.35 97.5%= 13.65	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Backhoe 3	Normal	37.0 g/gallon	2.5%= 34.04 97.5%= 39.96	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Backhoe 3	Normal	100.7 g/gallon	2.5%= 97.68 97.5%= 103.7	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Backhoe 3	Normal	14.0 g/gallon	2.5%= 13.3 97.5%= 14.7	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Backhoe 3	Normal	10489 g/gallon	2.5%= 10279 97.5%= 10699	Precision of the PEMS [c]

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Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Petroleum Diesel Tailpipe HC Emission for Backhoe 4	Normal	7.1 g/gallon	2.5%= 6.75 97.5%= 7.46	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Backhoe 4	Normal	50.6 g/gallon	2.5%= 46.55 97.5%= 54.65	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Backhoe 4	Normal	107.3 g/gallon	2.5%= 104.1 97.5%= 110.5	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Backhoe 4	Normal	15.0 g/gallon	2.5%= 14.25 97.5%= 15.75	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Backhoe 4	Normal	10489 g/gallon	2.5%= 10279 97.5%= 10699	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Backhoe 5	Normal	9.9 g/gallon	2.5%= 9.41 97.5%= 10.4	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Backhoe 5	Normal	16.3 g/gallon	2.5%= 15.0 97.5%= 17.6	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Backhoe 5	Normal	102.0 g/gallon	2.5%= 98.94 97.5%= 105.1	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Backhoe 5	Normal	6.2 g/gallon	2.5%= 5.89 97.5%= 6.51	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Backhoe 5	Normal	10492 g/gallon	2.5%= 10282 97.5%= 10702	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Front-End Loader 1	Normal	18.0 g/gallon	2.5%= 17.1 97.5%= 18.9	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Front-End Loader 1	Normal	16.3 g/gallon	2.5%= 15.0 97.5%= 17.6	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Front-End Loader 1	Normal	110.0 g/gallon	2.5%= 106.7 97.5%= 113.3	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Front-End Loader 1	Normal	6.9 g/gallon	2.5%= 6.56 97.5%= 7.25	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Front-End Loader 1	Normal	10492 g/gallon	2.5%= 10282 97.5%= 10702	Precision of the PEMS [c]

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Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Petroleum Diesel Tailpipe HC Emission for Front-End Loader 2	Normal	16.7 g/gallon	2.5%= 15.9 97.5%= 17.5	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Front-End Loader 2	Normal	13.0 g/gallon	2.5%= 11.96 97.5%= 14.04	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Front-End Loader 2	Normal	128.7 g/gallon	2.5%= 124.8 97.5%= 132.6	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Front-End Loader 2	Normal	6.9 g/gallon	2.5%= 6.56 97.5%= 7.25	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Front-End Loader 2	Normal	10493 g/gallon	2.5%= 10283 97.5%= 10703	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Front-End Loader 3	Normal	13.0 g/gallon	2.5%= 12.35 97.5%= 13.65	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Front-End Loader 3	Normal	15.3 g/gallon	2.5%= 14.1 97.5%= 16.5	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Front-End Loader 3	Normal	127.0 g/gallon	2.5%= 123.2 97.5%= 130.8	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Front-End Loader 3	Normal	8.4 g/gallon	2.5%= 7.98 97.5%= 9.07	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Front-End Loader 3	Normal	10494 g/gallon	2.5%= 10284 97.5%= 10704	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Front-End Loader 4	Normal	5.6 g/gallon	2.5%= 5.32 97.5%= 5.88	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Front-End Loader 4	Normal	15.0 g/gallon	2.5%= 13.8 97.5%= 16.2	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Front-End Loader 4	Normal	95.0 g/gallon	2.5%= 92.2 97.5%= 97.9	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Front-End Loader 4	Normal	3.4 g/gallon	2.5%= 3.23 97.5%= 3.57	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Front-End Loader 4	Normal	10497 g/gallon	2.5%= 10287 97.5%= 10707	Precision of the PEMS [c]

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Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Petroleum Diesel Tailpipe HC Emission for Motor Grader 1	Normal	15.0 g/gallon	2.5%= 14.25 97.5%= 15.75	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Motor Grader 1	Normal	13.5 g/gallon	2.5%= 12.42 97.5%= 14.58	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Motor Grader 1	Normal	108.5 g/gallon	2.5%= 105.2 97.5%= 111.8	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Motor Grader 1	Normal	6.8 g/gallon	2.5%= 6.46 97.5%= 7.14	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Motor Grader 1	Normal	10493 g/gallon	2.5%= 10283 97.5%= 10703	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Motor Grader 2	Normal	12.0 g/gallon	2.5%= 11.4 97.5%= 12.6	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Motor Grader 2	Normal	12.0 g/gallon	2.5%= 11.04 97.5%= 12.96	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Motor Grader 2	Normal	98.0 g/gallon	2.5%= 95.06 97.5%= 100.9	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Motor Grader 2	Normal	2.9 g/gallon	2.5%= 2.76 97.5%= 3.05	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Motor Grader 2	Normal	10495 g/gallon	2.5%= 10285 97.5%= 10705	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Motor Grader 3	Normal	18.0 g/gallon	2.5%= 17.1 97.5%= 18.9	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Motor Grader 3	Normal	15.5 g/gallon	2.5%= 14.26 97.5%= 16.74	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Motor Grader 3	Normal	110.0 g/gallon	2.5%= 106.7 97.5%= 113.3	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Motor Grader 3	Normal	6.8 g/gallon	2.5%= 6.46 97.5%= 7.14	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Motor Grader 3	Normal	10492 g/gallon	2.5%= 10282 97.5%= 10702	Precision of the PEMS [c]

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Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Petroleum Diesel Tailpipe HC Emission for Motor Grader 4	Normal	18.5 g/gallon	2.5%= 17.6 97.5%= 19.4	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Motor Grader 4	Normal	30.5 g/gallon	2.5%= 28.1 97.5%= 32.9	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Motor Grader 4	Normal	130.0 g/gallon	2.5%= 126.1 97.5%= 133.9	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Motor Grader 4	Normal	18.0 g/gallon	2.5%= 17.1 97.5%= 18.9	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Motor Grader 4	Normal	10489 g/gallon	2.5%= 10279 97.5%= 10699	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Motor Grader 5	Normal	14.9 g/gallon	2.5%= 14.2 97.5%= 15.65	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Motor Grader 5	Normal	36.0 g/gallon	2.5%= 33.1 97.5%= 38.9	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Motor Grader 5	Normal	137.5 g/gallon	2.5%= 133.4 97.5%= 141.6	Precision of the PEMS [c]
Petroleum Diesel Tailpipe PM Emission for Motor Grader 5	Normal	16.0 g/gallon	2.5%= 15.2 97.5%= 16.8	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Motor Grader 5	Normal	10489 g/gallon	2.5%= 10279 97.5%= 10699	Precision of the PEMS [c]
Petroleum Diesel Tailpipe HC Emission for Motor Grader 6	Normal	6.2 g/gallon	2.5%= 5.89 97.5%= 6.51	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO Emission for Motor Grader 6	Normal	9.0 g/gallon	2.5%= 8.28 97.5%= 9.72	Precision of the PEMS [c]
Petroleum Diesel Tailpipe NO_x Emission for Motor Grader 6	Normal	68.0 g/gallon	2.5%= 66.0 97.5%= 70.0	Precision of the PEMS [c]

(Continued on next page)

Table 7.12 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Petroleum Diesel Tailpipe PM Emission for Motor Grader 6	Normal	1.8 g/gallon	2.5%= 1.71 97.5%= 1.89	Precision of the PEMS [c]
Petroleum Diesel Tailpipe CO_2 Emission for Motor Grader 6	Normal	10498 g/gallon	2.5%= 10289 97.5%= 10699	Precision of the PEMS [c]

a. These assumptions are based on default distributions in GREET 1.6 Model. When the GREET 1.6 model is opened with Crystal Ball software, the cells with green color have default distribution for uncertainty analysis.

b. The relative 95% confidence intervals of the mean are ±25% for NO_x and ±30% for HC based on Frey and Li (2003) and Frey and Abdel-Aziz (2003). The relative 95% confidence intervals of the mean for CO and PM are ±30% based on professional judgment.

c. For vehicle tailpipe emissions, the 95% confidence interval of the mean is ± 3% for HC, 8% for CO, 3% for NO_x, 2% for CO_2, and 5% for PM based on the precision of the PEMS.

Table 7.13 Probability Distribution of Uncertain Inputs for Biodiesel Life Cycle [a]

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
Soybean Use	Normal	5.9 lb./lb.	2.5%= 5.31 97.5%= 6.49	Professional Judgment [b]
Soyoil Use	Normal	1.04 lb./ lb.	2.5%= 0.99 97.5%=1.09	Professional Judgment [c]
Current Diesel Farming Tractor HC Emission Factor	Normal	90 g/MMBtu	2.5%= 97.5%=	Precision of the PEMS [d]
Current Diesel Farming Tractor CO Emission Factor	Normal	334 g/MMBtu	2.5%= 97.5%=	Precision of the PEMS [d]
Current Diesel Farming Tractor NO_x Emission Factor	Normal	939 g/MMBtu	2.5%= 97.5%=	Precision of the PEMS [d]
Current Diesel Farming Tractor PM Emission Factor	Normal	43.5 g/MMBtu	2.5%= 97.5%=	Precision of the PEMS [d]
Current Gasoline Farming Tractor HC Emission Factor	Normal	210 g/MMBtu	2.5%= 97.5%=	Precision of the PEMS [d]
Current Gasoline Farming Tractor CO Emission Factor	Normal	1200 g/MMBtu	2.5%= 97.5%=	Precision of the PEMS [d]
Current Gasoline Farming Tractor NO_x Emission Factor	Normal	662 g/MMBtu	2.5%= 97.5%=	Precision of the PEMS [d]
Current Gasoline Farming Tractor PM Emission Factor	Normal	7.81 g/MMBtu	2.5%= 97.5%=	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Backhoe 1	Normal	8.2 g/gallon	2.5%= 7.79 97.5%= 8.61	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Backhoe 1	Normal	7.7 g/gallon	2.5%= 7.08 97.5%= 8.32	Precision of the PEMS [d]

(Continued on next page)

Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe NOx Emission based on NCSU Data for Backhoe 1	Normal	98.8 g/gallon	2.5%= 95.8 97.5%= 101.8	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Backhoe 1	Normal	4.8 g/gallon	2.5%= 4.56 97.5%= 5.04	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Backhoe 1	Normal	10497 g/gallon	2.5%= 10287 97.5%= 10707	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Backhoe 1	Normal	8.7 g/gallon	2.5%= 8.27 97.5%= 9.14	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Backhoe 1	Normal	7.9 g/gallon	2.5%= 7.27 97.5%= 8.53	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Backhoe 1	Normal	99.7 g/gallon	2.5%= 96.7 97.5%= 102.7	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Backhoe 1	Normal	5.6 g/gallon	2.5%= 5.32 97.5%= 5.88	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Backhoe 1	Normal	10497 g/gallon	2.5%= 10287 97.5%= 10707	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Backhoe 1	Normal	9.7 g/gallon	2.5%= 9.22 97.5%= 10.2	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Backhoe 1	Normal	7.4 g/gallon	2.5%= 6.81 97.5%= 7.99	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Backhoe 1	Normal	98.3 g/gallon	2.5%= 95.4 97.5%= 101.2	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Backhoe 1	Normal	5.2 g/gallon	2.5%= 4.94 97.5%= 5.46	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Backhoe 1	Normal	10497 g/gallon	2.5%= 10287 97.5%= 10707	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Backhoe 2	Normal	13.9 g/gallon	2.5%= 13.21 97.5%= 14.6	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Backhoe 2	Normal	73.0 g/gallon	2.5%= 67.2 97.5%= 78.8	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe NOx Emission based on NCSU Data for Backhoe 2	Normal	110.0 g/gallon	2.5%= 106.7 97.5%= 113.3	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Backhoe 2	Normal	24.2 g/gallon	2.5%= 23.0 97.5%= 25.4	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Backhoe 2	Normal	10482 g/gallon	2.5%= 10272 97.5%= 10692	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Backhoe 2	Normal	12.1 g/gallon	2.5%= 11.5 97.5%= 12.7	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Backhoe 2	Normal	78.6 g/gallon	2.5%= 72.3 97.5%= 84.9	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Backhoe 2	Normal	106.8 g/gallon	2.5%= 103.6 97.5%= 110	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Backhoe 2	Normal	22.5 g/gallon	2.5%= 21.4 97.5%= 23.6	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Backhoe 2	Normal	10482 g/gallon	2.5%= 10272 97.5%= 10692	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Backhoe 2	Normal	13.5 g/gallon	2.5%= 12.8 97.5%= 14.2	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Backhoe 2	Normal	73.2 g/gallon	2.5%= 67.3 97.5%= 79.1	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Backhoe 2	Normal	105.3 g/gallon	2.5%= 102.1 97.5%= 108.5	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Backhoe 2	Normal	20.9 g/gallon	2.5%= 19.9 97.5%= 21.9	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Backhoe 2	Normal	10482 g/gallon	2.5%= 10272 97.5%= 10692	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Backhoe 3	Normal	11.9 g/gallon	2.5%= 11.3 97.5%= 12.5	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Backhoe 3	Normal	33.9 g/gallon	2.5%= 31.2 97.5%= 36.6	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe NOx Emission based on NCSU Data for Backhoe 3	Normal	86.5 g/gallon	2.5%= 83.9 97.5%= 89.1	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Backhoe 3	Normal	12.1 g/gallon	2.5%= 11.5 97.5%= 12.7	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Backhoe 3	Normal	10490 g/gallon	2.5%= 10280 97.5%= 10700	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Backhoe 3	Normal	10.3 g/gallon	2.5%= 9.79 97.5%= 10.8	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Backhoe 3	Normal	32.9 g/gallon	2.5%= 30.3 97.5%= 35.5	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Backhoe 3	Normal	102.7 g/gallon	2.5%= 99.6 97.5%= 105.8	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Backhoe 3	Normal	12.6 g/gallon	2.5%= 12.0 97.5%= 13.2	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Backhoe 3	Normal	10490 g/gallon	2.5%= 10280 97.5%= 10700	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Backhoe 3	Normal	11.5 g/gallon	2.5%= 10.9 97.5%= 12.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Backhoe 3	Normal	30.7 g/gallon	2.5%= 28.2 97.5%= 33.2	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Backhoe 3	Normal	101.3 g/gallon	2.5%= 98.3 97.5%= 104.3	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Backhoe 3	Normal	11.7 g/gallon	2.5%= 11.1 97.5%= 12.3	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Backhoe 3	Normal	10490 g/gallon	2.5%= 10280 97.5%= 10700	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Backhoe 4	Normal	5.5 g/gallon	2.5%= 5.23 97.5%= 5.78	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Backhoe 4	Normal	42.5 g/gallon	2.5%= 39.1 97.5%= 45.9	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe NOx Emission based on NCSU Data for Backhoe 4	Normal	105.2 g/gallon	2.5%= 102.1 97.5%= 108.4	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Backhoe 4	Normal	12.9 g/gallon	2.5%= 12.3 97.5%= 13.5	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Backhoe 4	Normal	10491 g/gallon	2.5%= 10281 97.5%= 10701	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Backhoe 4	Normal	5.6 g/gallon	2.5%= 5.32 97.5%= 5.88	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Backhoe 4	Normal	45.0 g/gallon	2.5%= 41.4 97.5%= 48.6	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Backhoe 4	Normal	109.4 g/gallon	2.5%= 106.1 97.5%= 112.7	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Backhoe 4	Normal	13.5 g/gallon	2.5%= 12.8 97.5%= 14.2	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Backhoe 4	Normal	10491 g/gallon	2.5%= 10281 97.5%= 10701	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Backhoe 4	Normal	6.3 g/gallon	2.5%= 6.0 97.5%= 6.62	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Backhoe 4	Normal	41.9 g/gallon	2.5%= 38.5 97.5%= 45.3	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Backhoe 4	Normal	107.9 g/gallon	2.5%= 104.7 97.5%= 111.1	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Backhoe 4	Normal	12.5 g/gallon	2.5%= 11.9 97.5%= 13.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Backhoe 4	Normal	10491 g/gallon	2.5%= 10281 97.5%= 10701	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Backhoe 5	Normal	3.5 g/gallon	2.5%= 3.3 97.5%= 3.68	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Backhoe 5	Normal	12.5 g/gallon	2.5%= 11.5 97.5%= 13.5	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe NOx Emission based on NCSU Data for Backhoe 5	Normal	100.5 g/gallon	2.5%= 97.5 97.5%= 103.5	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Backhoe 5	Normal	4.8 g/gallon	2.5%= 4.56 97.5%= 5.04	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Backhoe 5	Normal	10498 g/gallon	2.5%= 10288 97.5%= 10708	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Backhoe 5	Normal	7.8 g/gallon	2.5%= 7.41 97.5%= 8.19	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Backhoe 5	Normal	14.5 g/gallon	2.5%= 13.3 97.5%= 15.7	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Backhoe 5	Normal	104.0 g/gallon	2.5%= 100.9 97.5%= 107.1	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Backhoe 5	Normal	5.6 g/gallon	2.5%= 5.32 97.5%= 5.88	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Backhoe 5	Normal	10498 g/gallon	2.5%= 10288 97.5%= 10708	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Backhoe 5	Normal	8.7 g/gallon	2.5%= 8.27 97.5%= 9.14	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Backhoe 5	Normal	13.5 g/gallon	2.5%= 12.4 97.5%= 14.6	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Backhoe 5	Normal	102.6 g/gallon	2.5%= 99.5 97.5%= 105.7	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Backhoe 5	Normal	5.2 g/gallon	2.5%= 4.94 97.5%= 5.46	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe CO2 Emission based on NREL Data for Backhoe 5	Normal	10498 g/gallon	2.5%= 10288 97.5%= 10708	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Front-End Loader 1	Normal	7.5 g/gallon	2.5%= 7.13 97.5%= 7.88	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Front-End Loader 1	Normal	8.7 g/gallon	2.5%= 8.0 97.5%= 9.4	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Front-End Loader 1	Normal	113.0 g/gallon	2.5%= 109.6 97.5%= 116.4	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Front-End Loader 1	Normal	5.3 g/gallon	2.5%= 5.0 97.5%= 5.6	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Front-End Loader 1	Normal	10497 g/gallon	2.5%= 10287 97.5%= 10707	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Front-End Loader 1	Normal	14.2 g/gallon	2.5%= 13.5 97.5%= 14.9	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Front-End Loader 1	Normal	14.5 g/gallon	2.5%= 13.3 97.5%= 15.7	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Front-End Loader 1	Normal	112.2 g/gallon	2.5%= 108.8 97.5%= 115.6	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Front-End Loader 1	Normal	6.2 g/gallon	2.5%= 5.89 97.5%= 6.51	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe CO2 Emission based on EPA Data for Front-End Loader 1	Normal	10497 g/gallon	2.5%= 10287 97.5%= 10707	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Front-End Loader 1	Normal	15.9 g/gallon	2.5%= 15.1 97.5%= 16.7	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Front-End Loader 1	Normal	13.5 g/gallon	2.5%= 12.4 97.5%= 14.6	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Front-End Loader 1	Normal	110.7 g/gallon	2.5%= 107.4 97.5%= 114	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Front-End Loader 1	Normal	5.8 g/gallon	2.5%= 5.51 97.5%= 6.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Front-End Loader 1	Normal	10497 g/gallon	2.5%= 10287 97.5%= 10707	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Front-End Loader 2	Normal	8.6 g/gallon	2.5%= 8.2 97.5%= 9.0	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Front-End Loader 2	Normal	10.5 g/gallon	2.5%= 9.66 97.5%= 11.3	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Front-End Loader 2	Normal	122.9 g/gallon	2.5%= 119.2 97.5%= 126.6	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Front-End Loader 2	Normal	5.3 g/gallon	2.5%= 5.04 97.5%= 5.57	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Front-End Loader 2	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Front-End Loader 2	Normal	13.2 g/gallon	2.5%= 12.5 97.5%= 13.9	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Front-End Loader 2	Normal	11.6 g/gallon	2.5%= 10.7 97.5%= 12.5	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Front-End Loader 2	Normal	131.3 g/gallon	2.5%= 127.4 97.5%= 135.2	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Front-End Loader 2	Normal	6.2 g/gallon	2.5%= 5.89 97.5%= 6.51	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Front-End Loader 2	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Front-End Loader 2	Normal	14.8 g/gallon	2.5%= 14.1 97.5%= 15.5	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Front-End Loader 2	Normal	10.8 g/gallon	2.5%= 9.94 97.5%= 11.7	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Front-End Loader 2	Normal	129.5 g/gallon	2.5%= 125.6 97.5%= 133.4	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Front-End Loader 2	Normal	5.8 g/gallon	2.5%= 5.51 97.5%= 6.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Front-End Loader 2	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe HC Emission based on NCSU Data for Front-End Loader 3	Normal	10.3 g/gallon	2.5%= 9.8 97.5%= 10.8	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Front-End Loader 3	Normal	8.9 g/gallon	2.5%= 8.2 97.5%= 9.6	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Front-End Loader 3	Normal	134.1 g/gallon	2.5%= 130 97.5%= 138	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Front-End Loader 3	Normal	6.4 g/gallon	2.5%= 6.1 97.5%= 6.7	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Front-End Loader 3	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Front-End Loader 3	Normal	10.3 g/gallon	2.5%= 9.8 97.5%= 10.8	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Front-End Loader 3	Normal	13.6 g/gallon	2.5%= 12.5 97.5%= 14.7	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Front-End Loader 3	Normal	129.5 g/gallon	2.5%= 125.6 97.5%= 133.4	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Front-End Loader 3	Normal	7.6 g/gallon	2.5%= 7.2 97.5%= 7.98	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Front-End Loader 3	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe HC Emission based on NREL Data for Front-End Loader 3	Normal	11.5 g/gallon	2.5%= 10.9 97.5%= 12.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Front-End Loader 3	Normal	12.7 g/gallon	2.5%= 11.7 97.5%= 13.7	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Front-End Loader 3	Normal	127.8 g/gallon	2.5%= 124 97.5%= 132	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Front-End Loader 3	Normal	7.0 g/gallon	2.5%= 6.65 97.5%= 7.35	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Front-End Loader 3	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Front-End Loader 4	Normal	5.1 g/gallon	2.5%= 4.8 97.5%= 5.4	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Front-End Loader 4	Normal	11.2 g/gallon	2.5%= 10.3 97.5%= 12.1	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Front-End Loader 4	Normal	94.7 g/gallon	2.5%= 91.9 97.5%= 97.5	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Front-End Loader 4	Normal	3.1 g/gallon	2.5%= 2.95 97.5%= 3.3	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Front-End Loader 4	Normal	10498 g/gallon	2.5%= 10288 97.5%= 10708	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe HC Emission based on EPA Data for Front-End Loader 4	Normal	4.4 g/gallon	2.5%= 4.2 97.5%= 4.6	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Front-End Loader 4	Normal	13.4 g/gallon	2.5%= 12.3 97.5%= 14.5	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Front-End Loader 4	Normal	96.9 g/gallon	2.5%= 94.0 97.5%= 99.8	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Front-End Loader 4	Normal	3.1 g/gallon	2.5%= 2.95 97.5%= 3.26	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Front-End Loader 4	Normal	10498 g/gallon	2.5%= 10288 97.5%= 10708	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Front-End Loader 4	Normal	5.0 g/gallon	2.5%= 4.75 97.5%= 5.25	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Front-End Loader 4	Normal	12.4 g/gallon	2.5%= 11.4 97.5%= 13.4	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Front-End Loader 4	Normal	95.6 g/gallon	2.5%= 92.7 97.5%= 98.5	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Front-End Loader 4	Normal	2.8 g/gallon	2.5%= 2.66 97.5%= 2.94	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Front-End Loader 4	Normal	10498 g/gallon	2.5%= 10288 97.5%= 10708	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe HC Emission based on NCSU Data for Motor Grader 1	Normal	11.7 g/gallon	2.5%= 11.1 97.5%= 12.3	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Motor Grader 1	Normal	13.8 g/gallon	2.5%= 12.7 97.5%= 14.9	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Motor Grader 1	Normal	105.9 g/gallon	2.5%= 102.7 97.5%= 109.1	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Motor Grader 1	Normal	5.6 g/gallon	2.5%= 5.3 97.5%= 5.9	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Motor Grader 1	Normal	10495 g/gallon	2.5%= 10285 97.5%= 10705	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Motor Grader 1	Normal	11.8 g/gallon	2.5%= 11.2 97.5%= 12.4	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Motor Grader 1	Normal	12.0 g/gallon	2.5%= 11.0 97.5%= 13.0	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Motor Grader 1	Normal	110.7 g/gallon	2.5%= 107.4 97.5%= 114.0	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Motor Grader 1	Normal	6.1 g/gallon	2.5%= 5.8 97.5%= 6.4	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Motor Grader 1	Normal	10495 g/gallon	2.5%= 10285 97.5%= 10705	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Motor Grader 1	Normal	13.3 g/gallon	2.5%= 12.6 97.5%= 14.0	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Motor Grader 1	Normal	11.2 g/gallon	2.5%= 10.3 97.5%= 12.1	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Motor Grader 1	Normal	109.2 g/gallon	2.5%= 105.9 97.5%= 112.5	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Motor Grader 1	Normal	5.7 g/gallon	2.5%= 5.4 97.5%= 6.0	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe CO2 Emission based on NREL Data for Motor Grader 1	Normal	10495 g/gallon	2.5%= 10285 97.5%= 10705	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Motor Grader 2	Normal	8.9 g/gallon	2.5%= 8.5 97.5%= 9.3	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Motor Grader 2	Normal	11.0 g/gallon	2.5%= 10.1 97.5%= 11.9	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Motor Grader 2	Normal	103.8 g/gallon	2.5%= 100.7 97.5%= 106.9	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Motor Grader 2	Normal	2.4 g/gallon	2.5%= 2.28 97.5%= 2.52	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Motor Grader 2	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Motor Grader 2	Normal	9.5 g/gallon	2.5%= 9.0 97.5%= 10.0	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Motor Grader 2	Normal	10.7 g/gallon	2.5%= 9.8 97.5%= 11.6	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Motor Grader 2	Normal	100.0 g/gallon	2.5%= 97 97.5%= 103	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Motor Grader 2	Normal	2.6 g/gallon	2.5%= 2.47 97.5%= 2.73	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Motor Grader 2	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Motor Grader 2	Normal	10.6 g/gallon	2.5%= 10.1 97.5%= 11.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Motor Grader 2	Normal	9.9 g/gallon	2.5%= 9.1 97.5%= 10.7	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Motor Grader 2	Normal	98.6 g/gallon	2.5%= 95.6 97.5%= 101.6	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe CO2 Emission based on NREL Data for Motor Grader 2	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Motor Grader 3	Normal	14.8 g/gallon	2.5%= 14.1 97.5%= 15.5	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Motor Grader 3	Normal	14.3 g/gallon	2.5%= 13.2 97.5%= 15.4	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Motor Grader 3	Normal	114.5 g/gallon	2.5%= 111 97.5%= 118	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Motor Grader 3	Normal	5.6 g/gallon	2.5%= 5.32 97.5%= 5.88	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Motor Grader 2	Normal	10496 g/gallon	2.5%= 10286 97.5%= 10706	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Motor Grader 3	Normal	10493 g/gallon	2.5%= 10283 97.5%= 10703	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Motor Grader 3	Normal	14.2 g/gallon	2.5%= 13.5 97.5%= 14.9	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Motor Grader 3	Normal	13.8 g/gallon	2.5%= 12.7 97.5%= 14.9	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Motor Grader 3	Normal	112.2 g/gallon	2.5%= 108.8 97.5%= 115.6	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Motor Grader 3	Normal	6.1 g/gallon	2.5%= 5.8 97.5%= 6.4	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Motor Grader 3	Normal	10493 g/gallon	2.5%= 10283 97.5%= 10703	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Motor Grader 3	Normal	15.9 g/gallon	2.5%= 15.1 97.5%= 16.7	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Motor Grader 3	Normal	12.8 g/gallon	2.5%= 11.8 97.5%= 13.8	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe NOx Emission based on NREL Data for Motor Grader 3	Normal	110.7 g/gallon	2.5%= 107.4 97.5%= 114	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Motor Grader 3	Normal	5.7 g/gallon	2.5%= 5.4 97.5%= 6.0	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Motor Grader 3	Normal	10493 g/gallon	2.5%= 10283 97.5%= 10703	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Motor Grader 4	Normal	15.3 g/gallon	2.5%= 14.5 97.5%= 16.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Motor Grader 4	Normal	28.5 g/gallon	2.5%= 26.2 97.5%= 30.8	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Motor Grader 4	Normal	125.2 g/gallon	2.5%= 121.4 97.5%= 129	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Motor Grader 4	Normal	15.4 g/gallon	2.5%= 14.6 97.5%= 16.2	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Motor Grader 4	Normal	10490 g/gallon	2.5%= 10280 97.5%= 10700	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Motor Grader 4	Normal	14.6 g/gallon	2.5%= 13.9 97.5%= 15.3	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe CO Emission based on EPA Data for Motor Grader 4	Normal	27.1 g/gallon	2.5%= 24.9 97.5%= 29.3	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Motor Grader 4	Normal	132.6 g/gallon	2.5%= 129 97.5%= 137	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Motor Grader 4	Normal	16.2 g/gallon	2.5%= 15.4 97.5%= 17.0	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Motor Grader 4	Normal	10490 g/gallon	2.5%= 10280 97.5%= 10700	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Motor Grader 4	Normal	16.4 g/gallon	2.5%= 15.6 97.5%= 17.2	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Motor Grader 4	Normal	25.3 g/gallon	2.5%= 23.3 97.5%= 27.3	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Motor Grader 4	Normal	130.8 g/gallon	2.5%= 127 97.5%= 135	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Motor Grader 4	Normal	15.0 g/gallon	2.5%= 14.3 97.5%= 15.8	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Motor Grader 4	Normal	10490 g/gallon	2.5%= 10280 97.5%= 10700	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Motor Grader 5	Normal	14.7 g/gallon	2.5%= 14.0 97.5%= 15.4	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Motor Grader 5	Normal	23.9 g/gallon	2.5%= 22.0 97.5%= 25.8	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Motor Grader 5	Normal	140.5 g/gallon	2.5%= 136 97.5%= 145	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Motor Grader 5	Normal	13.7 g/gallon	2.5%= 13.0 97.5%= 14.4	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Motor Grader 5	Normal	10491 g/gallon	2.5%= 10281 97.5%= 10701	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	Distribution	Point Estimate	Parameters	Reference:
B20 LCI Tailpipe HC Emission based on EPA Data for Motor Grader 5	Normal	11.8 g/gallon	2.5%= 11.2 97.5%= 12.4	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Motor Grader 5	Normal	32.0 g/gallon	2.5%= 29.4 97.5%= 34.6	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Motor Grader 5	Normal	140.3 g/gallon	2.5%= 136 97.5%= 144.5	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Motor Grader 5	Normal	14.4 g/gallon	2.5%= 13.7 97.5%= 15.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Motor Grader 5	Normal	10491 g/gallon	2.5%= 10281 97.5%= 10701	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Motor Grader 5	Normal	13.2 g/gallon	2.5%= 12.5 97.5%= 13.9	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Motor Grader 5	Normal	29.8 g/gallon	2.5%= 27.4 97.5%= 32.2	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Motor Grader 5	Normal	138.3 g/gallon	2.5%= 134 97.5%= 142	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Motor Grader 5	Normal	13.4 g/gallon	2.5%= 12.7 97.5%= 14.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Motor Grader 5	Normal	10491 g/gallon	2.5%= 10281 97.5%= 10701	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NCSU Data for Motor Grader 6	Normal	5.1 g/gallon	2.5%= 4.8 97.5%= 5.36	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NCSU Data for Motor Grader 6	Normal	5.5 g/gallon	2.5%= 5.1 97.5%= 5.94	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NCSU Data for Motor Grader 6	Normal	70.2 g/gallon	2.5%= 68.1 97.5%= 72.3	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NCSU Data for Motor Grader 6	Normal	1.5 g/gallon	2.5%= 1.43 97.5%= 1.58	Precision of the PEMS [d]

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Table 7.13 Continued.

Assumption Description	**Distribution**	**Point Estimate**	**Parameters**	**Reference:**
B20 LCI Tailpipe CO2 Emission based on NCSU Data for Motor Grader 6	Normal	10499 g/gallon	2.5%= 10289 97.5%= 10709	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on EPA Data for Motor Grader 6	Normal	4.9 g/gallon	2.5%= 4.66 97.5%= 5.1	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on EPA Data for Motor Grader 6	Normal	8.0 g/gallon	2.5%= 7.36 97.5%= 8.64	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on EPA Data for Motor Grader 6	Normal	69.4 g/gallon	2.5%= 67.3 97.5%= 71.5	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on EPA Data for Motor Grader 6	Normal	1.6 g/gallon	2.5%= 1.52 97.5%= 1.68	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on EPA Data for Motor Grader 6	Normal	10499 g/gallon	2.5%= 10289 97.5%= 10709	Precision of the PEMS [d]
B20 LCI Tailpipe HC Emission based on NREL Data for Motor Grader 6	Normal	5.5 g/gallon	2.5%= 5.23 97.5%= 5.78	Precision of the PEMS [d]
B20 LCI Tailpipe CO Emission based on NREL Data for Motor Grader 6	Normal	7.5 g/gallon	2.5%= 6.9 97.5%= 8.1	Precision of the PEMS [d]
B20 LCI Tailpipe NOx Emission based on NREL Data for Motor Grader 6	Normal	68.4 g/gallon	2.5%= 66.3 97.5%= 70.5	Precision of the PEMS [d]
B20 LCI Tailpipe PM Emission based on NREL Data for Motor Grader 6	Normal	1.5 g/gallon	2.5%= 1.43 97.5%= 1.58	Precision of the PEMS [d]
B20 LCI Tailpipe CO2 Emission based on NREL Data for Motor Grader 6	Normal	10499 g/gallon	2.5%= 10289 97.5%= 10709	Precision of the PEMS [d]

[a] As petroleum diesel is the process energy of biodiesel life cycle, all of input assumptions in the petroleum diesel life cycle are also used in biodiesel life cycle.

[b] Soybean use per lb. of soyoil throughput. A survey was submitted to three professionals in soy-based biodiesel production. The uncertainty of soybean use is estimated based on the average 95% probabilistic range provided by three professionals.

[c] Soyoil use per lb of biodiesel throughput. A survey was submitted to three professionals in soy-based biodiesel production. The uncertainty of soyoil use is estimated based on the average 95% probabilistic range provided by three professionals.

[d.] For vehicle tailpipe emissions, the 95% confidence interval of the mean is ± 3% for HC, 8% for CO, 3% for NO_x, 2% for CO_2, and 5% for PM based on the precision of the PEMS.

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PART VIII LIFE CYCLE INVENTORY ENERGY CONSUMPTION AND EMISSIONS FOR BIODIESEL VERSUS PETROLEUM DIESEL FUELED CONSTRUCTION VEHICLES

Abstract

This paper focuses on whether substitution of soy-based biodiesel fuels for petroleum diesel would produce an overall reduction in emissions of selected pollutants. A life cycle inventory model was developed to estimate energy consumption and emissions of selected pollutants and greenhouse gases. Real-world measurements using portable emission measurement system (PEMS) were made for five backhoes, four front-end loaders, and six motor graders on both petroleum diesel and soy-based B20 biodiesel. These data are used as the basis for vehicle tailpipe emission factors of CO_2, CO, HC, NO_x, and PM. The fossil energy reductions are 9% for B20 versus petroleum diesel and 42% for B100 versus petroleum diesel, respectively. As vehicle tailpipe emissions are reduced from newer engines, the fuel cycle emissions are getting more important. B20 local urban emissions are estimated to be 24.3% lower for HC, 20.2% lower for CO, 16.9% lower for PM, and 0.9% lower for NO_x compared to petroleum diesel local emissions. The results imply that biodiesel is a promising alternative fuel for diesel, but that there are some environmental trade-offs. Recommendations are made regarding priorities for reduction of vehicle tailpipe emissions to improve urban air quality and related studies of vehicle NO_x emissions.

8.1 Introduction

In the United States, more than half of the biodiesel is made from soybean oil. The production of biodiesel accounted for 1.42% of total U.S. soybean oil consumption in 2004. Biodiesel can be used in a diesel engine without major modifications and has lower emissions of hydrocarbon (HC), carbon monoxide (CO), and particulate matters (PM) based on dynamometer testing of engines (Duffield *et al.* 1998, EPA 2002). Based on 43 heavy duty diesel engine dynamometer tests summarized by EPA, the average percentage changes when comparing B20 biodiesel versus petroleum diesel of NO_x, PM, CO, and HC are +2%, -10%, -11%, and -21%, respectively (EPA 2002). The test cycles employed in EPA study include both transient and steady state cycles. Chassis dynamometer tests were done by National Renewable Energy Laboratory (NREL) for 3 transit buses, 2 school buses, 2 trucks, and one motor coach (McCormick *et al.* 2006). The test cycles include five different driving cycles which represent high speed interstate driving, low-speed driving, and stop-and-go driving. The average percentage changes of NREL study when comparing B20 biodiesel versus petroleum diesel for NO_x, PM, CO, and HC are +0.6%, -16%, -17%, and -12%, respectively. North Carolina State University (NCSU) has done 35 in-use measurement testes using portable emission measurement system (Frey *et. al*, 2006, 2007, 2008).

The tested vehicles include 12 dump trucks, 8 cement mixers, 5 backhoes, 4 front-end loaders, and 6 motor graders. The average percentage changes of NCSU study when comparing B20 biodiesel versus petroleum diesel for NO_x, PM, CO, and HC are -3.5%, -16%, -22%, and -25%, respectively. In general, these studies show an average decrease on vehicle tailpipe emissions of PM, CO, and HC when using B20 biodiesel.

The recent NREL study concludes the impact of B20 biodiesel on vehicle NO_x emissions is not significant and agrees on the Frey and Kim (Frey and Kim 2006) that show a decrease in NO_x for B20 if the blend stock meets the ASTM standard.

In the United States, more than half of the biodiesel is made from soybean oil. The production of biodiesel accounted for 1.42% of total U.S. soybean oil consumption in 2004. Biodiesel can be used in a diesel engine without major modifications and has lower emissions of hydrocarbon (HC), carbon monoxide (CO), and particulate matters (PM) based on dynamometer testing of engines (Duffield *et al.* 1998, EPA 2002). Based on engine dynamometer data from EPA and chassis dynamometer data from National Renewable Energy Laboratory (NREL), the percentage changes when comparing B20 biodiesel versus petroleum diesel of NO_x, PM, CO, and HC are +2%, -10%, -11%, and -21%, respectively, for the EPA data and +0.6%, -16%, -17%, and -12%, respectively, for the NREL data (EPA 2002, McCormick *et al.* 2006). The recent NREL study agrees on the Frey and Kim (2006) and other studies that show a decrease in NO_x for B20 if the blend stock meets the ASTM standard.

Nonroad construction equipment is a significant source of nonroad mobile source air pollutant emissions (EPA 2006). Emissions from nonroad construction equipment are typically quantified based on steady-state modal engine dynamometer tests. However, such tests do not represent real-world activity. There is a need to quantify energy use and emissions from construction equipment based on in-use measurement methods. Three common types of construction vehicles are backhoes, front-end loaders, and motor graders. These vehicle types contribute to 26.5% of NO_x, 29.1% of CO, 27.6% of HC and 28.3% of PM_{10} among all construction vehicles.

In-use measurements on construction vehicles were conducted by Frey *et al.* for both soy-based B20 and petroleum diesel (Frey *et al.* 2007, 2008). Data collection procedures include: (1) pre-installation; (2) installation; (3) field data collection; and (4) decommissioning. Field data were reviewed by standard quality assurance procedures to determine whether any errors exist in the data, and corrected such errors if possible. HC, CO, NO_x, and PM emission factors were developed based on typical duty cycles performed by each vehicle.

Life cycle inventories are used for a more complete assessment of comparisons between fuels, taking into account energy consumption and emissions for fuel production and fuel use. Life cycle inventory approaches include process flow diagrams, matrix representation of product system, and input-output methods (MacLean *et al.* 2003, Sheehan *et al.* 1998, Suh *et al.* 2005). Process flow diagrams are the most common method for representing the energy use and emissions of processes in a product system.

An example is the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model. GREET has been used to estimate fuel cycle upstream energy use and air emissions in life cycle inventories of bio-based products and lubricants (Landis *et al.* 2007, Miller *et al.* 2007).

Soy-based B100 biodiesel production includes three major processes: soybean farming, soybean oil extraction, and biodiesel production. In the United States, most soybean oil production plants use a solvent extraction process to remove the oil from the soybeans (Erickson 1995). Soybean oil extraction was found to be the most significant source of HC emissions in the biodiesel life cycle (Sheehan *et al.* 1998). In November 2004, EPA promulgated national emission standards for the solvent extraction process (EPA 2004). The standards require reduction of emissions of air toxics and volatile organic compounds from vegetable oil production facilities.

Based on Sheehan et al. (1998), soy-based B20 biodiesel was estimated to have lower life cycle emissions of carbon monoxide and PM, but higher LCI emissions of NO_x and HC. Since that study, EPA has promulgated new emission standards applicable to soyoil plants and more recent emission factor data are available for many processes in the LCI.

An improved quantification of the LCI is developed here in order to evaluate the benefits of biodiesel and to assess the tailpipe emissions of selected types of construction vehicles. The key improvements include update of combustion emission factors based on 2006 US national average emission rates, inclusion of Pre-New Source Performance Standard (NSPS) and NSPS soyoil plants, and the use of PEMS data for real-world fuel use and emissions and comparisons based on 15 construction vehicles. The key research questions addressed here are: (1) What are the best estimates of energy use and emissions associated with fuel production and tailpipe emissions for petroleum diesel and B20?; (2) What is the uncertainty in these estimates?; (3) What are the key sources of uncertainty?; and (4) What are the emissions implications of the use of biodiesel fuel for nonroad construction vehicles?

8.2 Methodology

The key elements of the methodology include defining the system boundaries of the life cycle inventory, quantifying the fuel life cycles of petroleum diesel and biodiesel, quantifying tailpipe emissions of backhoes, front-end loaders, and motor graders, and applying the life cycle inventory model to quantify energy use, emissions, and uncertainties.

8.2.1 System Boundary

An LCI involves quantification of energy use, raw material requirements, and air pollutant emissions throughout the life cycle of a fuel product (Fava *et al.* 1991). The LCI here is based on a process flow diagram that includes the typical processes associated with the production of petroleum diesel and biodiesel. Figure 8.1 represents the system boundaries for the life cycle of petroleum diesel and biodiesel B100.

The system boundaries of petroleum diesel production include crude oil recovery, crude oil transport, crude oil refining, diesel transport, and vehicle operation. Because 64% of crude oil supply in the United States was imported from foreign countries in 2005 (EIT 2005), both domestic and foreign crude oil recovery are included.

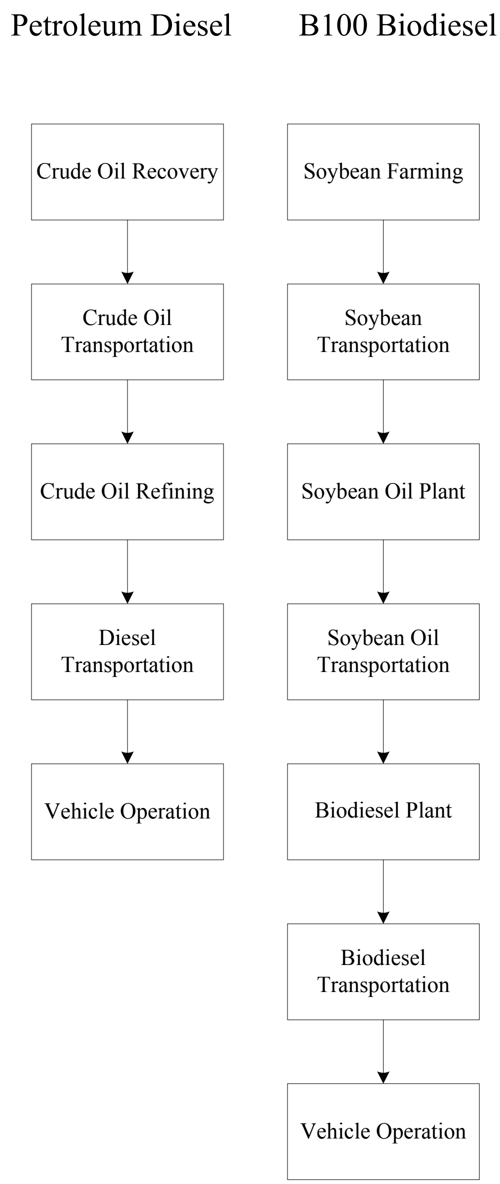


Figure 8.1 System Boundaries for Petroleum Diesel and Biodiesel Life Cycle Inventory

The system boundaries of biodiesel production include soybean agriculture, soybean oil production plant, soybean oil transport, biodiesel production plant, biodiesel transport, and vehicle operation. Fossil energy is consumed for operating farm equipment and manufacturing, procuring, and distributing fertilizers, herbicides, and pesticides (Sheehan *et al.* 1998, Wang 1999, Delucchi 2003). Most soybeans are transported to an oil production plant within 75 miles of the farming area (Sheehan *et al.* 1998). At the soybean oil production plant, soybeans are cleaned, dried, dehulled and cracked into flakes (Gerpen *et al.* 2004, Gerpen *et al.* 2005). Solvent extraction is used to extract soybean oil from the flakes. Then the soybean oil is transported to a biodiesel plant. The average distance in the U.S. from a soyoil production plant to a biodiesel plant is estimated to be approximately 600 miles (Sheehan *et al.* 1998). At the biodiesel plant, biodiesel is produced by transesterification that convert soybean oil to biodiesel.

8.2.2 Fuel Life Cycle

The fuel cycle energy use and air emissions were calculated based on GREET 1.6 (Wang 1999) run in Microsoft EXCEL, and updated with the following inputs:

- Update of combustion source emission factors, such as for coal-fired utility and industrial boilers based on 2006 US national average emission rates;

– Vehicle tailpipe emission rates based on real-world measurement data for petroleum diesel and B20 biodiesel;

– Inclusion of Pre-NSPS and NSPS soyoil plants;

– Inclusion of soyoil transport; and

– Inclusion of biogenic HC emissions during soybean farming, which is estimated based on measurements of air-surface exchange rates of HC compounds (Kang *et. al* 2004).

Fuel cycle emissions are generally from combustion processes and fuel transport. Emission factors for each combustion source were updated based on the U.S. national average emission rate (EPA 2006, EIA 2005):

$$\mathrm{EF}_{\mathrm{i,j,k}} = \frac{\mathrm{E}_{\mathrm{i,j,k}}}{\mathrm{EC}_{\mathrm{j,k}}}$$

where

$EF_{i,j,k}$ = Emission factor of pollutant i , fuel j , and combustion technology k $(\frac{lb}{10^6 Btu})$

$E_{i,j,k}$ = The U.S. national total emissions of pollutant i , fuel j , and combustion technology k (lb)

$EC_{j,k}$ = The U.S. national total energy consumption of fuel j and combustion technology k ($10^6 Btu$)

For combustion emissions from the fuel life cycle, the emissions were estimated based on energy consumption and emission factors for each combustion technology:

$$EM_{i,l} = EF_{i,j,k} \times EC_{j,k,l}$$

where

$EM_{i,l}$ = Emissions of pollutant i and stage l (g/gallon fuel throughput)

$EF_{i,j,k}$ = Emission factor of pollutant i, fuel j and combustion technology k (g/Btu)

$EC_{j,k,l}$ = Energy consumption of fuel j, combustion technology k and stage l (Btu/gallon fuel throughput)

Emissions during the transport of raw materials and fuel products are estimated based upon distances traveled and gram-per-mile emission factors in GREET 1.6 (He *et al.* 2000).

8.2.3 Vehicle Tailpipe Emissions

The tailpipe emissions data were collected from five backhoes, four front-end loaders, and six motor graders using a portable emission measurement system (PEMS). Each vehicle was tested once on petroleum diesel and once on B20 biodiesel. The details of the instrumentation, data collection, data quality assurance, and results are given in Frey *et al.* (2007). The vehicle characteristics are given in Table 8.1.

Table 8.1 Characteristics of Tested Vehicles

Vehicle ID [1]	Chassis Characteristics				Engine Characteristics				
	Manufacturer	Year	Model [2]	GVW (lbs)	Tier	Displacement	Cylinders	Horsepower	Cumulative Hours
BH1	CATERPILLAR	2004	420D	22,000	2	4.0	4	97	78
BH2	JCB	2001	215	16,540	0	4.2	4	90	11,528
BH3	JCB	2001	2.15E-01	16,540	1	4.2	4	90	2,792
BH4	CASE	1999	590SL	19,578	1	3.9	4	99	3,874
BH5	CATERPILLAR	2004	420D	22,000	2	4.0	4	97	740
FL1	HYUNDAI	2002	HL740-TM3	29,000	1	5.9	6	130	3,645
FL2	HYUNDAI	2002	HL740-TM3	29,000	1	5.9	6	130	9,345
FL3	CASE	2002	621B XT	28,000	1	5.9	6	126	3,569
FL4	HYUNDAI	2005	HL740-TM7	29,000	2	5.9	6	133	446
MG1	VOLVO	2001	G720VHP	37,000	1	8.27	6	195	4,367
MG2	VOLVO	2004	G720B	37,000	2	7.1	6	195	841
MG3	VOLVO	2001	G720VHP	37,000	1	8.27	6	195	3,044
MG4	DRESSER	1990	850	37,000	0	8.27	6	167	440
MG5	CHAMPION	1993	G720	37,000	0	8.27	6	160	4,554
MG6	VOLVO	2007	G930	37,000	3	7.2	6	198	3

[1] BH = Backhoe
FL = Front-End Loader
MG = Motor Grader

[2] All tested vehicles are turbocharged.

The PEMS used here is the OEM-2100 "Montana" system manufactured by Clean Air Technologies International, Inc. (Vojtisek-Lom, and Cobb 1997), which is comprised: two parallel five-gas analyzers; a PM measurement system; an engine sensor array for measuring engine RPM, manifold absolute pressure, and intake air temperature; a global position system (GPS); and an on-board computer. PM measurements are based on a light scattering method, which is analogous to opacity. Measurements were made for each vehicle for one day on petroleum diesel and one day on soy-based B20 biodiesel.

The PEMS light scattering-based PM measurement is adequate for relative comparisons between petroleum diesel and B20 biodiesel. However, in order to estimate the absolute value of PM emission factors, the NONROAD model was used to estimate PM emission factors based on petroleum diesel (EPA 2004). The PM emission factors for B20 biodiesel (EF_{B20}) are estimated as:

$$EF_{B20} = EF_{PD} \times \frac{Opacity_{B20}}{Opacity_{PD}}$$

where

EF_{B20} = PM emission rate for B20 biodiesel (g/gallon);

EF_{PD} = PM emission rate for petroleum diesel (g/gallon);

$Opacity_{B20}$ = Opacity for B20 biodiesel based on PEMS measurements; and

$Opacity_{PD}$ = Opacity for petroleum diesel based on PEMS measurements;

8.2.4 Study Design

The fuel life cycle scenarios include: baseline petroleum diesel; B20 biodiesel produced from Pre-NSPS soyoil plant; and B20 biodiesel produced from NSPS soyoil plant. The vehicle emissions scenarios include: baseline petroleum diesel in-use measurement data based on NCSU (Frey *et al.* 2007, 2008); B20 biodiesel in-use measurement data based on NCSU (Frey *et al.* 2007, 2008); estimated B20 biodiesel vehicle emissions based on EPA's engine dynamometer data (EPA 2002); and estimated B20 biodiesel vehicle emissions based on NREL's chassis dynamometer data (McCormick *et al.* 2006). Because there are several possible configurations, in order to show all of the possibility in the life cycle inventory, there are seven scenarios designed for each vehicle shown in Table 8.2. Petroleum diesel LCI with in-use measurement data is the baseline scenario. For B20 LCI, each vehicle has two fuel cycle scenarios and three vehicle emissions scenarios, which include 6 scenarios in total. For comparison of B20 versus petroleum diesel (B20/PD), there are 6 case studies for each vehicle.

Table 8.2. Study Design of Life Cycle Inventory

Scenarios	Fuel Cycle	Vehicle Emissions	Label of B20/PD Ratio
(1)	Petroleum Diesel	In-Use Measurement	
(2)	Pre-NSPS Soyoil Plant	In-Use Measurement	Pre-NSPS, NCSU
(3)	Pre-NSPS Soyoil Plant	Engine Dynamometer	Pre-NSPS, EPA
(4)	Pre-NSPS Soyoil Plant	Chassis Dynamometer	Pre-NSPS, NREL
(5)	NSPS Soyoil Plant	In-Use Measurement	NSPS, NCSU
(6)	NSPS Soyoil Plant	Engine Dynamometer	NSPS, EPA
(7)	NSPS Soyoil Plant	Chassis Dynamometer	NSPS, NREL

8.2.5 Uncertainty Analysis: Comparison of Fuels

Uncertainty in life cycle assessment arises from the lack of knowledge regarding the true value of inputs (Cullen and Frey, 1999). Monte Carlo simulation is sometimes used to quantify uncertainty in LCI model (Sonnemann *et al.* 2003, Lo *et al.* 2005). The GREET 1.6 model includes default probability distributions for each parameter in the fuel life cycle (GM 2002). Probability Distributions of combustion emission factors inherent of the LCI were assigned based upon professional judgment. Based upon Frey and Li (2003), the average relative 95% confidence intervals on AP-42 emission factors are -34% to +47% for NO_x and -33% to +37% for HC. Professional judgment was made that the relative 95% confidence intervals on the combustion emission factors are ±40% for NO_x, ±35% for HC, ±30% for CO, and ±30% for PM. For coal-fired power plant, the 95% confidence intervals on NO_x emission factors is ±25% based on Abdel-Aziz and Frey (2003). For vehicle tailpipe emissions, the relative 95% confidence interval on the mean is ± 3% for HC, 8% for CO, 3% for NO_x, 2% for CO2, and 5% for PM based on the precision of the PEMS.

These input assumptions are propagated through the LCI model. Crystal Ball was used to quantify uncertainty in the inputs and estimate uncertainty in the outputs of the LCI based on Monte Carlo simulation. Rank correlation was used to identify which probabilistic input is most highly correlated with each of several selected model outputs. Examples of selected key input assumptions are given in Table 8.3. Additional inputs are given shown in supporting information.

Table 8.3 Examples of Best Estimates and Uncertainty Assumptions for Key Inputs for Selected Vehicle

Petroleum Diesel Life Cycle Inventory			B20 Biodiesel Life Cycle Inventory		
Description and units	Best Estimate	Distribution and parameters [a]	Description and units [a]	Best Estimate	Distribution and parameters [a]
Crude Oil Recovery Efficiency, %	97.7 [c]	T:96.0-99.0 (98.0)	Soybean Use; soybean use per lb. of soyoil throughput	5.9 [c]	N: 5.3-6.5
Petroleum Diesel Refining Efficiency	89.0 [c]	N: 88.0-90.0	Soyoil Use; soyoil use per lb of biodiesel throughput	1.04 [c]	N: 5.74-6.06
Petroleum Diesel Tailpipe HC Emission, g/gal D.E. [b]	18 [d]	N: 17.1-18.9	B20 Tailpipe HC Emission, g/gal D.E. [b]	7.5 [d]	N: 7.1-7.9
Petroleum Diesel Tailpipe CO Emission, g/gal D.E. [b]	16.3 [d]	N: 15.0-17.6	B20 Tailpipe CO Emission, g/gal D.E. [b]	8.7 [d]	N: 8.0-9.4
Petroleum Diesel Tailpipe NO_x Emission, g/gal D.E. [b]	110 [d]	N: 106.7-113.3	B20 Tailpipe NO_x Emission, g/gal D.E. [b]	113 [d]	N: 109.6-116.4
Petroleum Diesel Tailpipe PM Emission, g/gal D.E. [b]	6.9 [d]	N: 6.6-7.3	B20 Tailpipe PM Emission, g/gal D.E. [b]	5.3 [d]	N: 5.0-5.6

a. T = triangular distribution; N = normal distribution. For the triangular distribution, the range of minimum to maximum is shown with the mode given in parentheses. For normal distributions,the 2.5th and 97.5th percentile are given.

b Selected cases are converted to a per gallon of petroleum diesel equivalent basis. Per gallon diesel equivalent on an energy basis is 128,500 Btu/gallon.

c. Based on GREET 1.6 Model.

d. Based on NCSU PEMS results.

8.3 Results

The results of life cycle fossil energy consumption and emissions are presented here. The key sources of uncertainty are identified by Monte Carlo simulation. The spatial distribution of biodiesel life cycle emissions is evaluated to help assess the possibility for improving urban air quality.

8.3.1 Quantification of Petroleum Diesel and Biodiesel LCI

An example of the distributions of life cycle energy consumption and emissions obtained from this study is shown in Figure 8.2 based on Front-End Loader 1 with Scenarios 1, 2, and 5. For petroleum diesel, the fuel cycle energy use contributes approximately 16% of total life cycle energy consumption. While the operation of the vehicle itself consumes more energy than does the fuel cycle for producing the fuel, the amount of energy consumed during the fuel cycle is not negligible. Crude oil refining contributes most to the fuel cycle energy consumption and to PM, CO, and CO_2 emissions.

A NSPS plant consumes less energy than Pre-NSPS soyoil plants due to the improvement of efficiency. However, the difference in total LCI energy consumption between NSPS and Pre-NSPS soyoil plants is less than 2%. The soyoil plant is the most significant source of HC emissions in the biodiesel fuel cycle. The average percentage differences (%) of B20 versus petroleum diesel in LCI Emissions per gallon of diesel equivalent are shown in Table 8.4. On average of six scenarios, the B20 life cycle emissions are 3.2% higher for NO_x, 13.7% lower for PM, 2.1% lower for HC, and 7.8% lower for CO.

In recent years, the U.S. Environmental Protection Agency (EPA) has set progressively more stringent Tier 1 to Tier 4 emission standards for engines used in construction vehicles. As the tailpipe emissions are reduced from newer engines (Tier 2 or Tier 3), the vehicle emissions are contributing less and less to the LCI, as shown in Table 8.5.

The distribution between fossil and renewable energy consumption is shown in Figure 8.3. The total energy consumption in order to produce B20 or B100 is higher than for petroleum diesel, but less fossil energy is used. The fossil energy contribution to the B20 life cycle is 83%, versus 37% for pure B100 blend stock. The use of B20 instead of petroleum diesel will reduce fossil energy consumption and CO_2 emissions by 9% based on NSPS soyoil plants. The reduction for B100 is 42%.

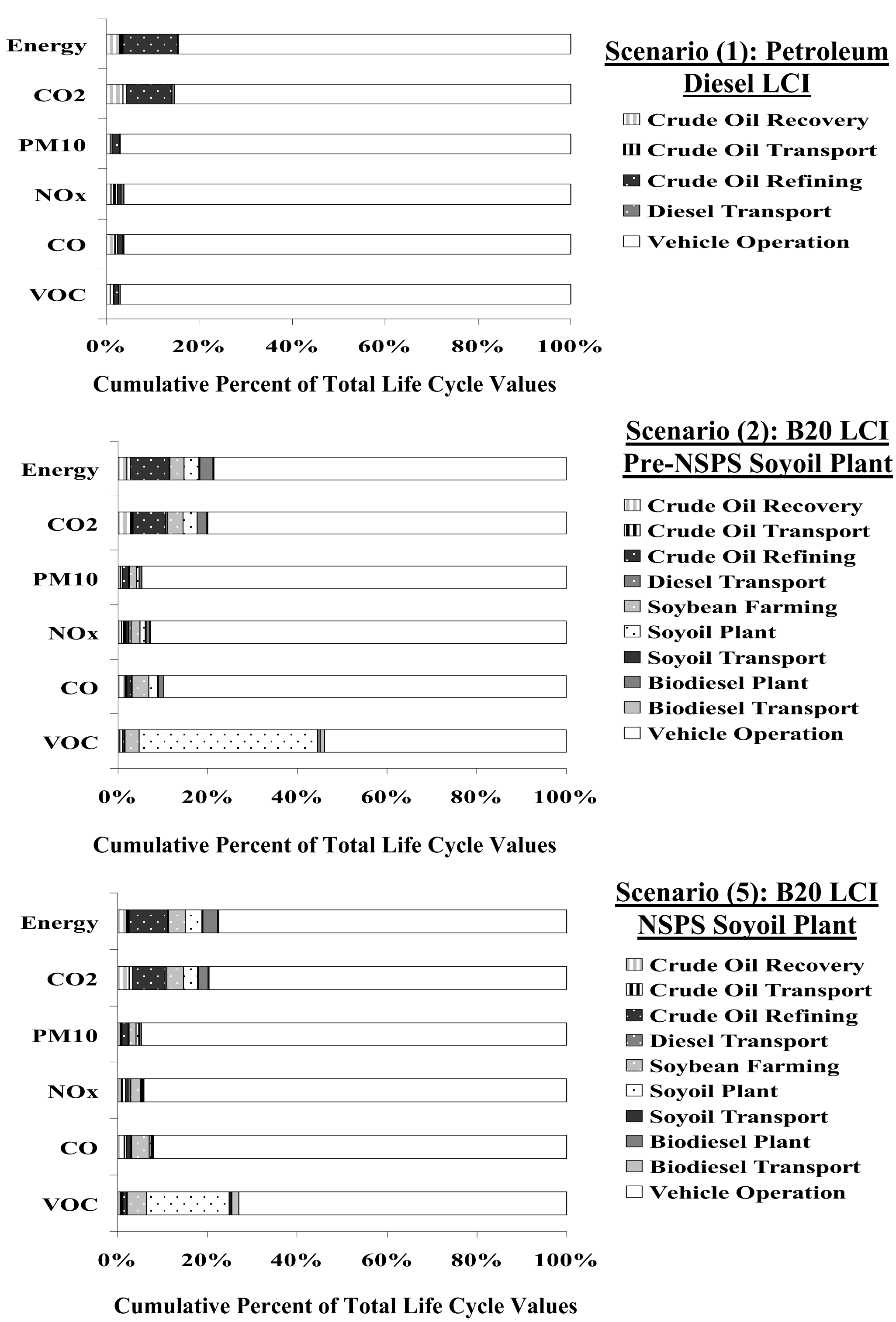


Figure 8.2. Example of Life Cycle Inventory (LCI) Results for Scenario (1), (2), and (5)

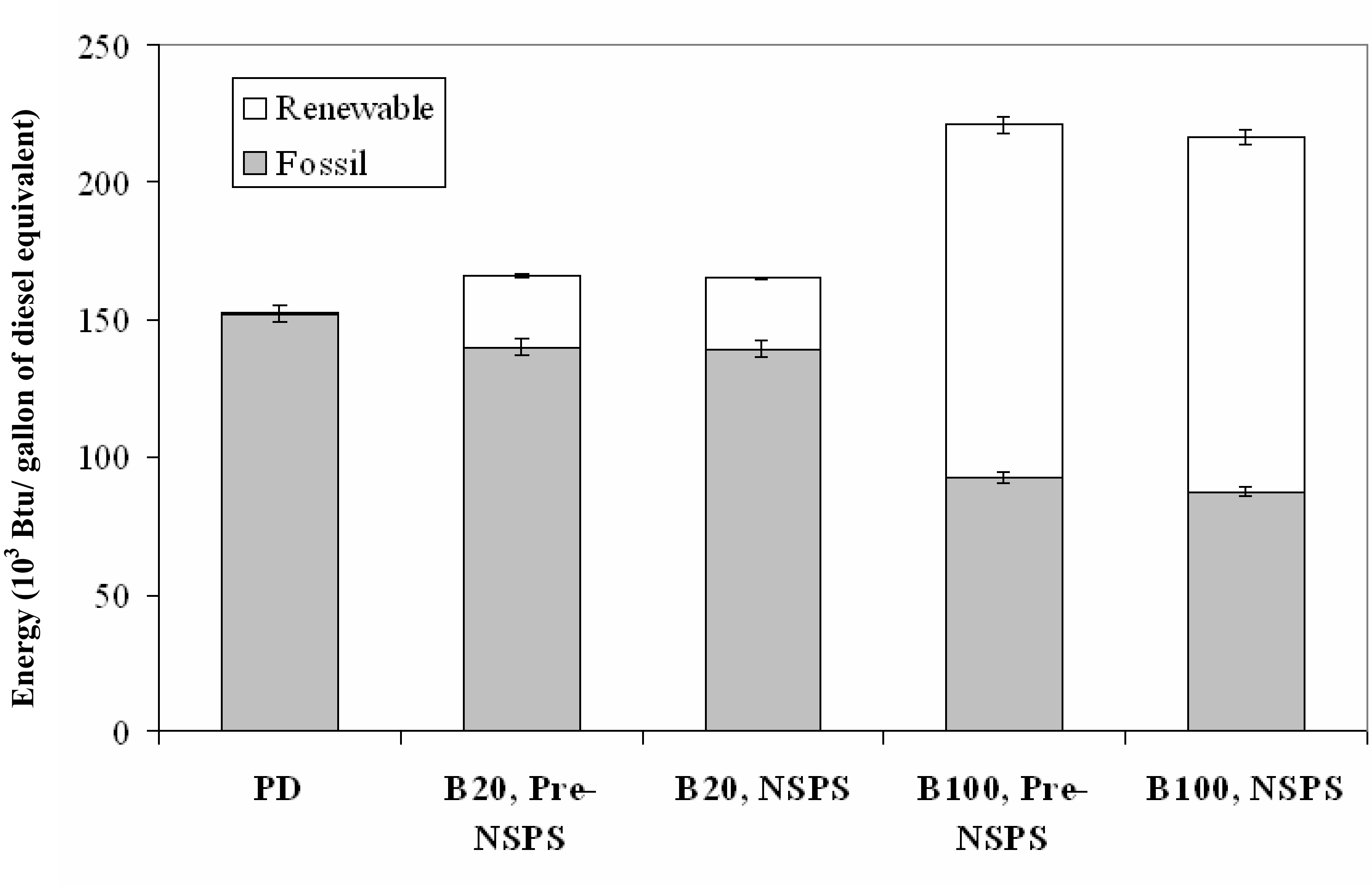
Table 8.4. Average Percentage Difference (%) of B20 versus Petroleum Diesel in LCI Emissions per Gallon of Diesel Equivalent

Scenarios	***Average Percentage Difference (%) of B20 versus Petroleum Diesel LCI (95% Probability Range)***			
	NO_x	PM	HC	CO
Pre-NSPS, NCSU	**+2.5** (+1.5 to +4.2)	**-14.0** (-15.7 to -12.2)	**+4.3** (+2.1 to +6.5)	**-5.2** (-8.4 to -2.0)
Pre-NSPS, EPA	**+5.2** (+4.3 to +6.0)	**-7.5** (-8.5 to -6.6)	**+7.6** (+5.9 to +9.3)	**+3.3** (+0.6 to +5.5)
Pre-NSPS, NREL	**+3.9** (+3.0 to +4.6)	**-13.5** (-14.4 to -12.7)	**+16.3** (+14.5 to +18.1)	**-2.3** (-4.9 to -0.3)
NSPS, NCSU	**+1.7** (+0.9 to +3.4)	**-14.3** (-15.7 to -12.6)	**-9.9** (-12.6 to -6.7)	**-10.7** (-13.9 to -6.8)
NSPS, EPA	**+4.5** (+3.8 to +5.3)	**-7.8** (-8.2 to -7.2)	**-6.6** (-8.9 to -3.8)	**-2.1** (-4.6 to +0.8)
NSPS, NREL	**+3.2** (+2.5 to +3.9)	**-13.7** (-14.2 to -13.2)	**-2.1** (-4.4 to +0.8)	**-7.8** (-10.2 to -4.8)
Average	**+3.2**	**-13.7**	**-2.1**	**-7.8**

Table 8.5. Proportion of Vehicle Tailpipe Emissions to Total LCI Emissions Based on Vehicle Types and Engine Tier (NCSU In-Use Measurement data)

Vehicle Type	Fuel Cycle [a]	Engine Tier	Percent of Tailpipe Emissions in the Entire Life Cycle					
			NO_x	PM	HC	CO	CO_2	Fossil CO_2
Backhoe	Petroleum Diesel	Tier 0	95.6	98.6	93.6	98.4	84.6	84.6
		Tier 1	95.5	97.7	89.9	96.7	84.6	84.6
		Tier 2	95.4	94.7	90.9	88.8	84.6	84.6
	B20 Pre-NSPS	Tier 0	92.7	98	75.7	94.8	79.4	72.9
		Tier 1	91.6	96.2	63.9	90.3	79.4	72.9
		Tier 2	92	90.7	54.6	70.6	79.4	72.9
	B20 NSPS	Tier 0	93.4	98.1	83.9	96	80.9	73.5
		Tier 1	92.4	96.3	74.5	92.6	80.9	73.5
		Tier 2	92.7	91.1	66.4	76.2	80.9	73.5
Front-End Loader	Petroleum Diesel	Tier 1	96.2	95.5	93.7	90.9	84.6	84.6
		Tier 2	95.2	90.7	84.3	91.1	84.6	84.6
	B20 Pre-NSPS	Tier 1	93.4	92	66.1	69.7	79.4	72.9
		Tier 2	91.7	86.6	53.2	73.5	79.4	72.9
	B20 NSPS	Tier 1	94	92.3	76.6	75.6	80.9	73.5
		Tier 2	92.4	87.1	65.6	78.8	80.9	73.5
Motor Grader	Petroleum Diesel	Tier 0	96.5	98	94	95.7	84.6	84.6
		Tier 1	95.8	95.1	94	91.2	84.6	84.6
		Tier 2	95.3	89.2	92	89.1	84.6	84.6
		Tier 3	93.4	83.7	85.6	86	84.6	84.6
	B20 Pre-NSPS	Tier 0	93.9	96.7	77.1	86.5	79.4	72.9
		Tier 1	92.7	92	74.6	77.6	79.4	72.9
		Tier 2	92.3	82.7	66.5	73.1	79.4	72.9
		Tier 3	89.1	75.8	53.2	57.6	79.4	72.9
	B20 NSPS	Tier 0	94.4	96.8	84.9	89.6	80.9	73.5
		Tier 1	93.3	92.3	83	82.2	80.9	73.5
		Tier 2	93	83.3	76.9	78.5	80.9	73.5
		Tier 3	90	76.5	65.6	64.6	80.9	73.5

[a] PD = Petroleum diesel fuel cycle;
B20 Pre-NSPS = B20 fuel cycle with Pre-NSPS soyoil plants; and
B20 NSPS = B20 fuel cycle with NSPS soyoil plant.



Note: 95% confidence intervals on the mean value are indicated in the figure.

Figure 8.3 Fossil Energy Consumption for Petroleum Diesel, B20, and B100 LCI per Gallon of Petroleum Diesel Equivalent

8.3.2 Uncertainty in LCI: Comparisons of Fuels

In order to illustrate the uncertainty in comparisons of LCIs B20 and petroleum diesel, the average percentage difference (%) in emissions per gallon of diesel equivalent are shown in Table 8.4. The 95% probability ranges for the average percentage difference are also indicated in Table 8.4. For example, the 95% probability range of percentage differences are +0.9% to +3.4% for NO_x, and -15.7% to -12.6% for PM, -12.6% to -6.7% for HC, -13.9% to -6.8% for CO, based on Scenario NSPS, NCSU. The results indicate that an increase in LCI NO_x emissions and decrease in LCI PM, HC, and CO emissions are significant for NSPS soyoil plant. However, the 95% probability range of percentage differences are +2.1% to +6.5% for HC, based on Scenario Pre-NSPS, NCSU, which indicate the increase of LCI HC emissions is also significant.

In general, LCI energy consumption and emissions were sensitive to only a few parameters. Since vehicle tailpipe emissions contribute to most of the life cycle emissions for B20 and petroleum diesel, vehicle tailpipe emissions are the most sensitive inputs to the life cycle HC, CO, NO_x, and PM emissions. For CO_2 emissions and energy consumption, the uncertainty in the B20 and petroleum diesel LCI was dominated by diesel refining efficiency.

8.3.3 Spatial Distribution of Biodiesel LCI Emissions

Most of the soybean yield in the U.S. is located in Iowa, Illinois, Minnesota, and Indiana (USDA 2002). The spatial distribution of soybean yield, biodiesel plants, and ozone non-attainment areas are shown in Figure 8.4. Biodiesel fuel production occurs mostly in Midwest states and ozone non-attainment areas are located mostly in California or the Northeast. There is a significant distance from the rural production plants to the urban ozone non-attainment areas where vehicles typically consume the fuel. Because soybean farming, soyoil plants, and biodiesel plants are typically located in rural areas, these LCI stages are assumed to emit in rural areas, whereas the local transport and vehicle tailpipe emissions are assumed to typically occur in urban areas.. Figure 8.5 differentiates the local HC, CO, NO_x, and PM emissions that would typically occur in ozone non-attainment areas. On average of all tested vehicles, the B20 local urban emissions from local fuel transport and vehicle tailpipe emissions are 24.3% lower for HC, 20.2% lower for CO, 16.9% lower for PM and 0.9% lower for NO_x compared to petroleum diesel local emissions based on NCSU data.

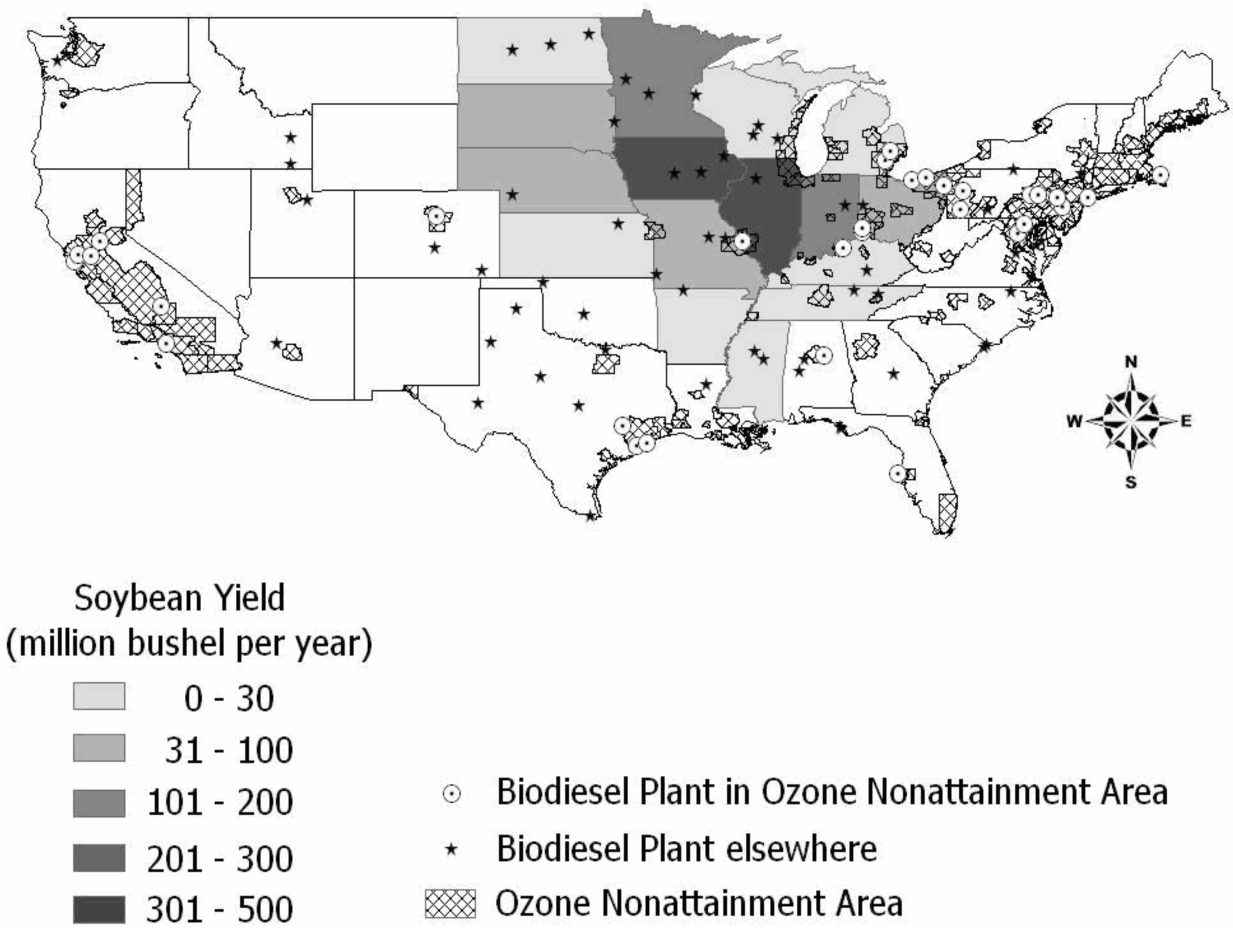


Figure 8.4 Soybean Yield, Biodiesel Plants and Air Quality in the U.S.

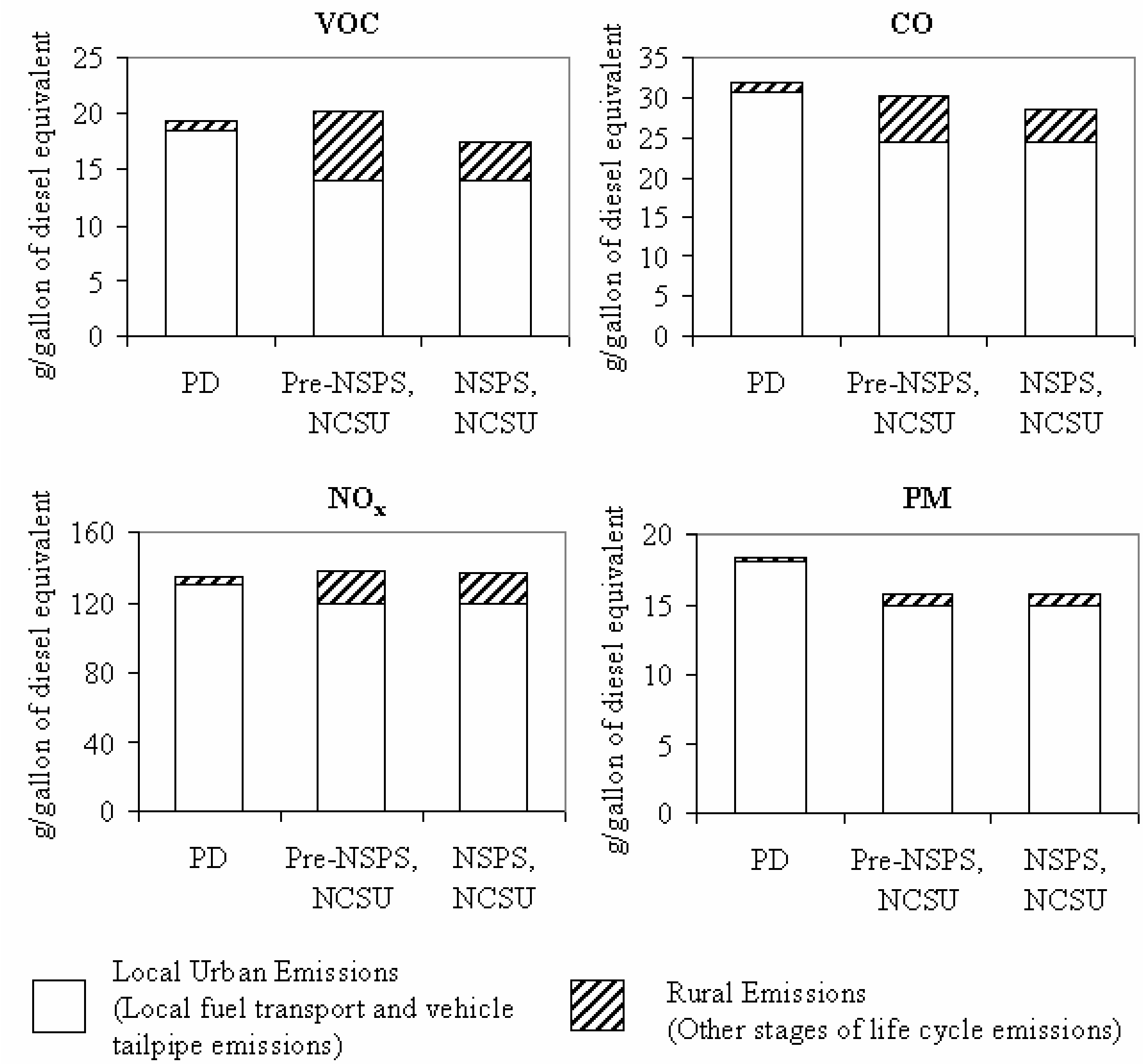


Figure 8.5 Comparison of Local Urban and Total Emissions Based on the Average of 15 NCSU Tested Vehicles

8.4 Discussion

With respect to the biodiesel fuel cycle, the largest portion of HC emissions results from soyoil plants. The new NSPS standard is expected to result in significant reduction of biodiesel fuel cycle HC emissions. If biodiesel fuel production occurred in the same airsheds as tailpipe emissions, local urban HC, CO, and PM emissions are decreased, but there may be an increase or a decrease in NO_x depending on vehicle tailpipe NO_x emissions. The air quality benefits of using biodiesel will depend on the geographic locations of the fuel production and of the vehicles consuming the fuel and on prevailing baseline air quality conditions. It is likely that the reduction in tailpipe emissions from use of B20 will occur in airsheds where air quality is a significant problem, whereas the emissions associated with the fuel cycle may occur in rural areas where air quality problems may be less pressing. However, highly localized air quality problems in rural area can be severe in some cases. Therefore, air quality in ozone non-attainment areas could be improved. The results imply that biodiesel is a promising alternative fuel for diesel, but that there are some environmental trade-offs. Recommendations are made regarding further pursue of biodiesel fuels, reduction of vehicle tailpipe emissions to improve urban air quality, and related studies of vehicle NO_x emissions.

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PART IX CONCLUSIONS AND RECOMMENDATIONS

The expected conclusions and recommendations are discussed in terms of life cycle inventory, data collection procedures, analysis of data for construction equipment, and micro-scale vehicle-specific model. The contributions of each work are also summarized below:

9.1 Conclusions

This chapter presents the key conclusions for applications of data collection procedures, analysis of emissions from construction vehicles, emission modeling of construction vehicles and life cycle inventory for biodiesel and petroleum diesel fueled construction vehicles.

9.1.1 Applications of Data Collection Procedures on Nonroad Construction Equipment

- The use of on-board emission data is recommended with the purpose of improving the accuracy of emission factors and inventories. The procedures described here are applicable to any construction site and type of nonroad construction equipment. The methodology developed here can be applied to further studies.

- Based on an example of this as well as other vehicles, manifold absolute pressure (MAP) has been consistently identified as the engine variable most highly correlated with variations in fuel use and emission rates. The rank correlation of MAP with each of these rates often exceeded 0.95, except for NO and opacity for which the rank correlation was typically approximately 0.8. While engine RPM is also highly correlated with these rates, the correlations were slightly weaker than those for MAP. Thus, MAP was found to be highly associated with variability in fuel use and emission rates and thus is a useful practical basis for developing modal emission rate on a per time basis.
- On a fuel-basis, emission rates are highly sensitive to idle versus non-idle operation. However, fuel-based emission factors are less sensitivity to engine load for non-idle than are time-based emission factors. Therefore, fuel-based emission factors are likely to be a more robust basis for estimating emission inventories, if fuel consumption data are available.
- The emission factors for NO, HC, and CO are comparable to those from other data sources. The opacity measurements are useful for relative comparisons but are not accurate for absolute determinations of the level of emission rates.

9.1.2 Emission Modeling of Fuel Use and Emissions from Nonroad Construction Equipment

- Task-oriented modes are useful to explain the variations of fuel use and emissions among different work activities. Typically, a peak in MAP is associated with a corresponding peak in fuel use and emission rates.
- For diesel engines, it is expected to be low for the HC and CO emission rates. In some cases, vibration can affect the precision and accuracy of the analyzer for HC and CO measurement during data collection. When the HC and CO measurements are below the detection limit of the instrument, the HC and CO concentrations have a random pattern, which results in low R^2.
- Generally, the R^2 for task-oriented modal models is lower than for the engine-based modal models. The results indicated that engine-based modal models perform better than task-oriented modal models.
- The R^2 for fuel use, CO_2, and NO is high for all engines based on time-based or fuel-based regression models. Similar to the other modeling approaches, the low emissions of CO and HC from diesel exhaust result in lower R^2 compared to the other pollutants for the physically-based regression models. Time-based regression models have the best explanatory capability among all models.

- The micro-scale emissions models will be used to estimate emissions to the natural environment to enable assessment of air quality impacts. The predictive micro-scale have the capability to estimate energy use and emissions for a wide variety of activity patterns and to aggregate energy use and emissions to larger spatial and temporal scales. The micro-scale model will perform well as a basis for estimating construction vehicle emissions for federal regulations.

9.1.3 Inter-Cycle and Inter-Engine Variability of Fuel Use and Emissions from Nonroad Construction Equipment

- Time-based inter-cycle and inter-engine variations of fuel use and emissions are significant. Fuel-based emission factors have less variability among cycles and engines than time-based emission factors. Fuel-based emission factors are more robust with respect to inter-engine and inter-cycle variations.
- The fuel-based emission rates are recommended in order to develop an emissions inventory for nonroad construction vehicles because of less inter-cycle and inter-vehicle variations.

9.1.4 The Benefits of Using Biodiesel Fuels with Respect to Life Cycle Inventory

- With respect to the biodiesel fuel cycle, the largest portion of HC emissions results from soyoil plants. The EPA new standards would result in a significant reduction of HC emissions in the biodiesel life cycle.
- Almost 100 percent of life cycle energy consumption for petroleum diesel is fossil energy compared to 83 percent for B20 biodiesel and 37 percent for B100 based on new soyoil plants. If bio-fuels are further pursued, the portion of renewable energy in the life cycle will be higher.
- The operation of the vehicle itself consumes more energy than does the fuel cycle for producing the fuel, the amount of energy consumed during the fuel cycle is not negligible. As the tailpipe emissions are reduced from newer engines, the fuel cycle emissions are contributing more to the entire LCI.
- For petroleum diesel life cycle, crude oil refining contributes most to the fuel cycle energy consumption and also contributes substantially to the PM, CO, and CO_2 emissions.
- In general, LCI energy consumption and emissions were sensitive to only a few parameters. Since vehicle tailpipe emissions contribute to most of the life cycle emissions for B20 and petroleum diesel, vehicle tailpipe emissions are the most sensitive parameters to the life cycle HC, CO, NO_x, and PM emissions.

- Biodiesel fuel production occurs mostly in Midwest states and ozone non-attainment areas are located mostly in California or the Northeast. There is a significant distance from the rural production plants to the urban ozone non-attainment areas where vehicles typically consume the fuel. It is possible that the reduction in tailpipe emissions will occur in airsheds where air quality was a significant problem, whereas the emissions associated with the fuel cycle may occur in more rural areas where air quality problems may be less pressing.
- The benefits of using biodiesel would depend on the geographic locations of the fuel production and of the vehicles consuming the fuel. It is possible that a reduction in tailpipe emissions might occur in an ozone non-attainment area, whereas the fuel cycle emissions might occur in a region that was in attainment area where air quality problems may be less pressing. Therefore, air quality in ozone non-attainment areas could be improved.
- Biodiesel is a promising alternative fuel for diesel, but there are some environmental trade-offs. The life cycle analysis quantifies air quality impacts of construction activities based upon the real-world measurements. The LCI will support future development of federal regulations and provide a scientific basis for such regulations.

9.2 Recommendations for Future Work

Key recommendations of this study are:

- Based on the experience gained in attempting to obtain valid fuel use and emissions data, foam should be placed under the main unit of the PEMS and under the safety cage to reduce vibration and equipment damage. This method does decrease the vibration of Montana system, but doing so does not completely eliminate the vibration. Further investigation of installation of the PEMS should be made to reduce the vibration from the vehicle chassis.
- Further pursue of biodiesel fuels is recommended to improve urban air quality, although there are some environmental trade-offs. The emissions associated with the fuel life cycle may be increased in rural areas where air quality problems are less pressing.
- Based on the results of life cycle inventory, vehicle tailpipe emissions contribute to most of the life cycle emissions for both B20 and petroleum diesel. Thus, recommendation is made regarding the priority of reducing vehicle tailpipe emissions from off-road construction vehicles.
- Some studies show an increase of vehicle NO_x emissions, whereas some other studies show a decrease of NO_x. Recommendation is made to conduct more real-world measurements on heavy duty diesel engines to identify the NO_x emissions when using B20 biodiesel fuels.

- The time-based regression model has the highest explanatory ability among six models and is recommended in order to predict fuel use and emission rate for diesel-fueled nonroad construction vehicles.
- Real-world in-use measurements should be a basis for developing duty cycle correction factors in models such as NONROAD.
- Database of heavy duty diesel engines should be developed for future diesel fueled vehicle research projects, including engine characteristics, regression coefficients, representative duty cycles, predicted fuel use and emission rates.
- Future improvement of the nonroad construction vehicle LCI framework, including needs for more in-use measurements of vehicle emissions for purposes of developing more accurate estimates for each type of construction vehicle.

APPENDIX A. MEASURED TIME-BASED MODAL FUEL USE AND EMISSION RATES AND FUEL-BASED EMISSION RATES FOR ENGINE AND TASK ORIENTED MODES FOR ALL TESTED VEHICLES

Appendix A provides supplementary Figures and Tables for modal models. Results for five front-end loaders, five dozers, three excavators, three off-highway trucks, eight backhoes, six motor graders, one skid steer loader, and one track loader are summarized in this appendix.

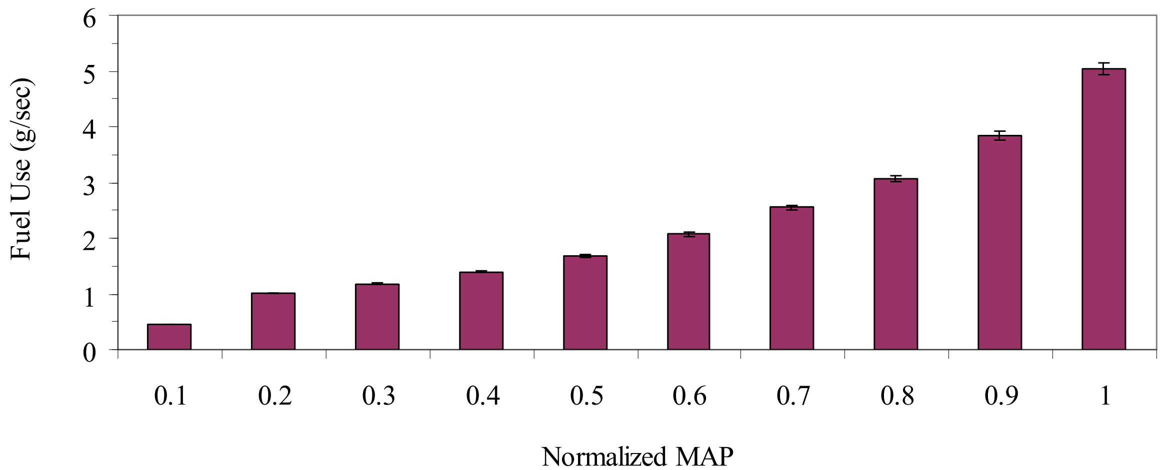
For each tested vehicle, there are four different types of figures:

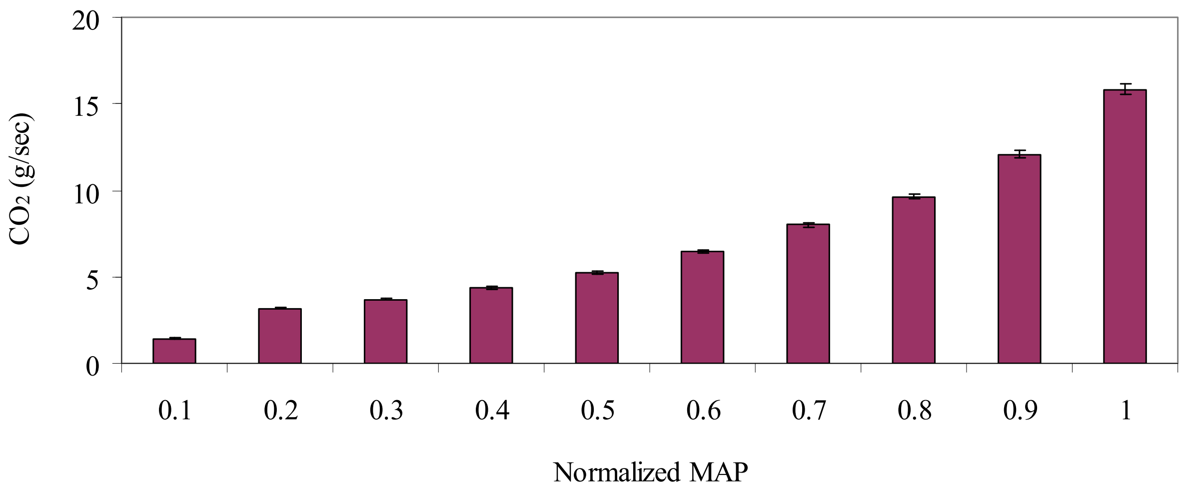
- Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes
- Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes
- Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes
- Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes

Based on engine-based MAP bins, modal emission rates for fuel use, CO_2, HC, CO, and opacity are presented on a time basis. The second figure provides a comparison of engine-based average modal emission rates on a per unit of fuel consumed basis.

Average fuel use and emission rates for the task-oriented modes are given in the third (for time basis) and fourth figures (for fuel consumed basis). The task-oriented modes do not explain as much of the variability in fuel use and emission rates as the engine-based data, but they provide some indication of how fuel use and emission rates change for task-oriented modes of operation.

FRONT-END LOADER 1





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 36 ^{o}F and the relative humidity was 49 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A1. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Front-End Loader 1 (continued on next page)

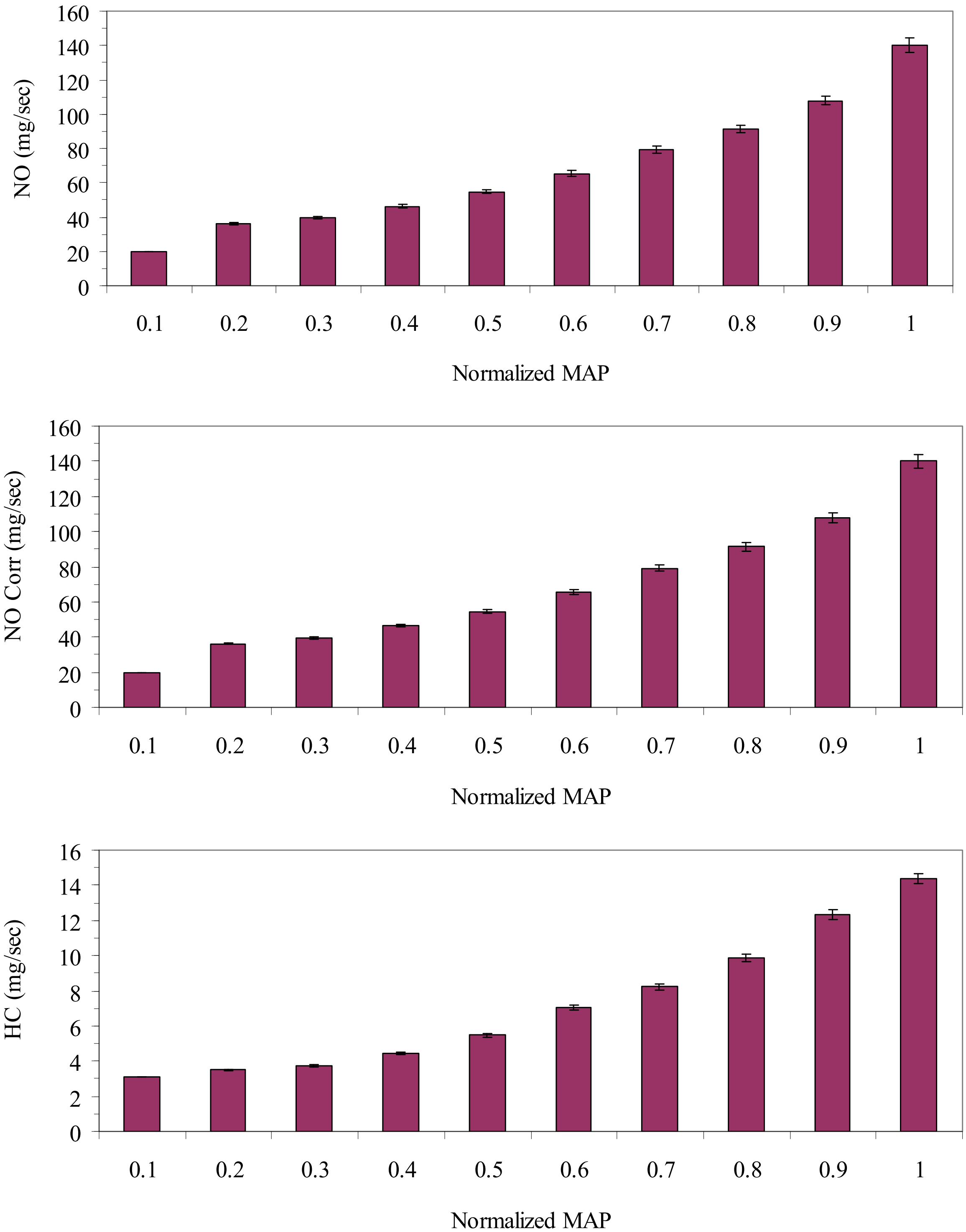
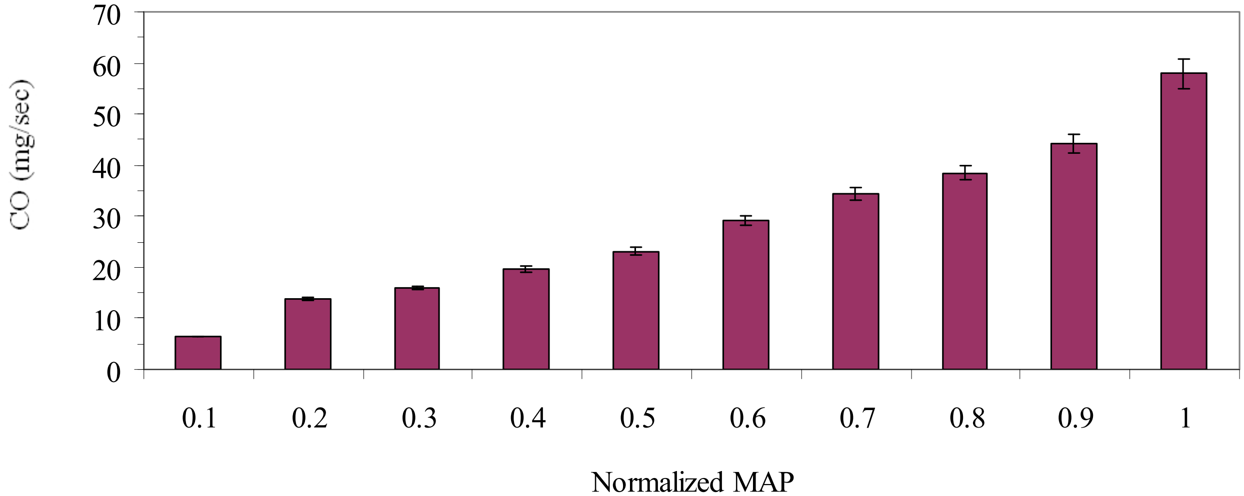


Figure A1. Continued



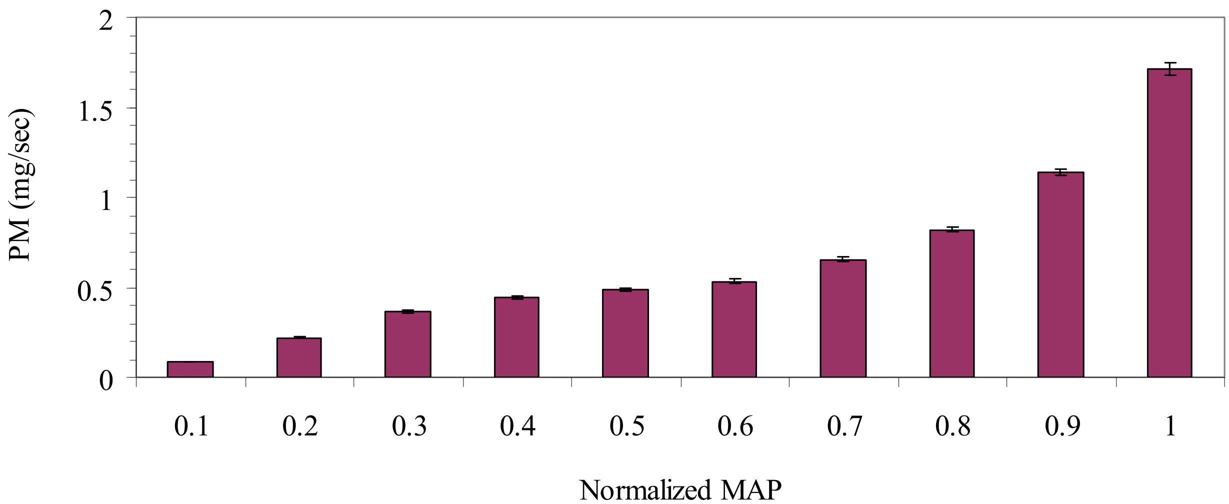
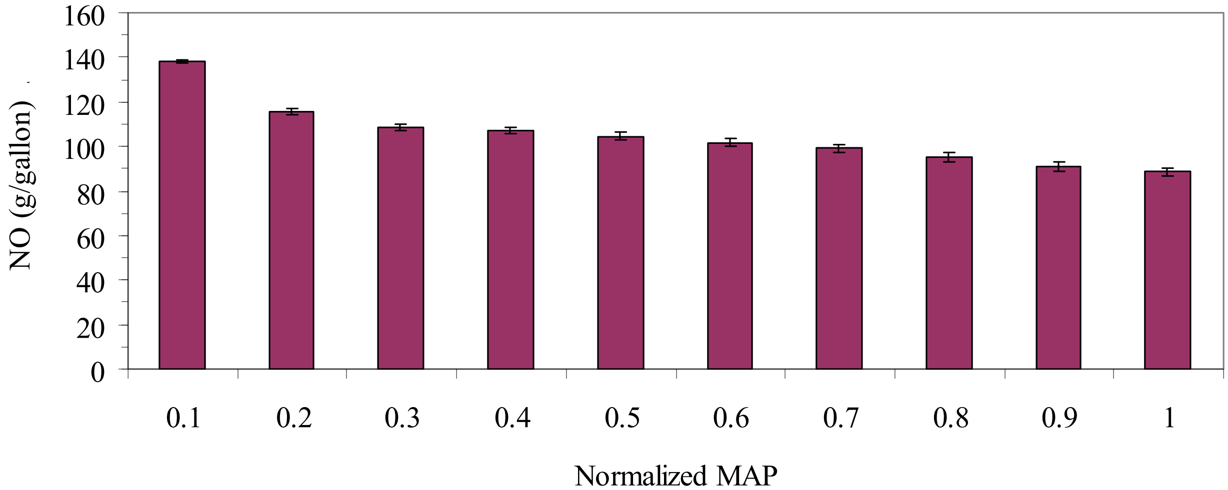
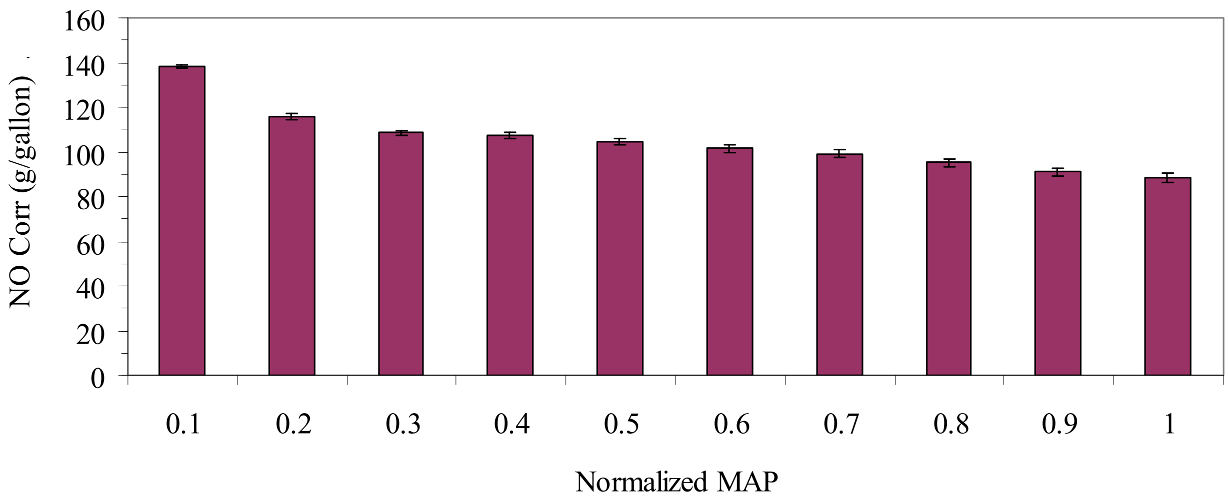


Figure A1. Continued

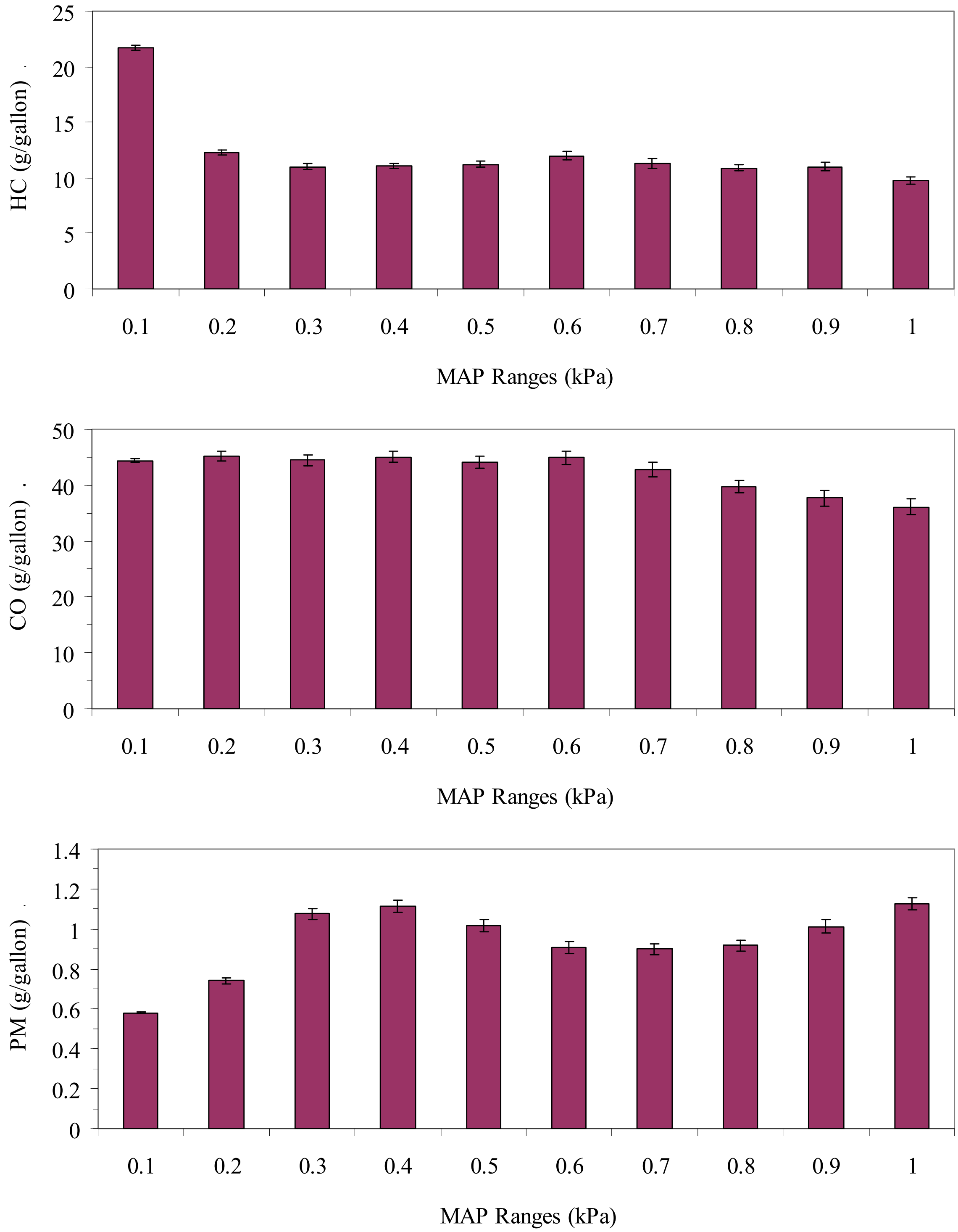




NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 36 ^{o}F and the relative humidity was 49 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A2. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Front-End Loader 1 (continued on next page)



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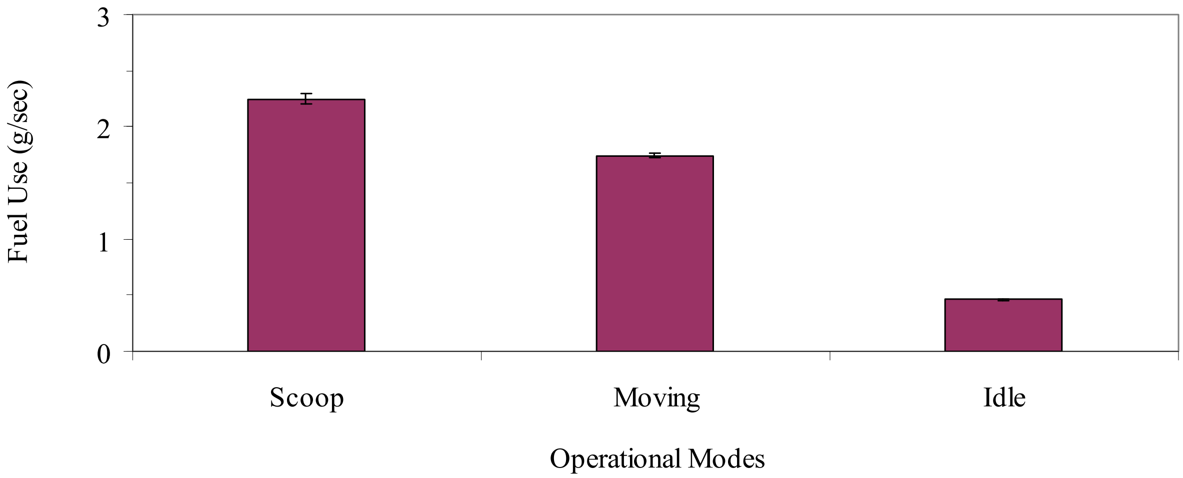
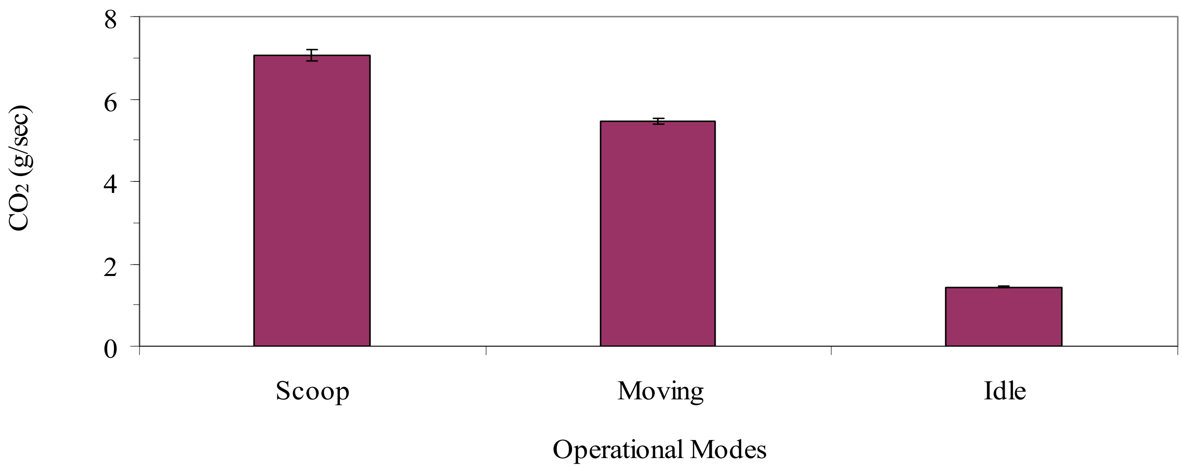
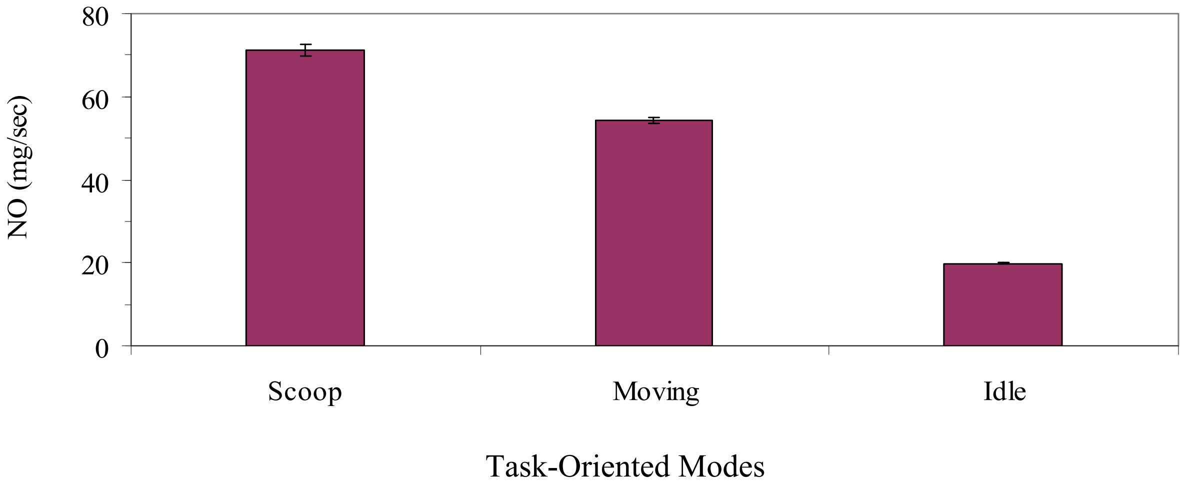


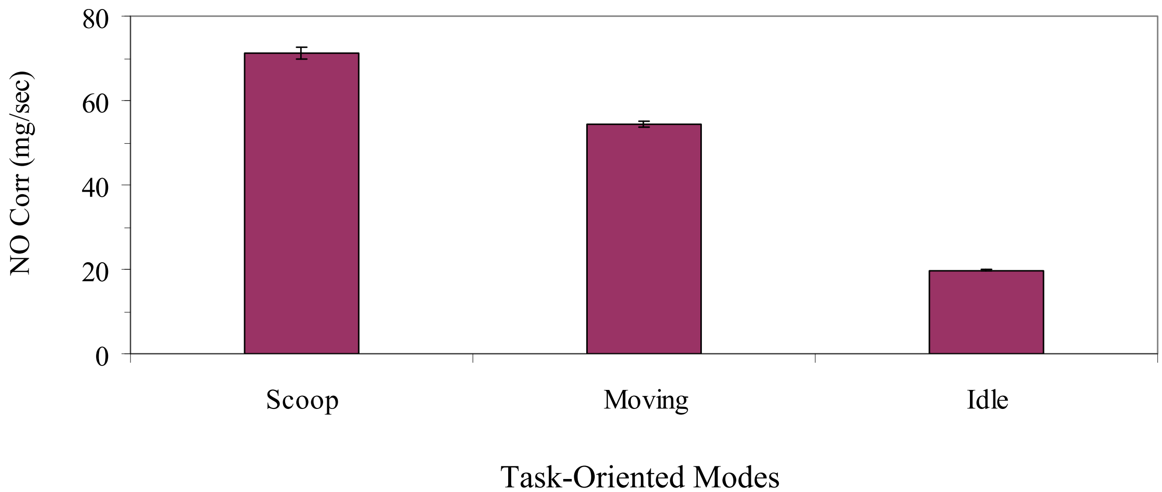


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 36 ^{o}F and the relative humidity was 49 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A3. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Front-End Loader 1 (continued on next page)





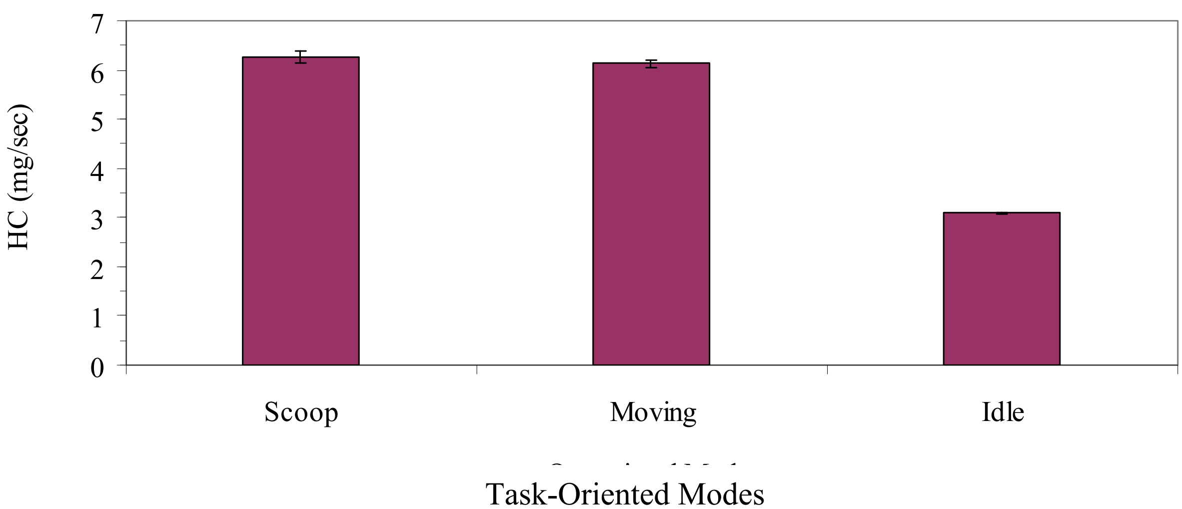
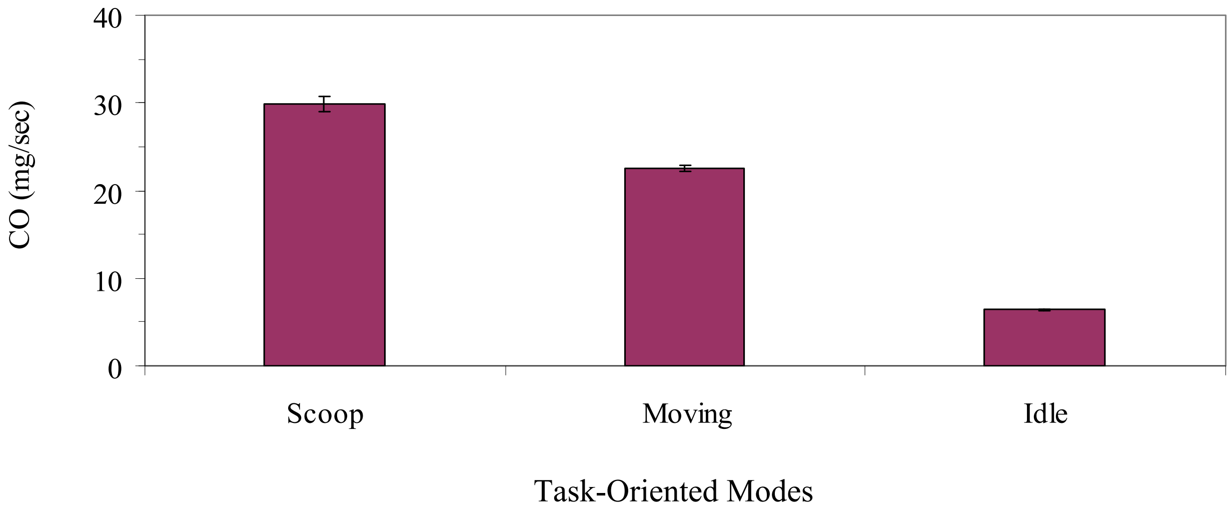


Figure A3. Continued



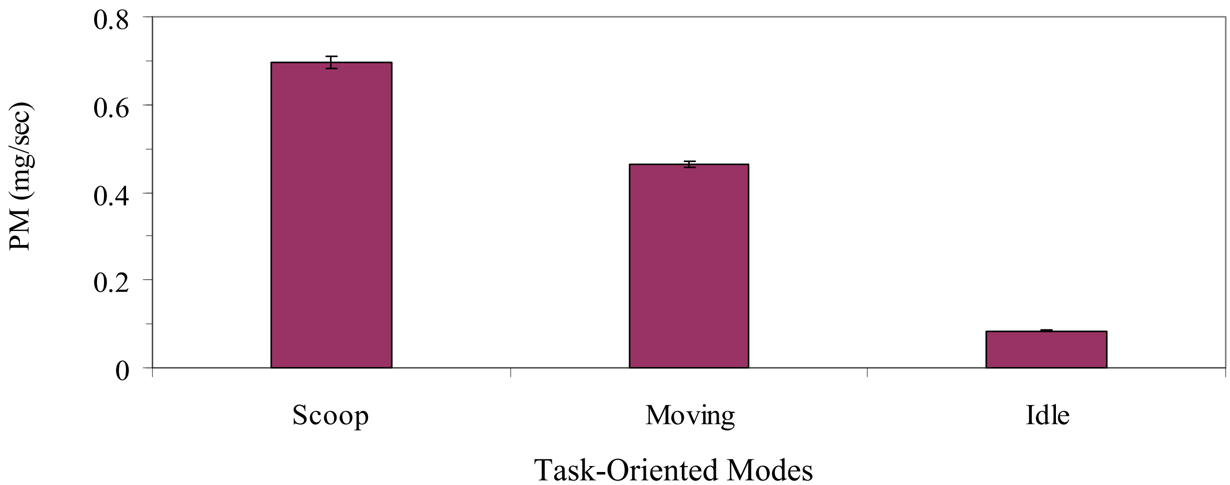
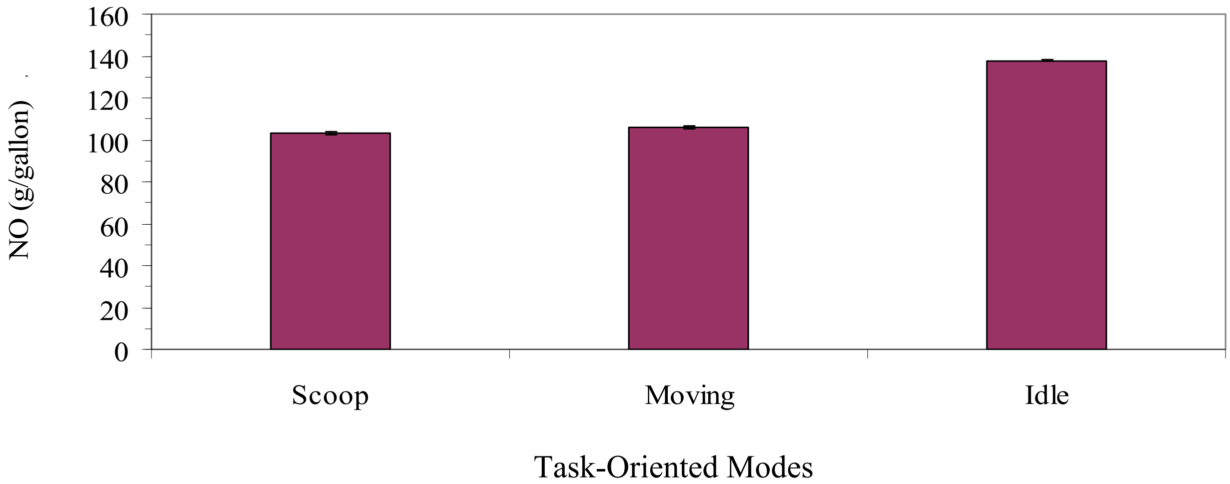
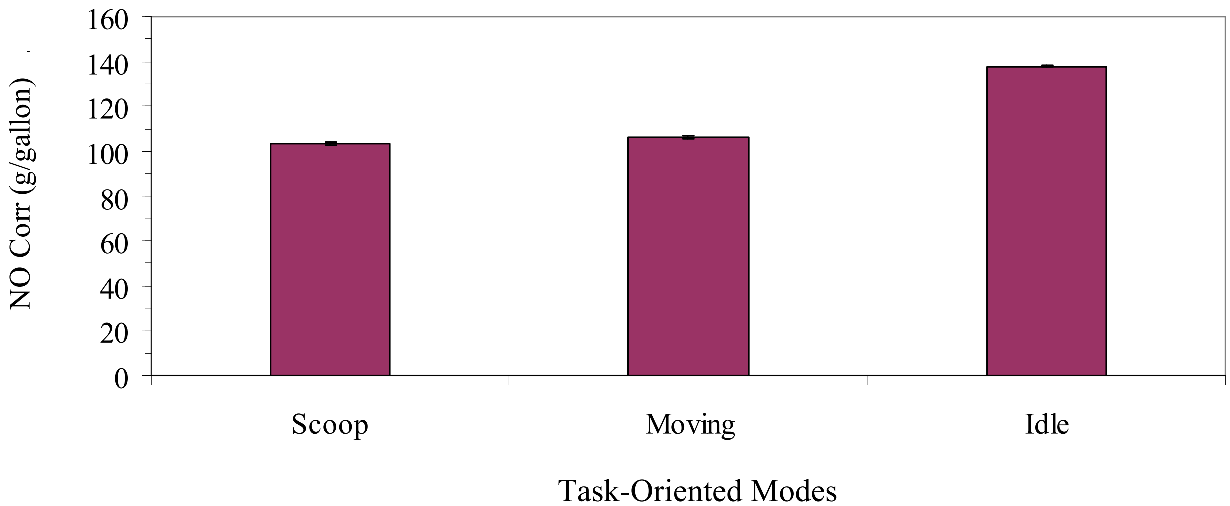


Figure A3. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 36 ^{o}F and the relative humidity was 49 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A4. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Front-End Loader 1
(continued on next page)

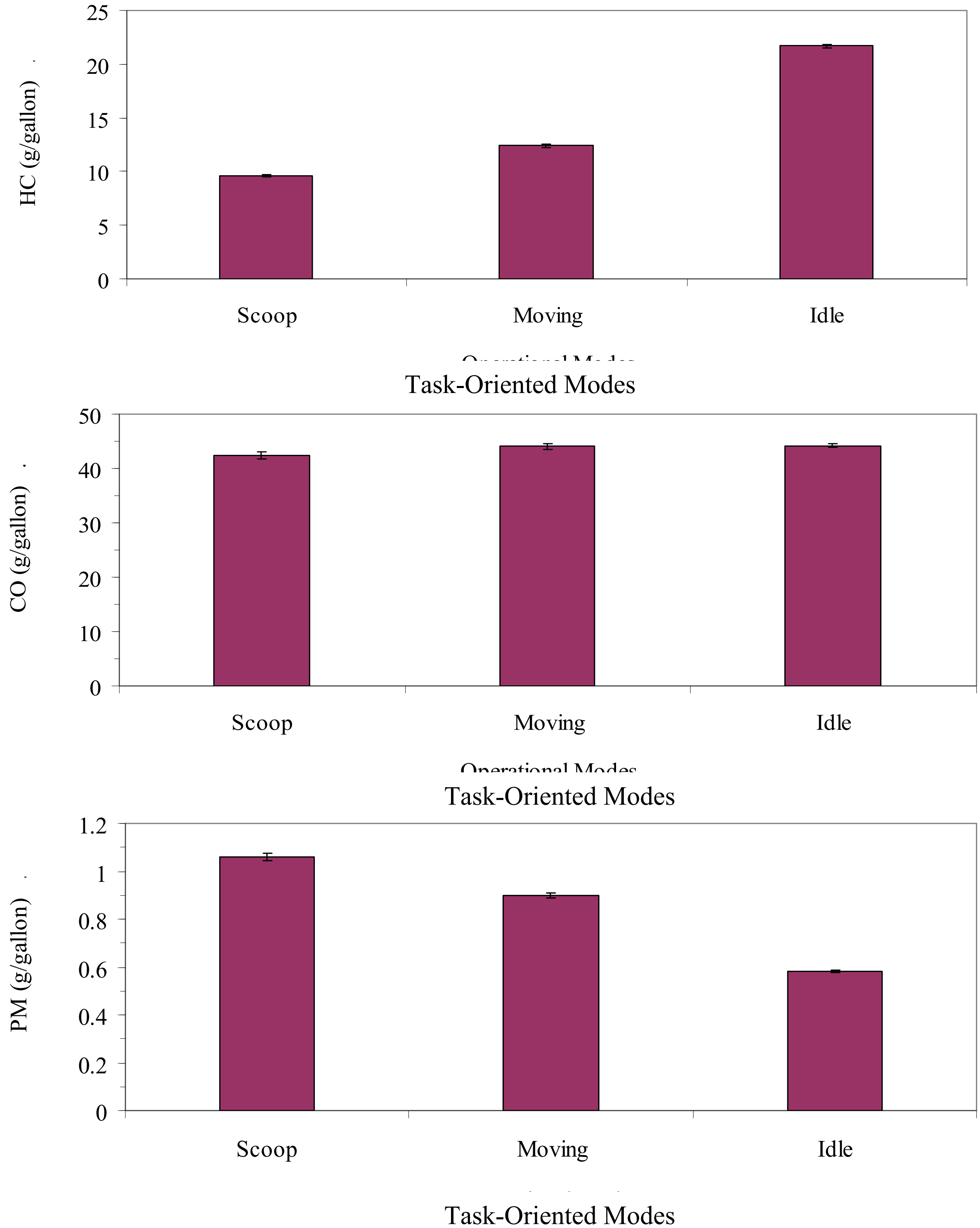
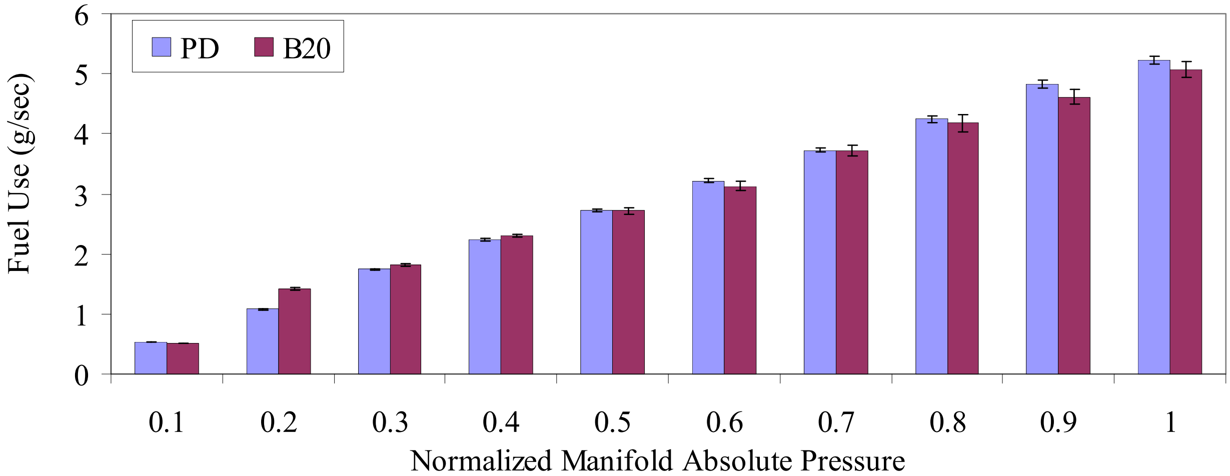
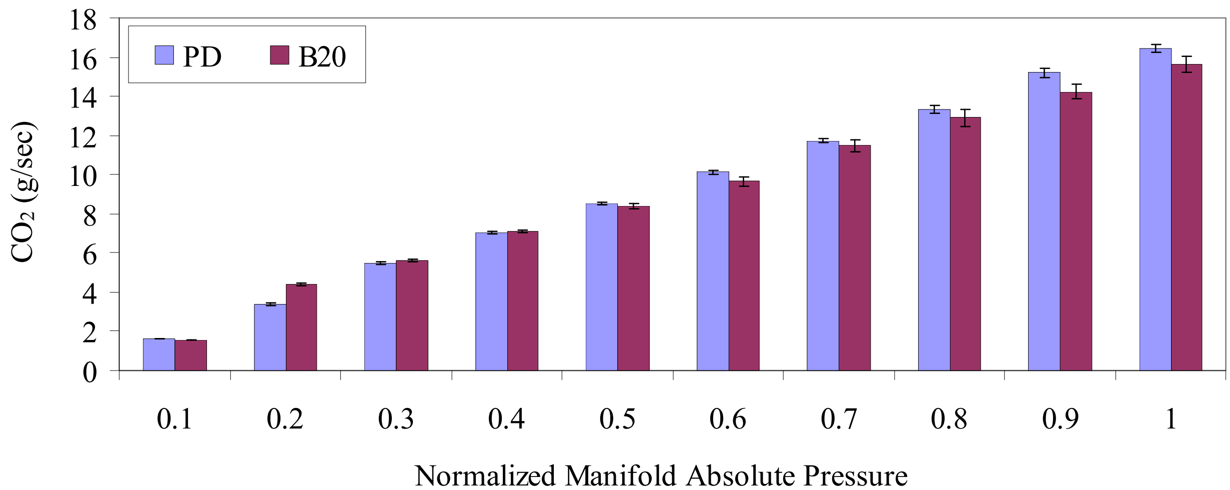


Figure A4. Continued

FRONT-END LOADER 2

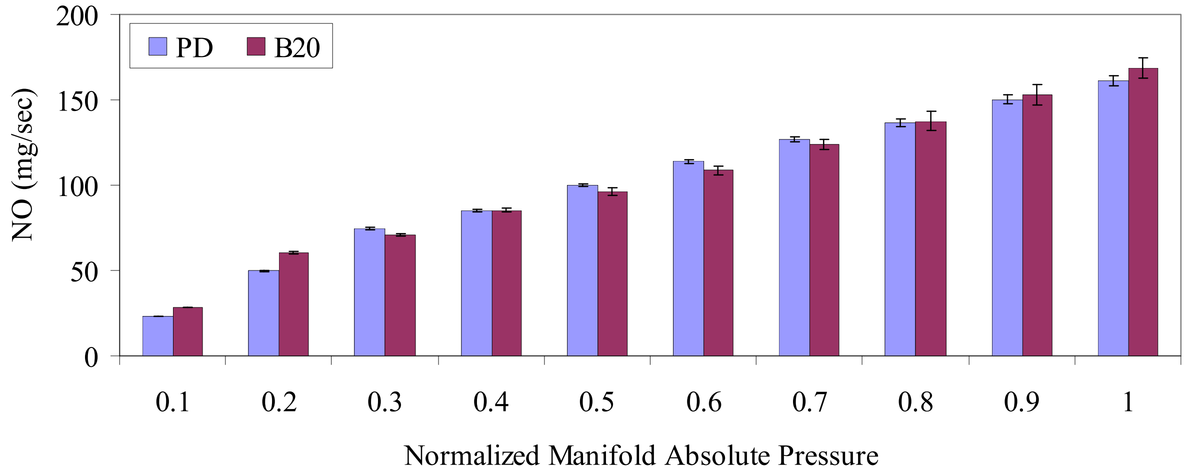


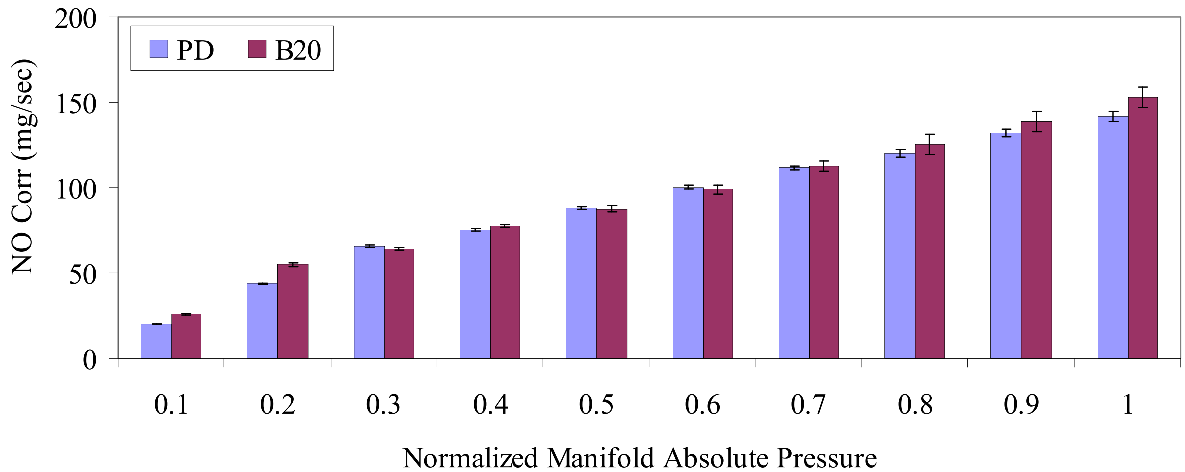


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 40 %. For the B20 biodiesel test, the ambient temperature was 49 ^{o}F and the relative humidity was 74 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A5. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Front-End Loader 2 (continued on next page)





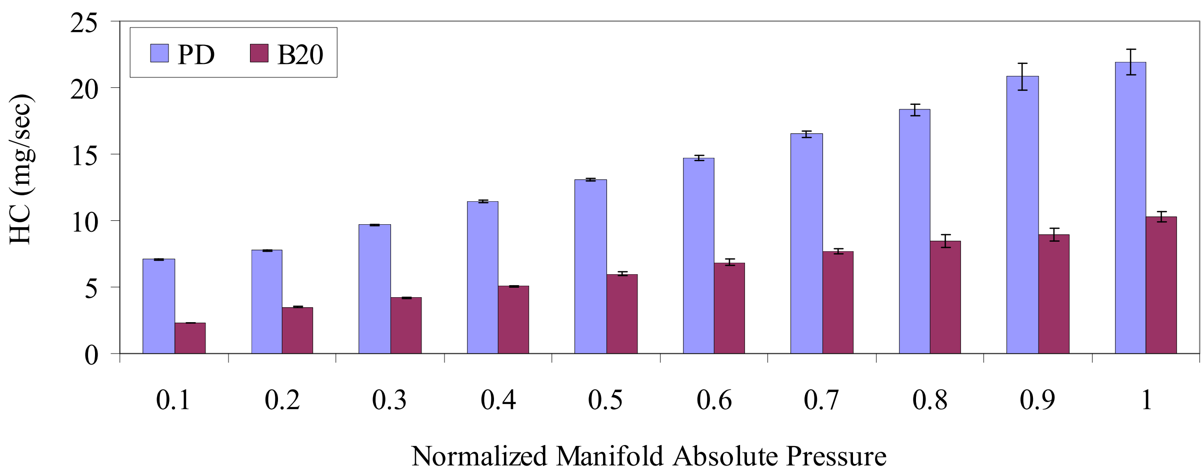


Figure A5. Continued

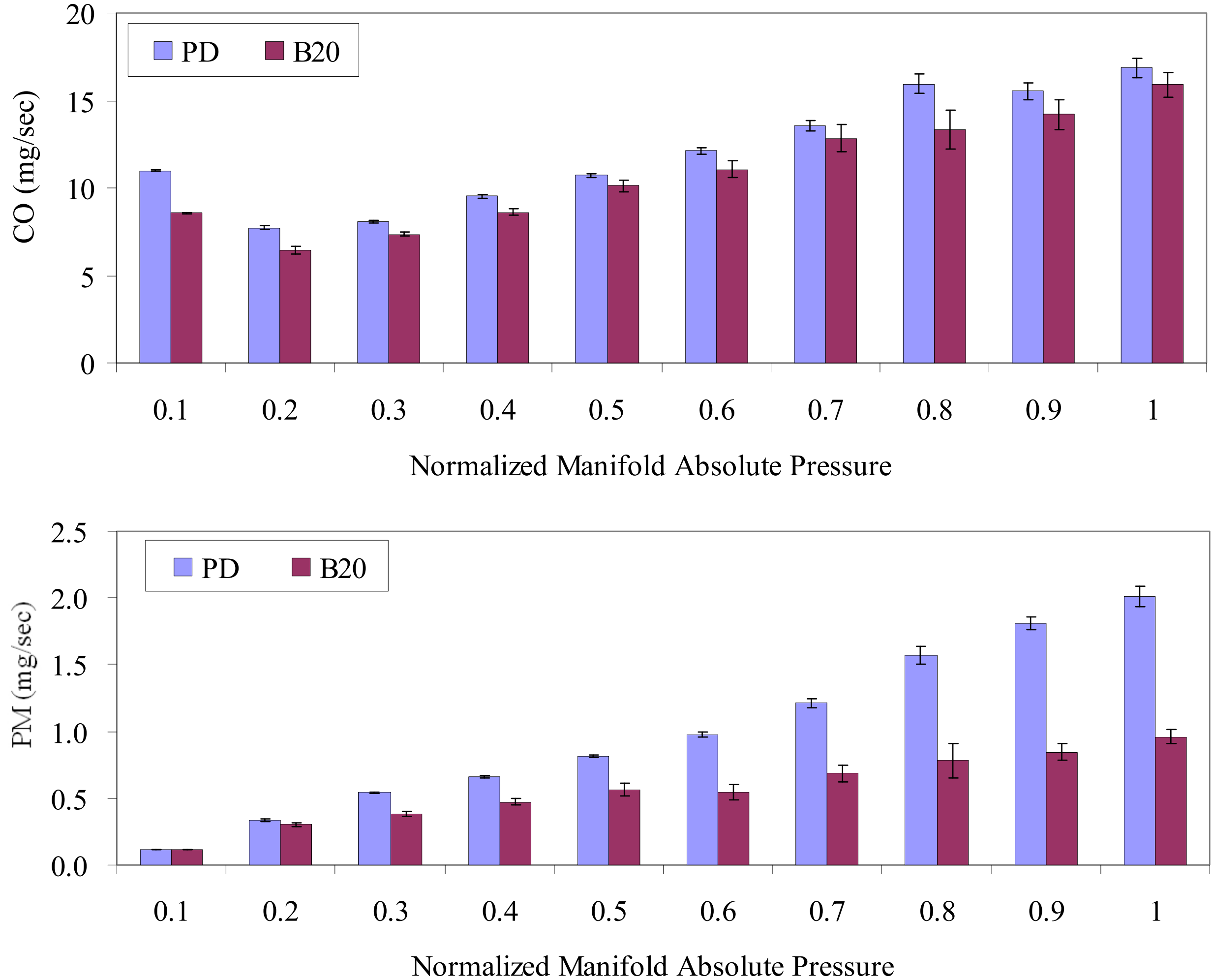
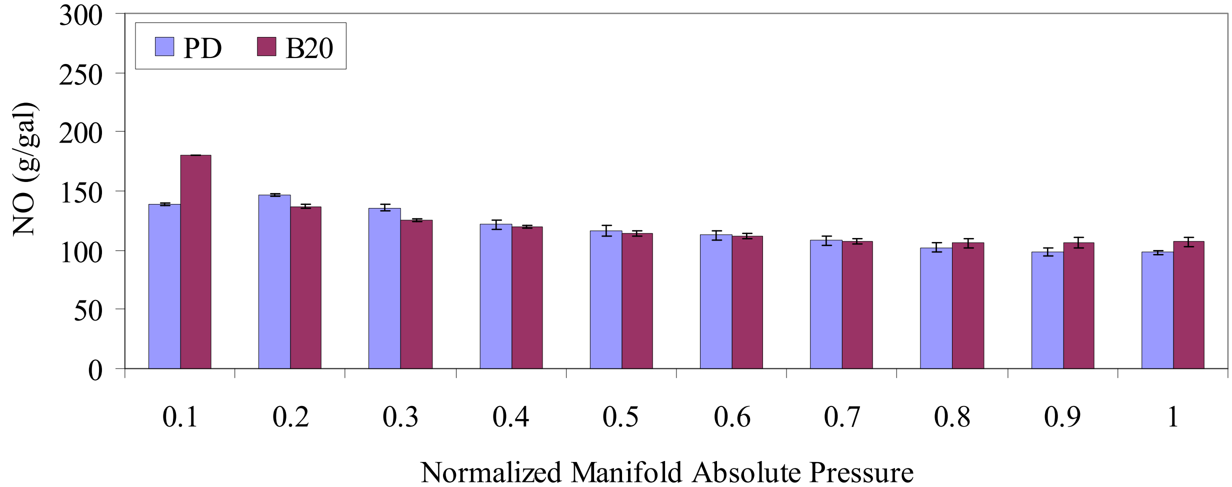
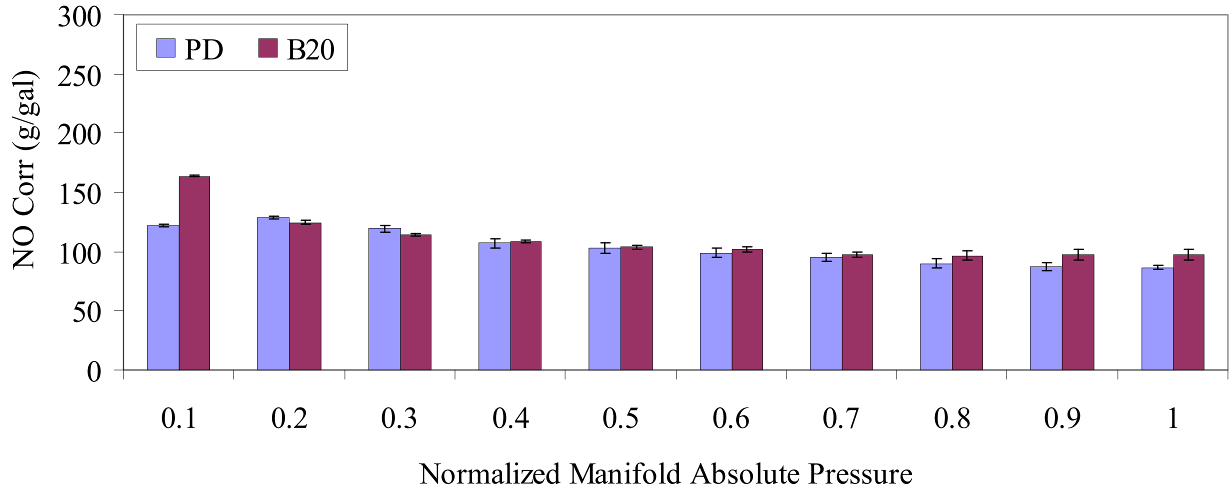


Figure A5. Continued

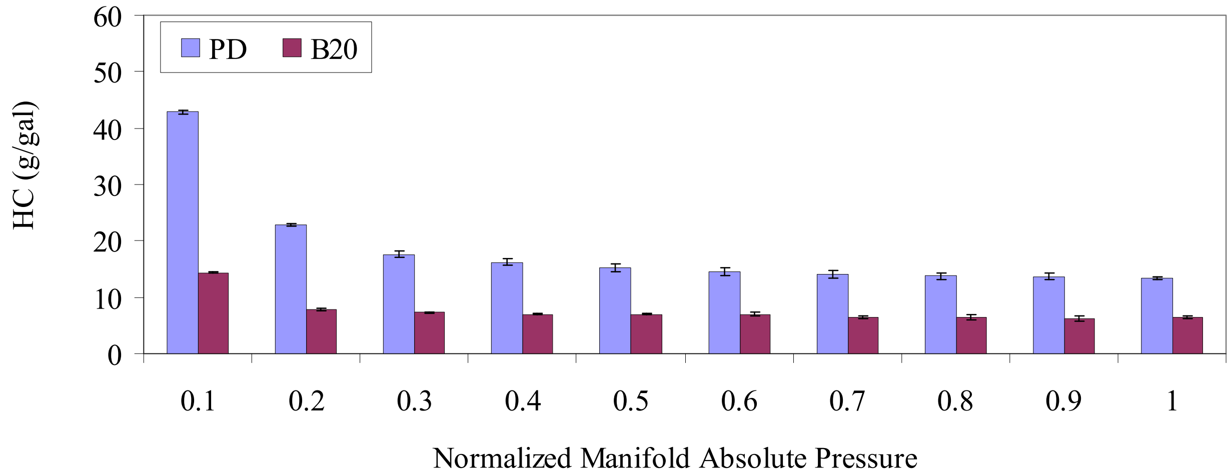


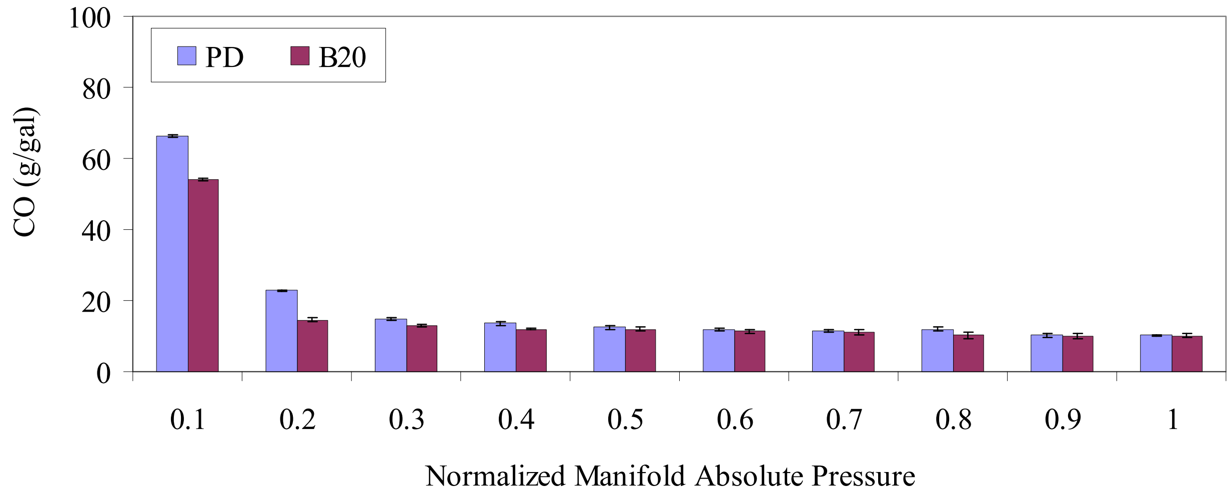


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 40 %. For the B20 biodiesel test, the ambient temperature was 49 ^{o}F and the relative humidity was 74 %.

Values shown in the figure are the upper end of the range: "0.1" = $0 \leq$ Normalized MAP < 0.1; "0.2" = $0.1 \leq$ Normalized MAP < 0.2, and so on.

Figure A6. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Front-End Loader 2 (continued on next page)





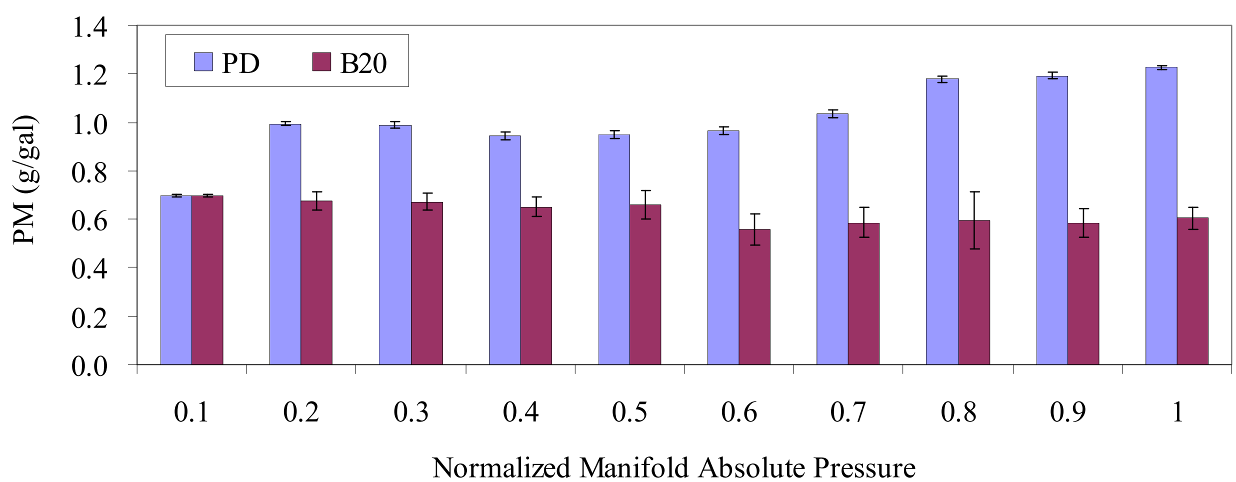
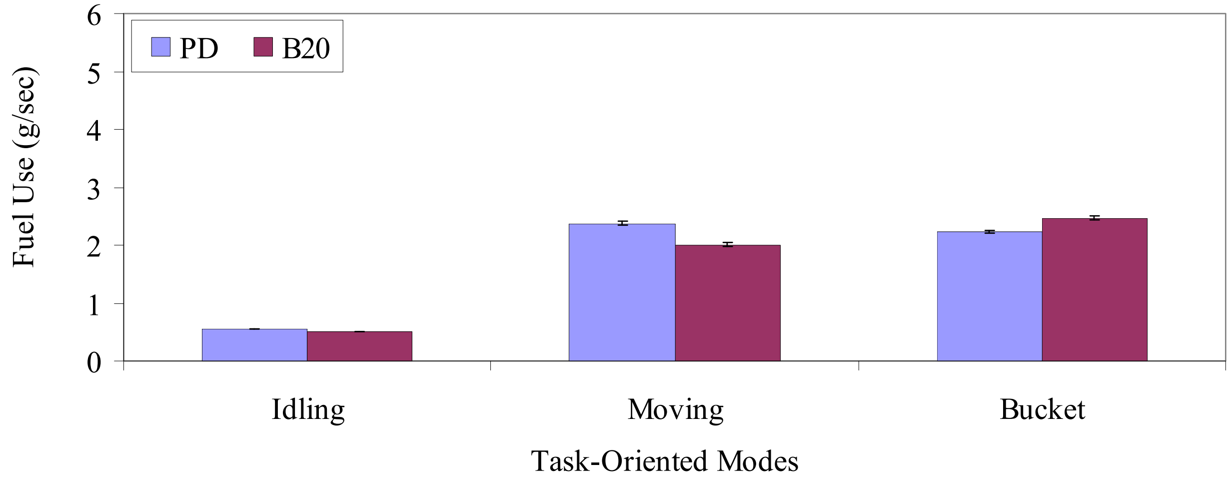
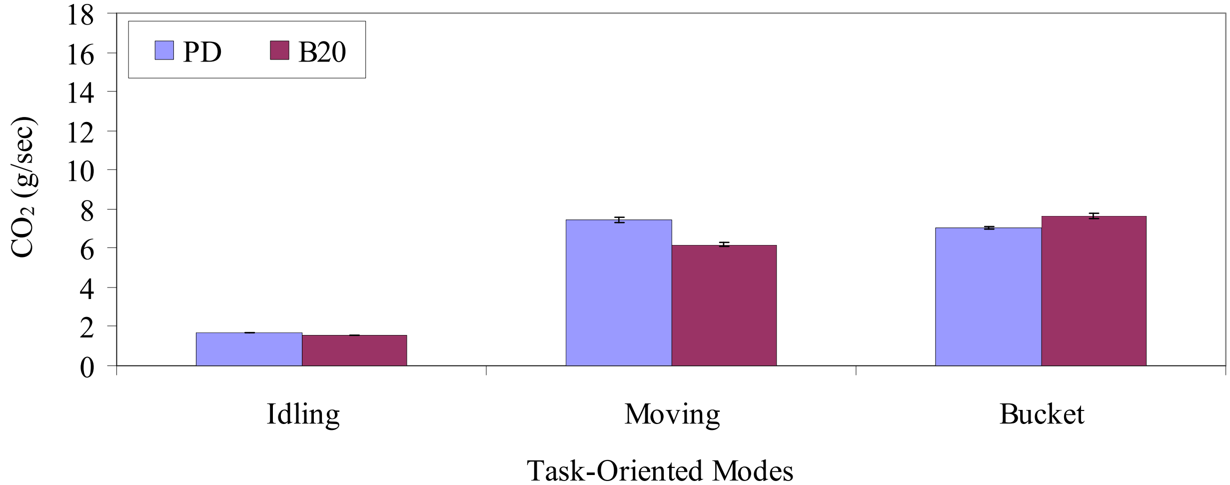


Figure A6. Continued

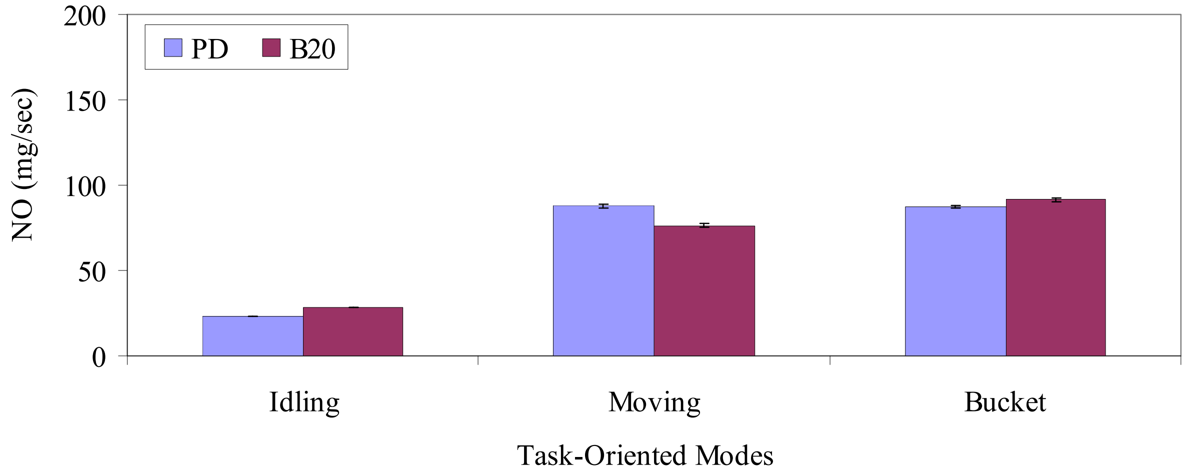


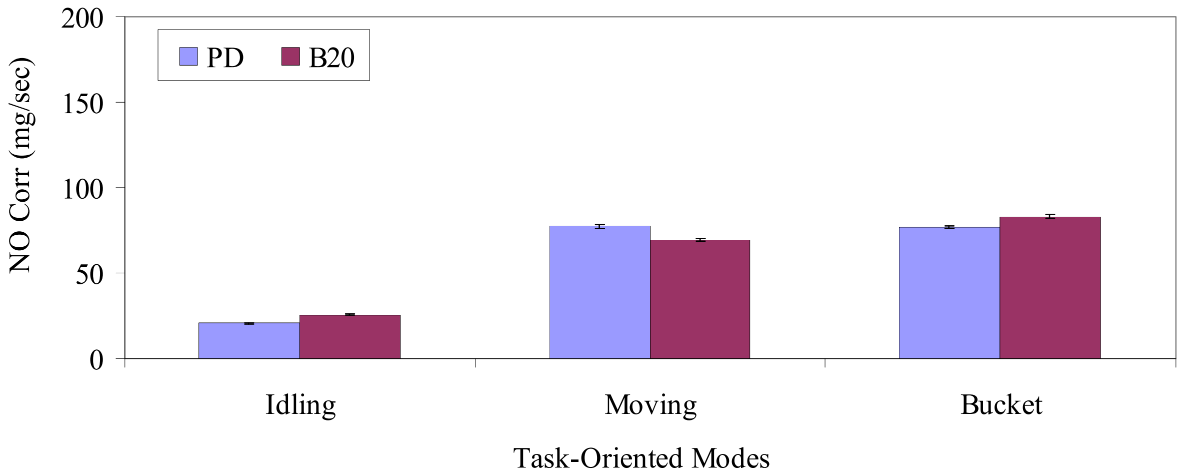


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 40 %. For the B20 biodiesel test, the ambient temperature was 49 ^{o}F and the relative humidity was 74 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A7. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Front-End Loader 2 (continued on next page)





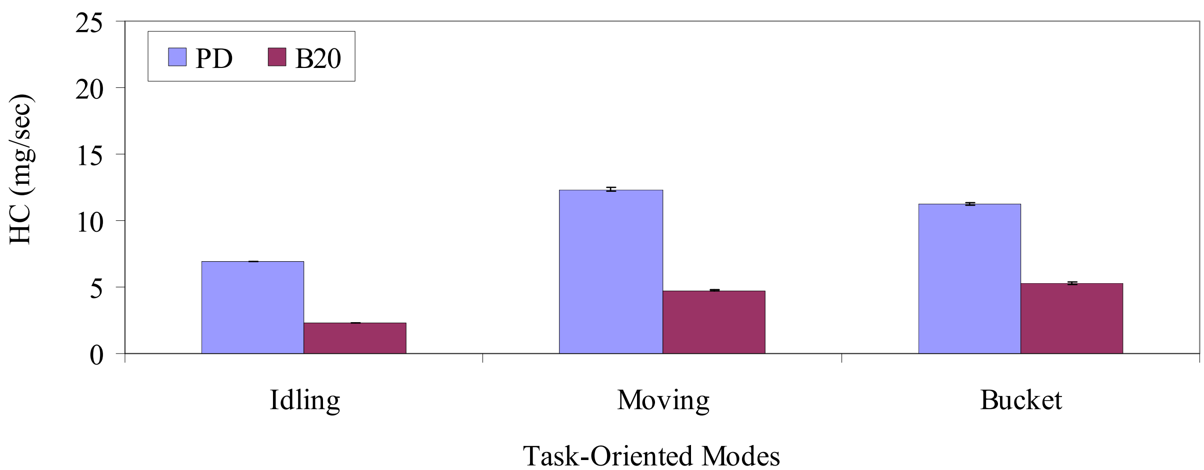
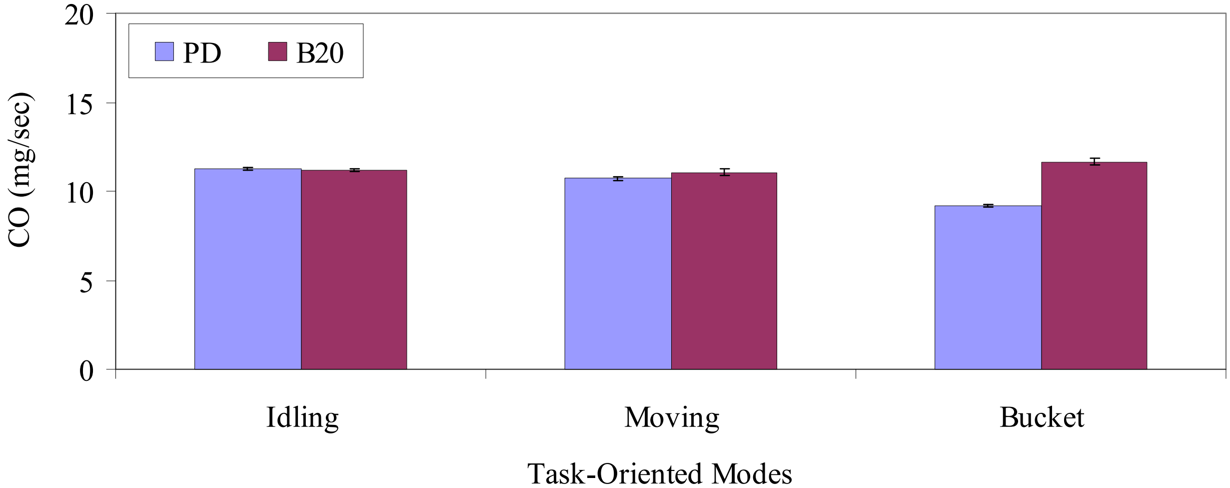


Figure A7. Continued



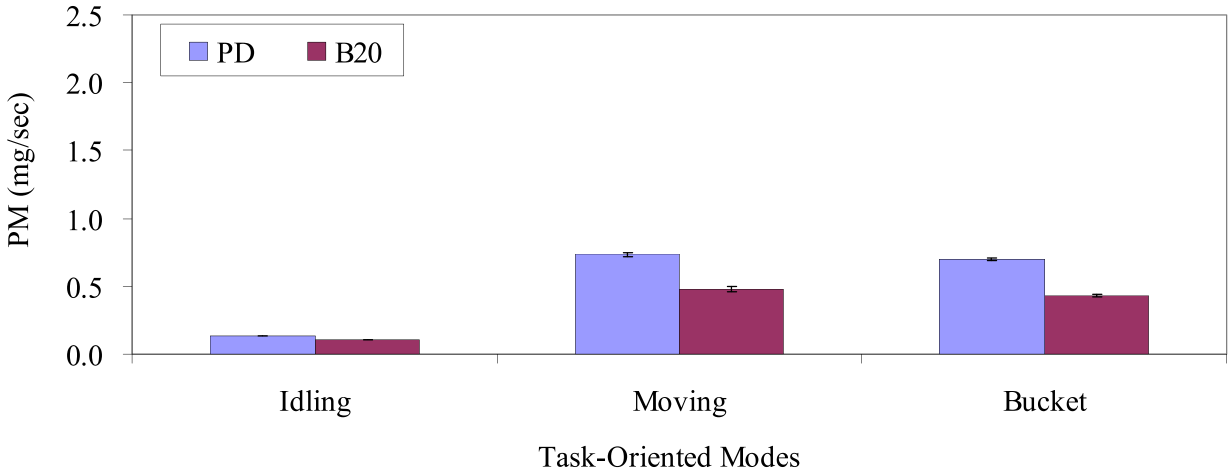
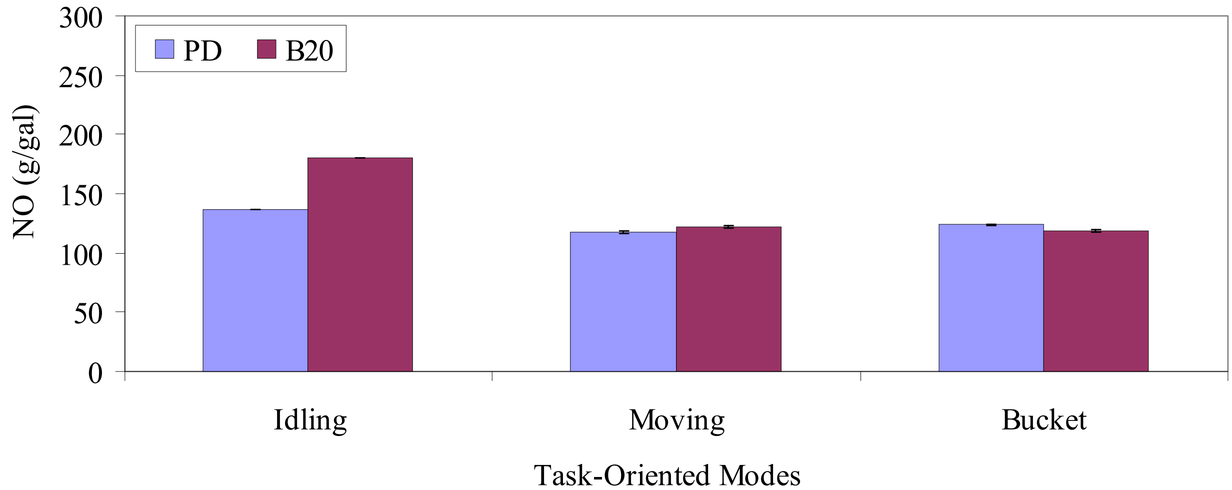
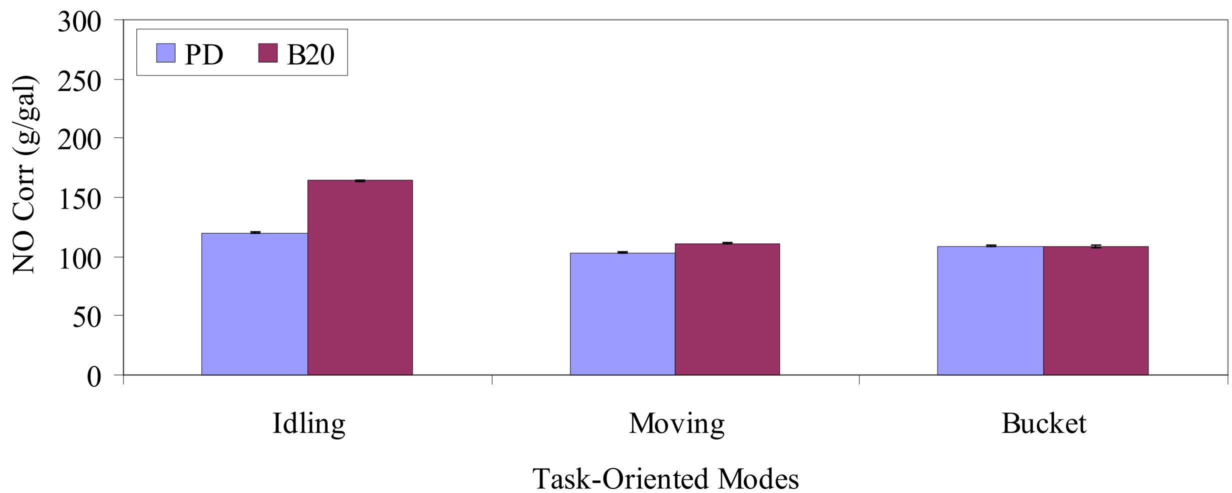


Figure A7. Continued

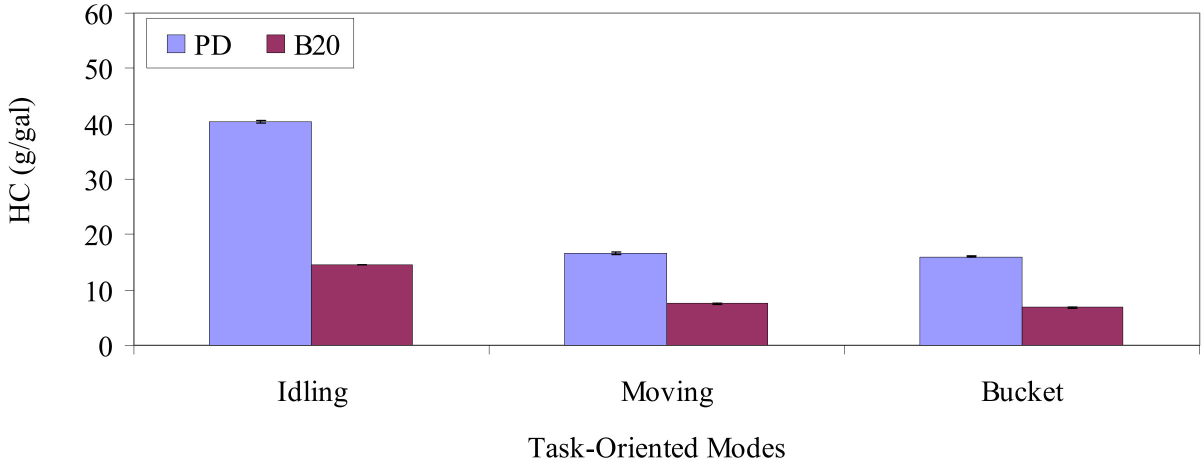


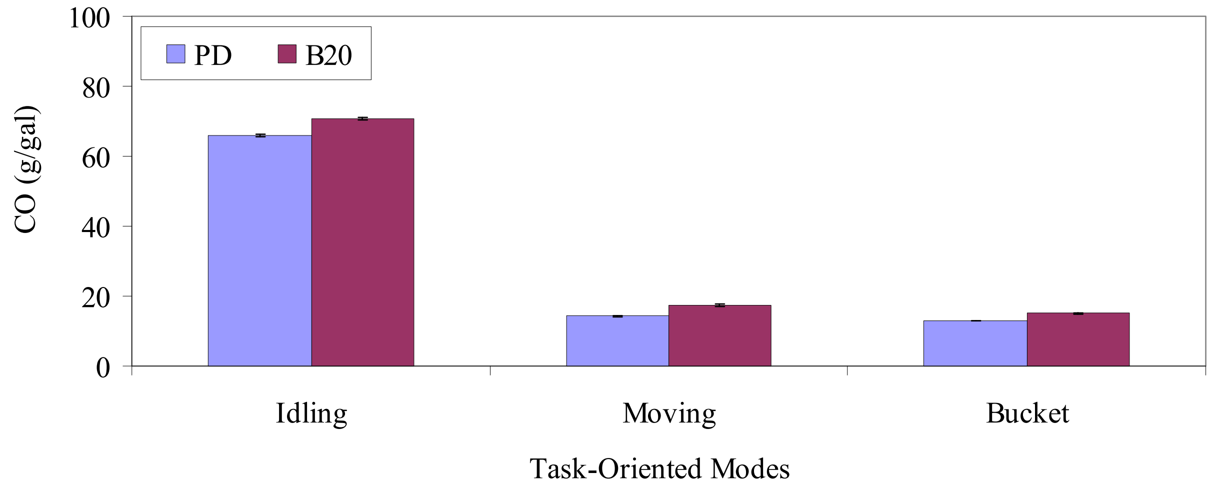


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 40 %. For the B20 biodiesel test, the ambient temperature was 49 ^{o}F and the relative humidity was 74 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A8. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Front-End Loader 2 (continued on next page)





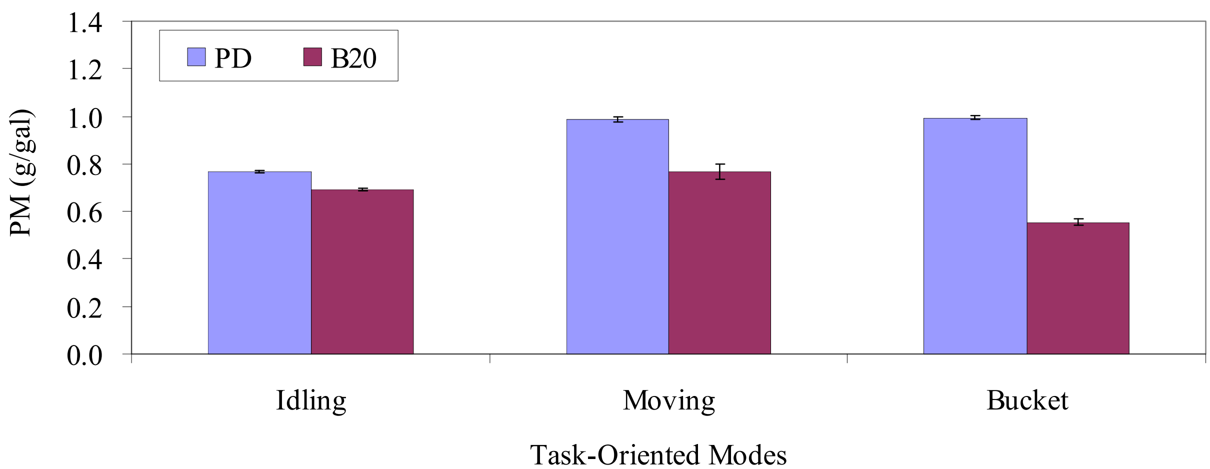
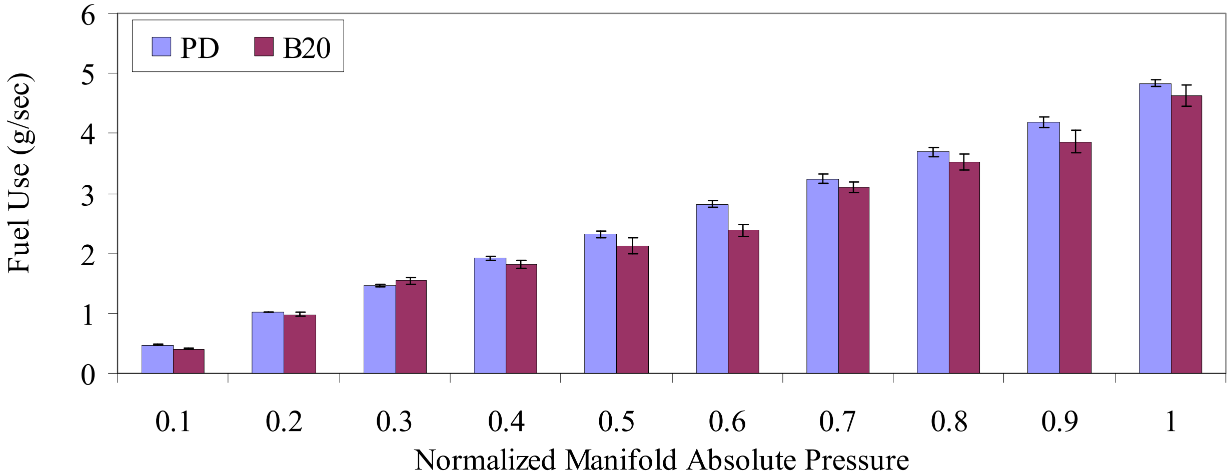
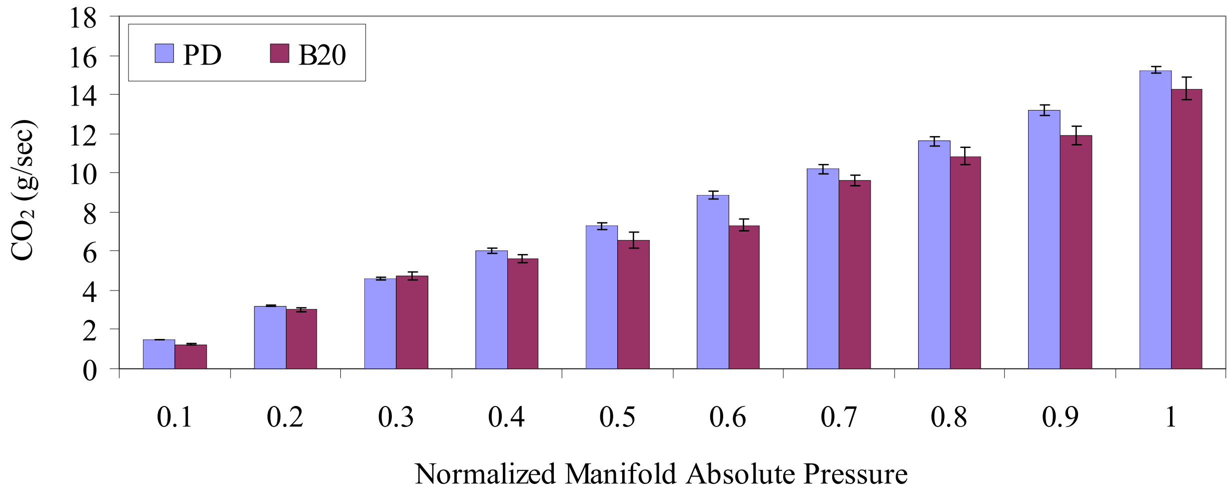


Figure A8. Continued

FRONT-END LOADER 3





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 71 °F and the relative humidity was 44 %. For the B20 biodiesel test, the ambient temperature was 50 °F and the relative humidity was 46 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A9. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Front-End Loader 3 (continued on next page)

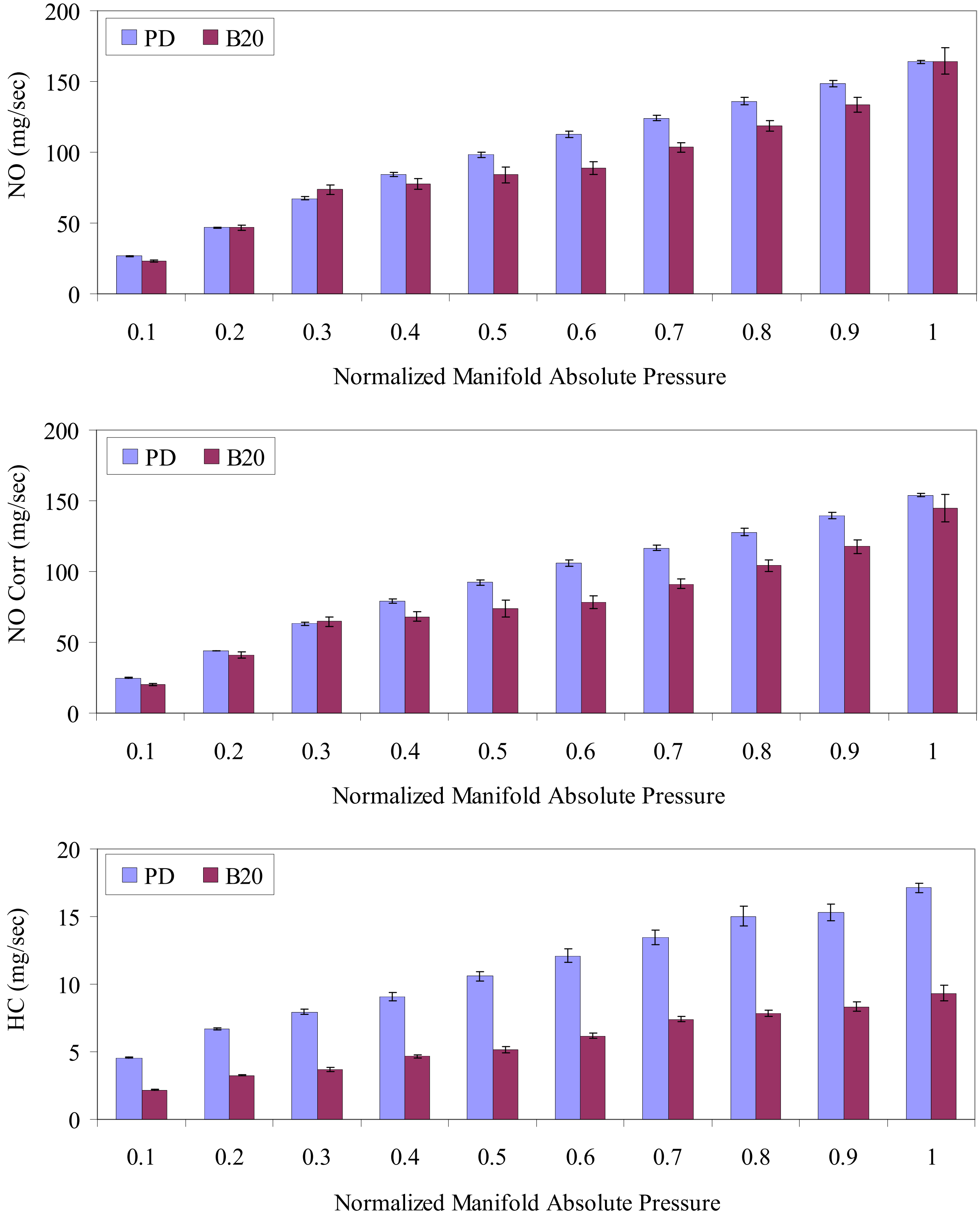
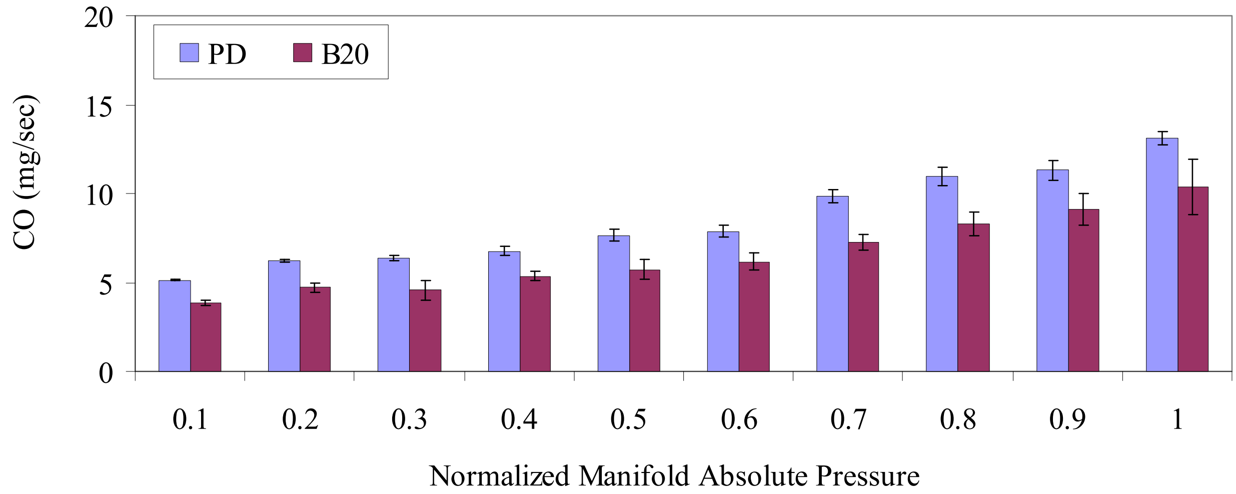


Figure A9. Continued



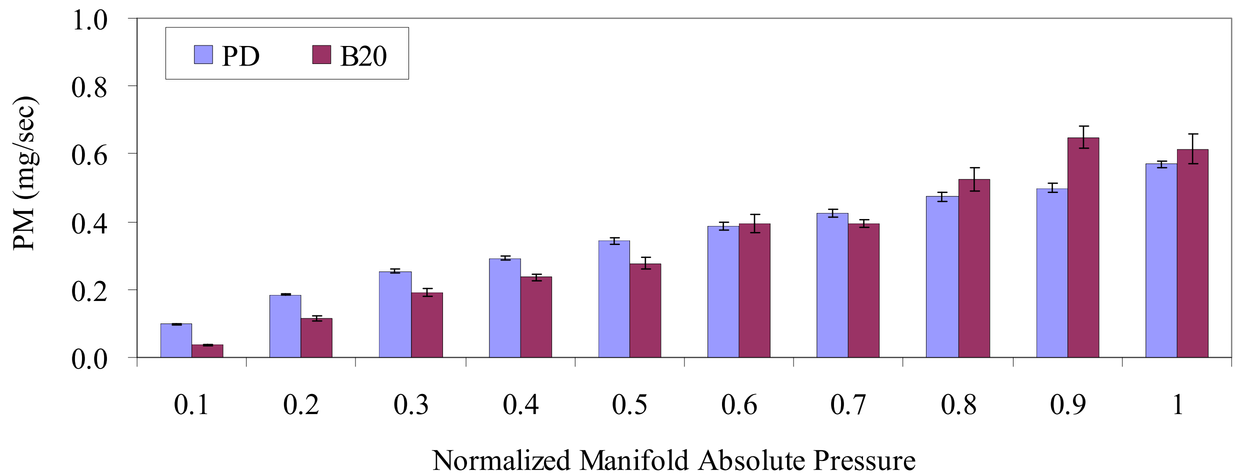
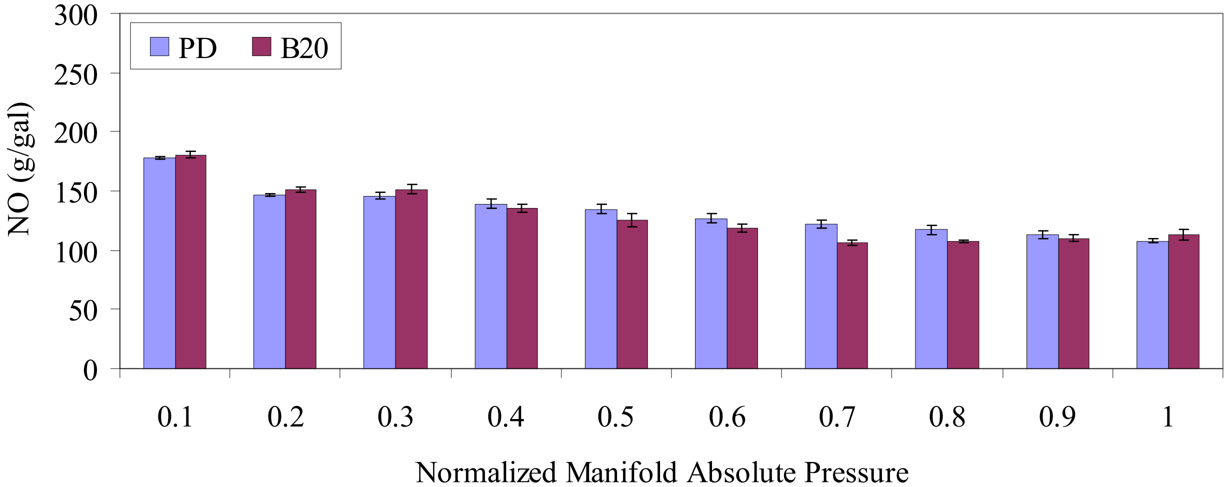
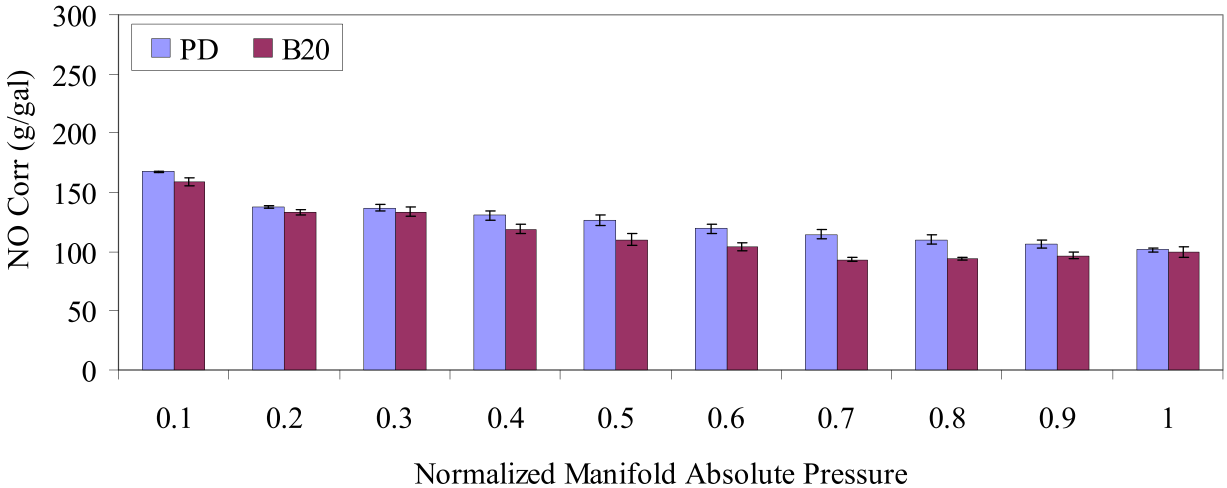


Figure A9. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 71 ^{o}F and the relative humidity was 44 %. For the B20 biodiesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 46 %.

Values shown in the figure are the upper end of the range: "0.1" = $0 \leq$ Normalized MAP < 0.1; "0.2" = $0.1 \leq$ Normalized MAP < 0.2, and so on.

Figure A10. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Front-End Loader 3 (continued on next page)

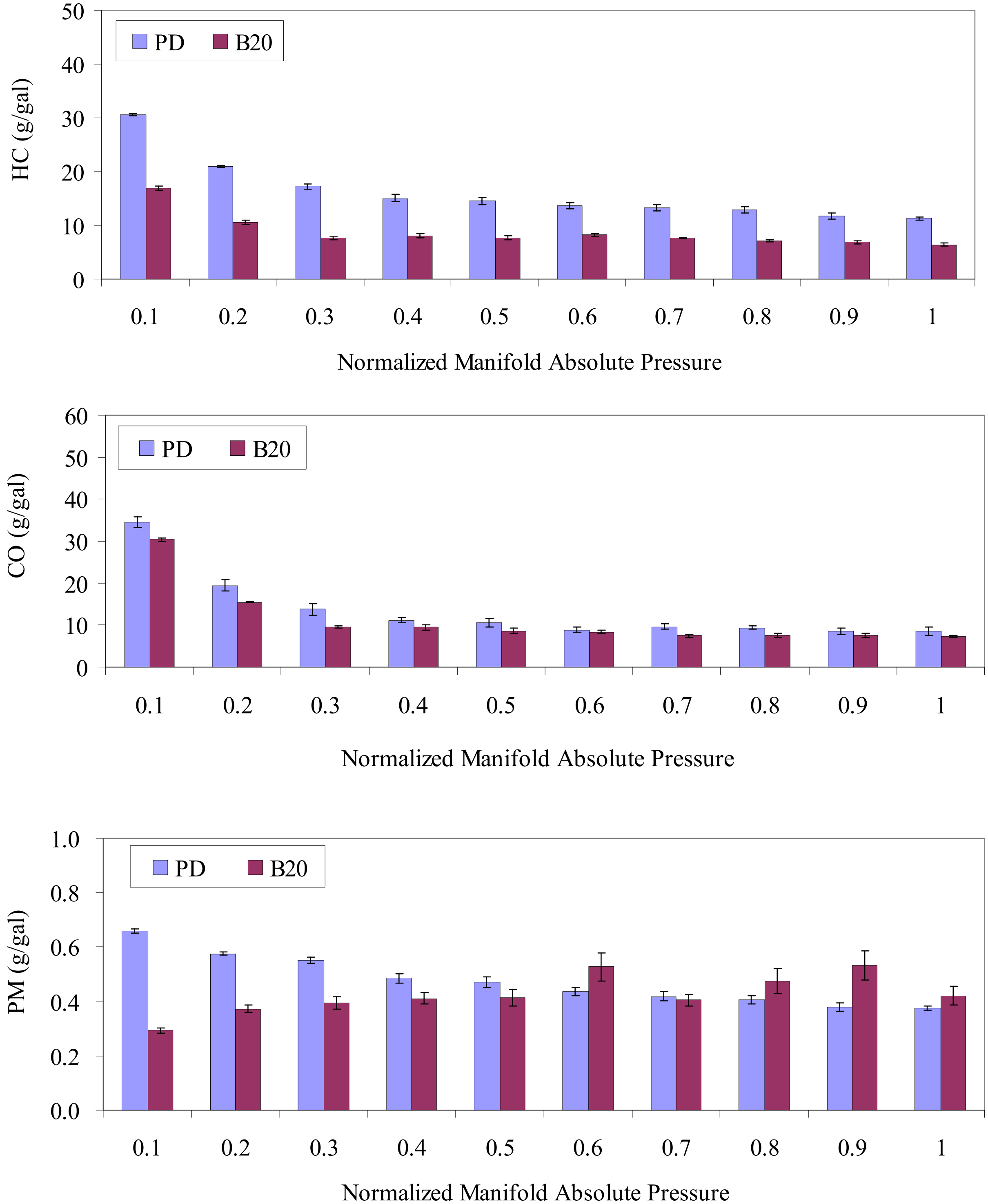
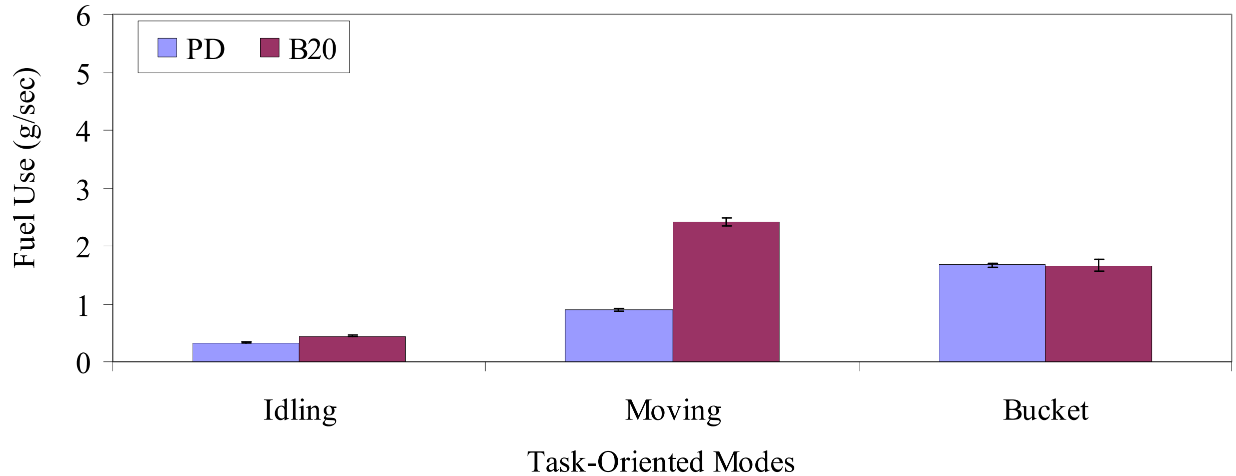
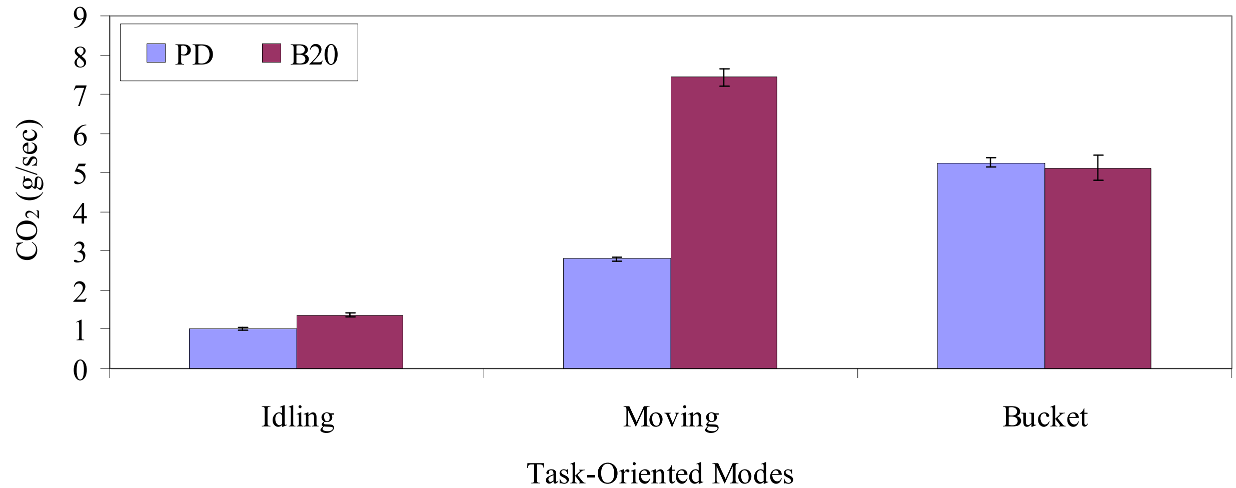


Figure A10. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 71 °F and the relative humidity was 44 %. For the B20 biodiesel test, the ambient temperature was 50 °F and the relative humidity was 46 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A11. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Front-End Loader 3 (continued on next page)

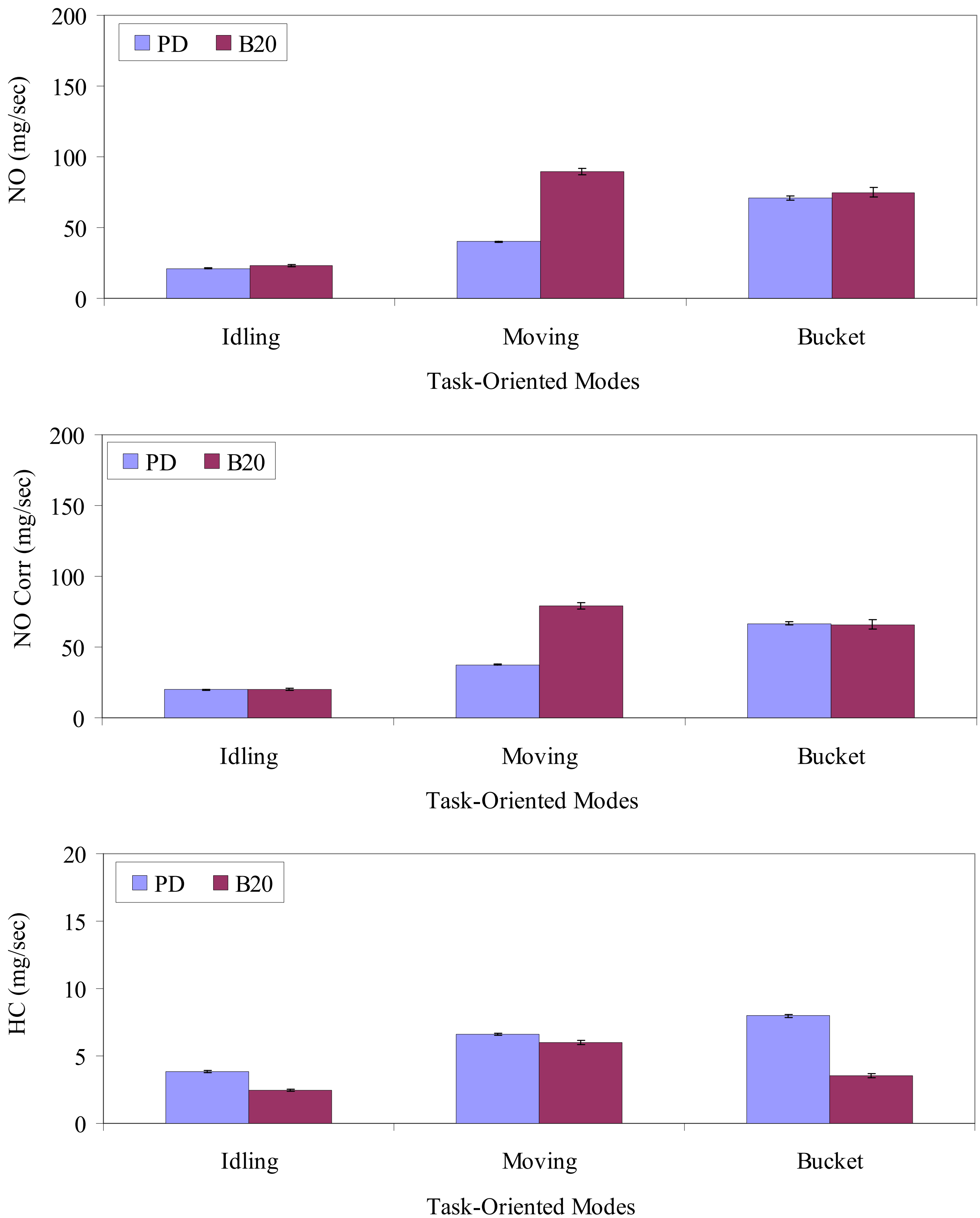


Figure A11. Continued

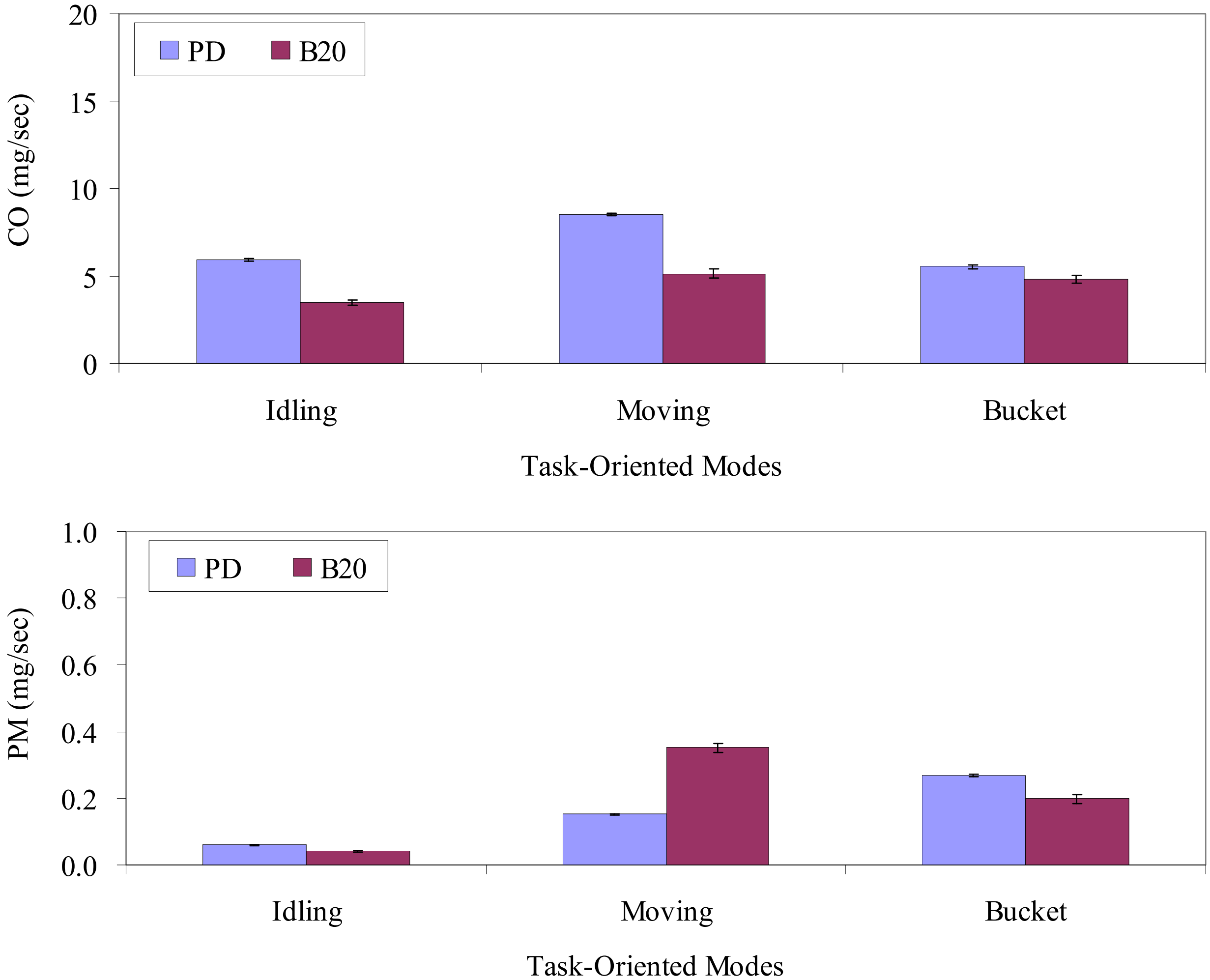
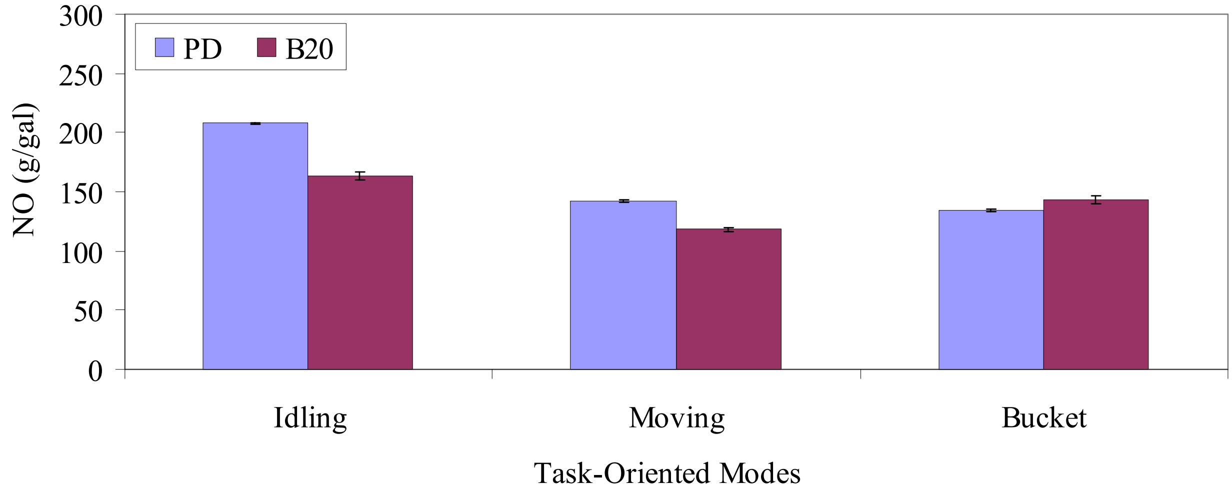
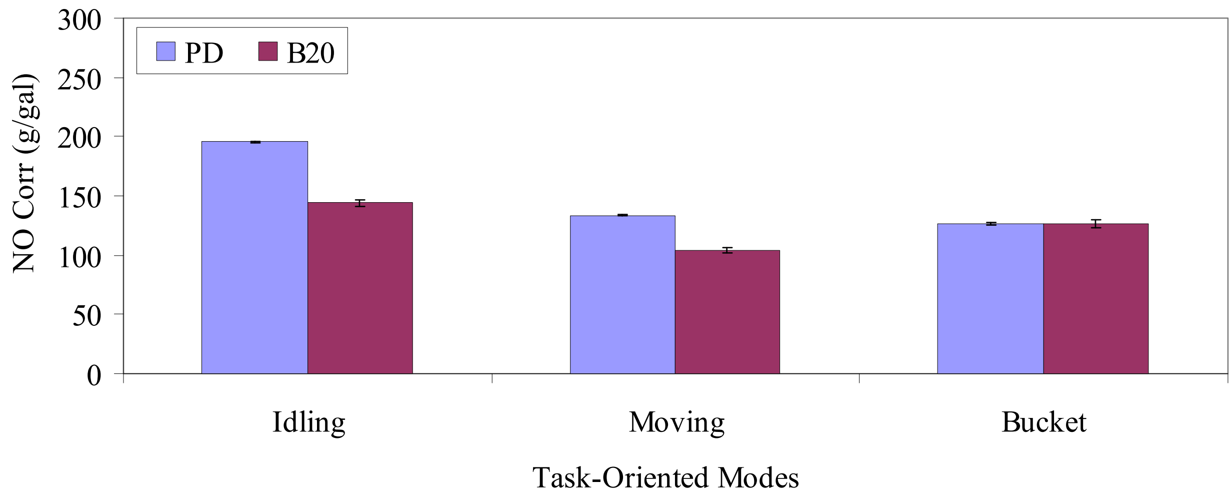


Figure A11. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 71 ^{o}F and the relative humidity was 44 %. For the B20 biodiesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 46 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A12. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Front-End Loader 3 (continued on next page)

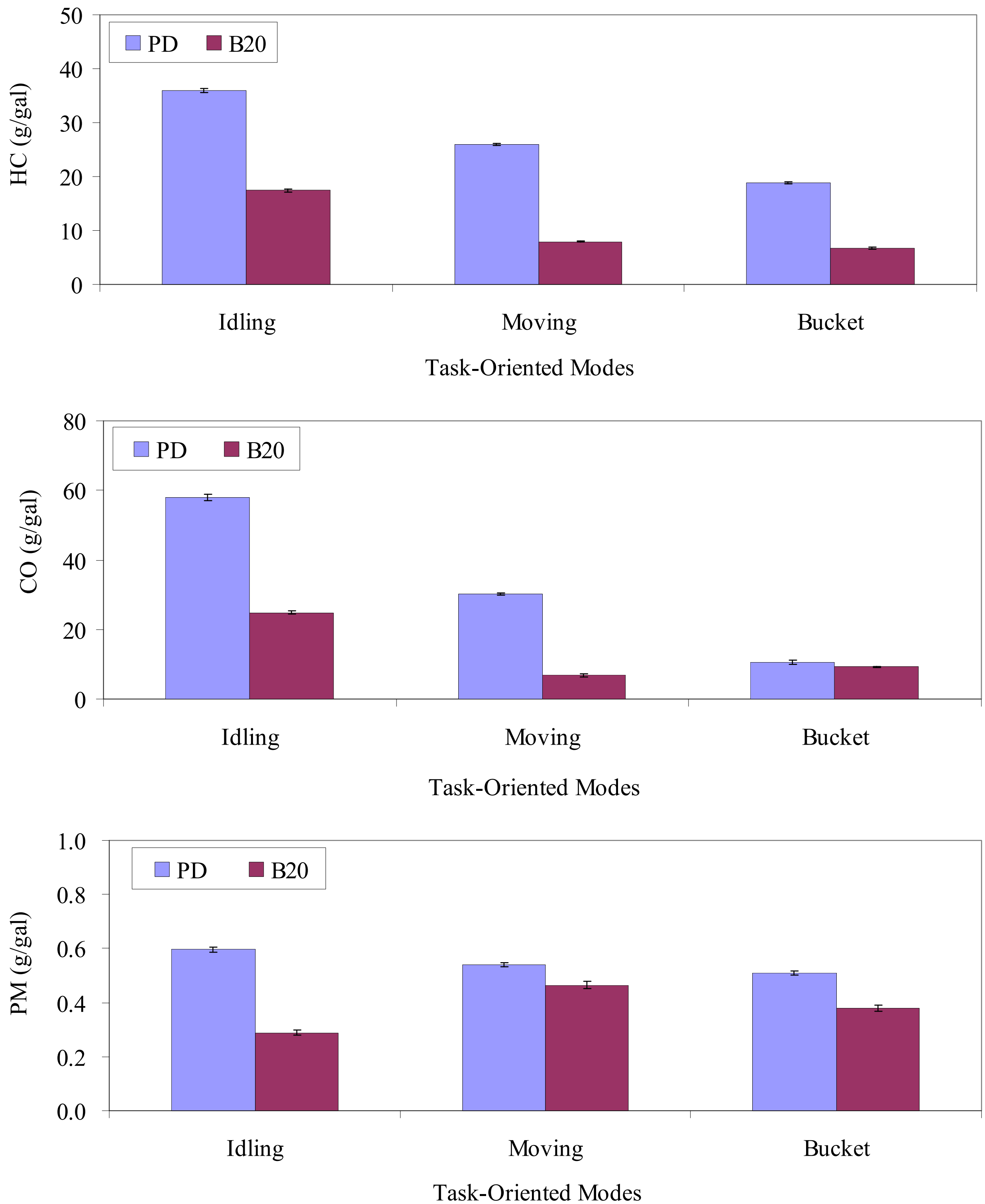
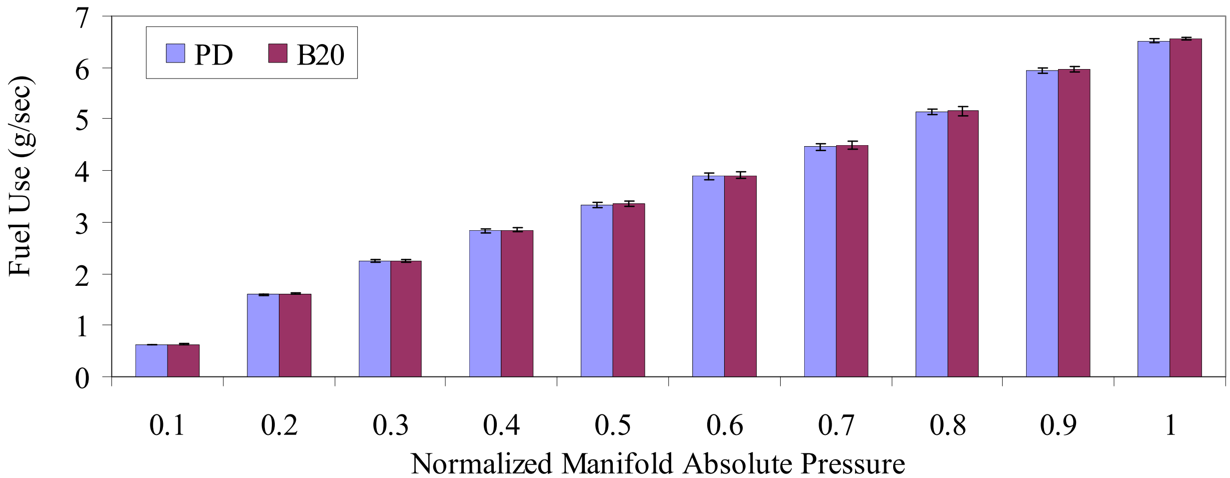
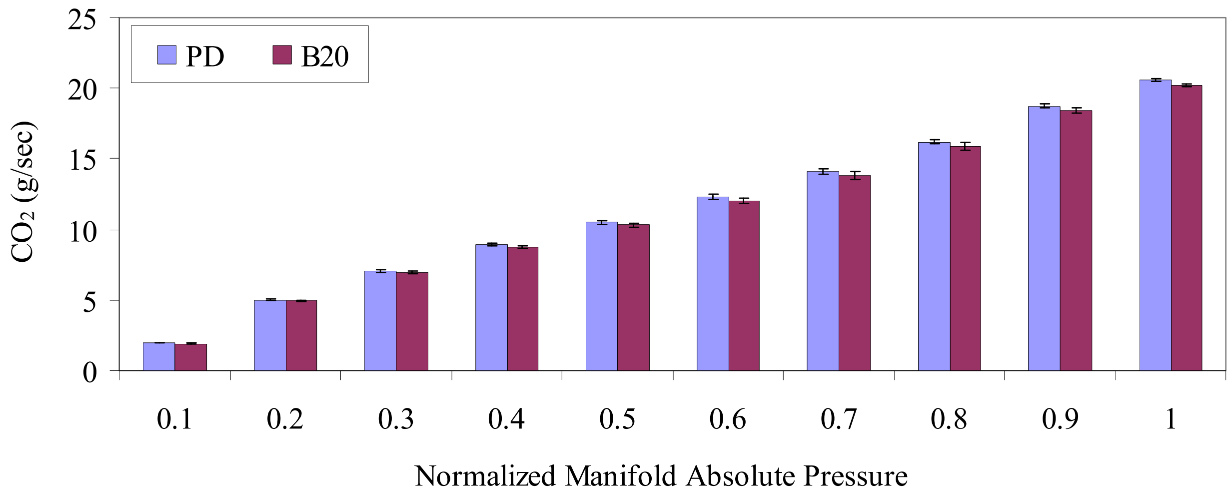


Figure A12. Continued

FRONT-END LOADER 4

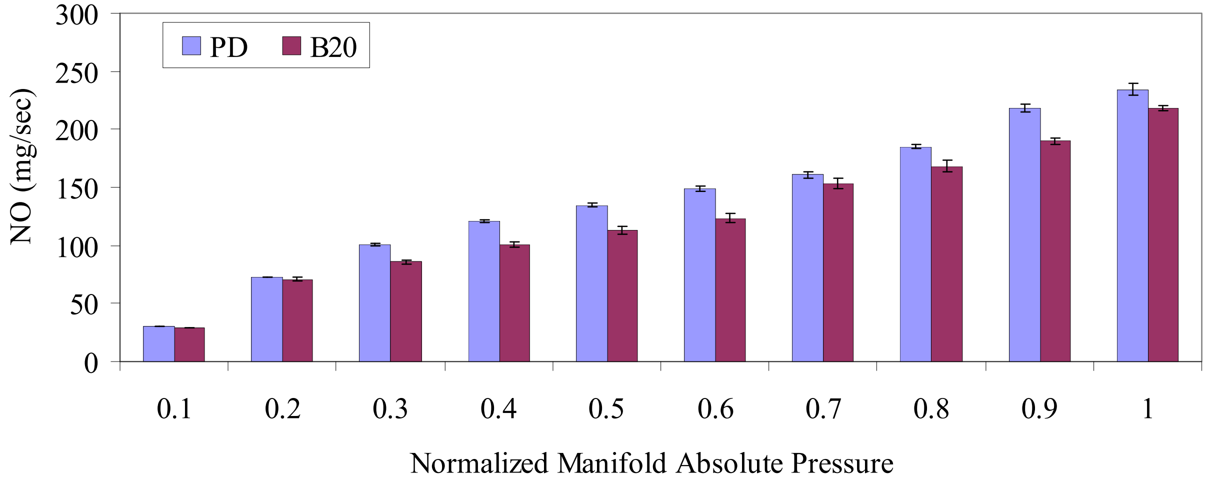


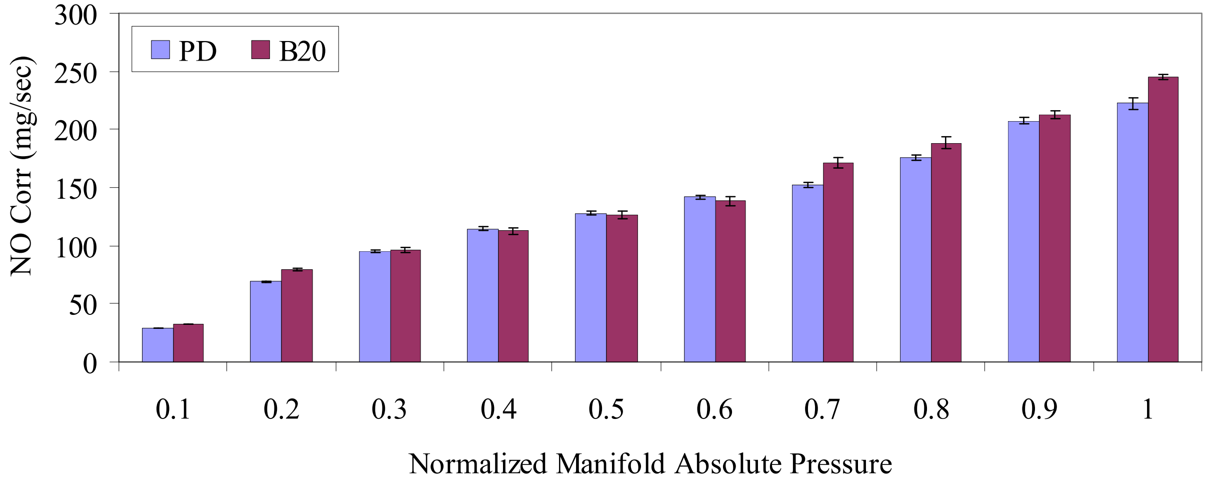


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 64 ^{o}F and the relative humidity was 63 %. For the B20 biodiesel test, the ambient temperature was 85 ^{o}F and the relative humidity was 64 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A13. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Front-End Loader 4 (continued on next page)





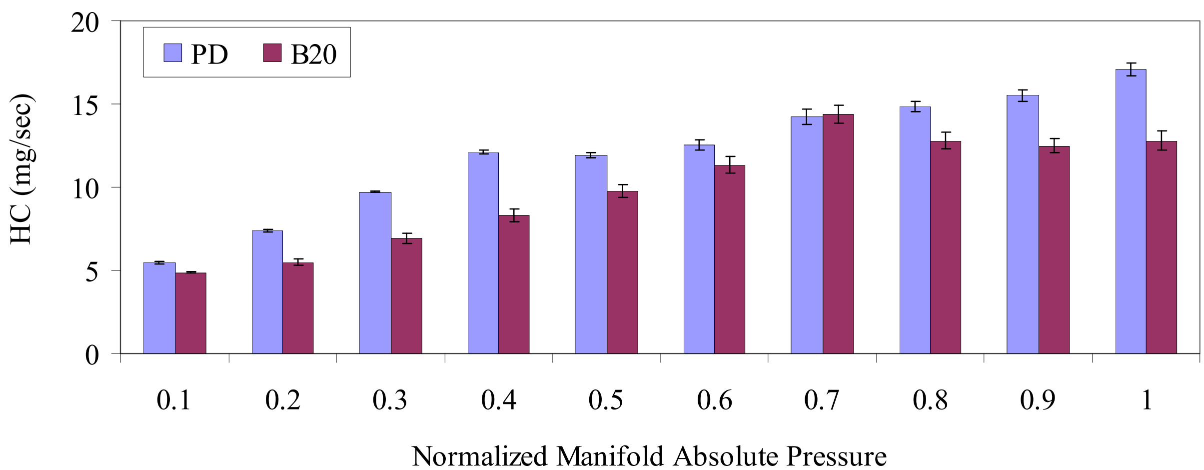
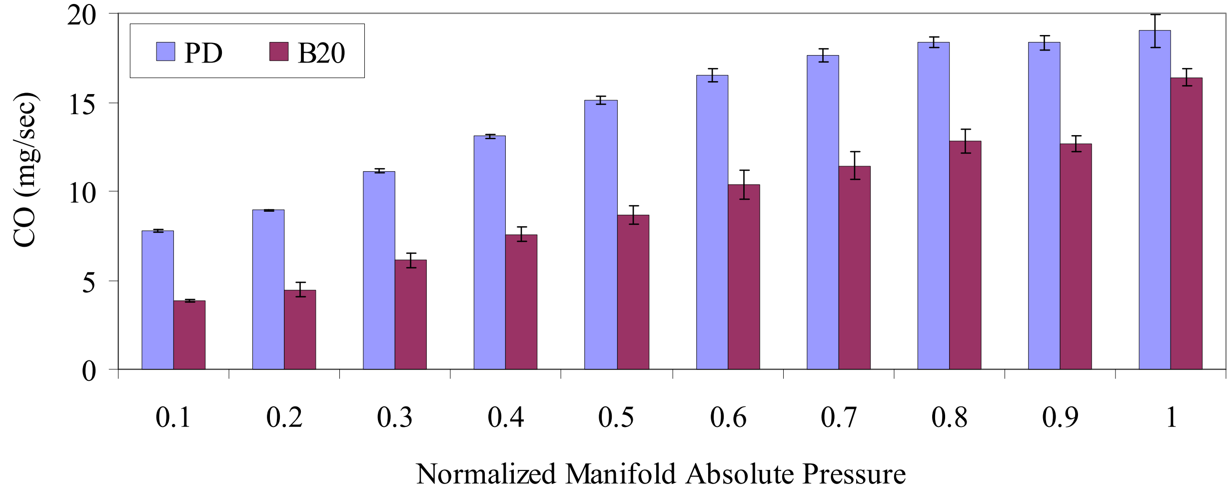


Figure A13. Continued



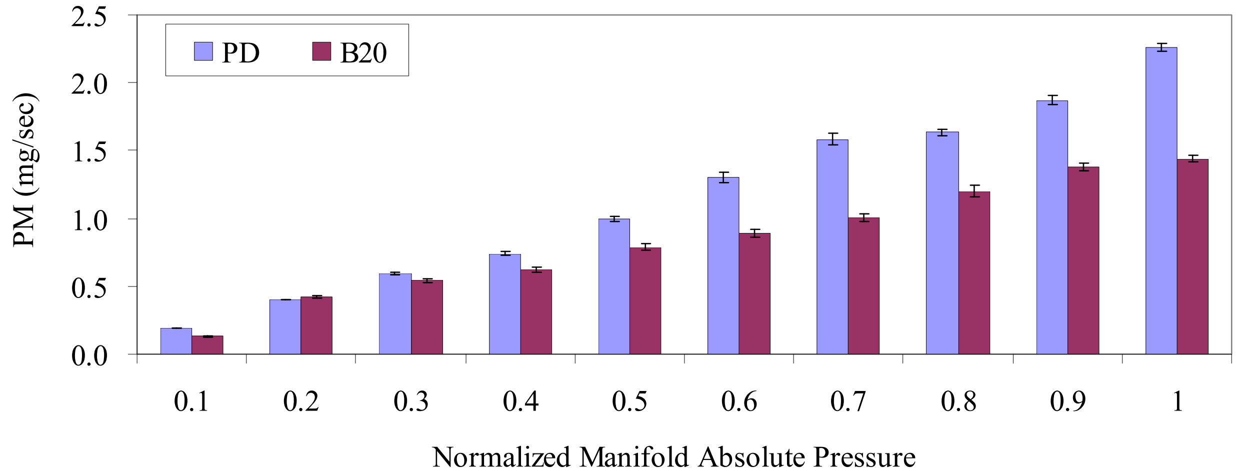
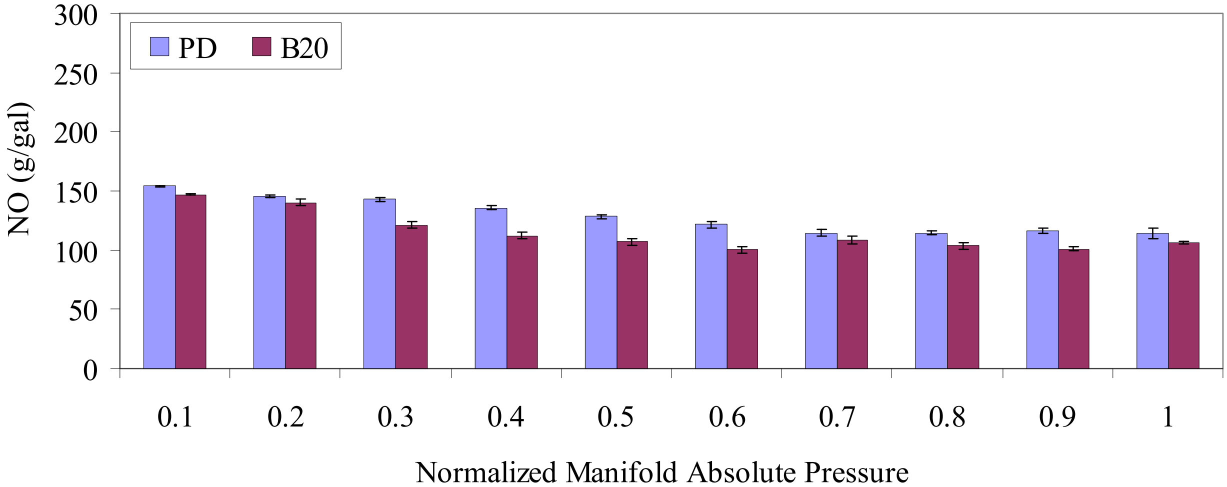
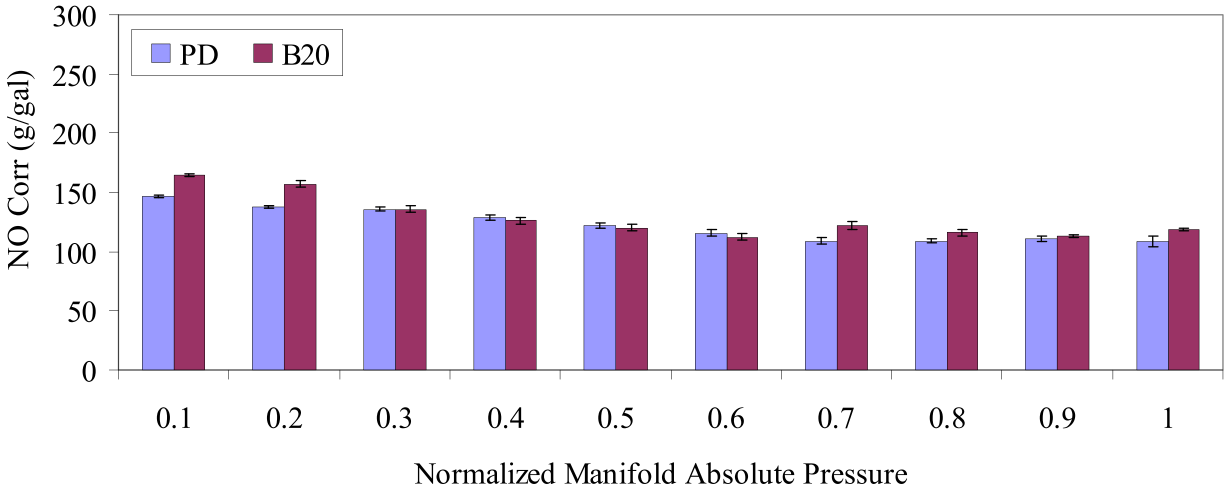


Figure A13. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 64 ^{o}F and the relative humidity was 63 %. For the B20 biodiesel test, the ambient temperature was 85 ^{o}F and the relative humidity was 64 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A14. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Front-End Loader 4 (continued on next page)

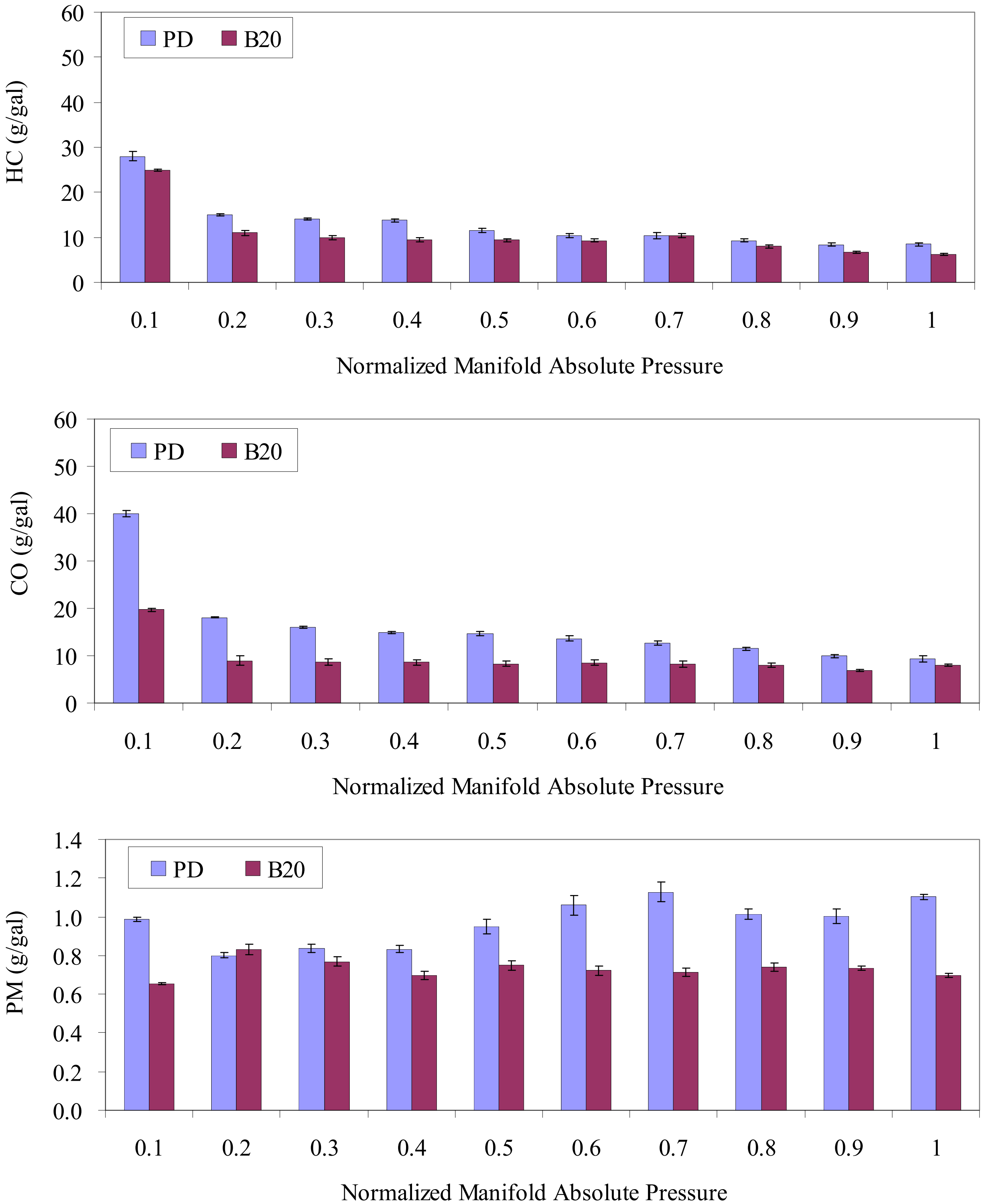
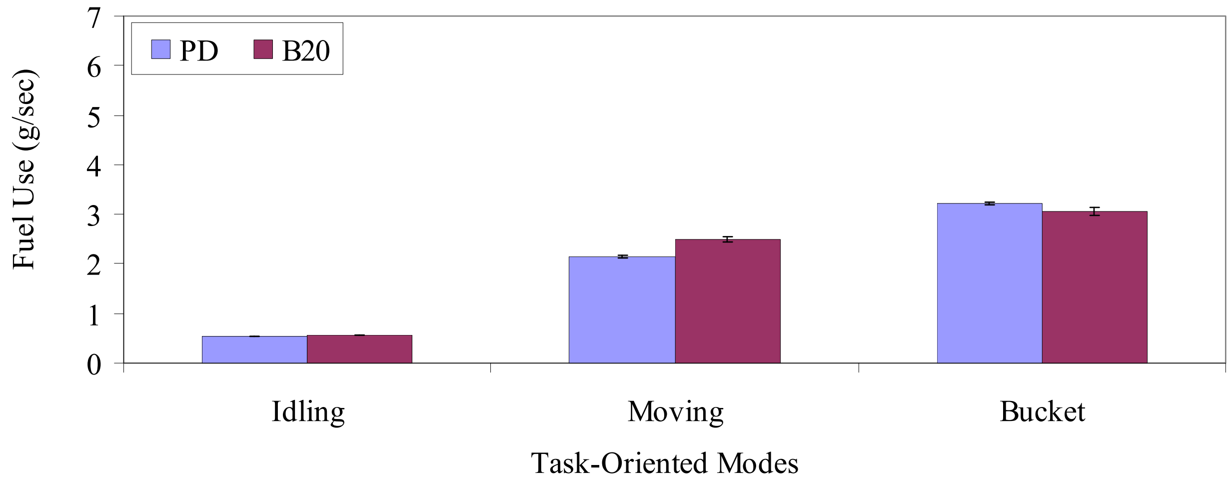
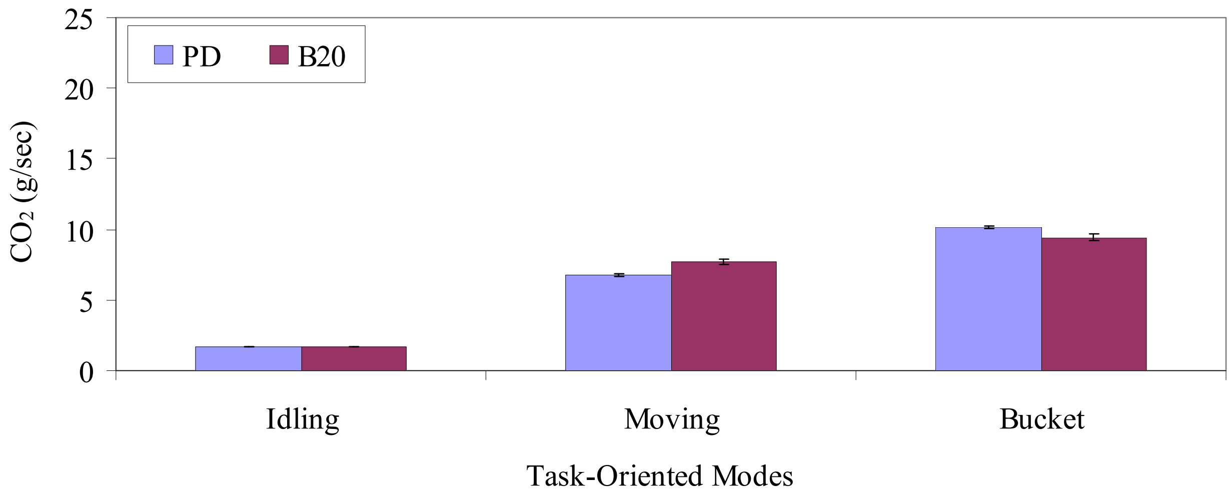


Figure A14. Continued

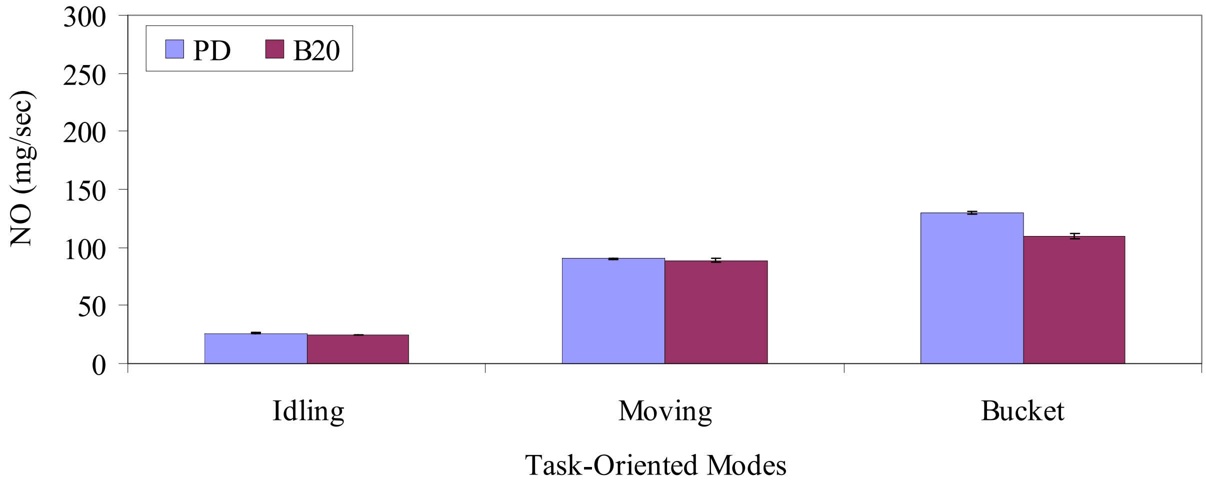


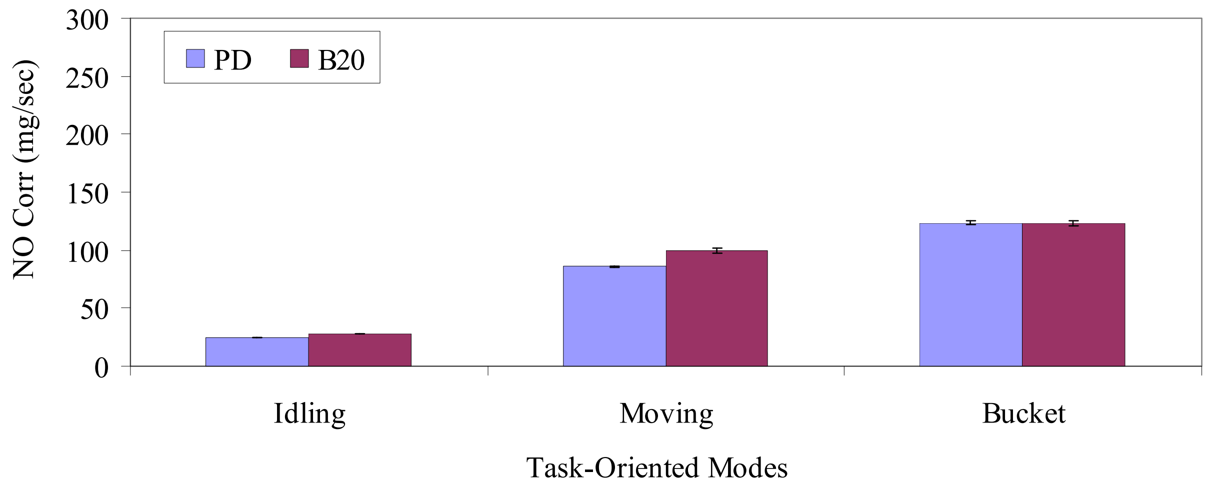


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 64 ^{o}F and the relative humidity was 63 %. For the B20 biodiesel test, the ambient temperature was 85 ^{o}F and the relative humidity was 64 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A15. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Front-End Loader 4 (continued on next page)





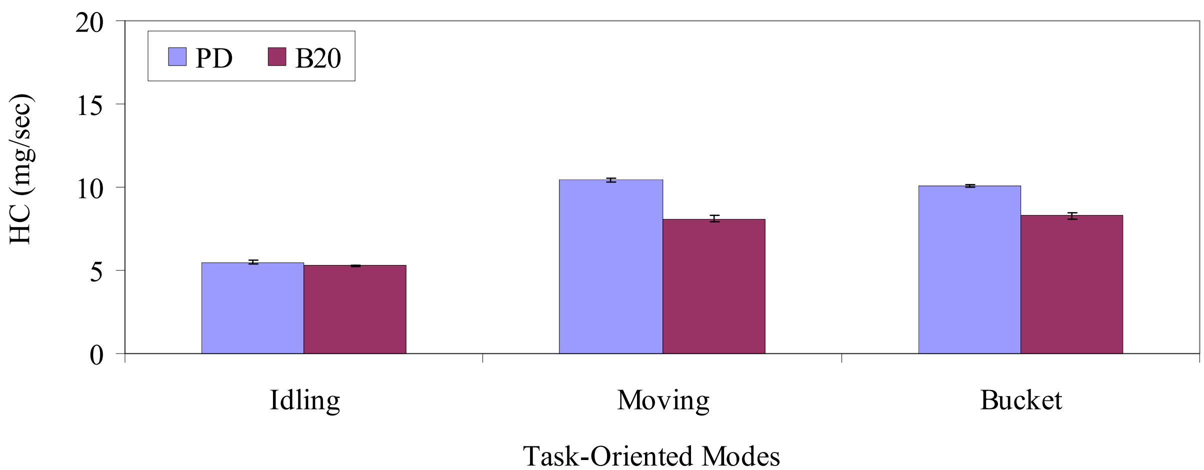
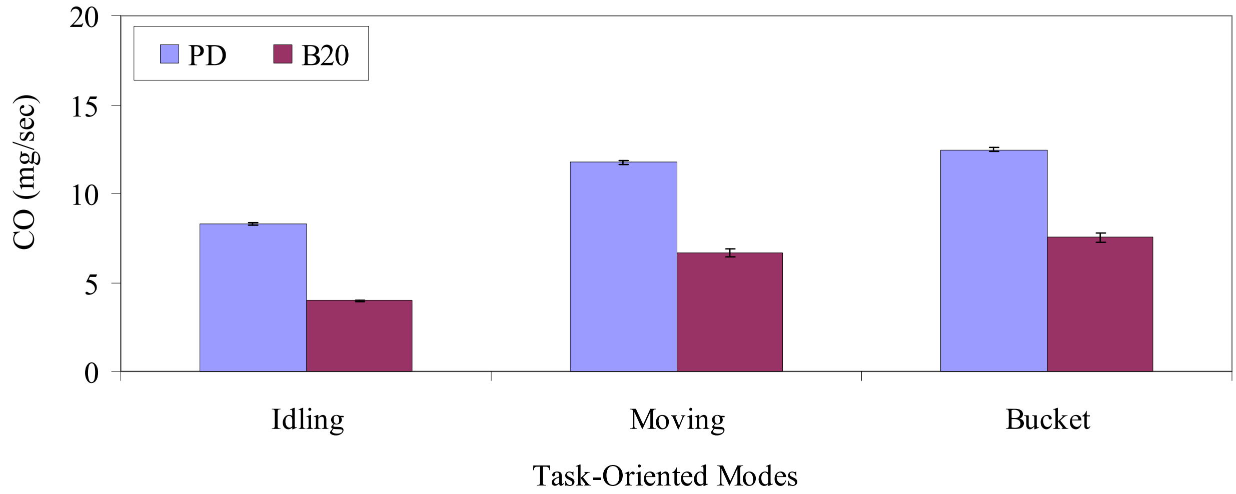


Figure A15. Continued



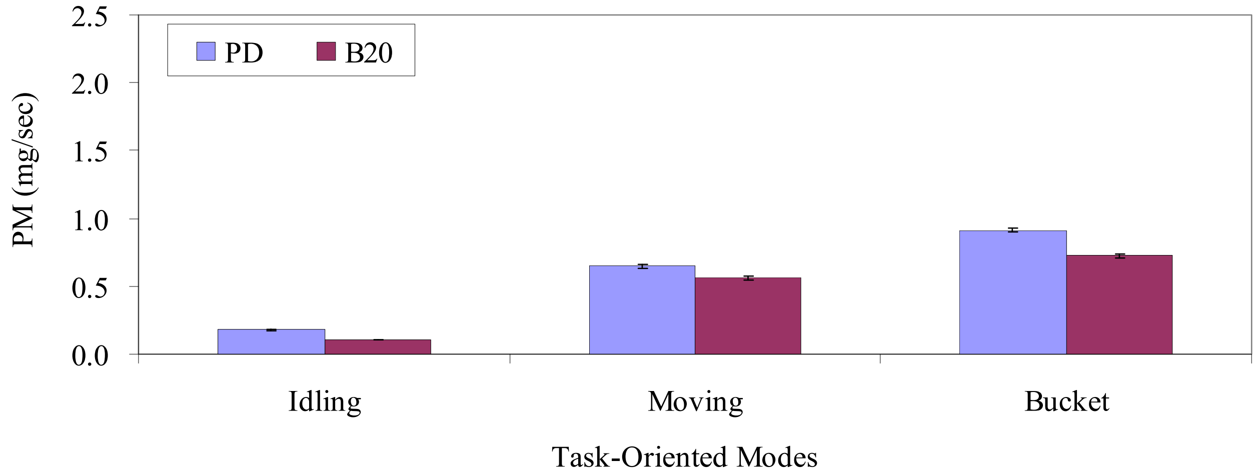
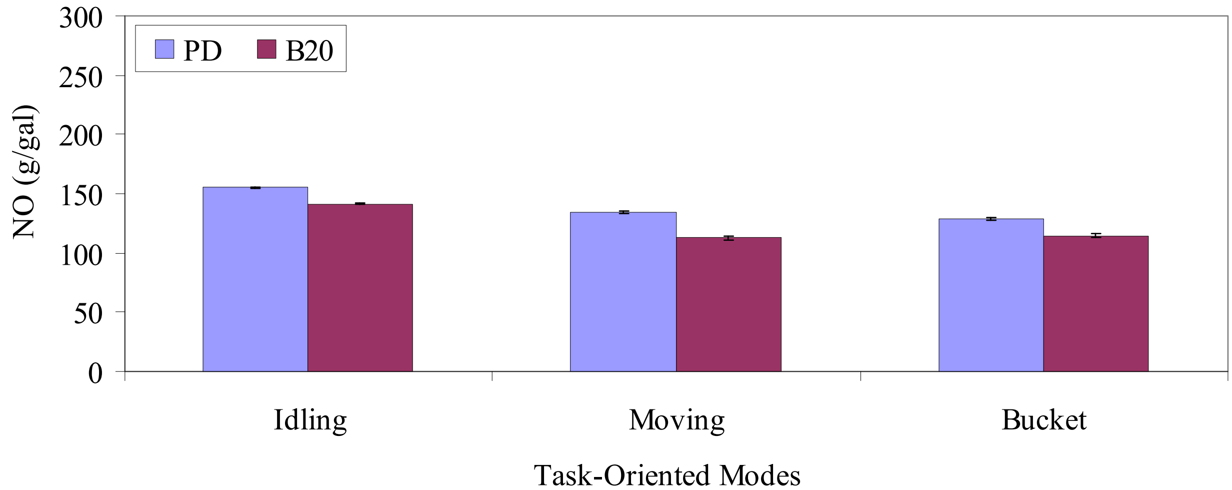
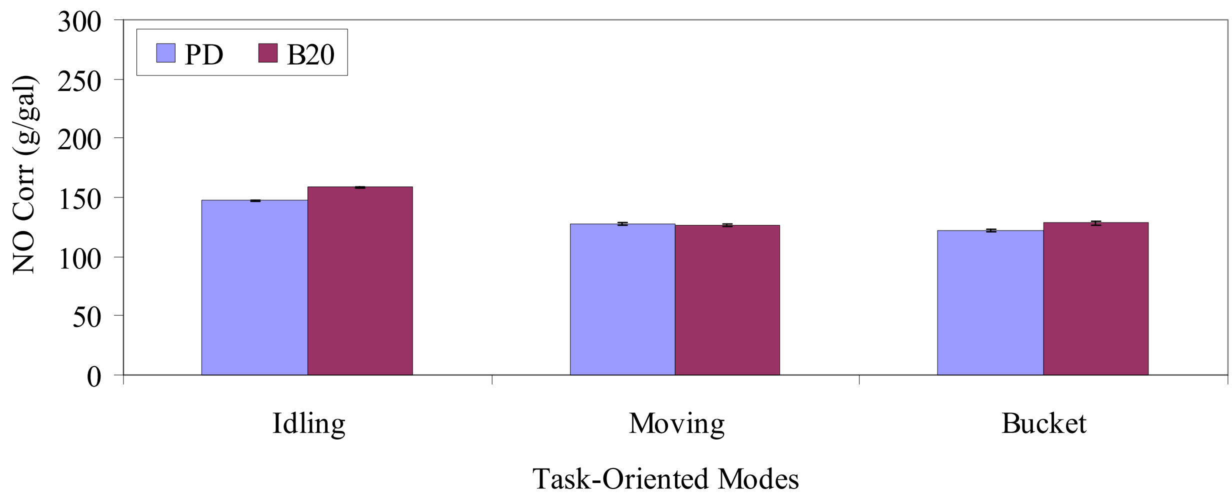


Figure A15. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 64 ^{o}F and the relative humidity was 63 %. For the B20 biodiesel test, the ambient temperature was 85 ^{o}F and the relative humidity was 64 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A16. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Front-End Loader 4 (continued on next page)

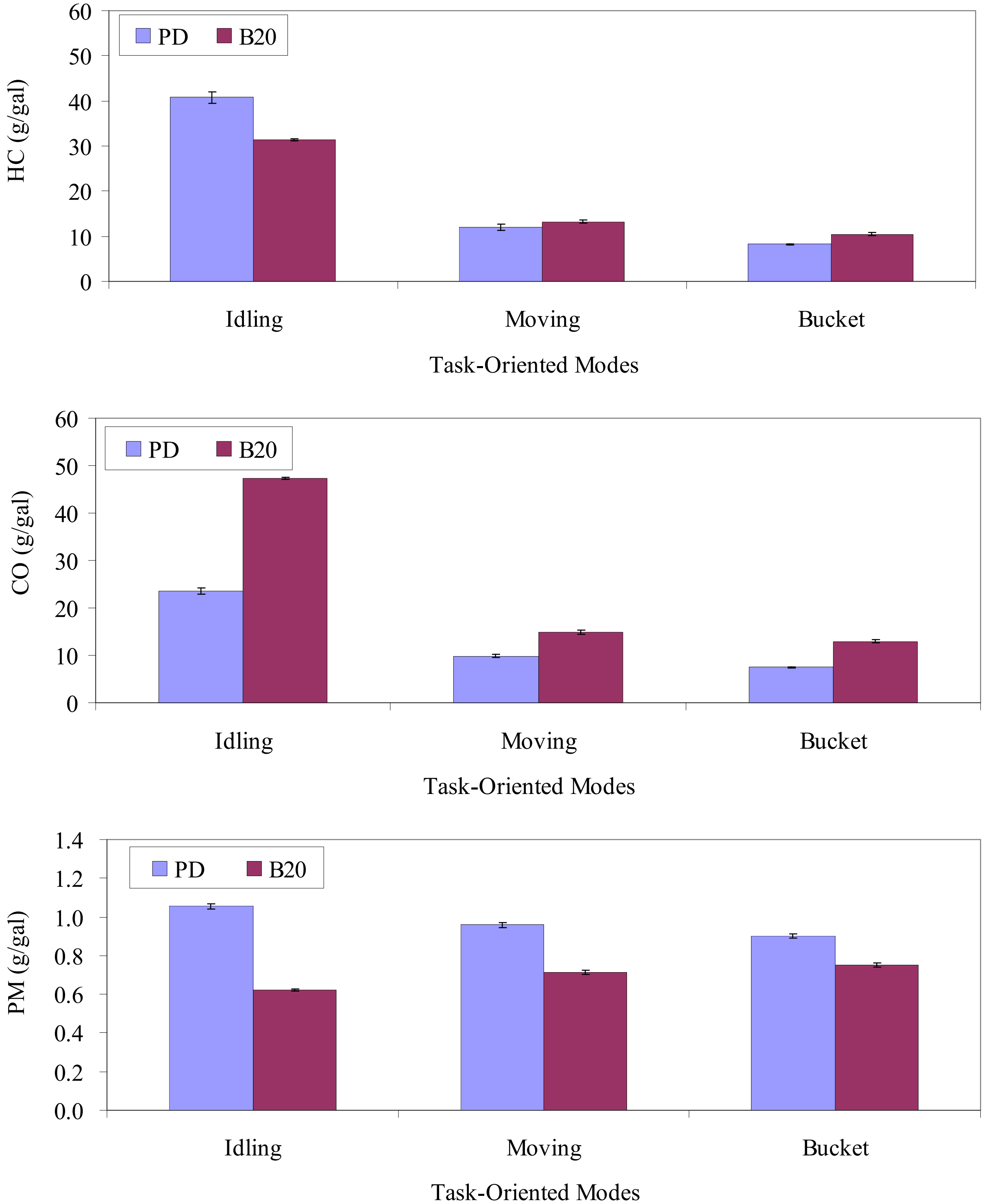
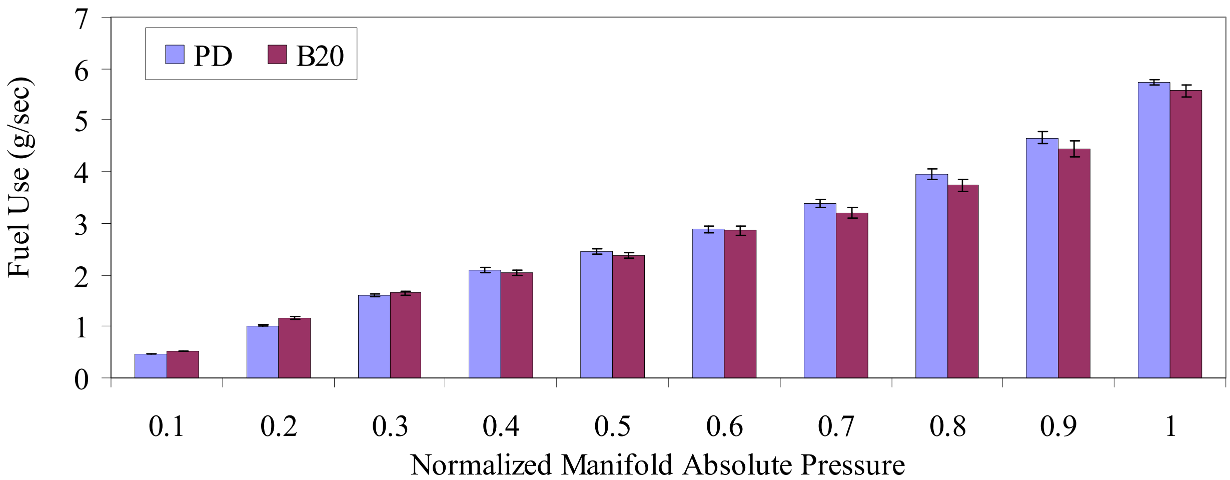
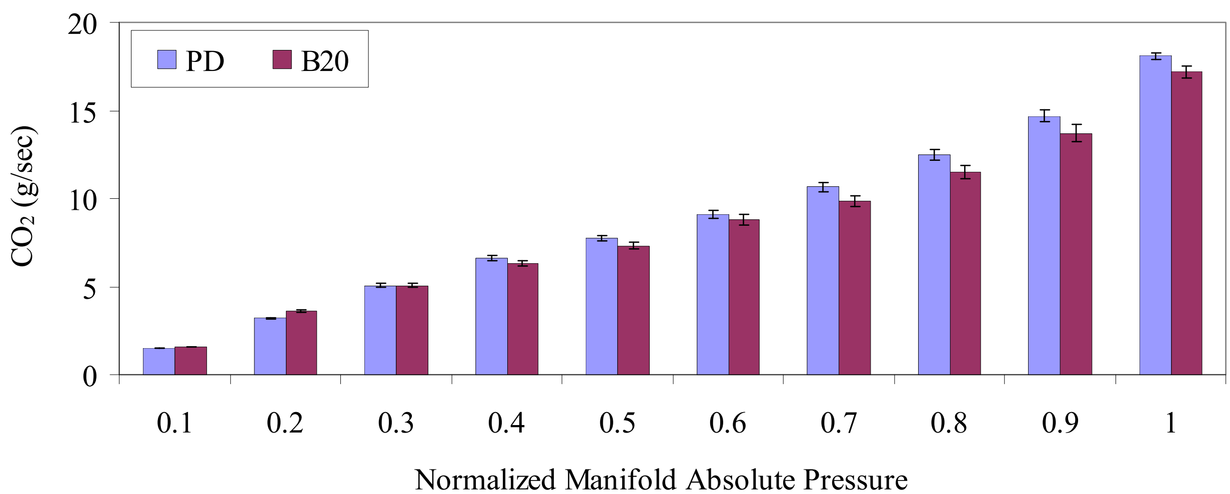


Figure A16. Continued

FRONT-END LOADER 5

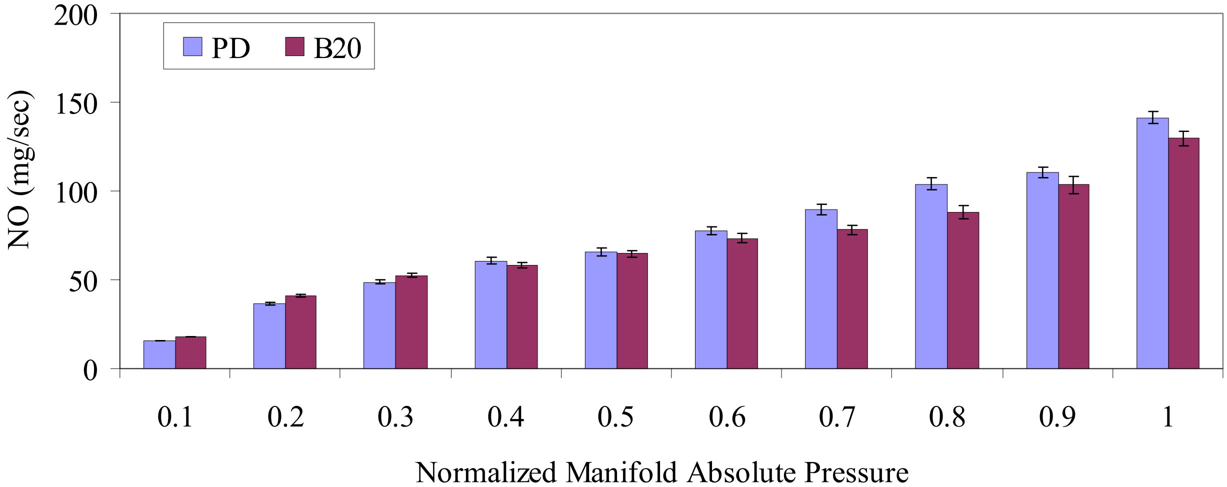


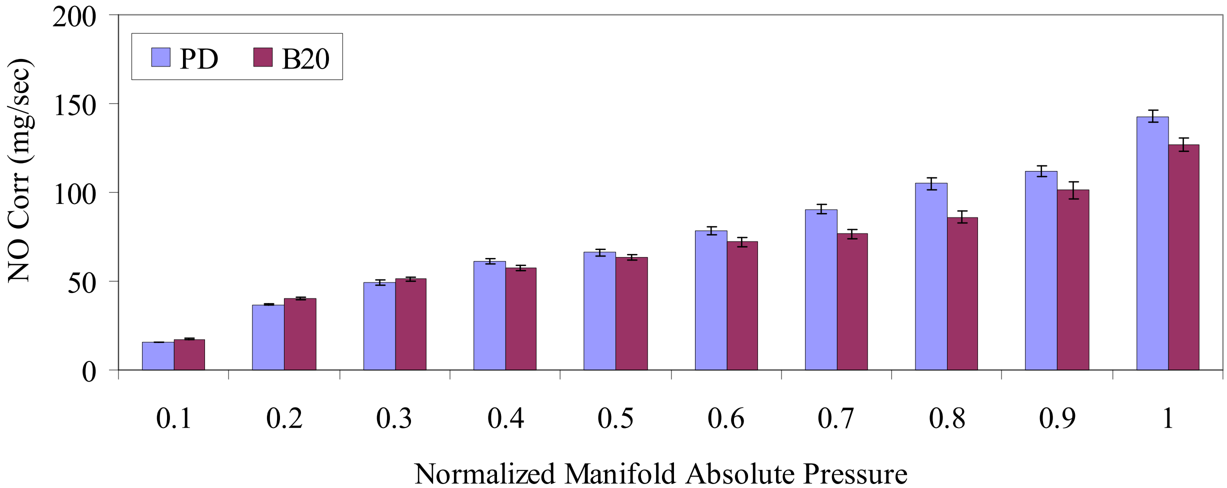


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 40 %. For the B20 biodiesel test, the ambient temperature was 49 ^{o}F and the relative humidity was 74 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A17. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Front-End Loader 5 (continued on next page)





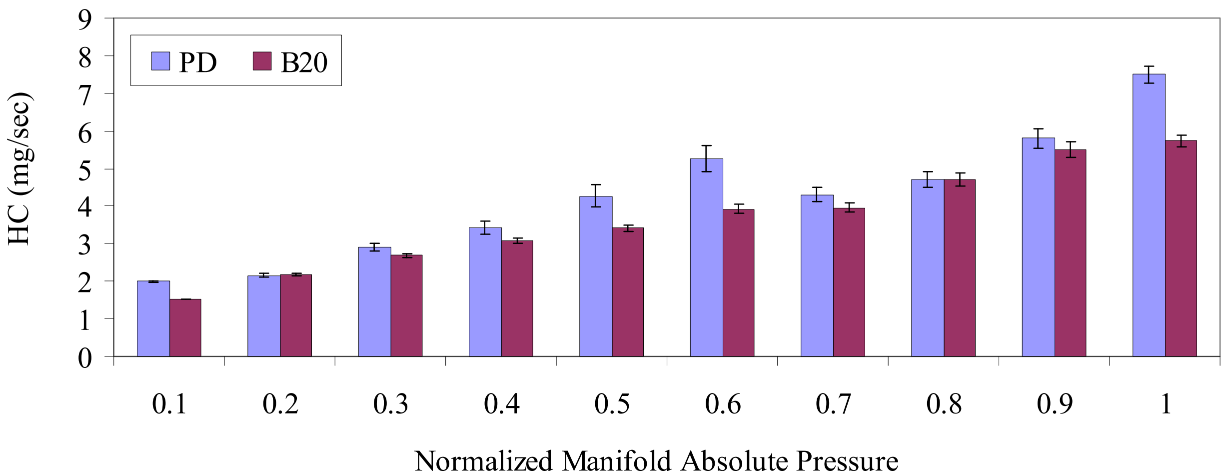


Figure A17. Continued

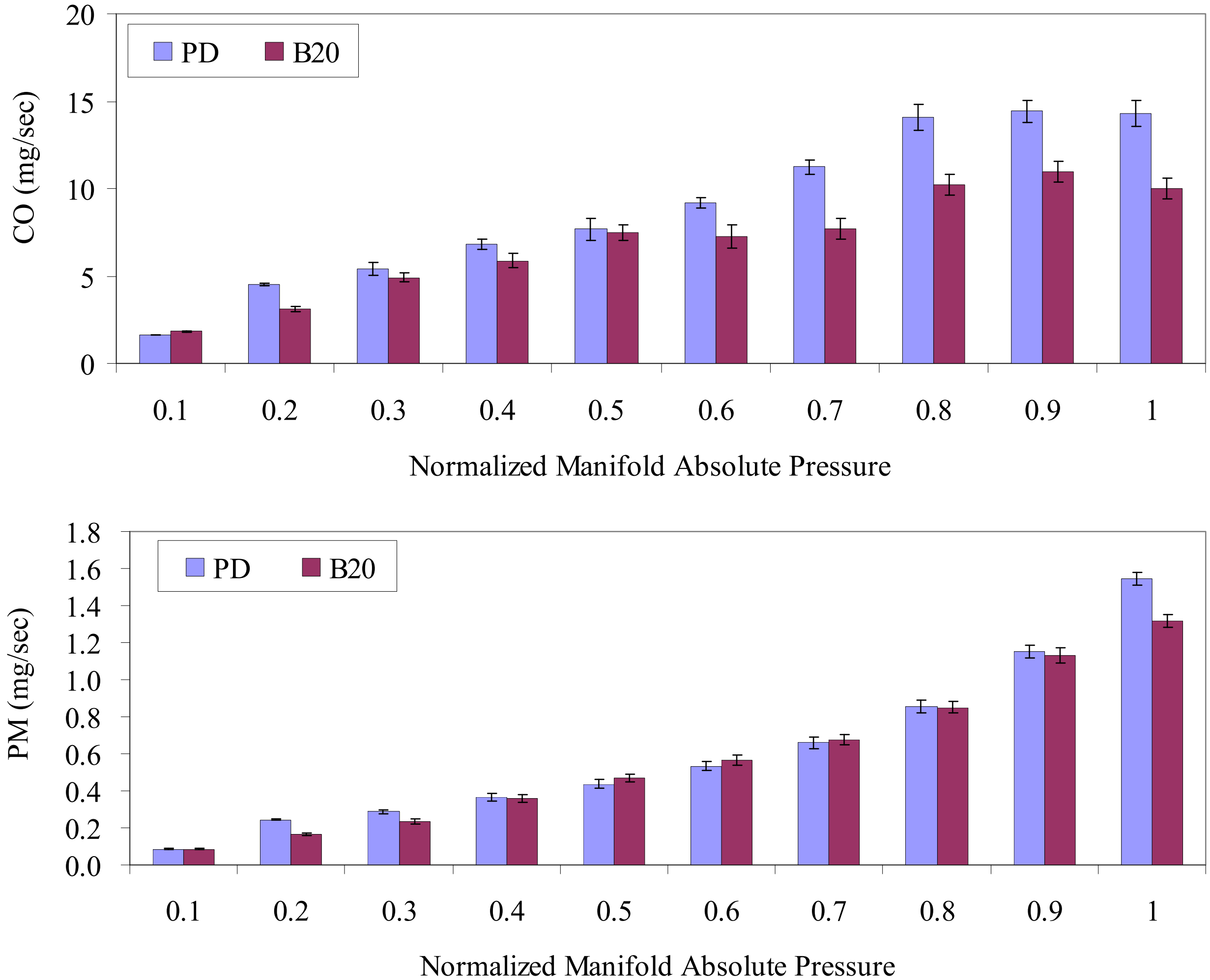
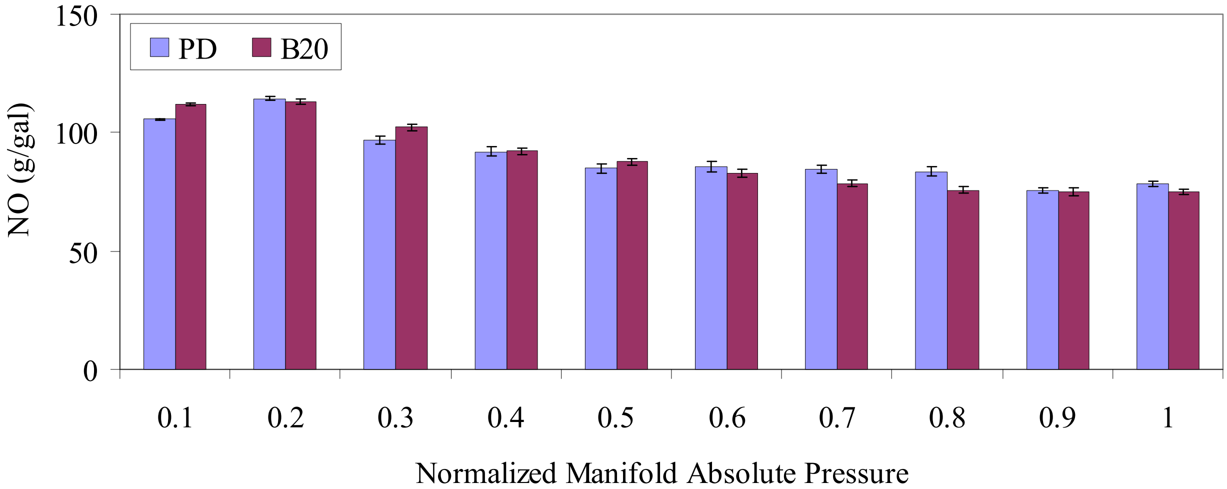
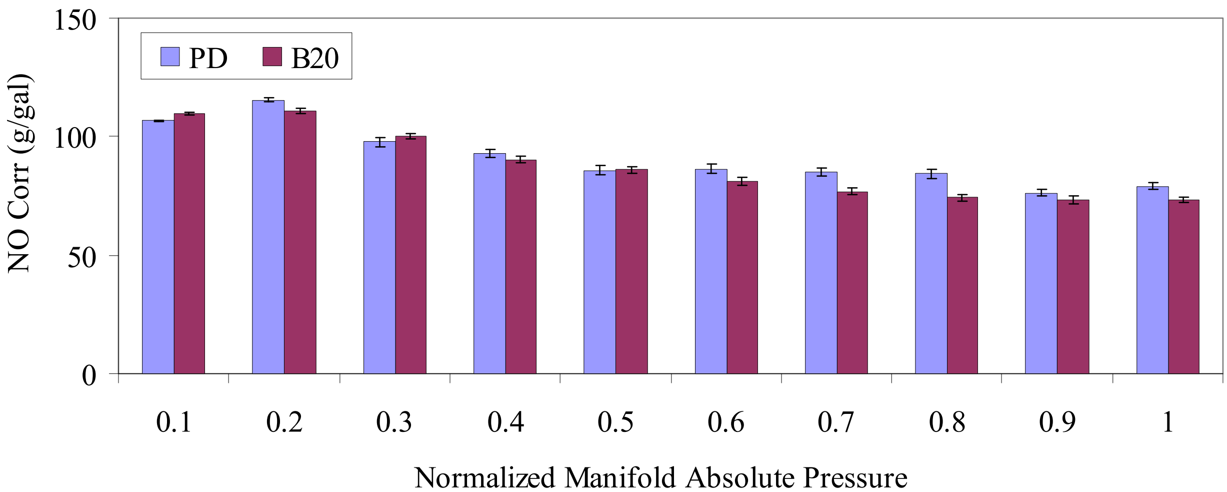


Figure A17. Continued

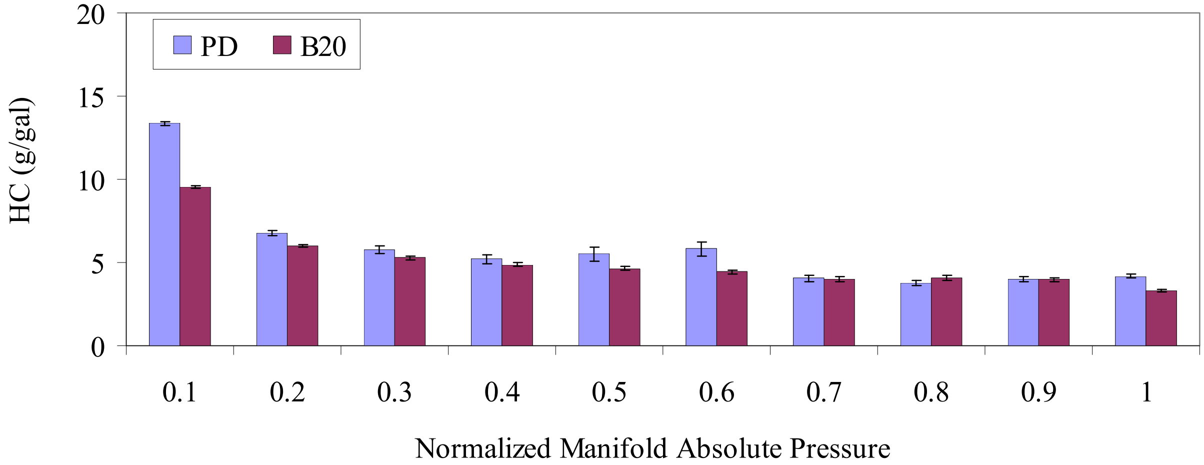


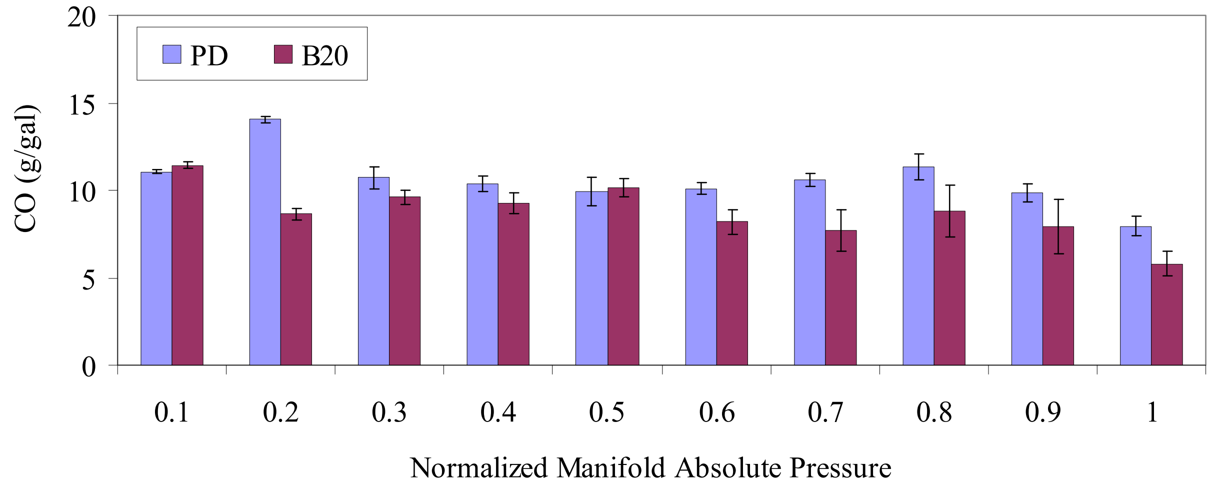


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 40 %. For the B20 biodiesel test, the ambient temperature was 49 ^{o}F and the relative humidity was 74 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A18. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Front-End Loader 5 (continued on next page)





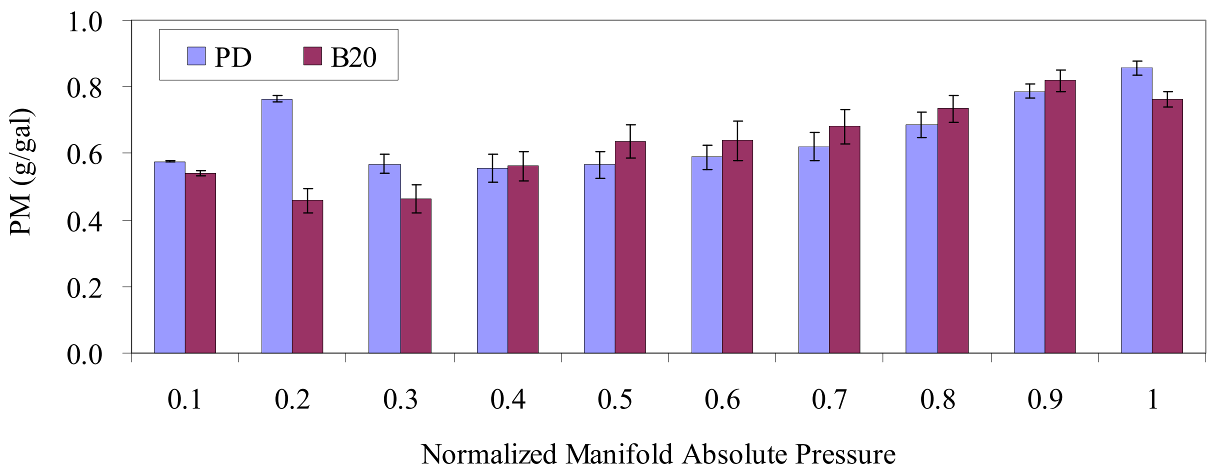
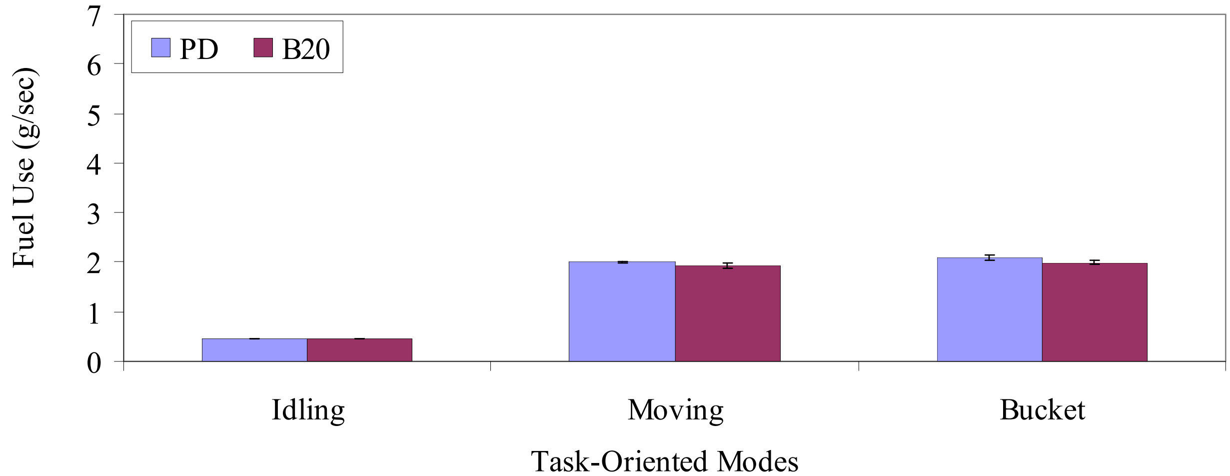
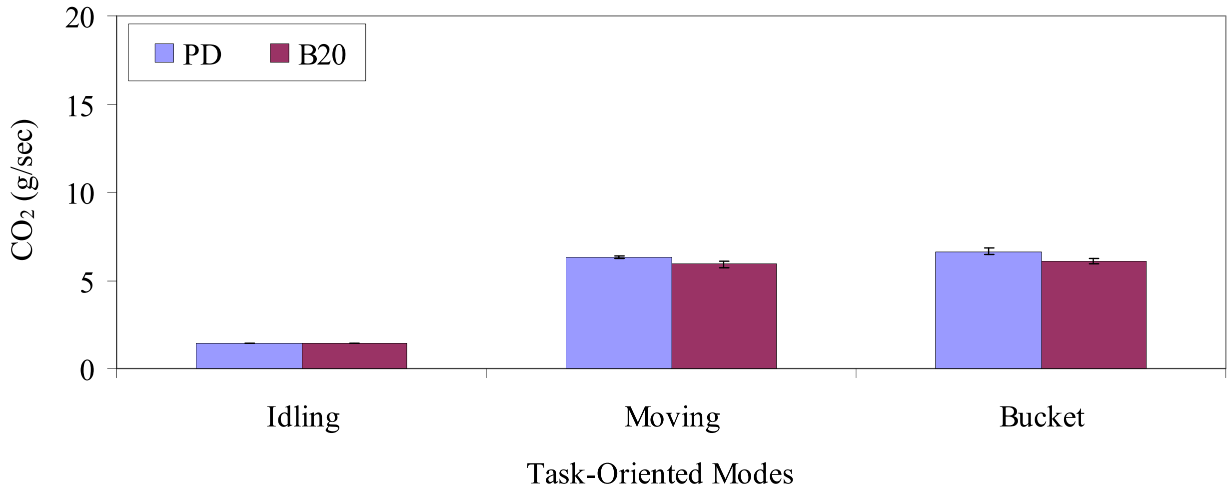


Figure A18. Continued

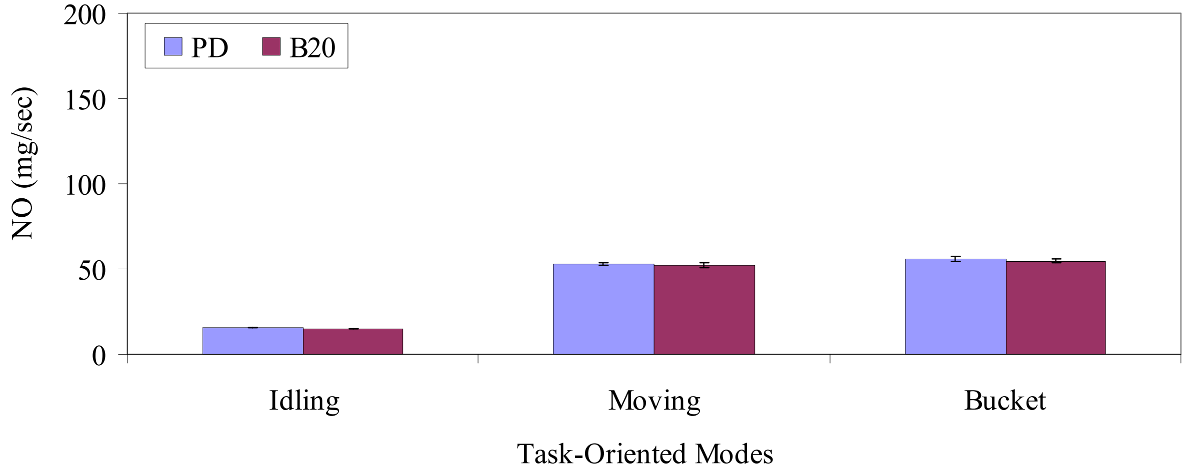


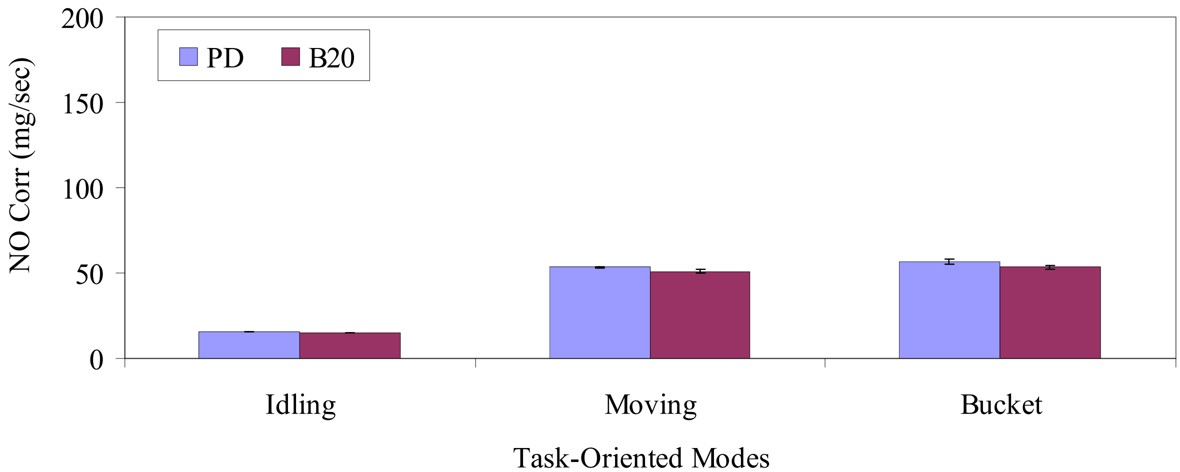


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 50 ^oF and the relative humidity was 40 %. For the B20 biodiesel test, the ambient temperature was 49 ^oF and the relative humidity was 74 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A19. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Front-End Loader 5 (continued on next page)





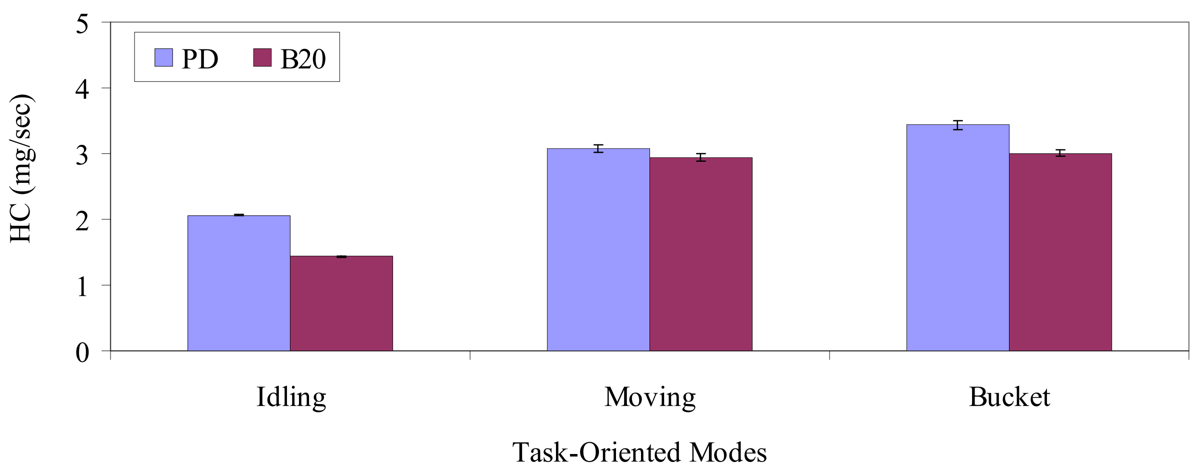
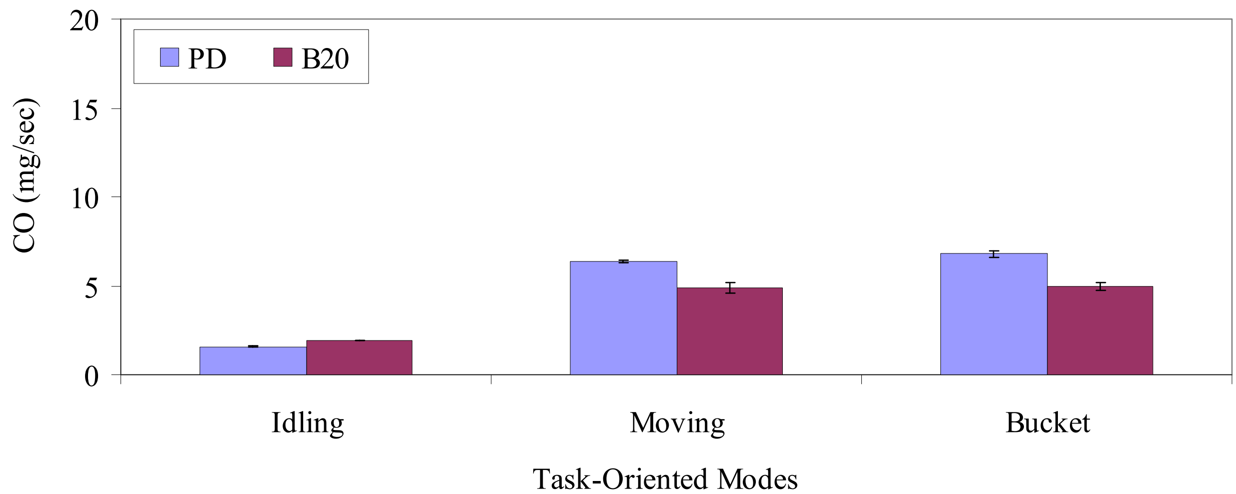


Figure A19. Continued



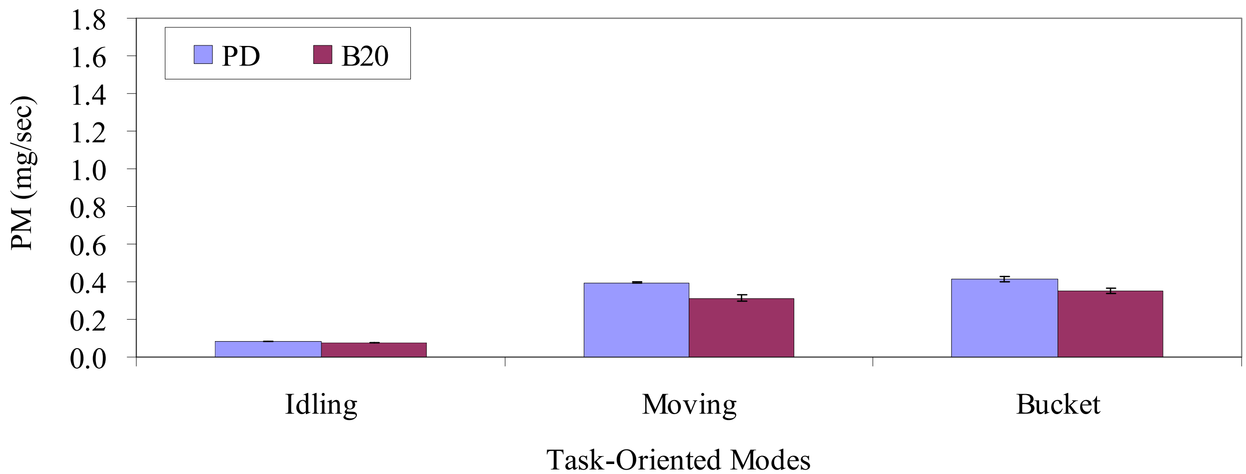
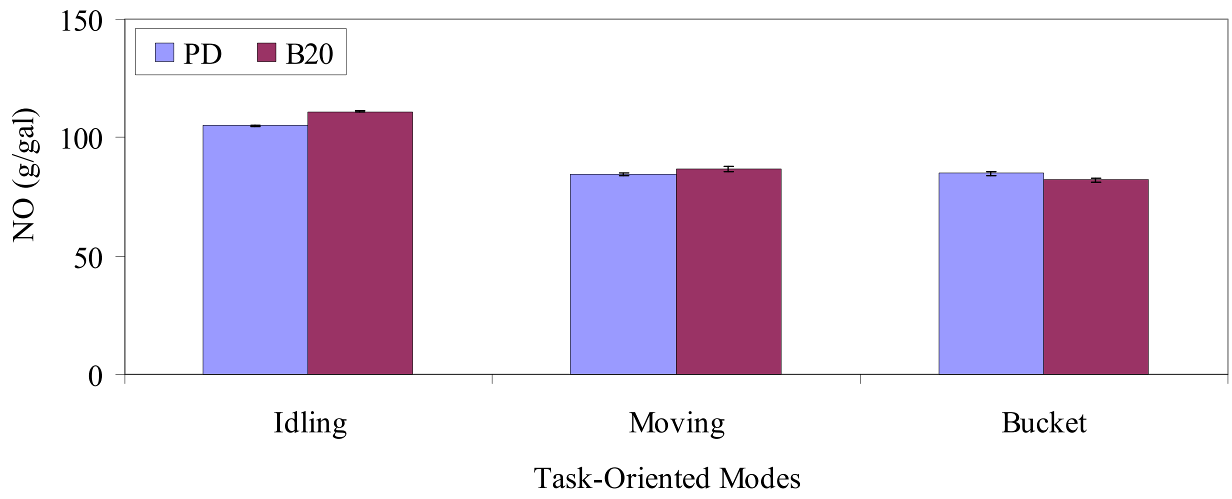
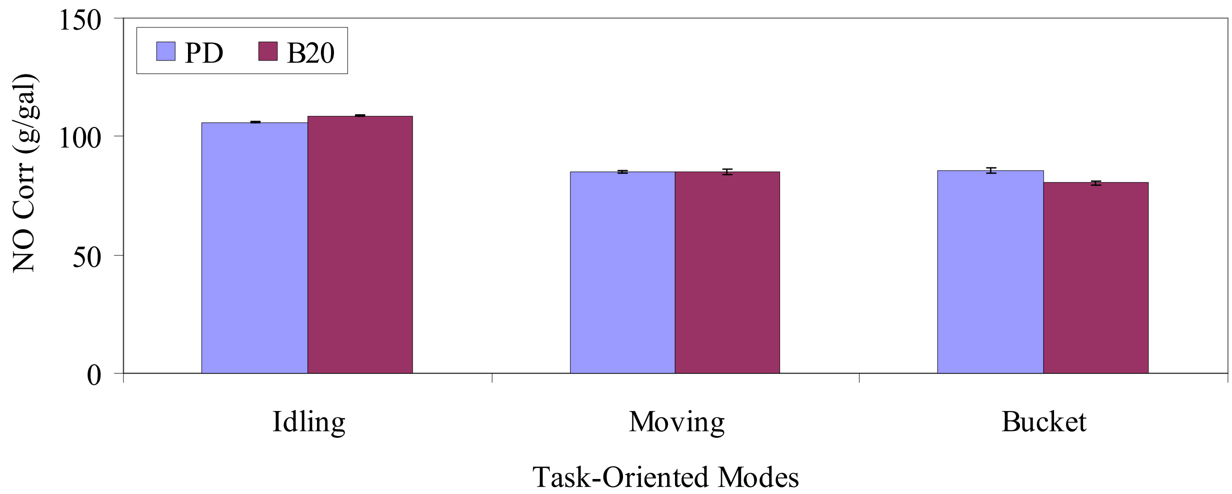


Figure A19. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 50 ^{o}F and the relative humidity was 40 %. For the B20 biodiesel test, the ambient temperature was 49 ^{o}F and the relative humidity was 74 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the front-end loader when the bucket is not in contact with the ground (forward or backward); *bucket*: movement of the front-end loader when the bucket is in contact with the ground.

Figure A20. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Front-End Loader 5 (continued on next page)

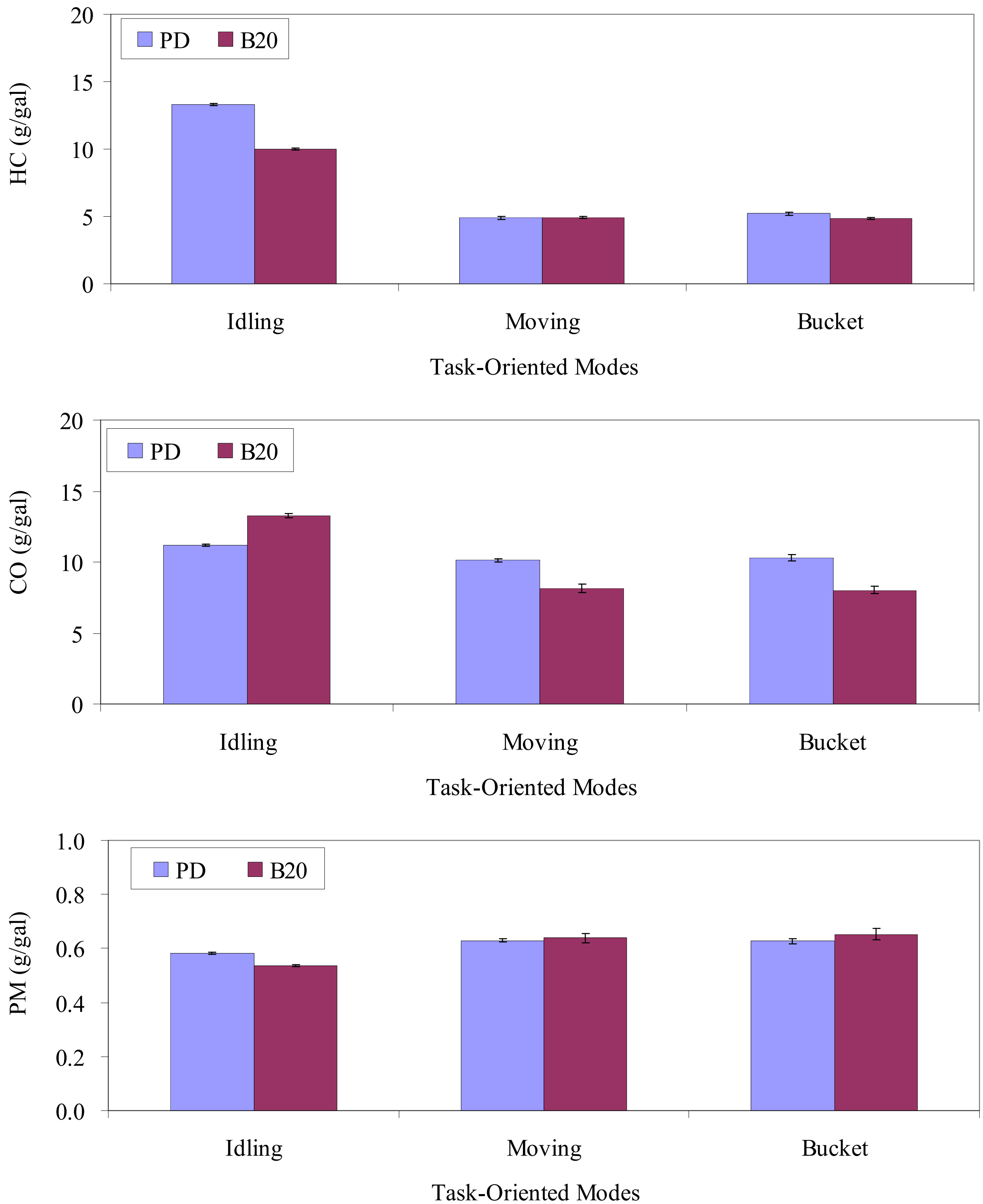
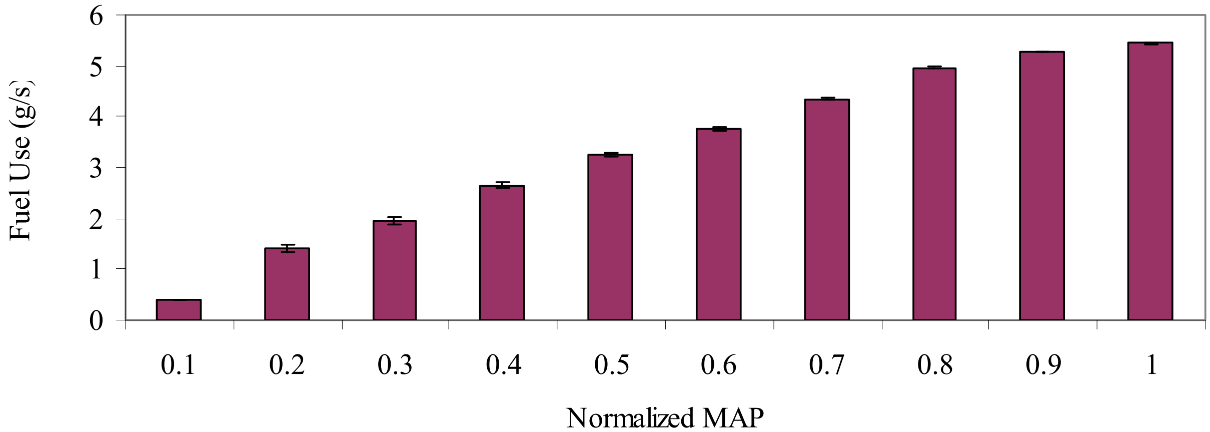
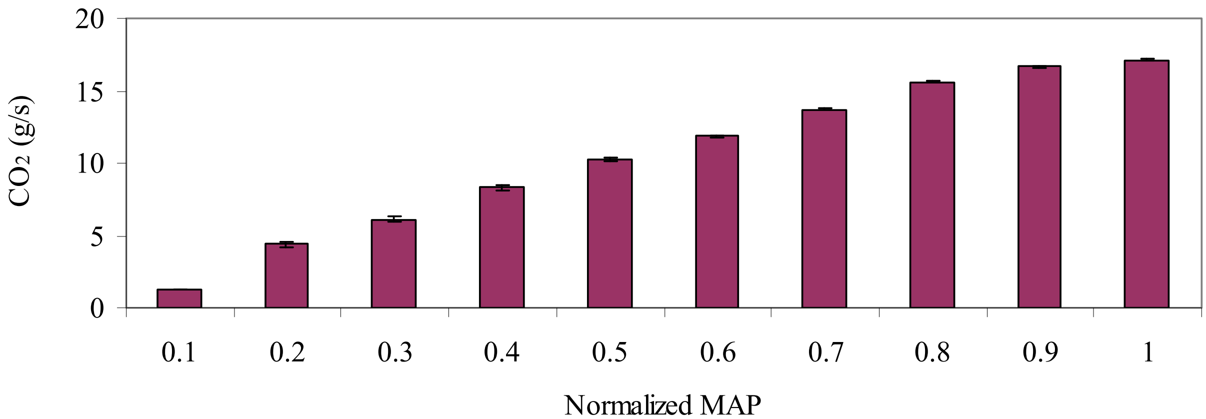


Figure A20. Continued

Dozer 1





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 78 ^{o}F and the relative humidity was 58 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 $\leq$ Normalized MAP < 0.1; "0.2" = 0.1 $\leq$ Normalized MAP < 0.2, and so on.

Figure A21. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Dozer 1 (continued on next page)

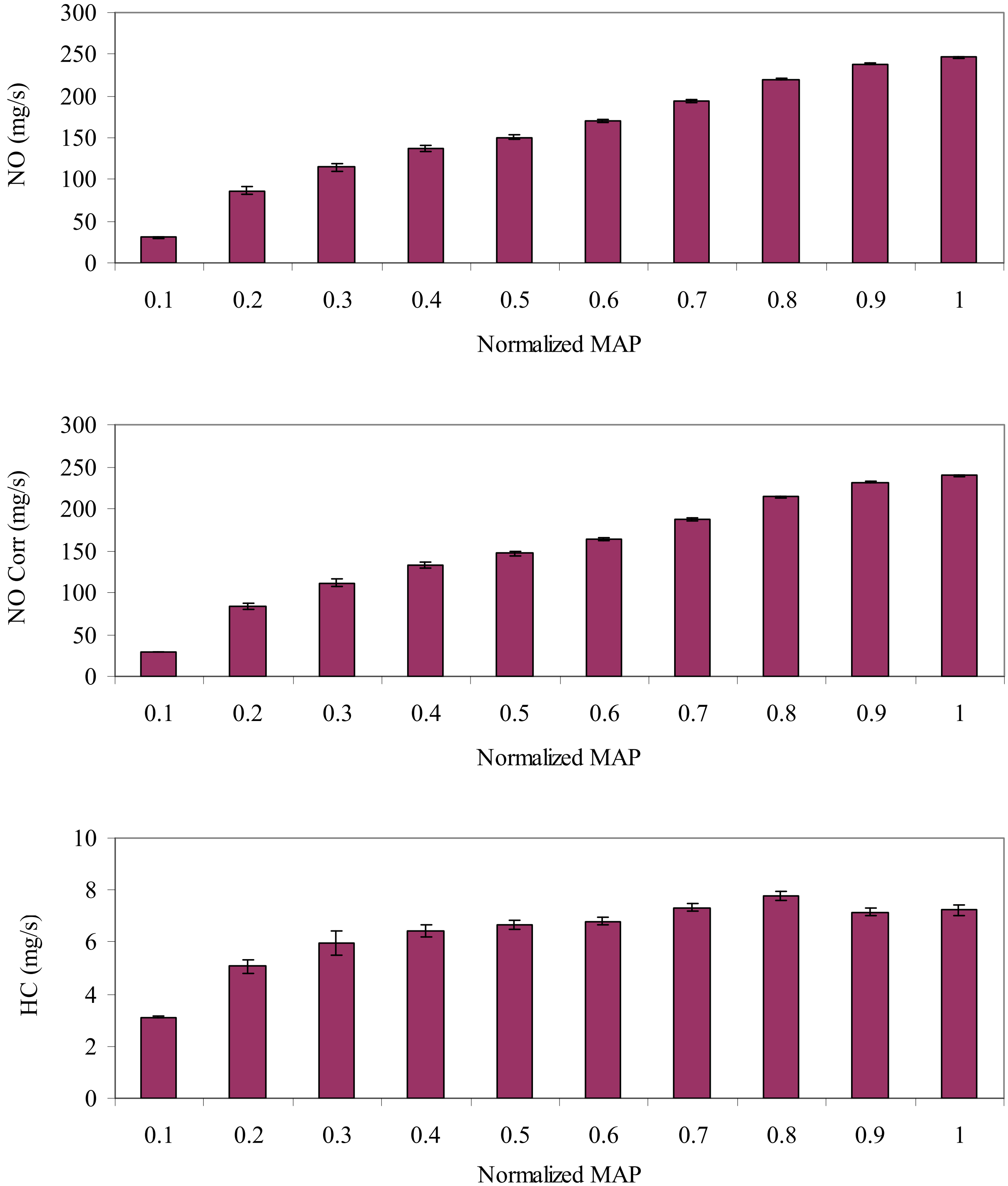
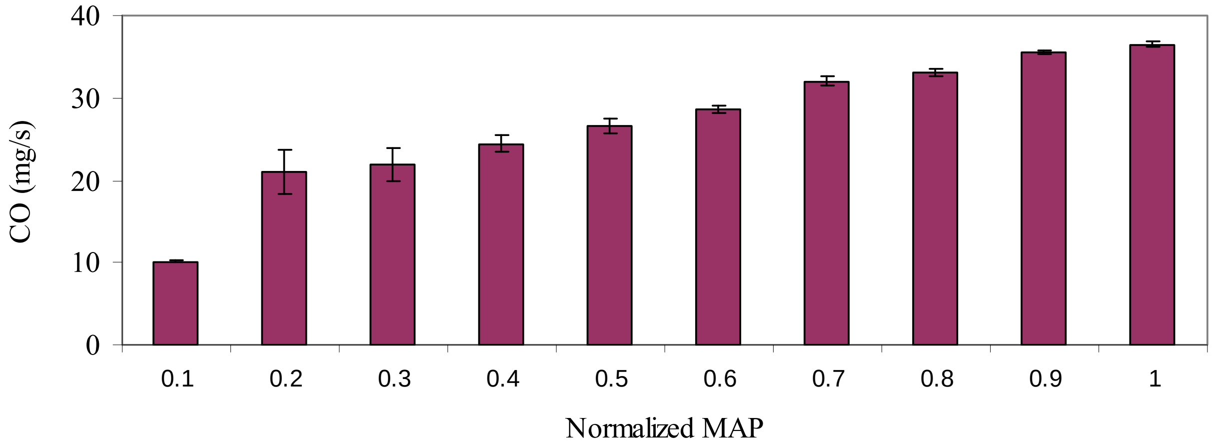


Figure A21. Continued



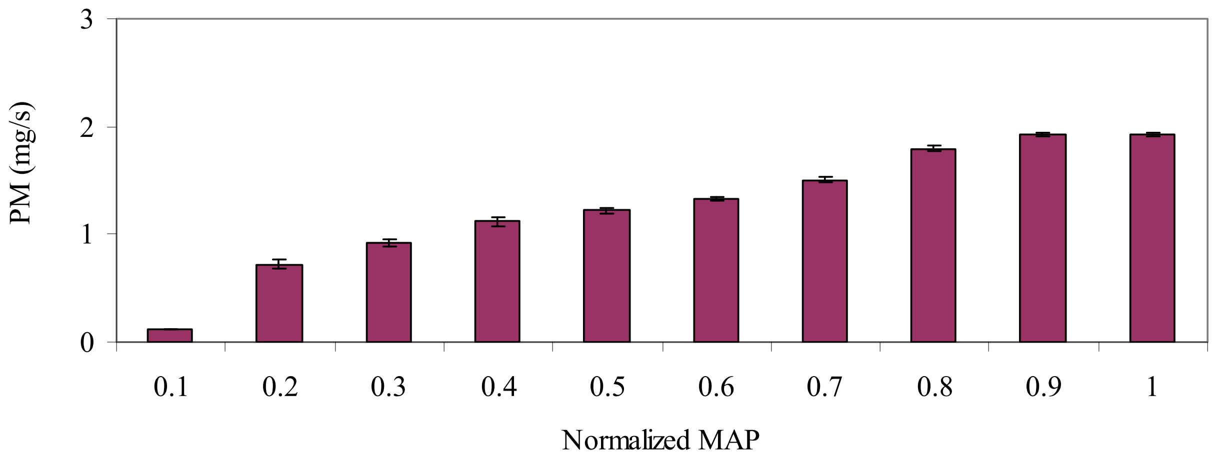
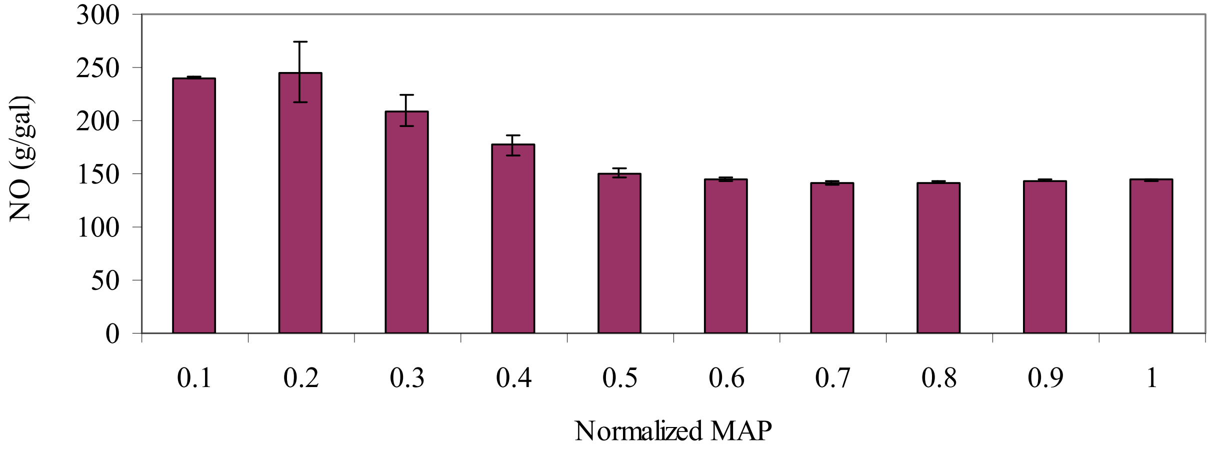
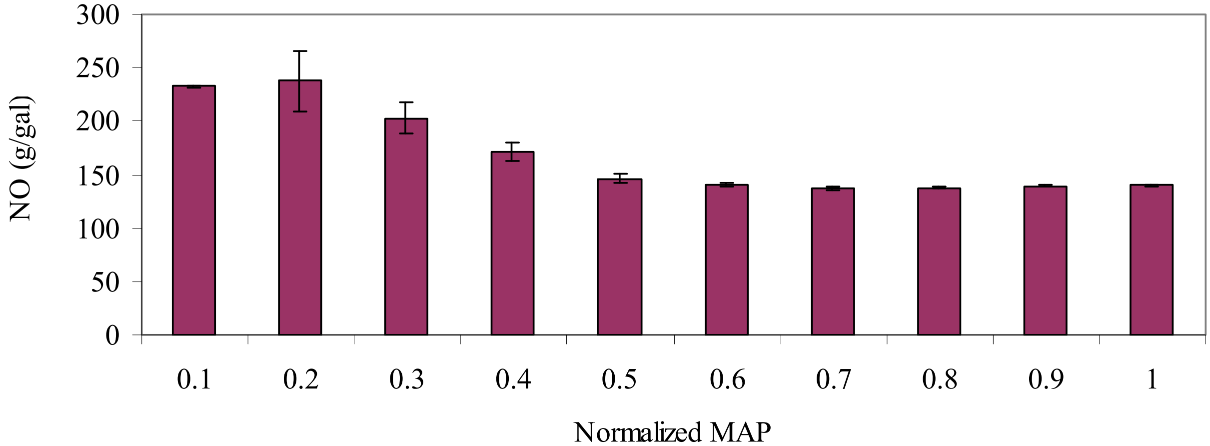


Figure A21. Continued

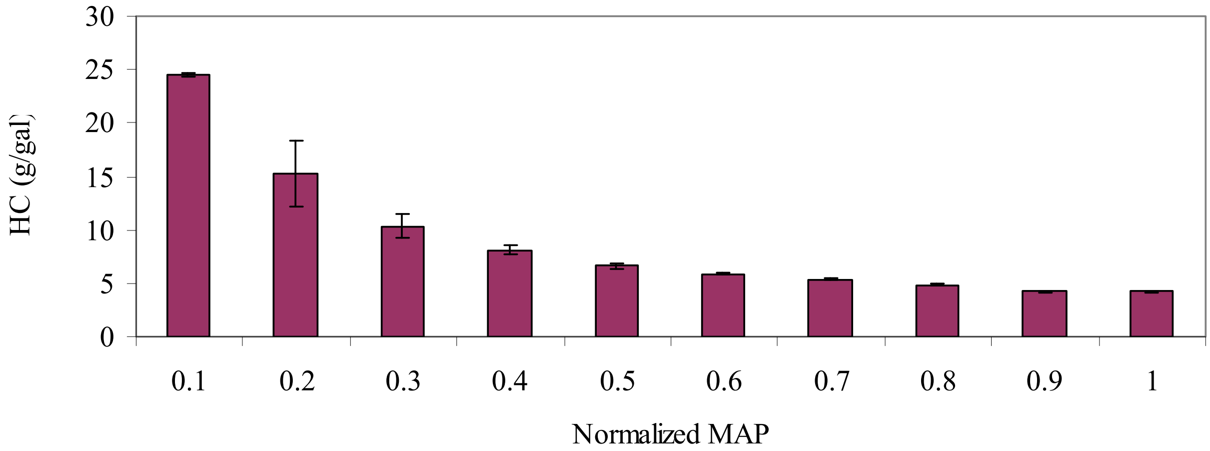


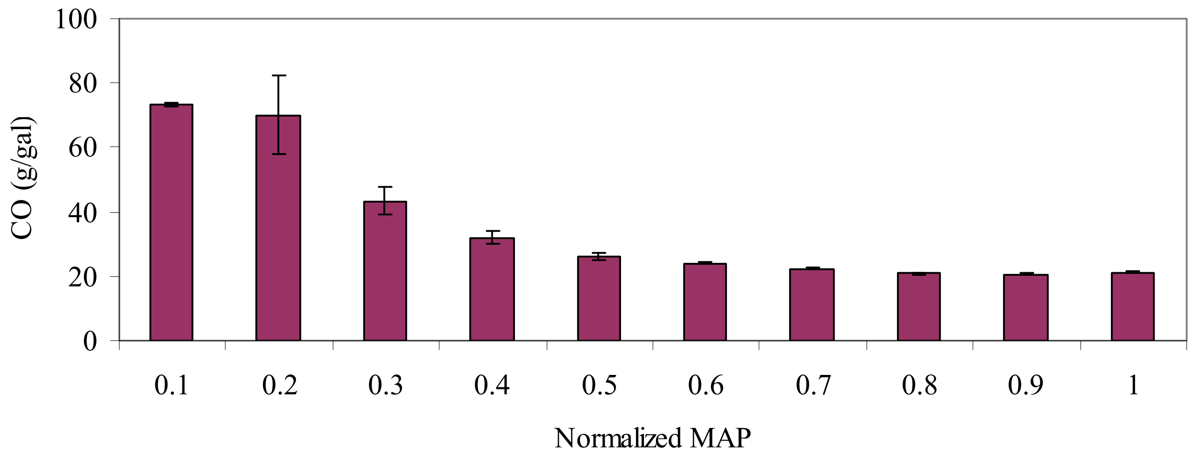


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 78 ^oF and the relative humidity was 58 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A22. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Dozer 1 (continued on next page)





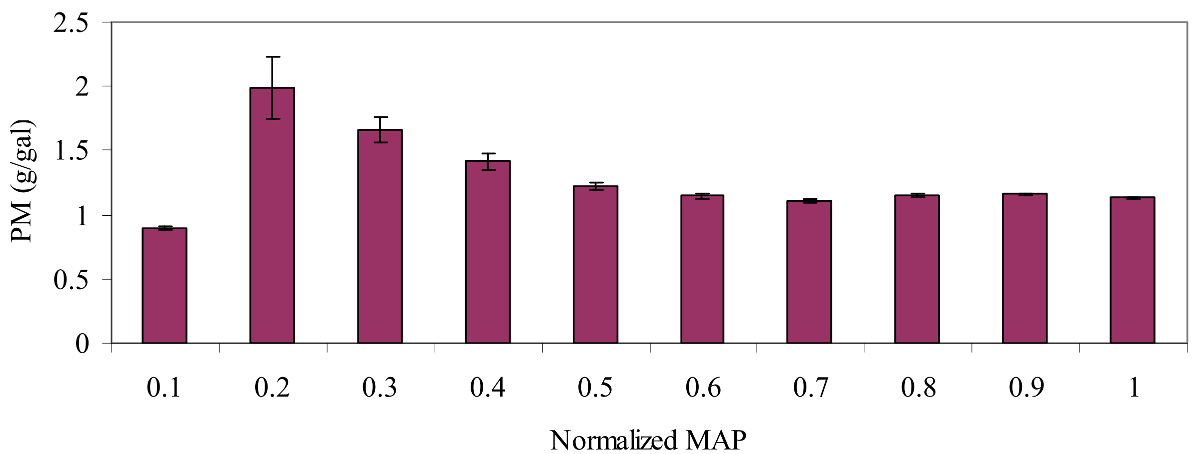
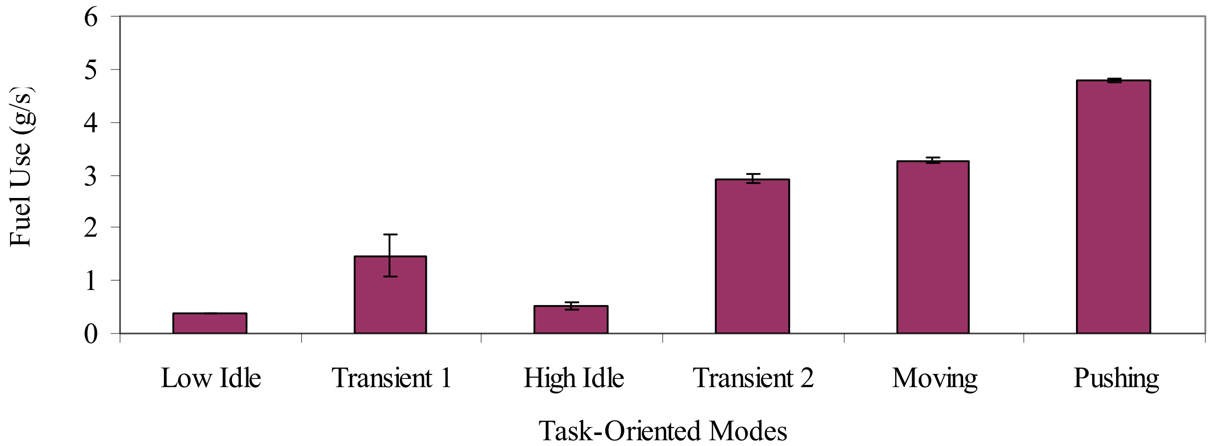
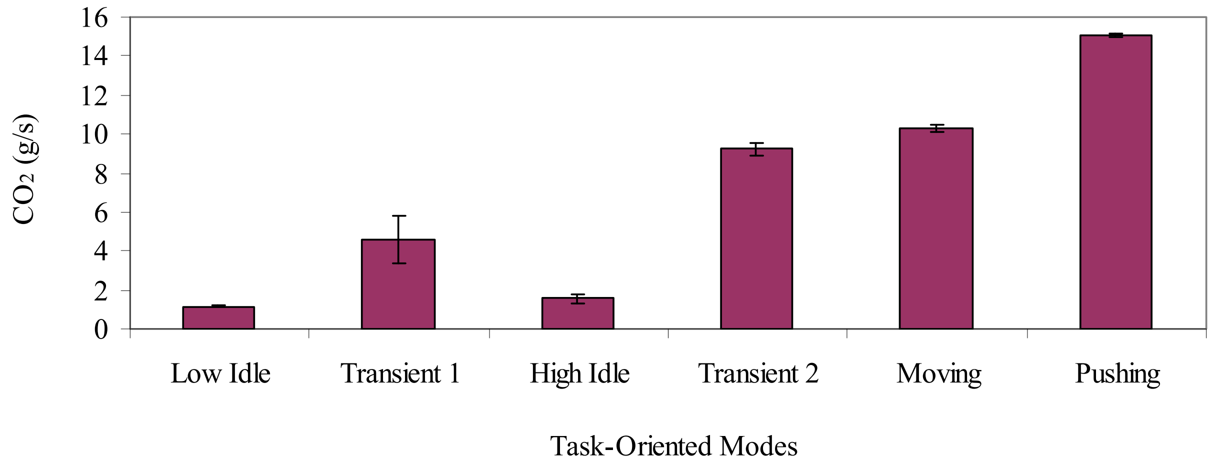


Figure A22. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 78 ^{o}F and the relative humidity was 58 %.

Task-oriented modes are: *low idle*: engine on at low RPM, but the vehicle is not working or moving; *transient 1*: engine RPM changes from low idle to high idle; *high idle*: engine on at high RPM, but the vehicle is not working or moving; *transient 2*: vehicle starts working from high idle; *moving*: movement of the dozer when the bucket is not in contact with the ground (forward or backward); *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A23. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Dozer 1 (continued on next page)

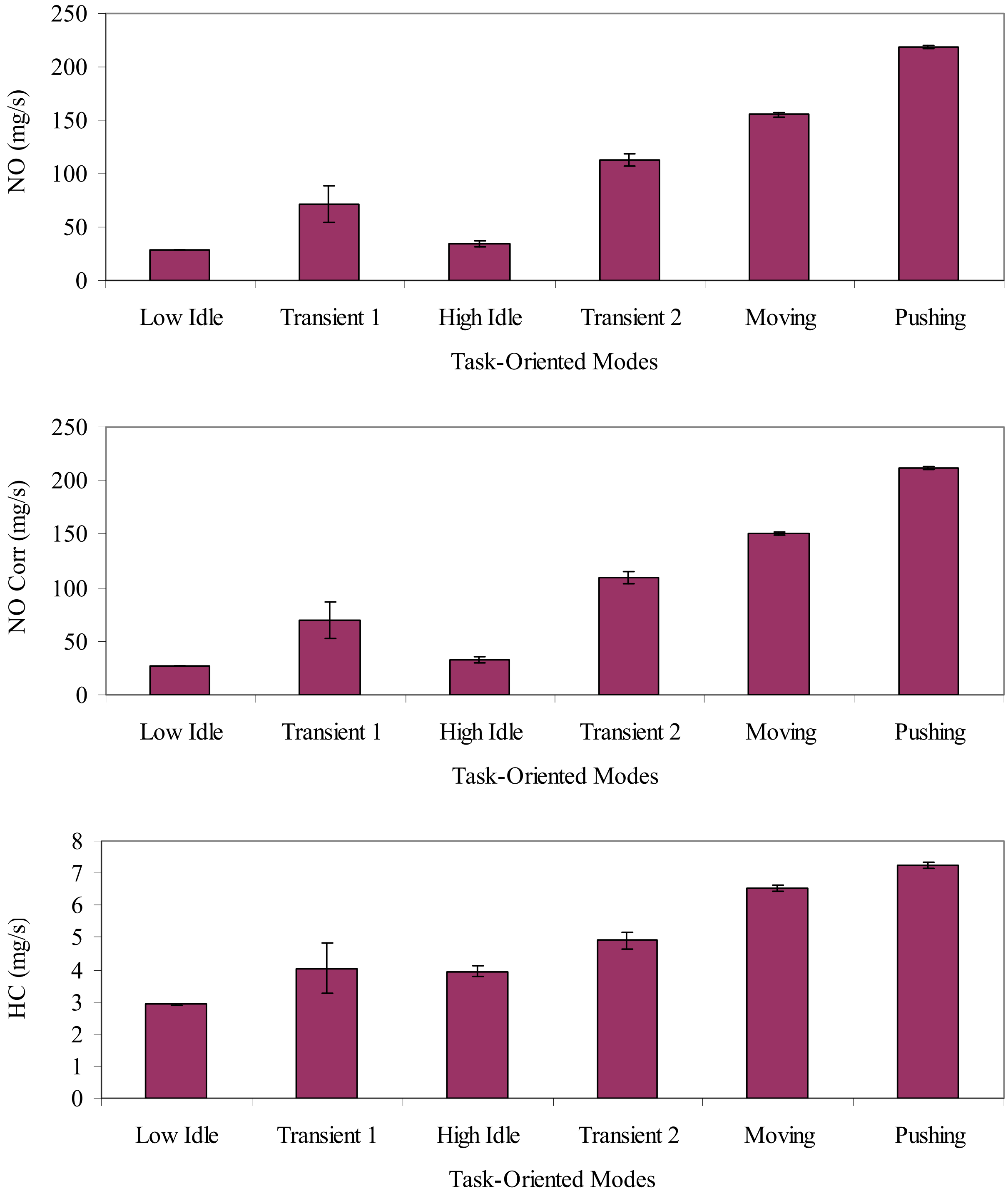


Figure A23. Continued

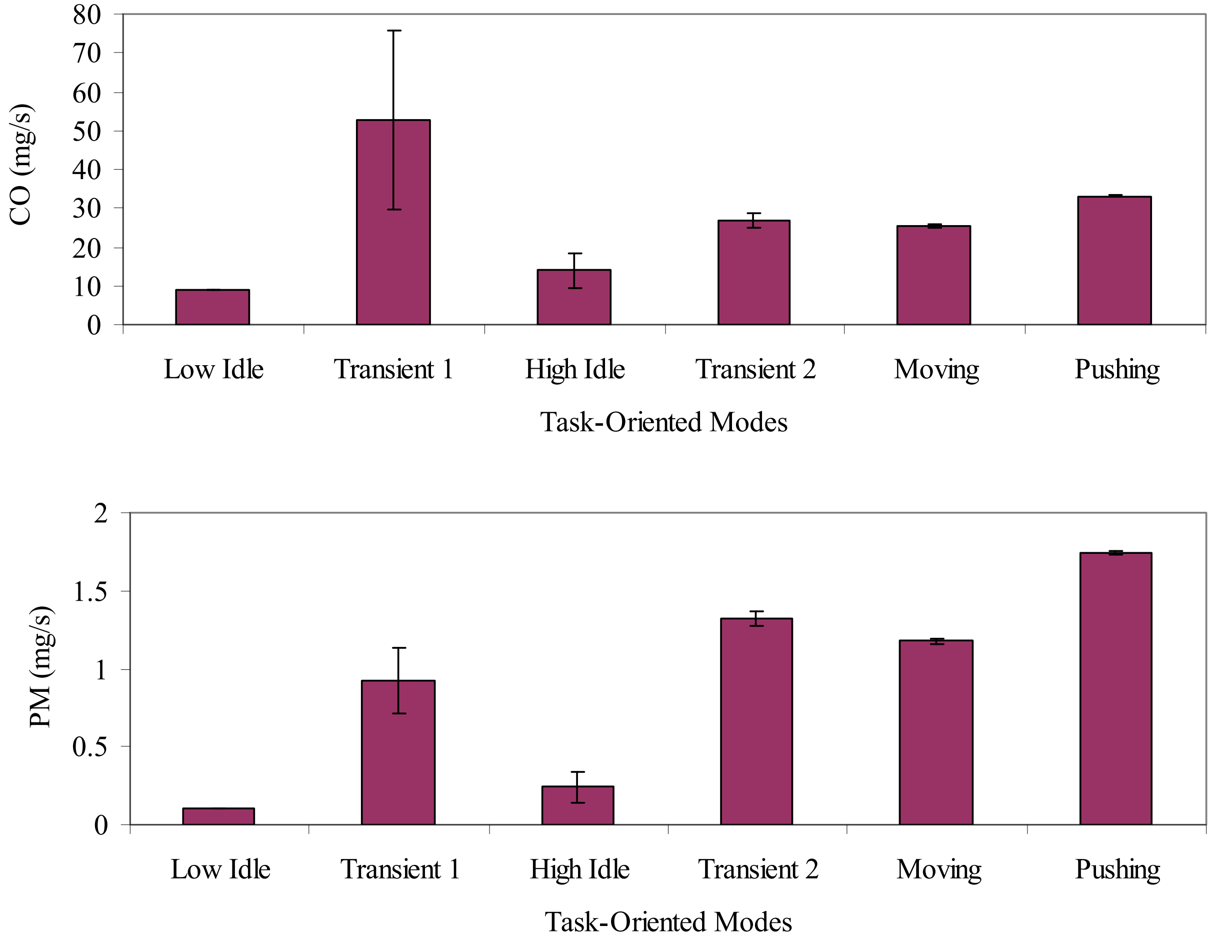
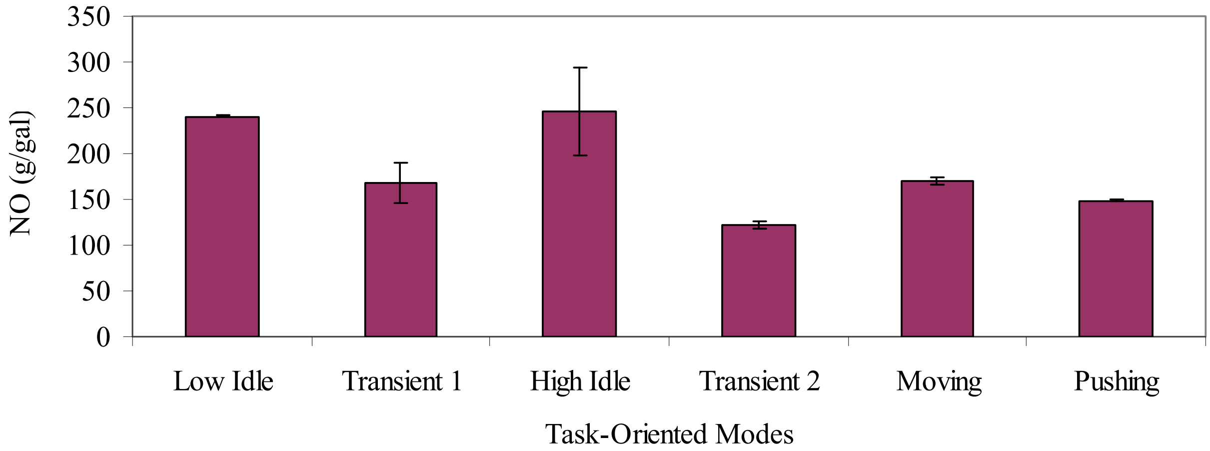
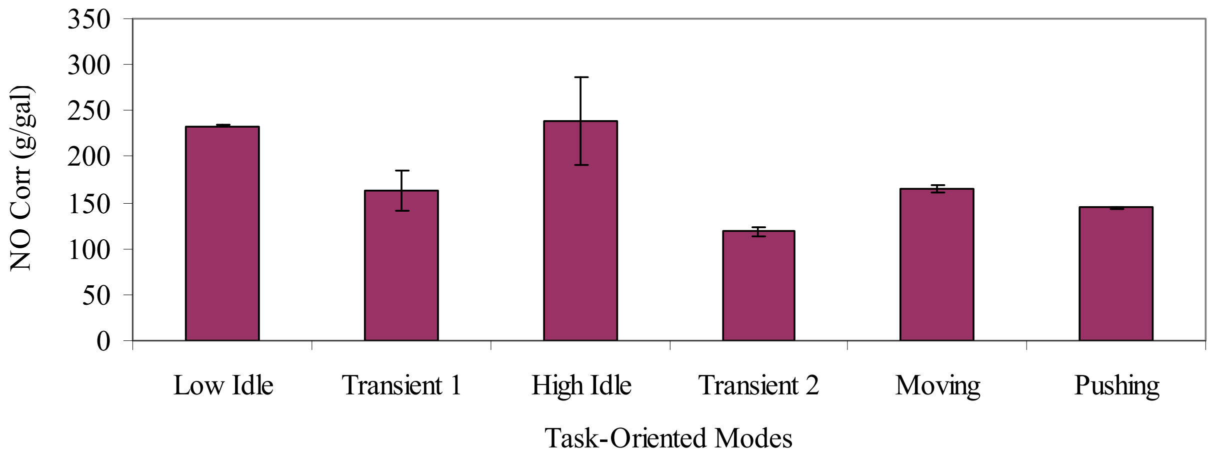


Figure A23. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 78 ^{o}F and the relative humidity was 58 %.

Task-oriented modes are: *low idle*: engine on at low RPM, but the vehicle is not working or moving; *transient 1*: engine RPM changes from low idle to high idle; *high idle*: engine on at high RPM, but the vehicle is not working or moving; *transient 2*: vehicle starts working from high idle; *moving*: movement of the dozer when the bucket is not in contact with the ground (forward or backward); *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A24. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Dozer 1 (continued on next page)

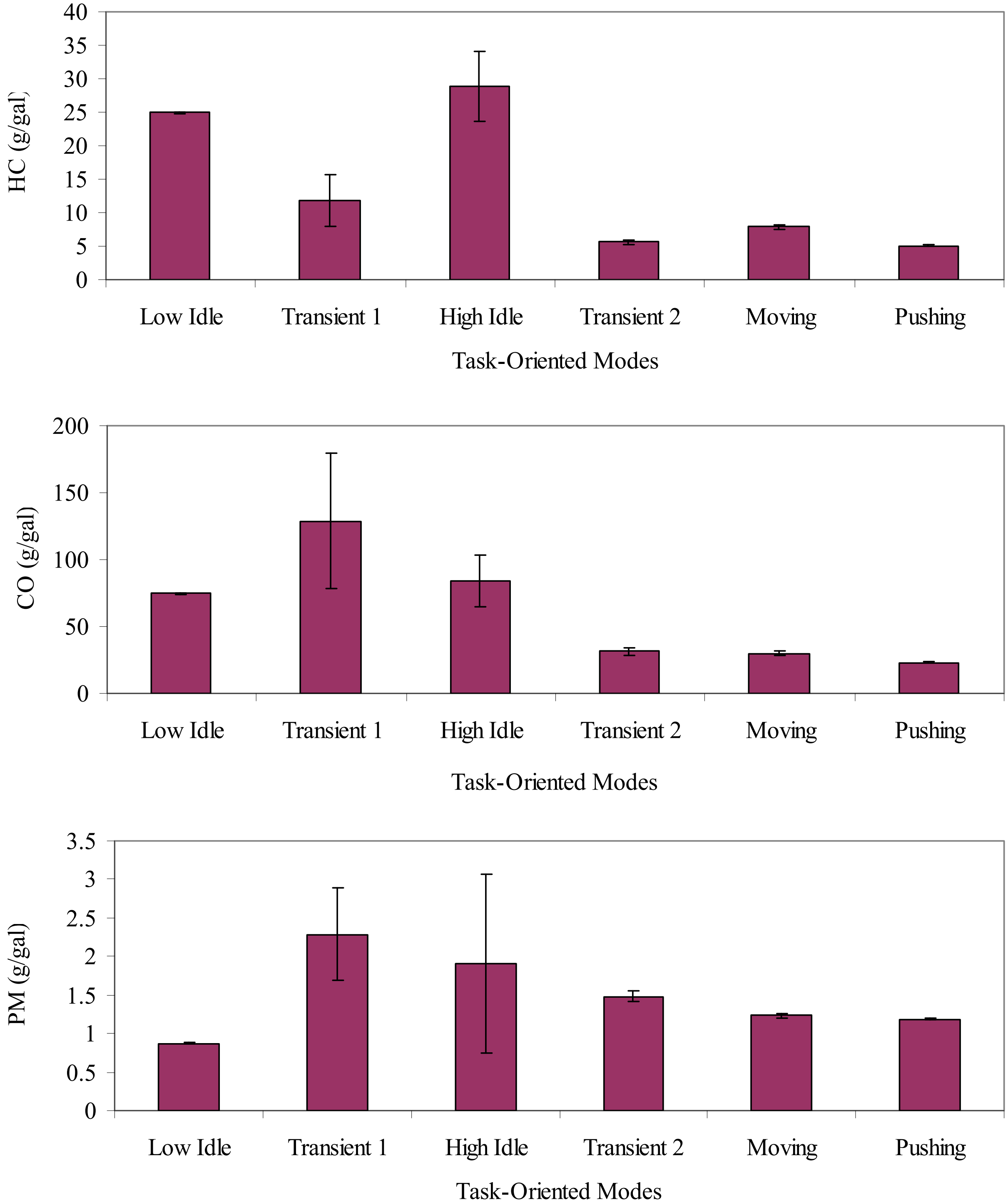
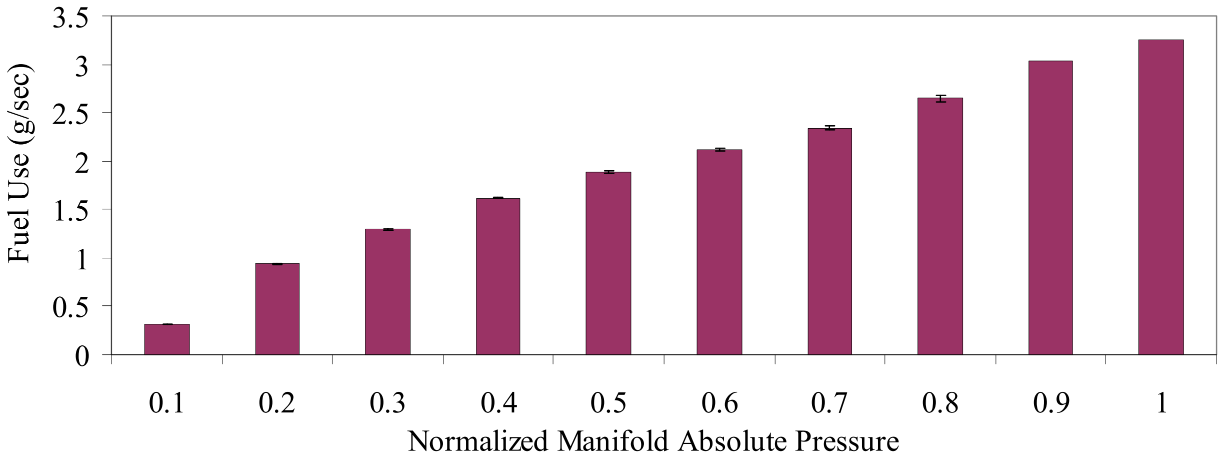
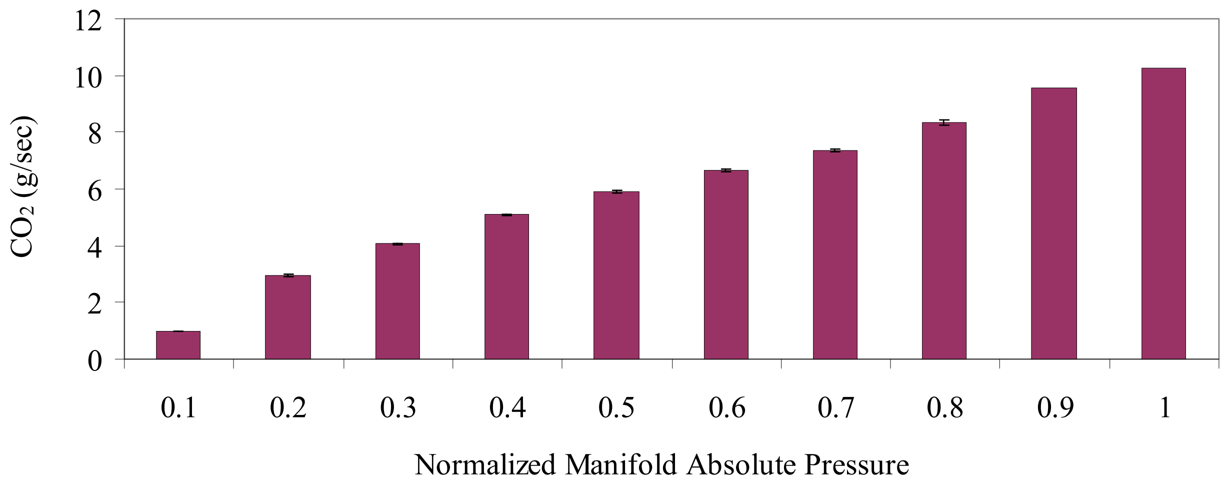


Figure A24. Continued

Dozer 2

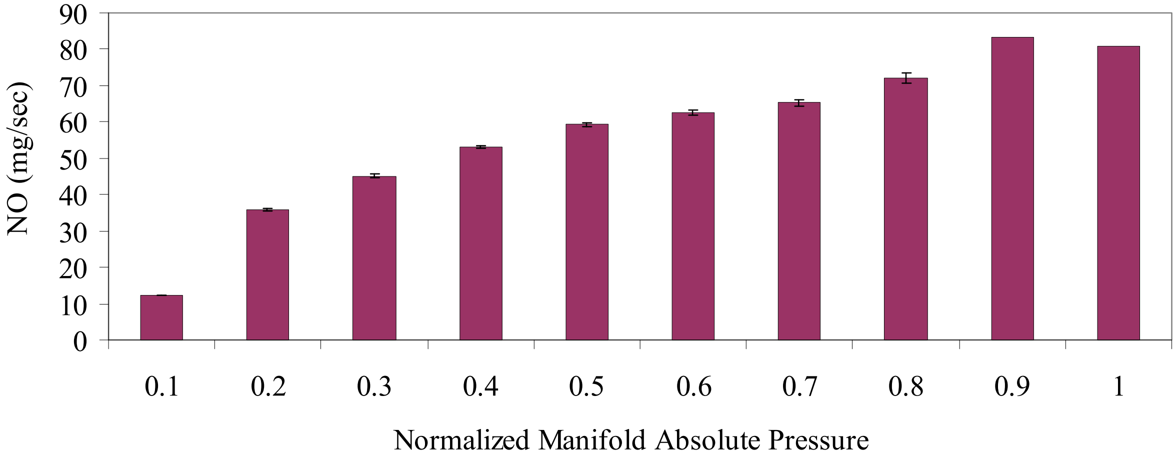


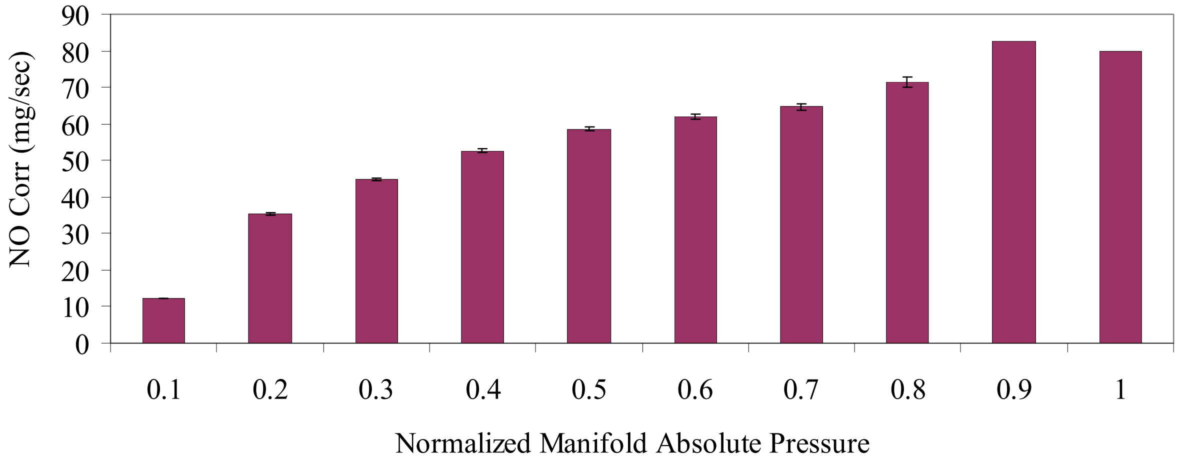


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 80 ^{o}F and the relative humidity was 54 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A25. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Dozer 2 (continued on next page)





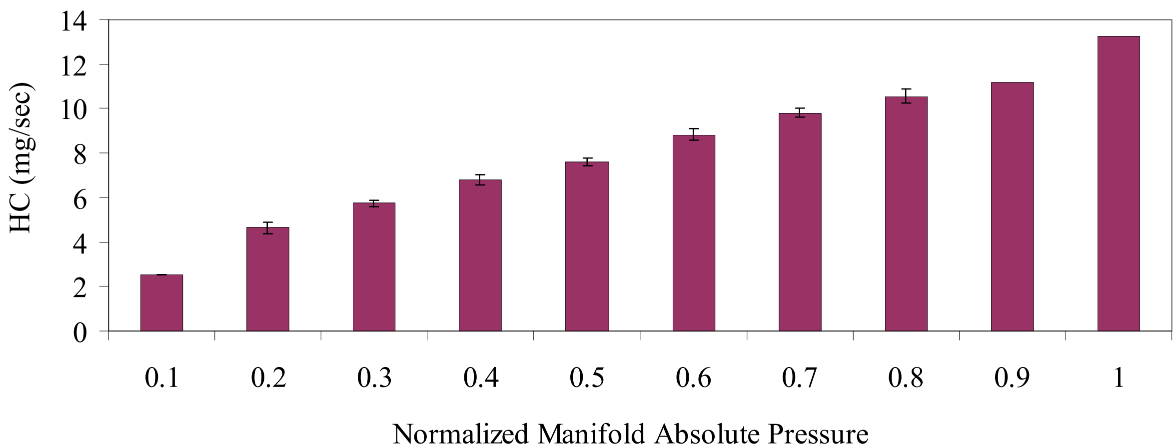
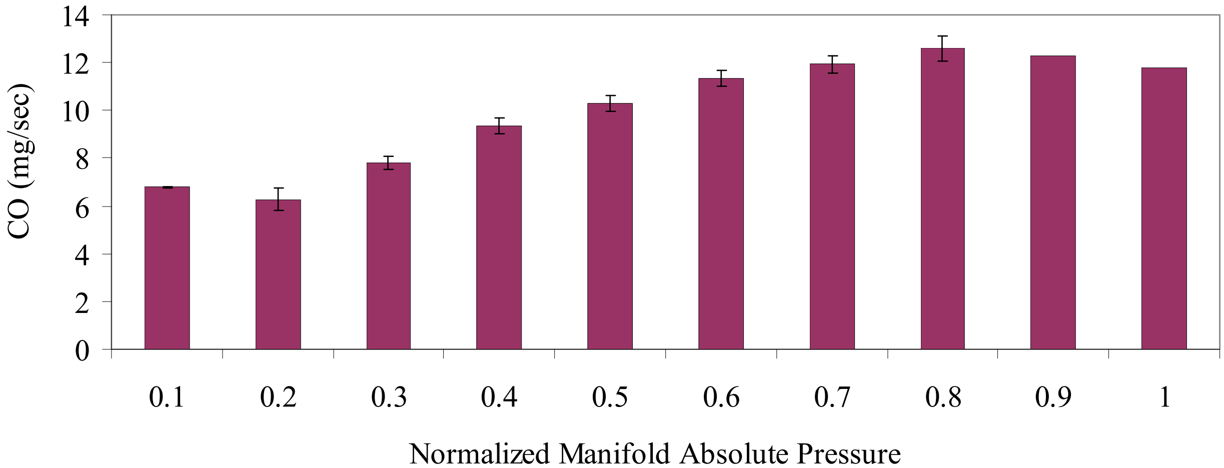


Figure A25. Continued



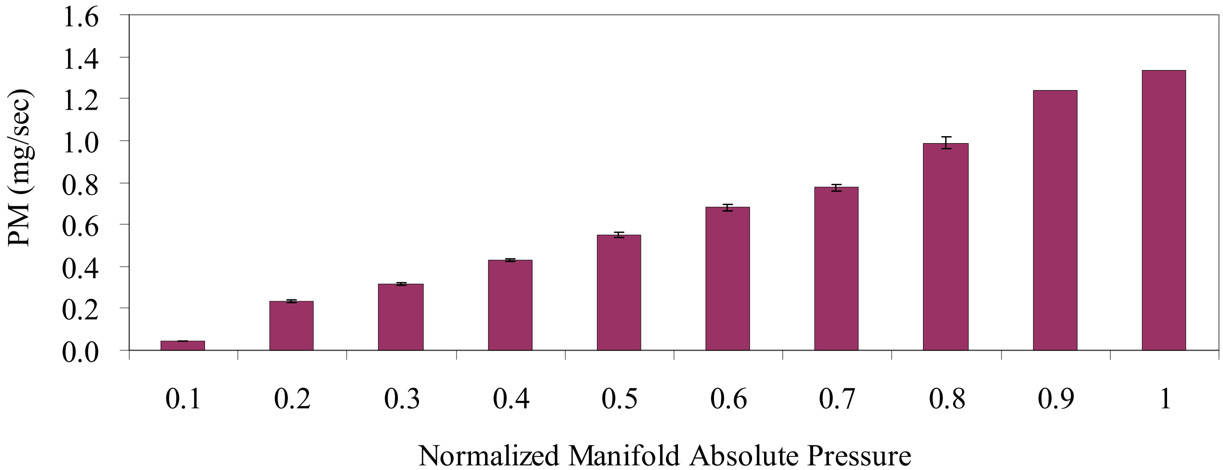
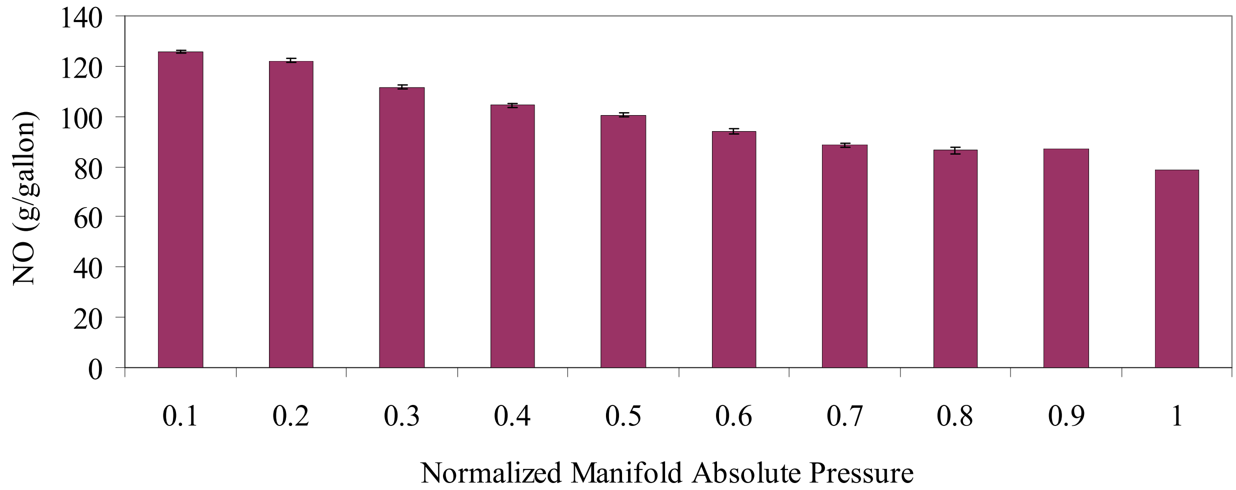
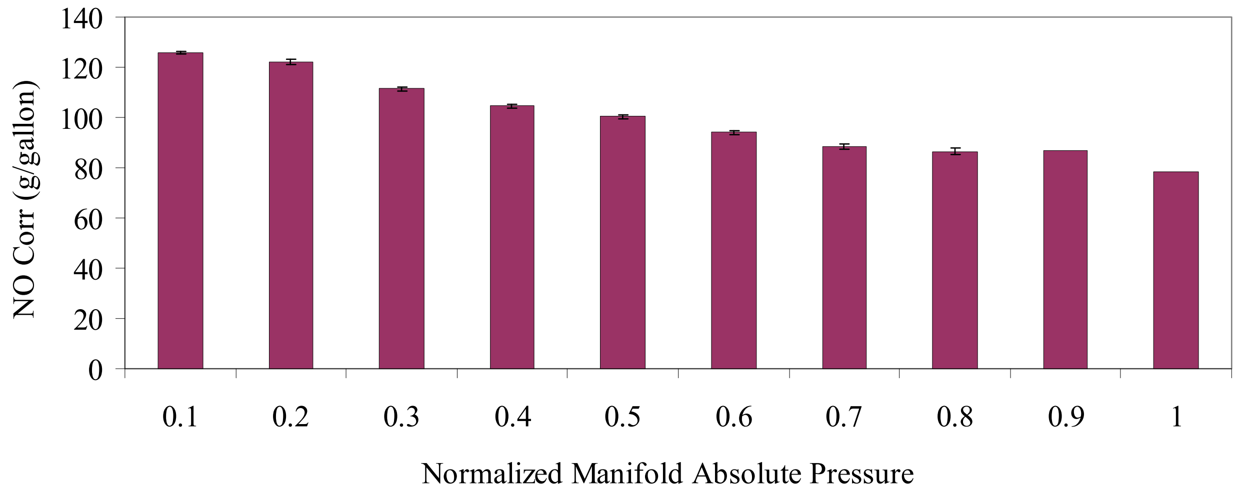


Figure A25. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 80 ^{o}F and the relative humidity was 54 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A26. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Dozer 2 (continued on next page)

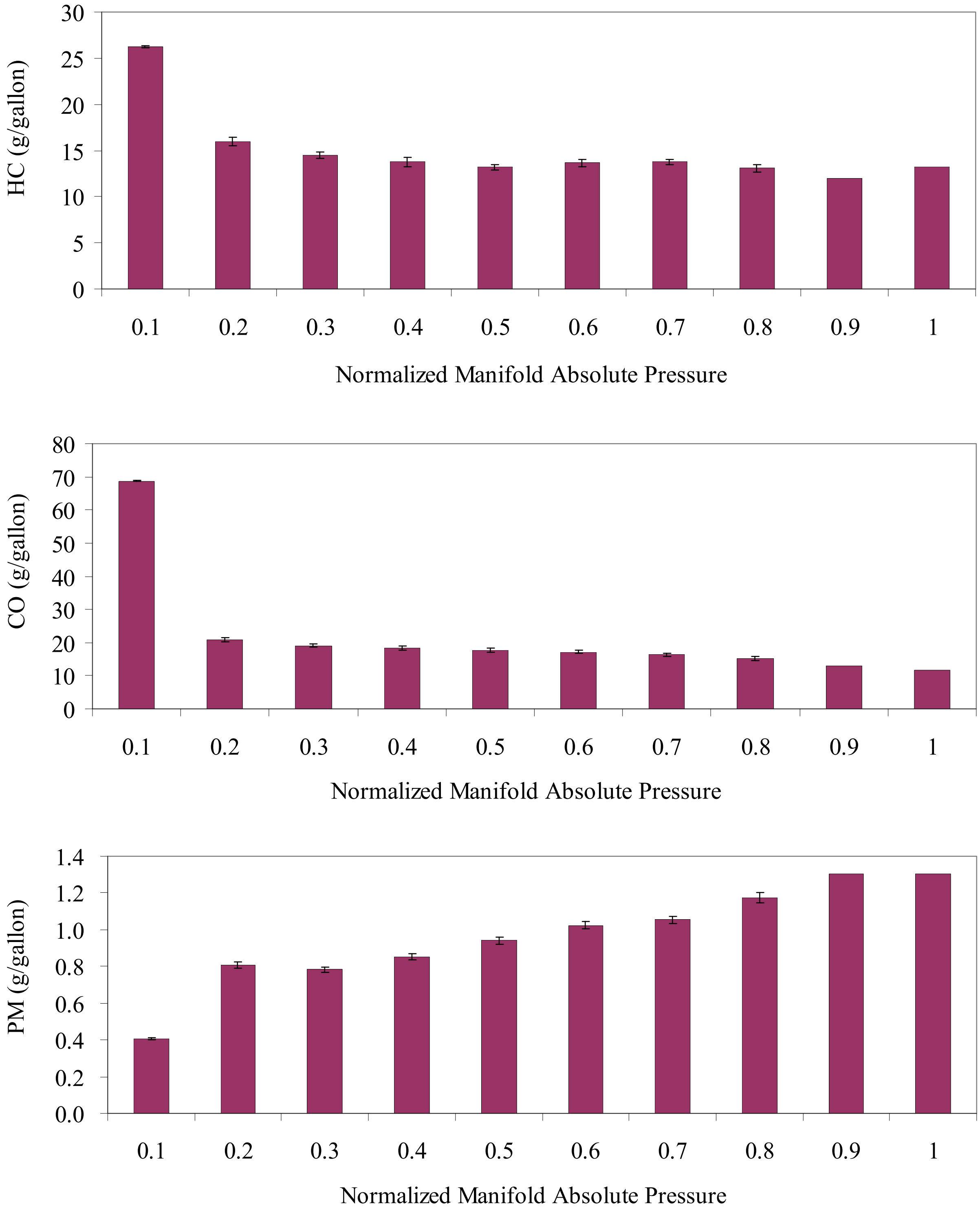
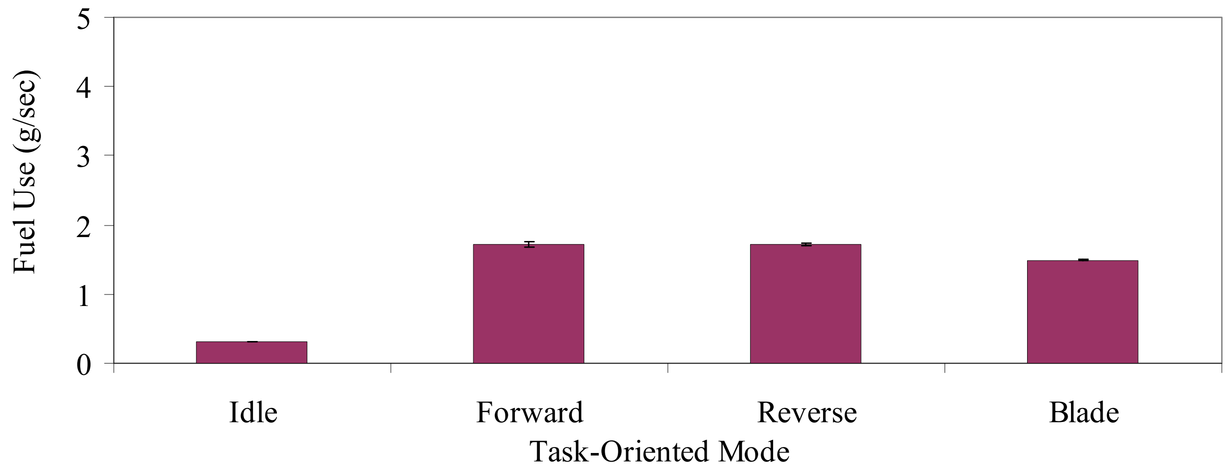
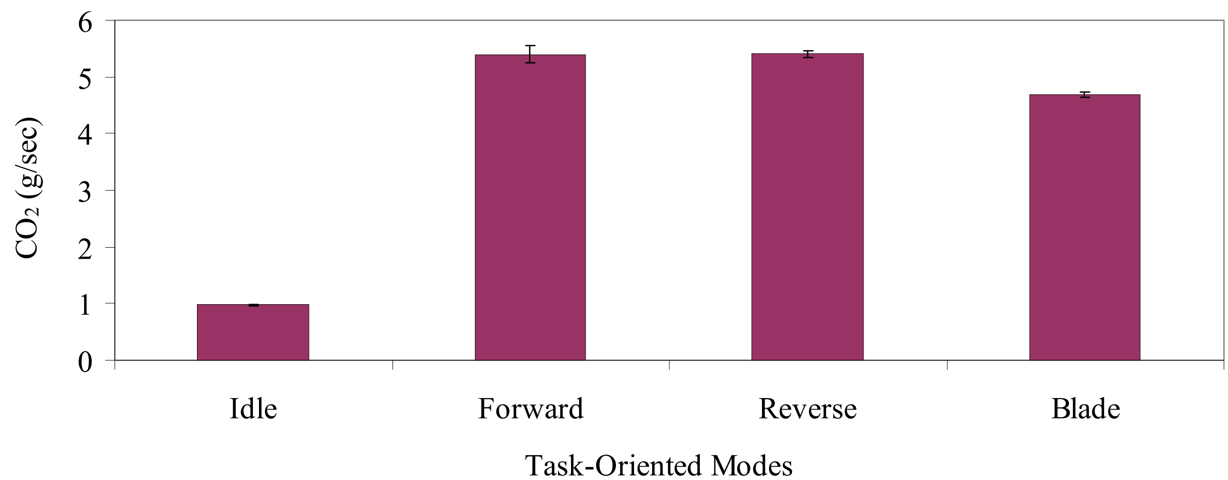


Figure A26. Continued

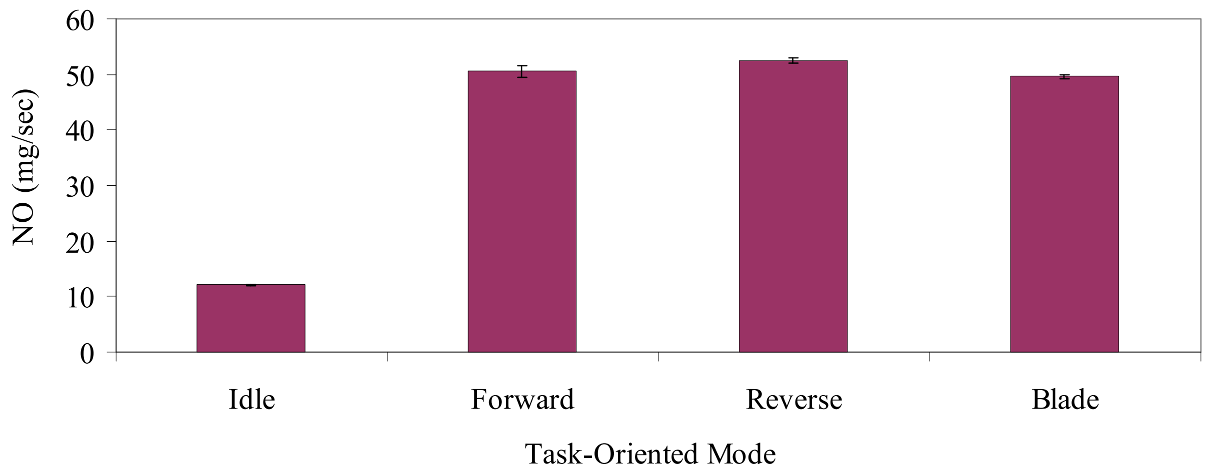


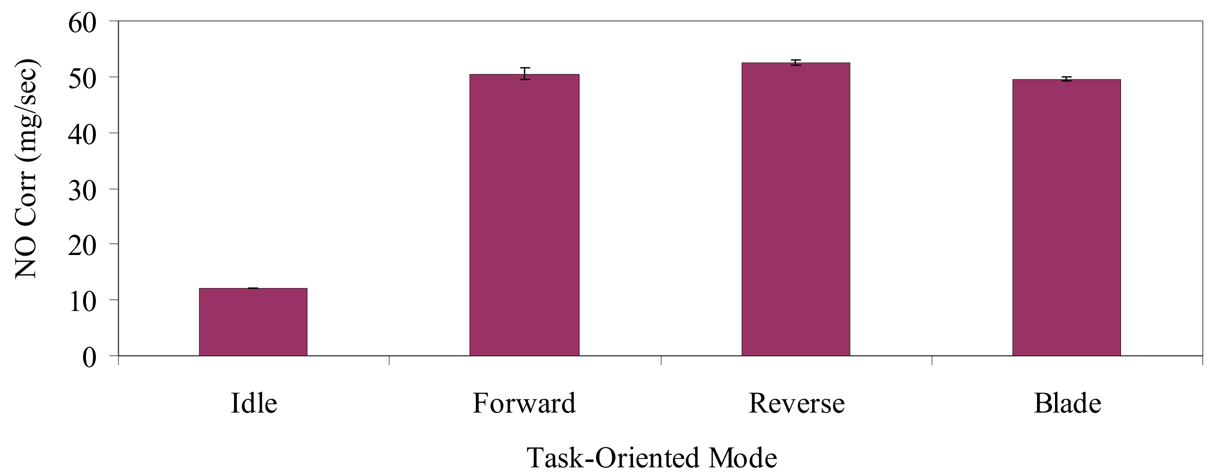


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 80 ^{o}F and the relative humidity was 54 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *forward*: forward movement of the dozer when the bucket is not in contact with the ground; *reverse*: reverse movement of the dozer when the bucket is not in contact with the ground ; *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A27. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Dozer 2 (continued on next page)





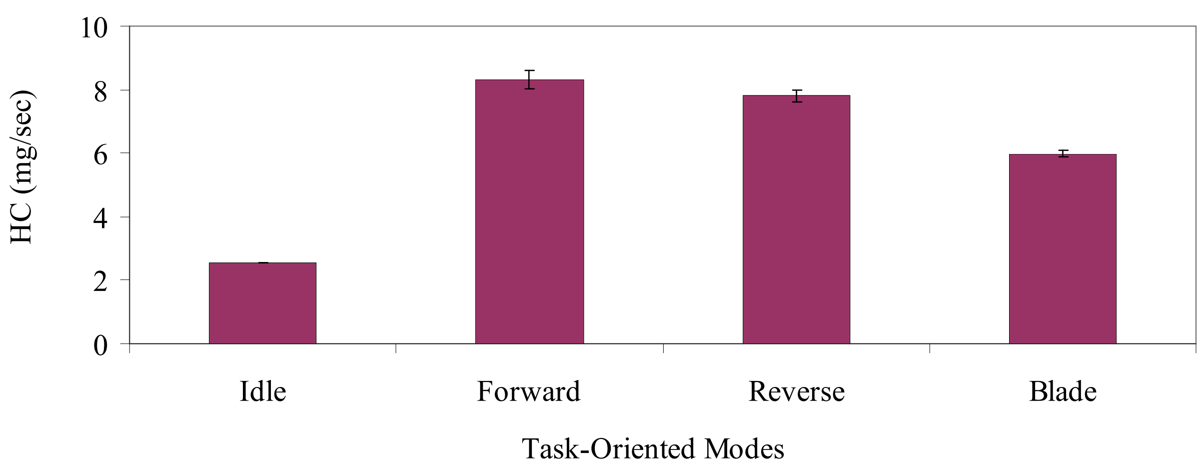
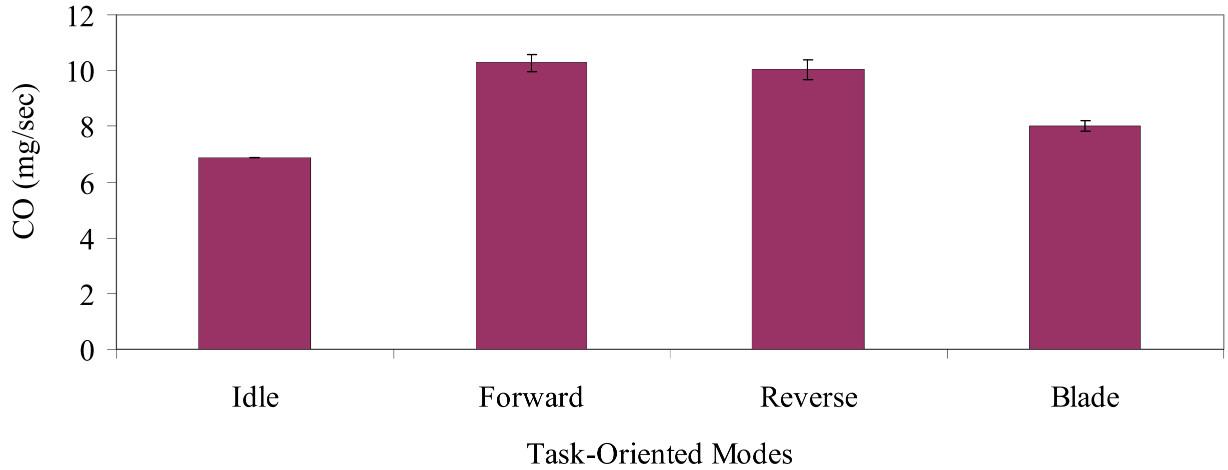


Figure A27. Continued



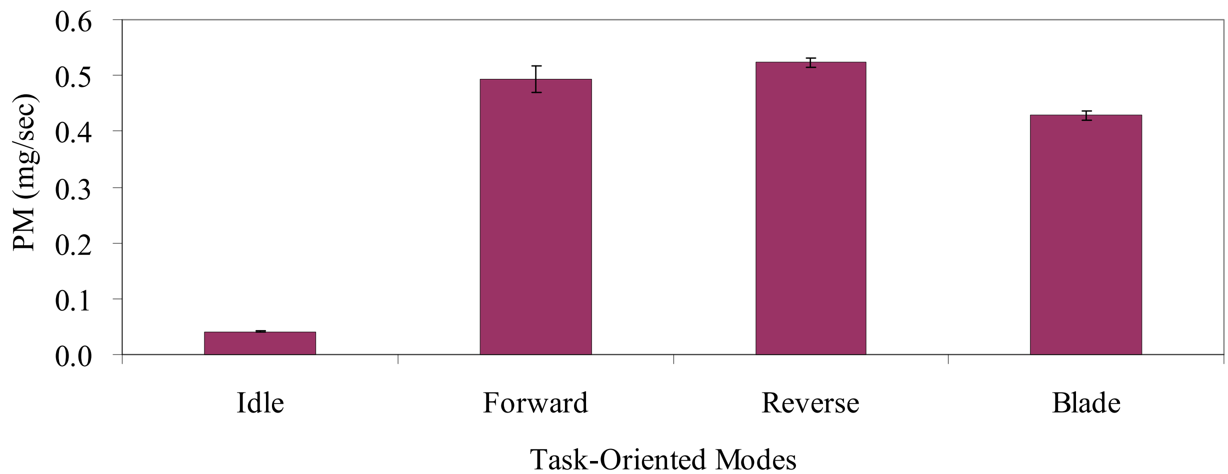
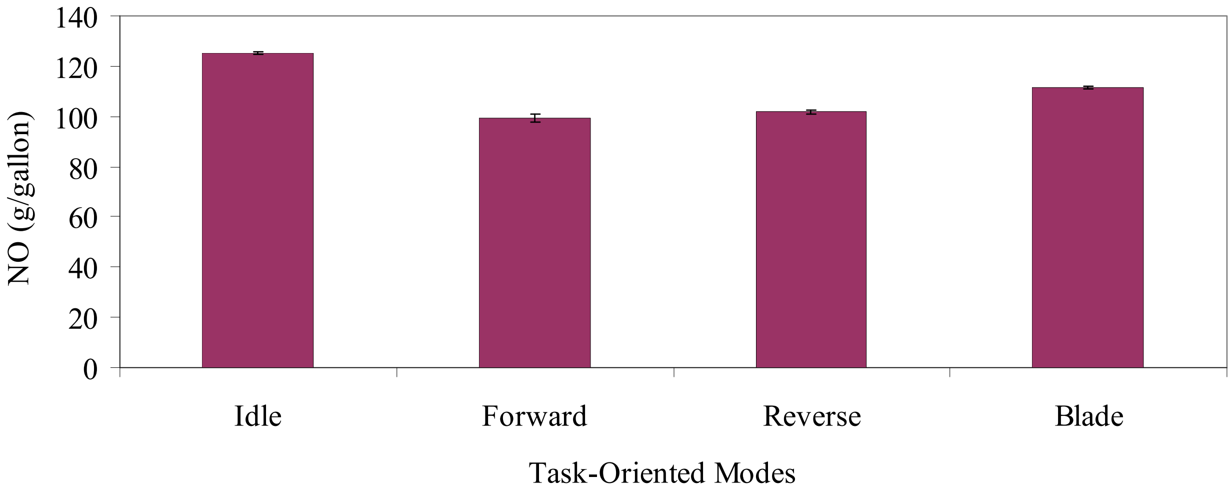
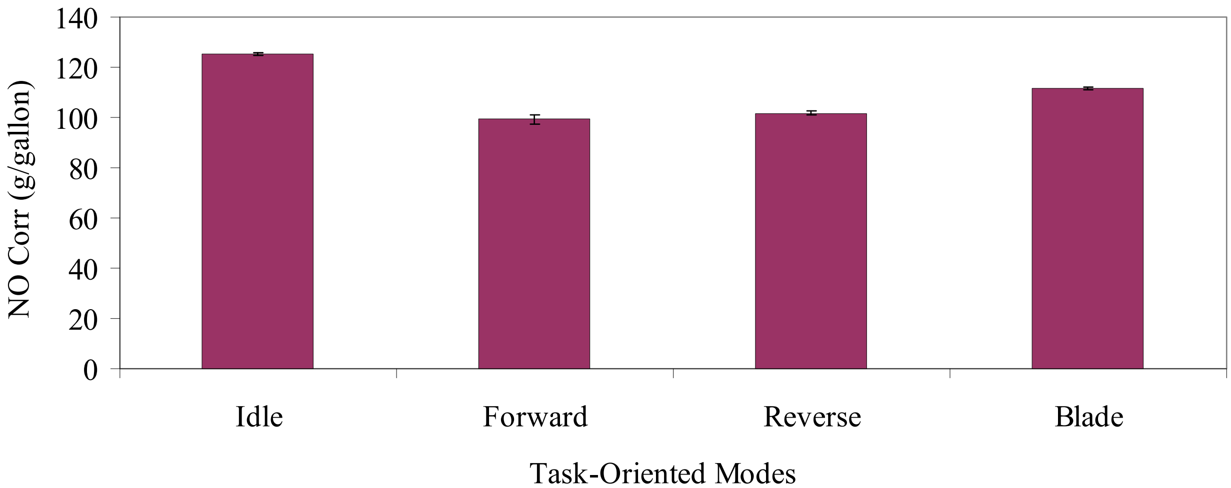


Figure A27. Continued

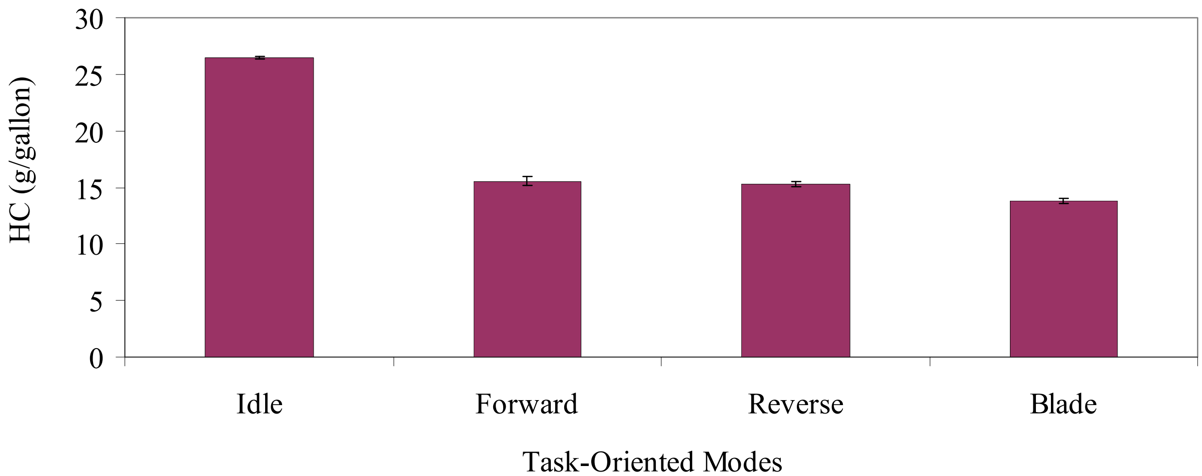


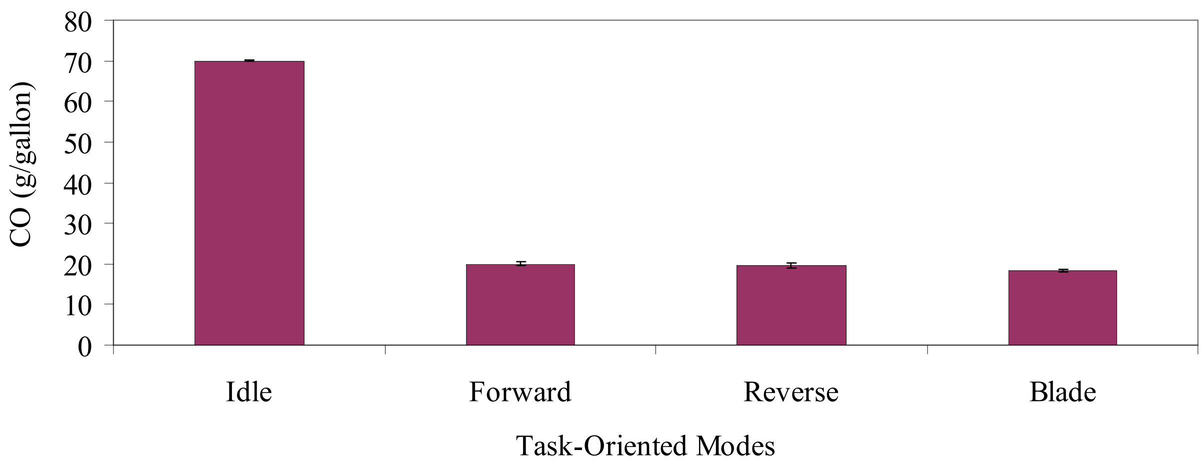


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 80 ^{o}F and the relative humidity was 54 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *forward*: forward movement of the dozer when the bucket is not in contact with the ground; *reverse*: reverse movement of the dozer when the bucket is not in contact with the ground; *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A28. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Dozer 2 (continued on next page)





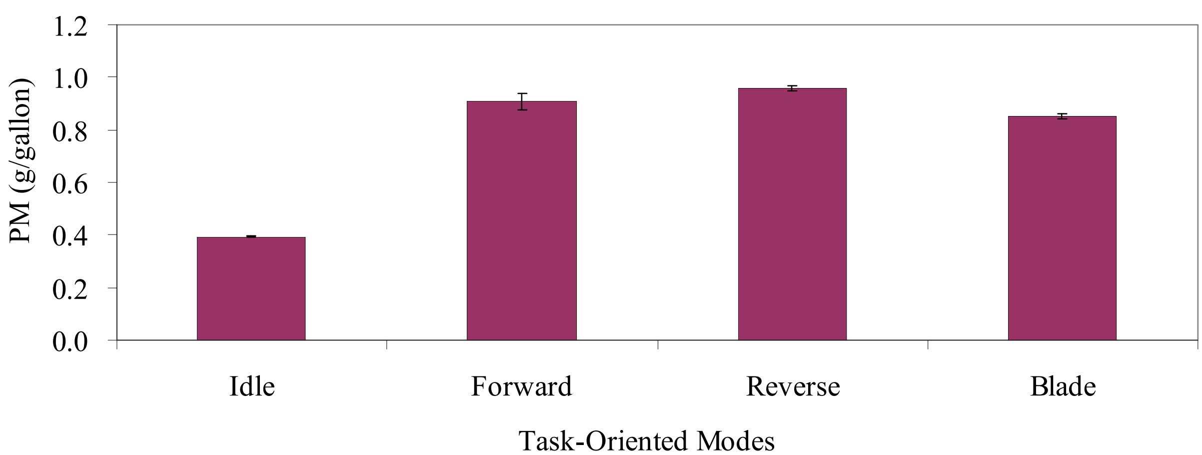
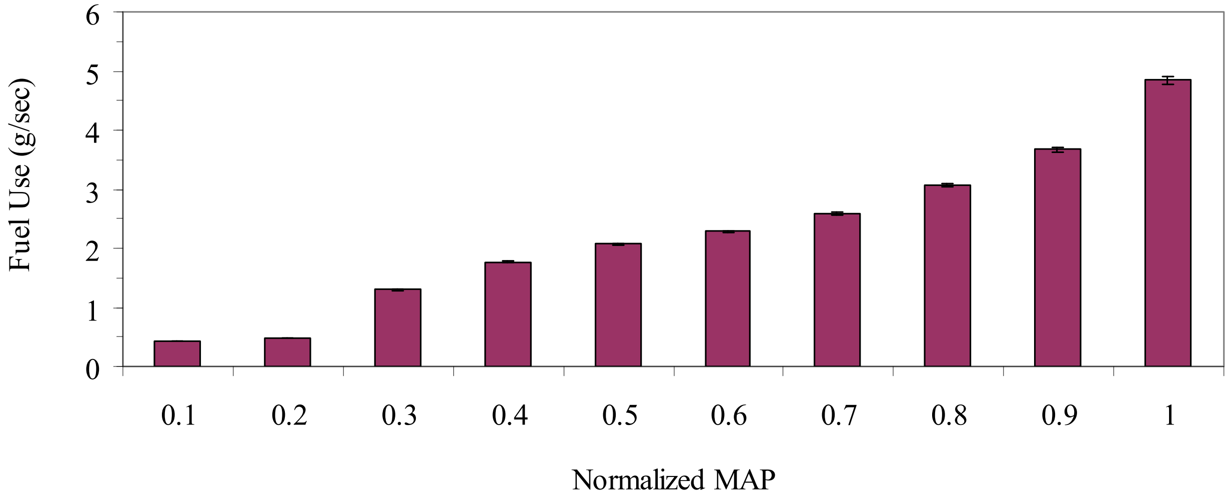
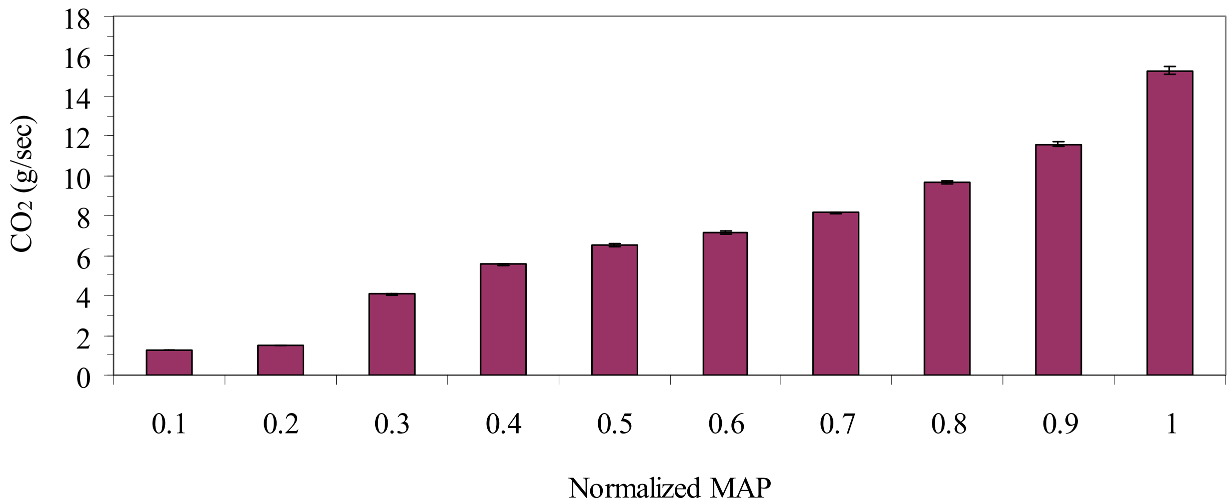


Figure A28. Continued

Dozer 3

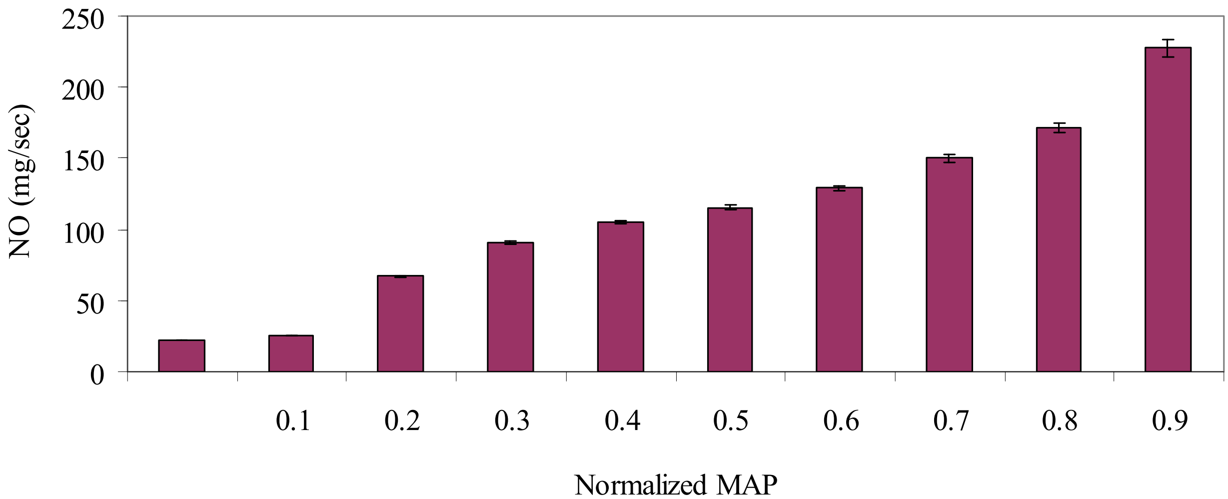


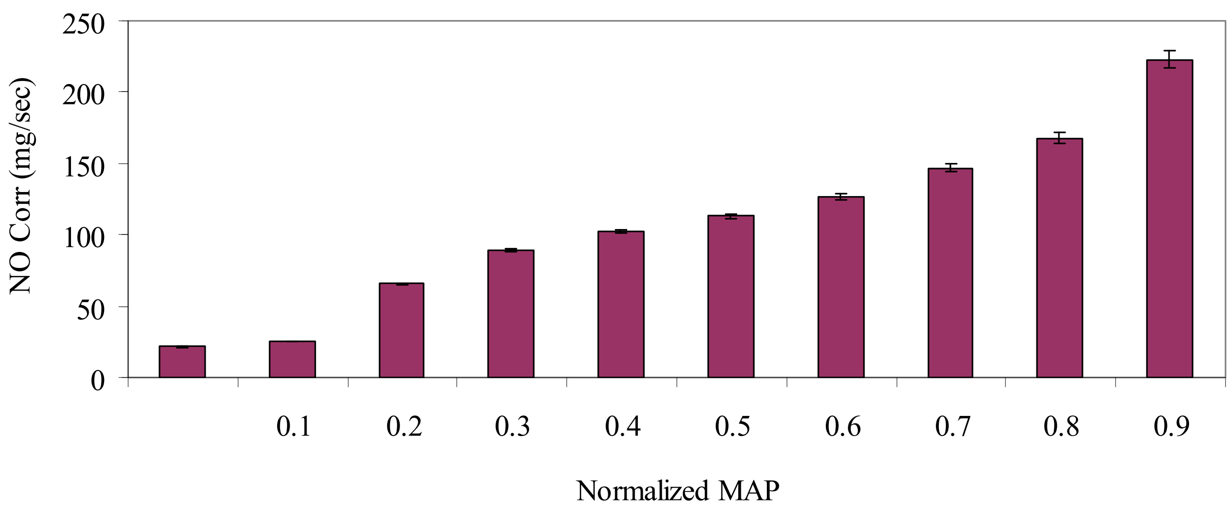


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 34 ^{o}F and the relative humidity was 58 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A29. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Dozer 3 (continued on next page)





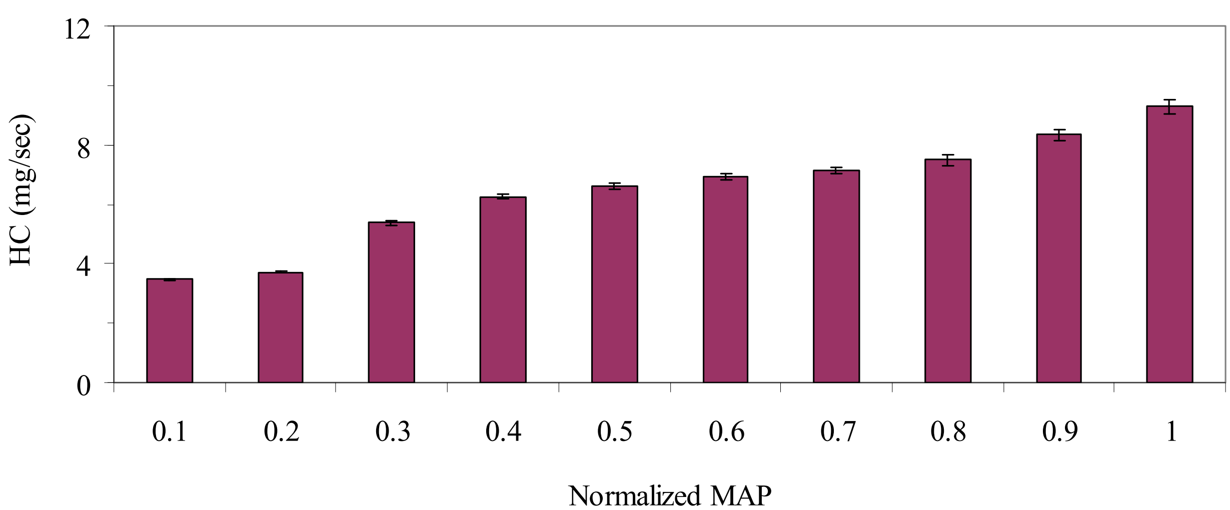
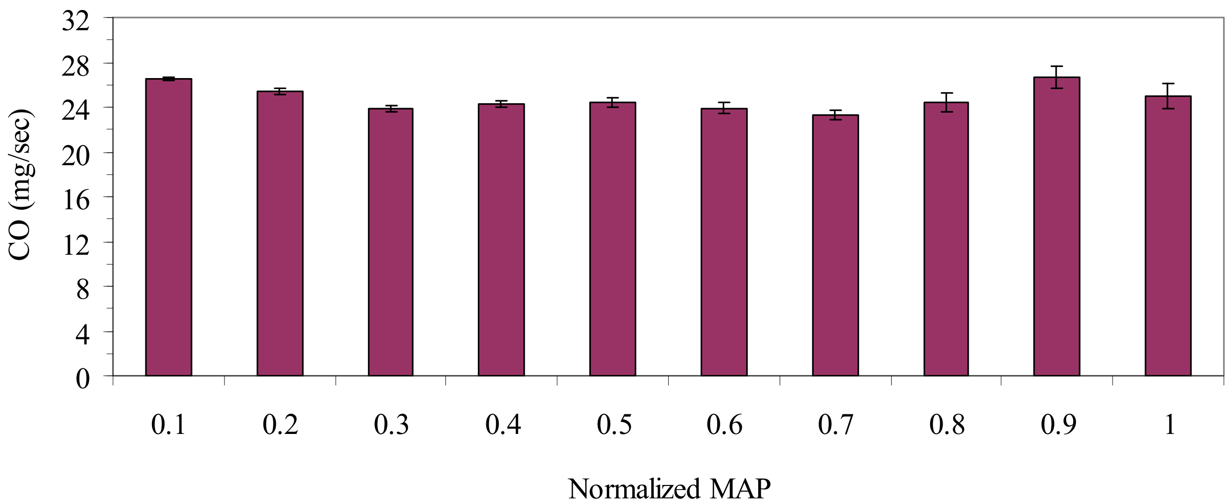


Figure A29. Continued



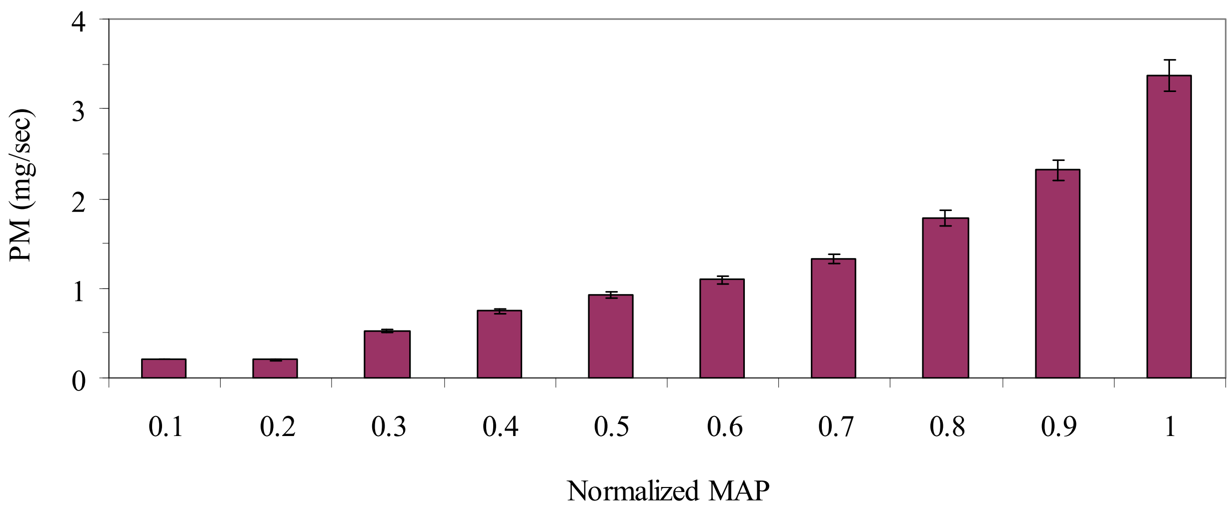
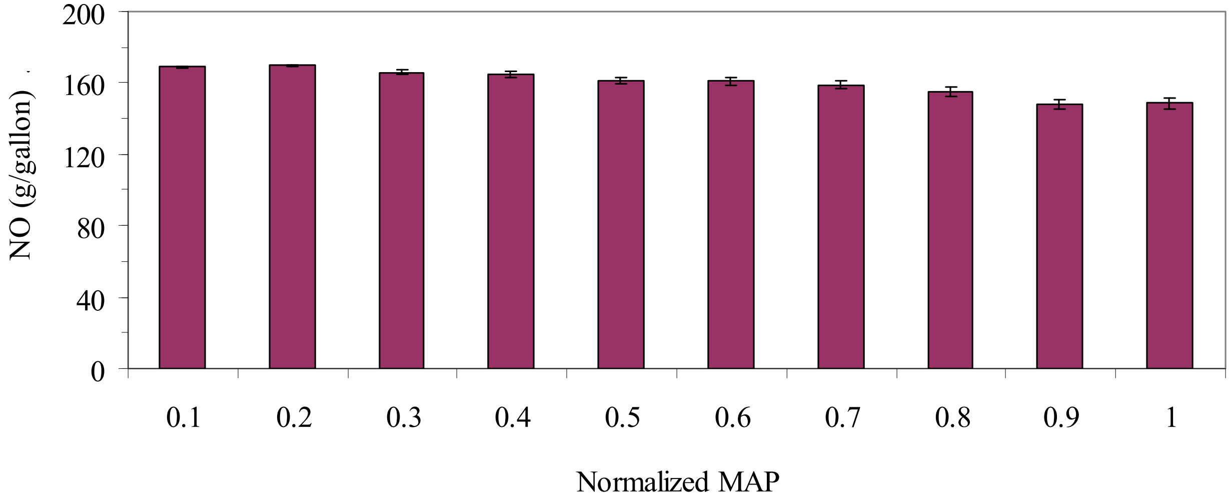
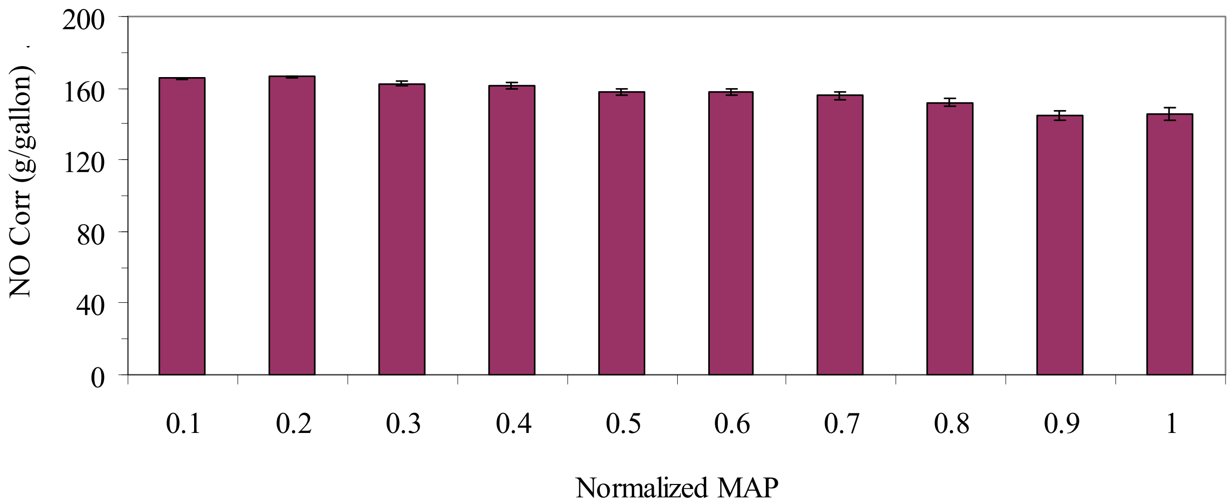


Figure A29. Continued

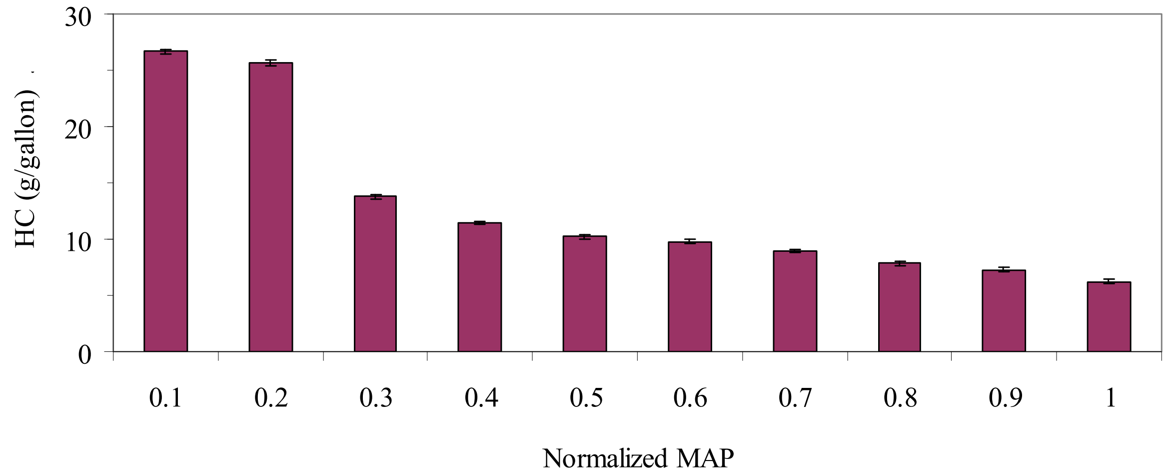


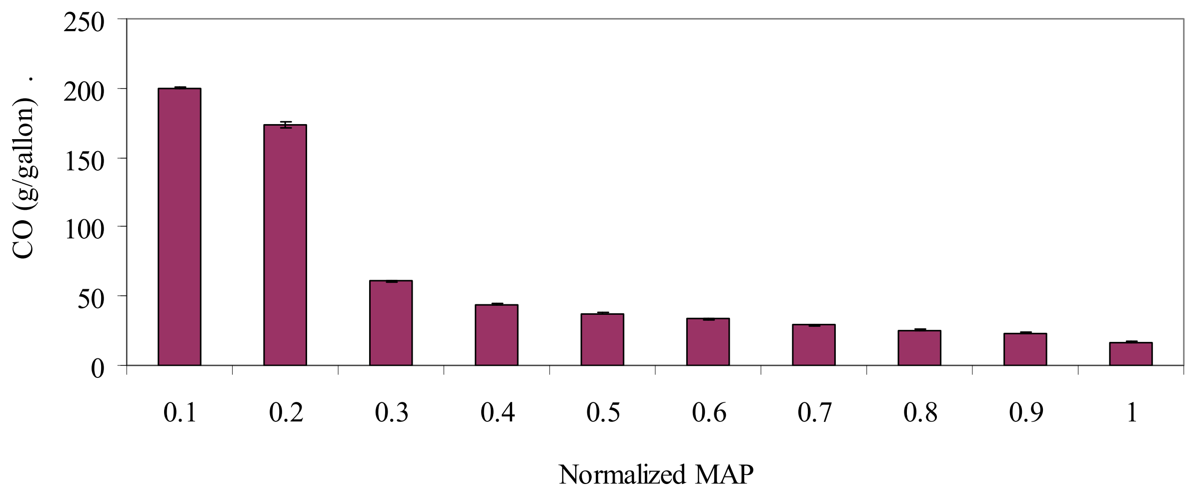


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 34 ^{o}F and the relative humidity was 58 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 $\leq$ Normalized MAP < 0.1; "0.2" = 0.1 $\leq$ Normalized MAP < 0.2, and so on.

Figure A30. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Dozer 3 (continued on next page)





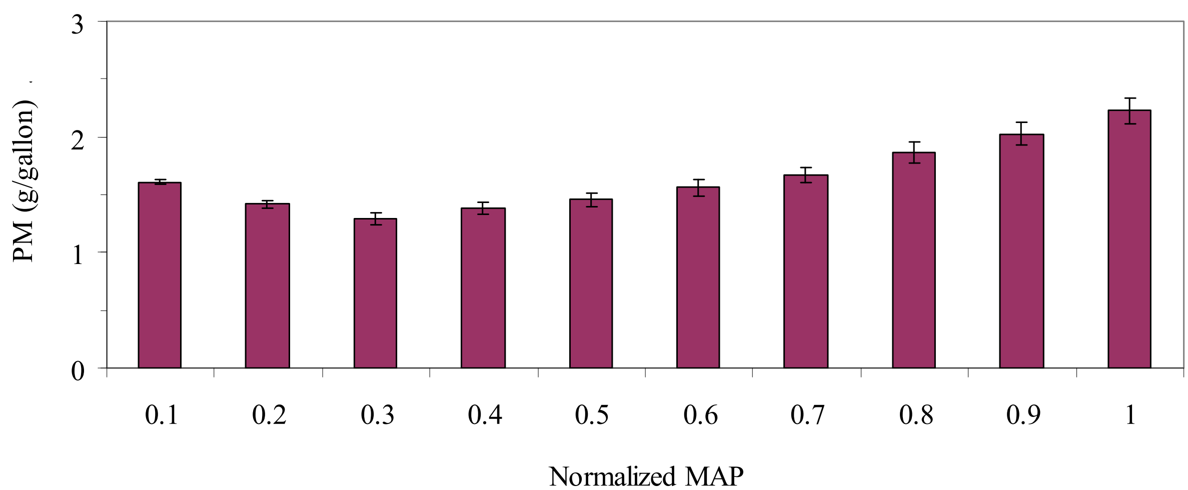
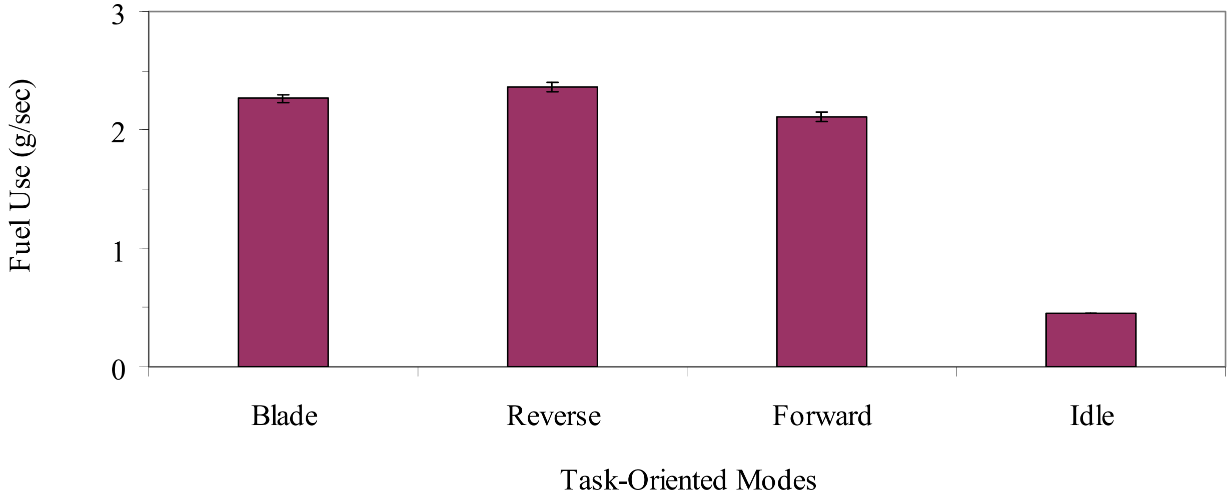
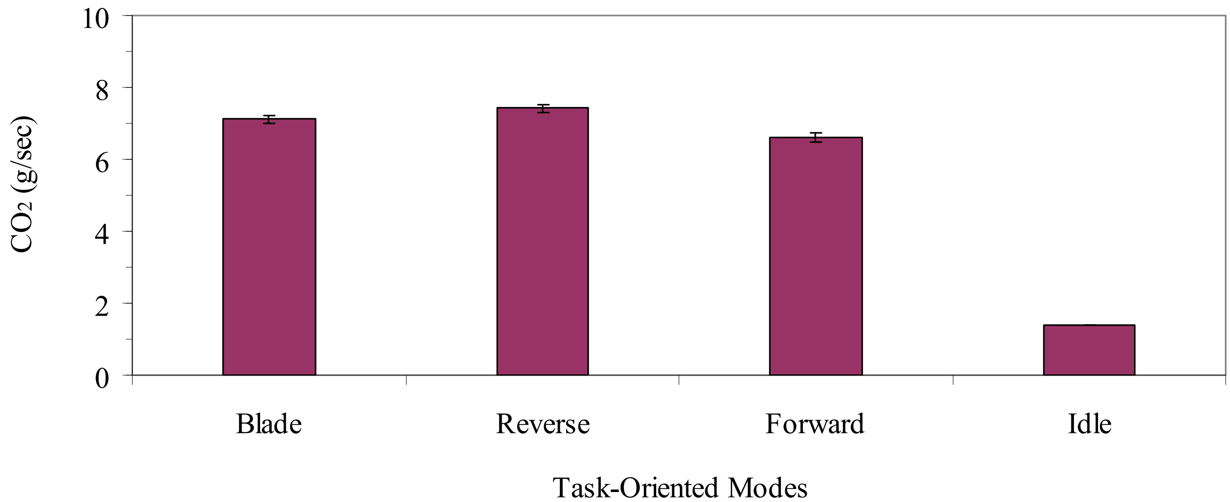


Figure A30. Continued

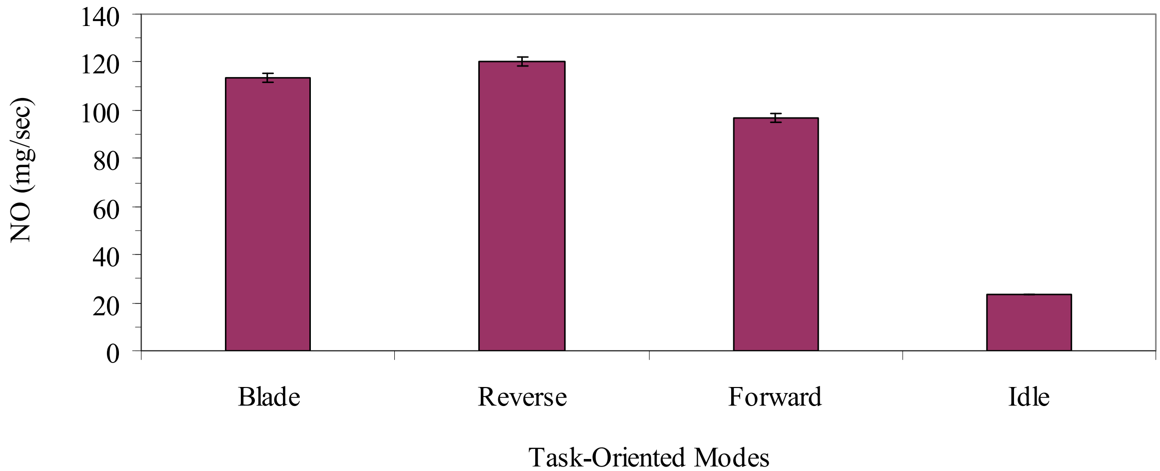


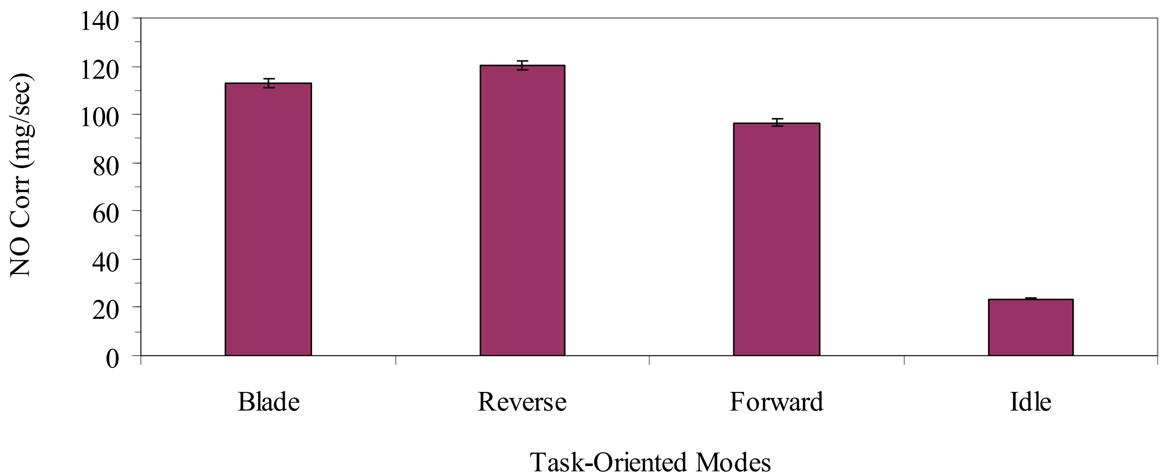


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 34 ^{o}F and the relative humidity was 58 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *forward*: forward movement of the dozer when the bucket is not in contact with the ground; *reverse*: reverse movement of the dozer when the bucket is not in contact with the ground; *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A31. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Dozer 3 (continued on next page)





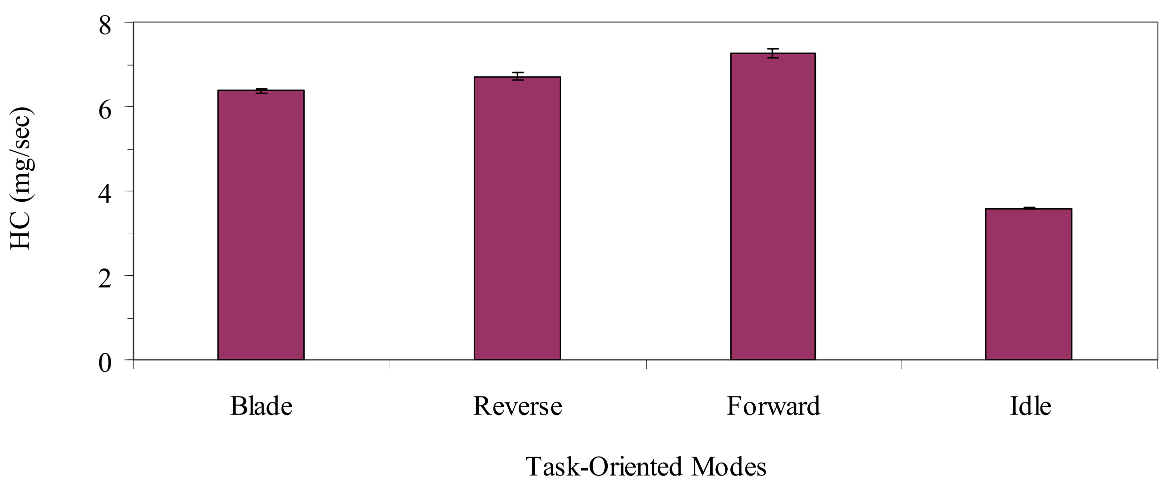


Figure A31. Continued

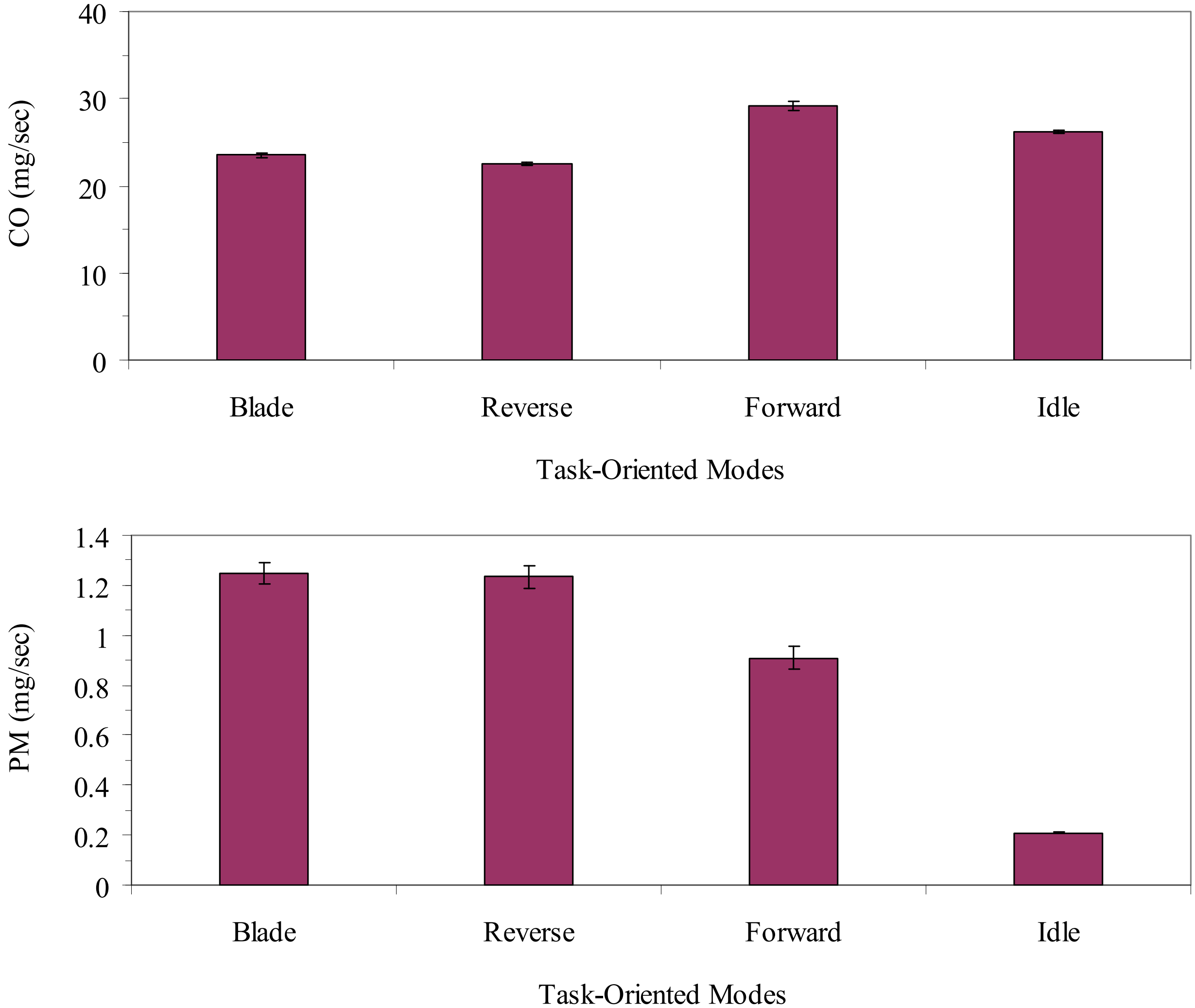
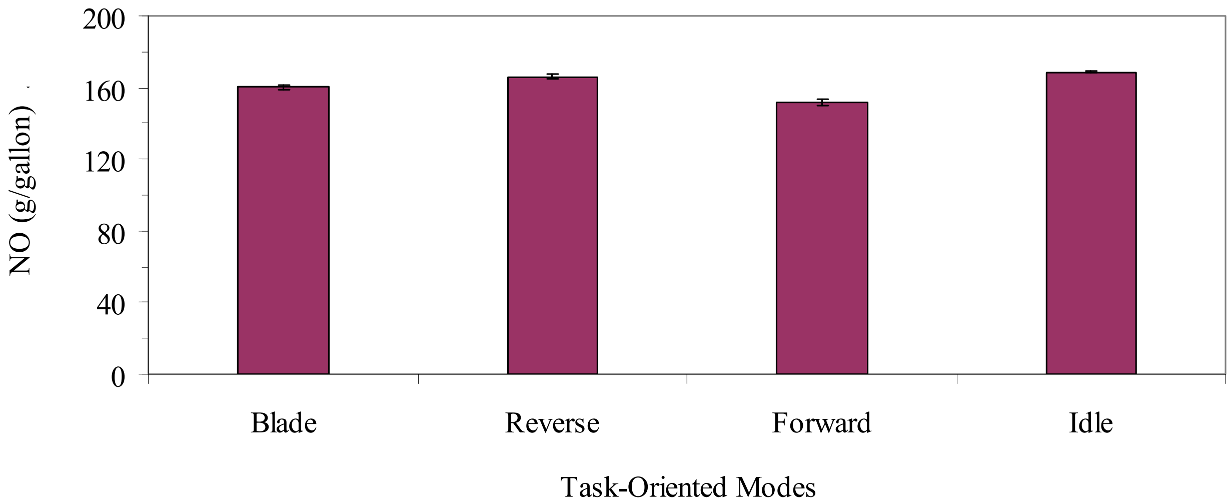
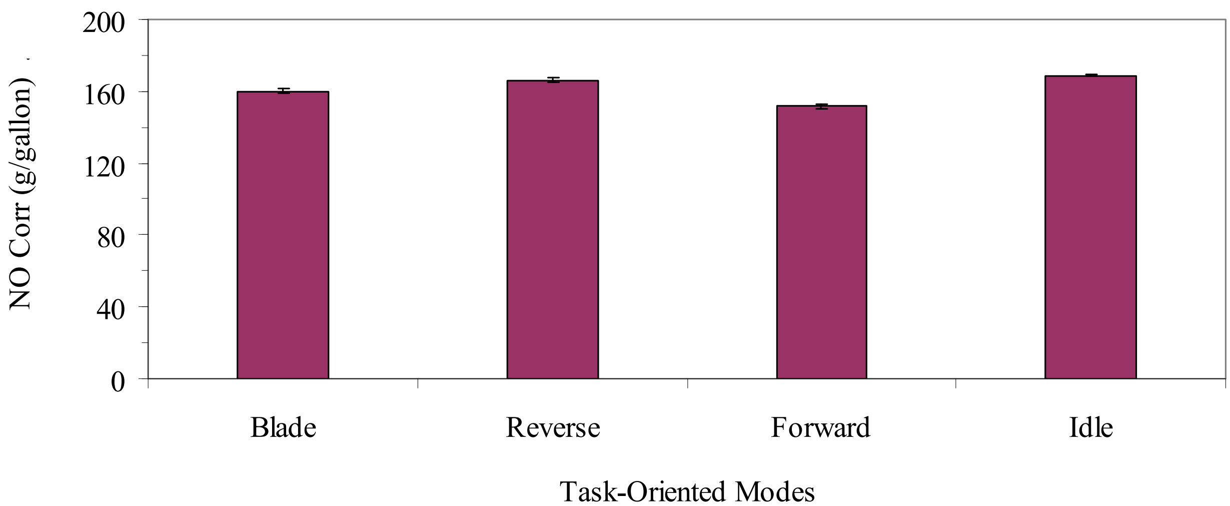


Figure A31. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 34 ^{o}F and the relative humidity was 58 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *forward*: forward movement of the dozer when the bucket is not in contact with the ground; *reverse*: reverse movement of the dozer when the bucket is not in contact with the ground; *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A32. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Dozer 3 (continued on next page)

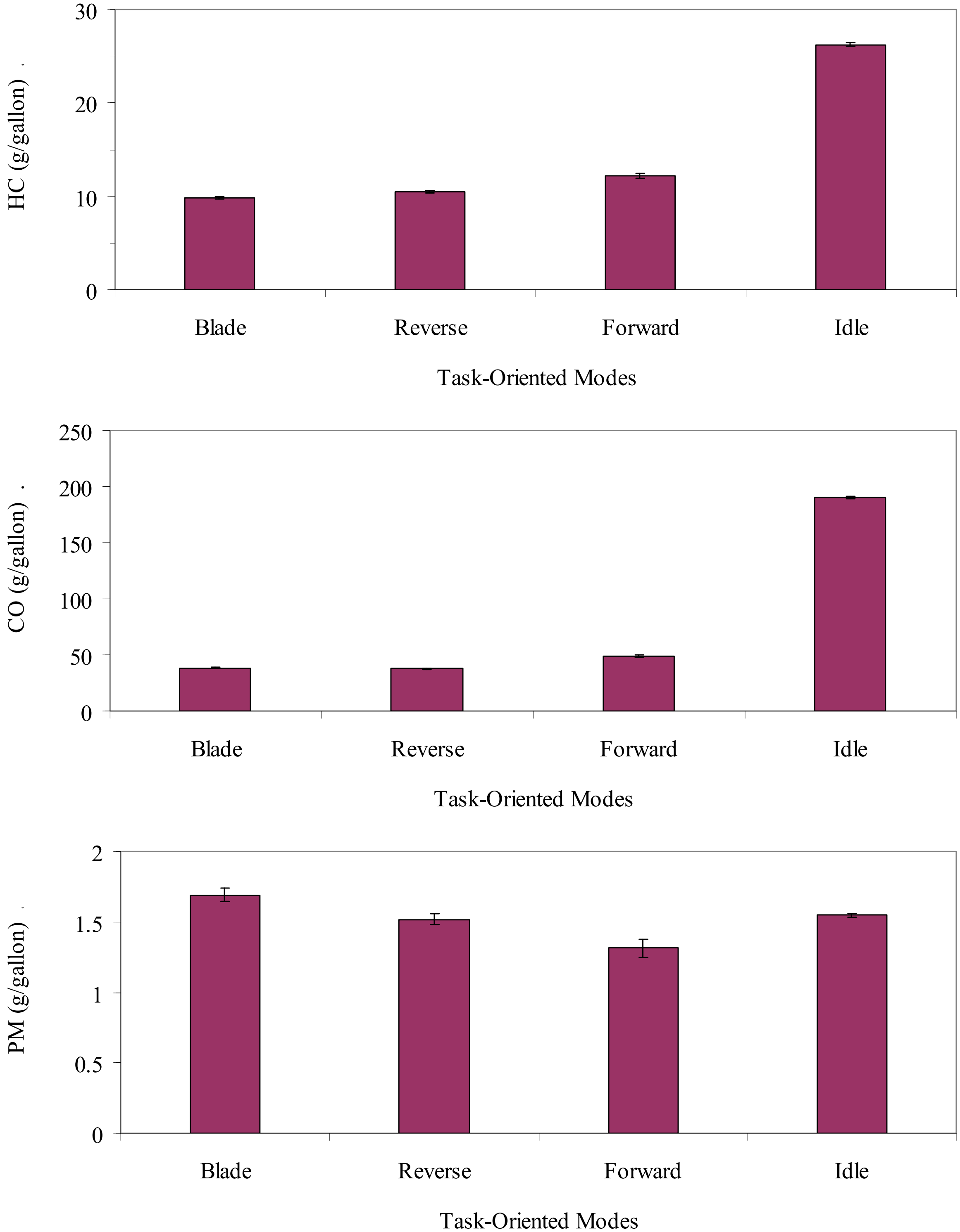
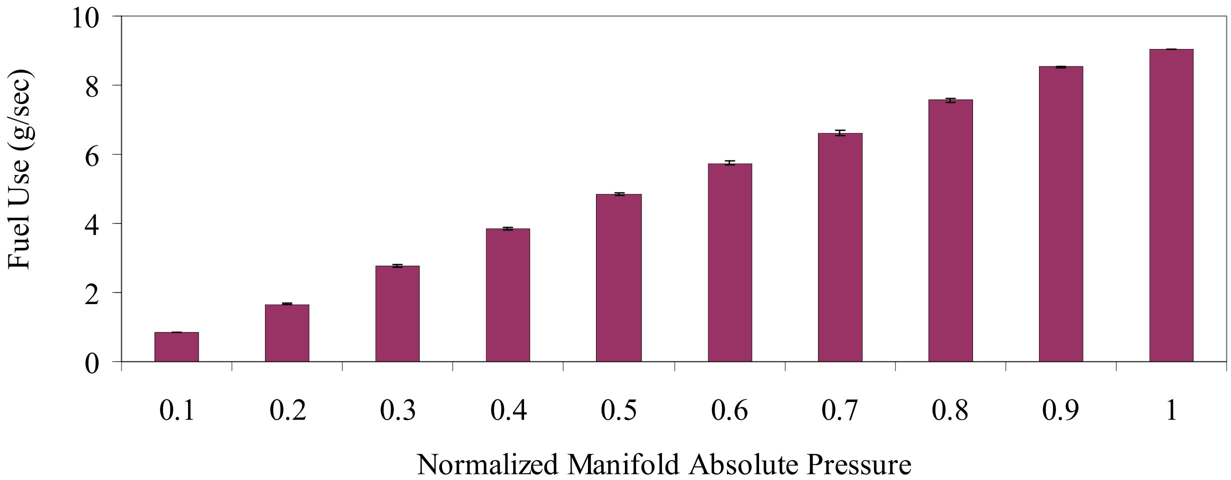
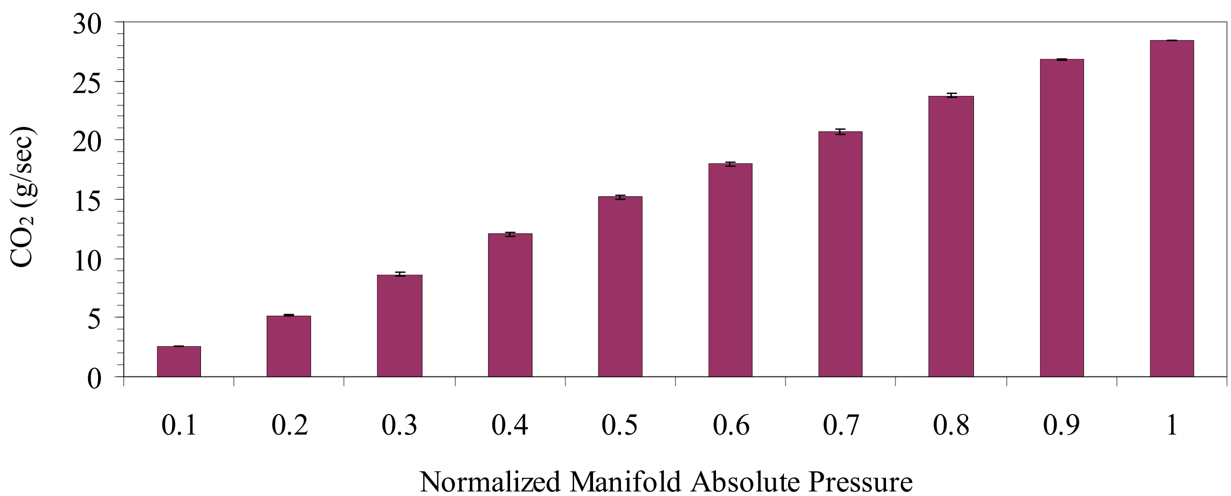


Figure A32. Continued

Dozer 4





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 75 ^oF and the relative humidity was 54 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A33. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Dozer 4 (continued on next page)

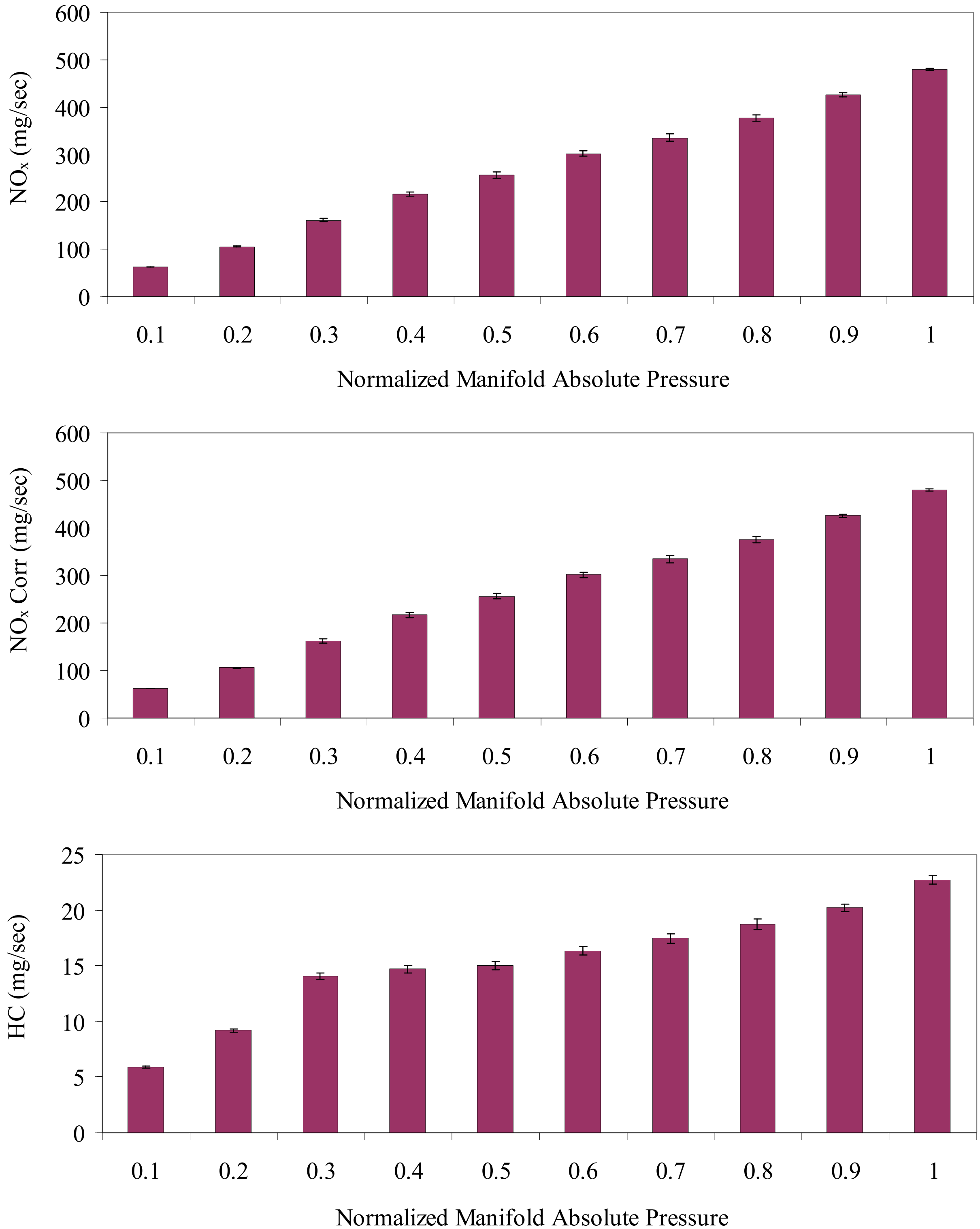
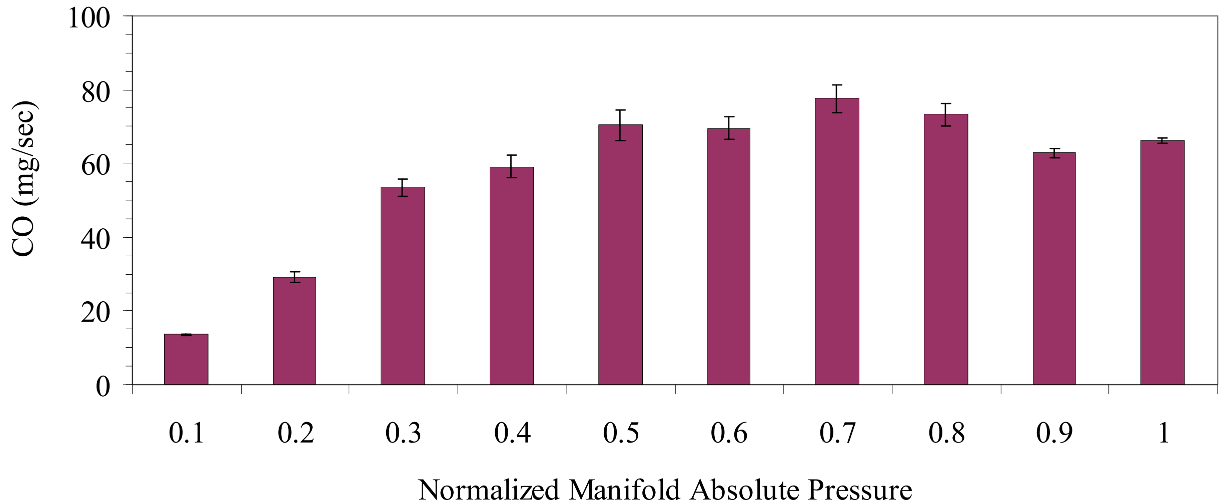


Figure A33. Continued



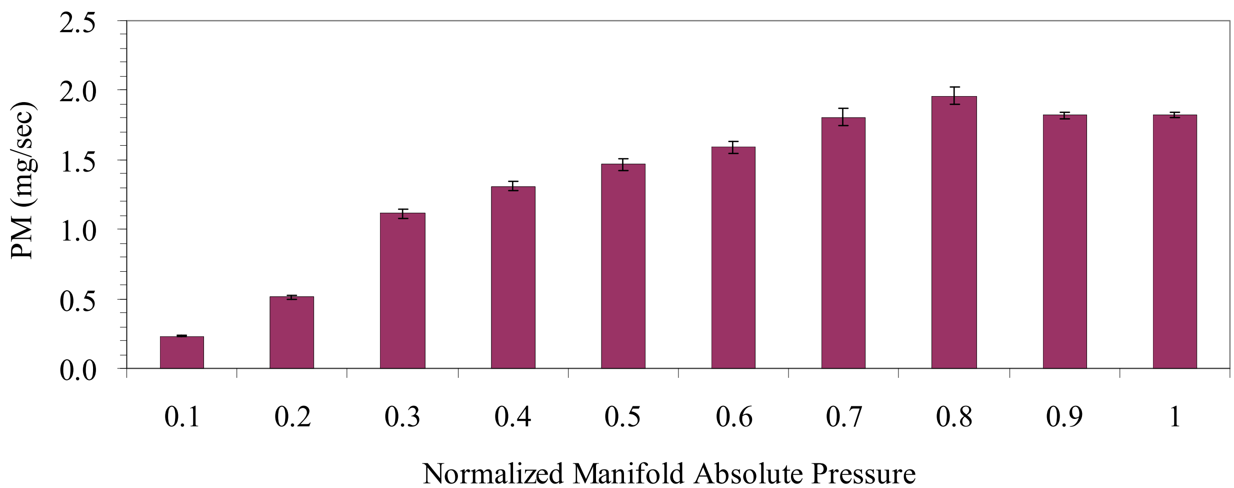
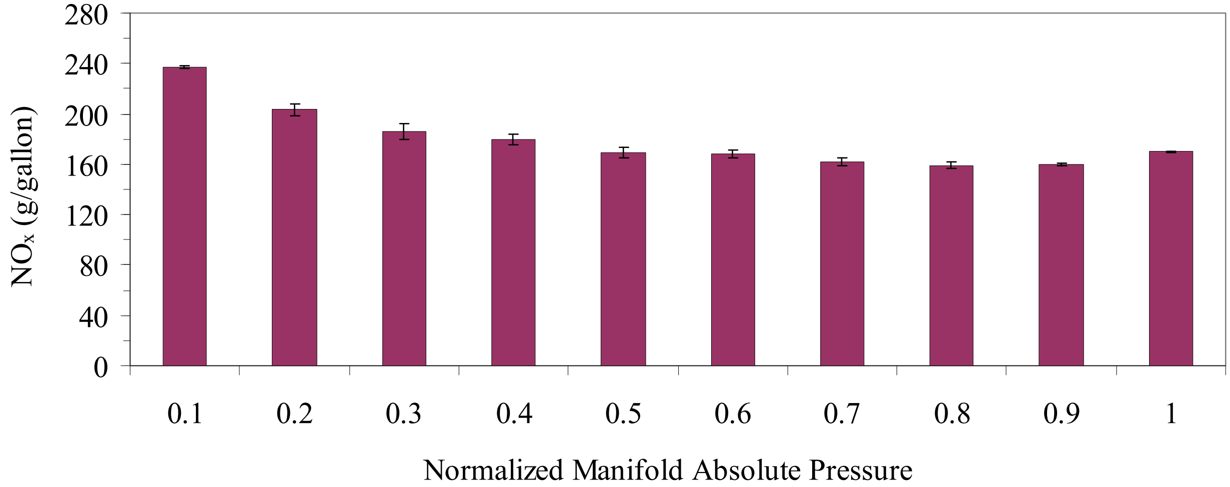
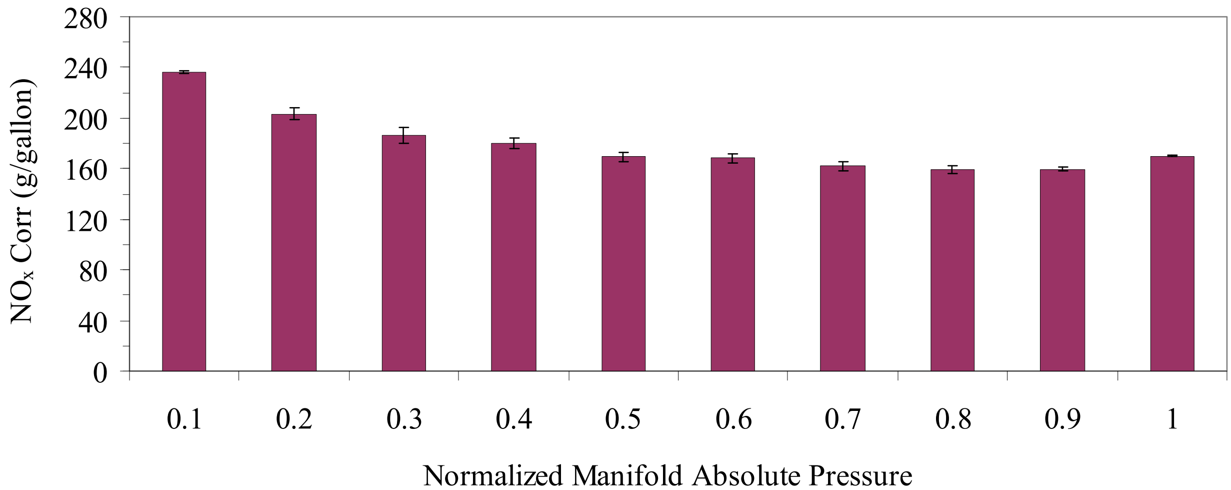


Figure A33. Continued

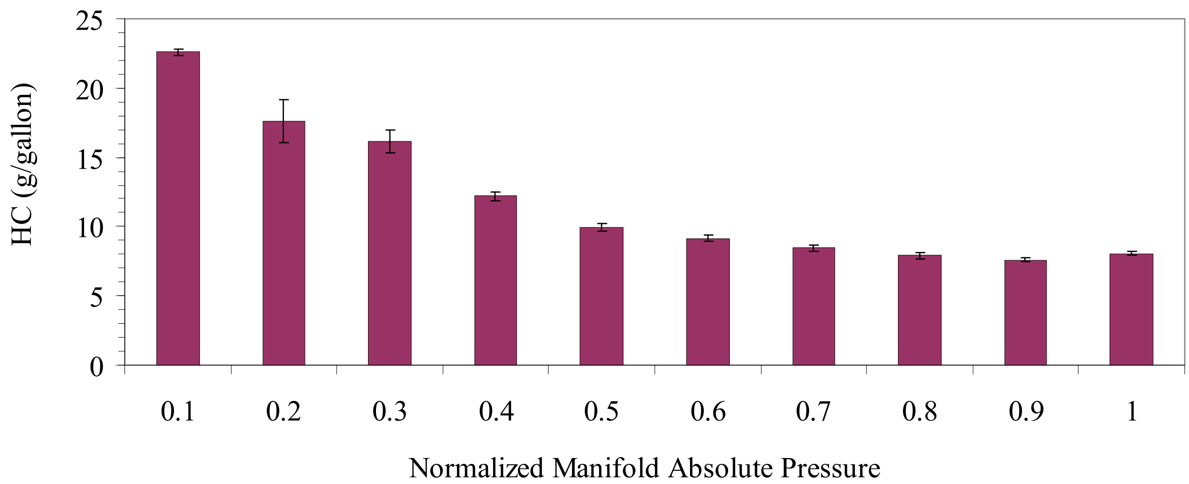


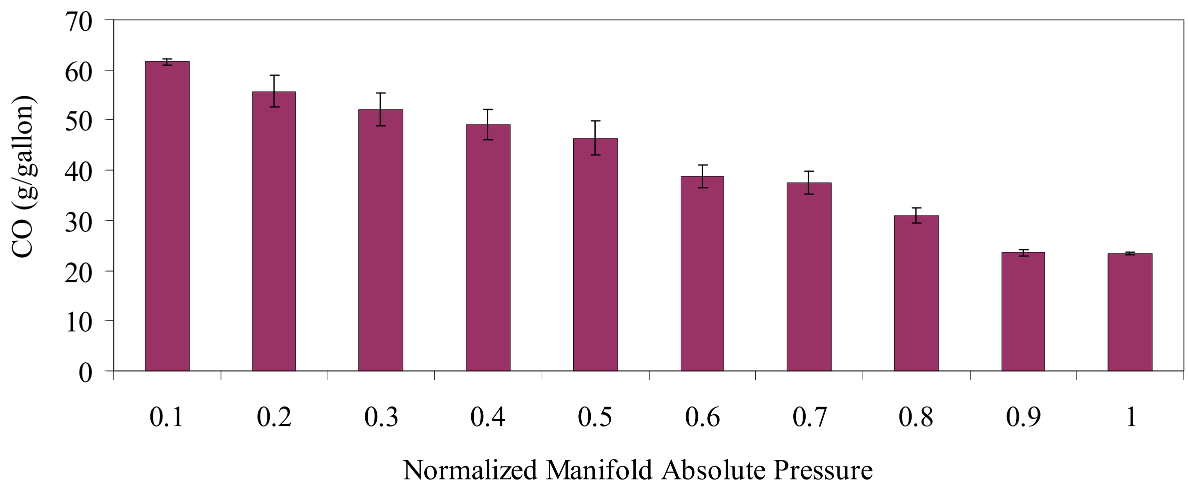


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 75 ^{o}F and the relative humidity was 54 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A34. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Dozer 4 (continued on next page)





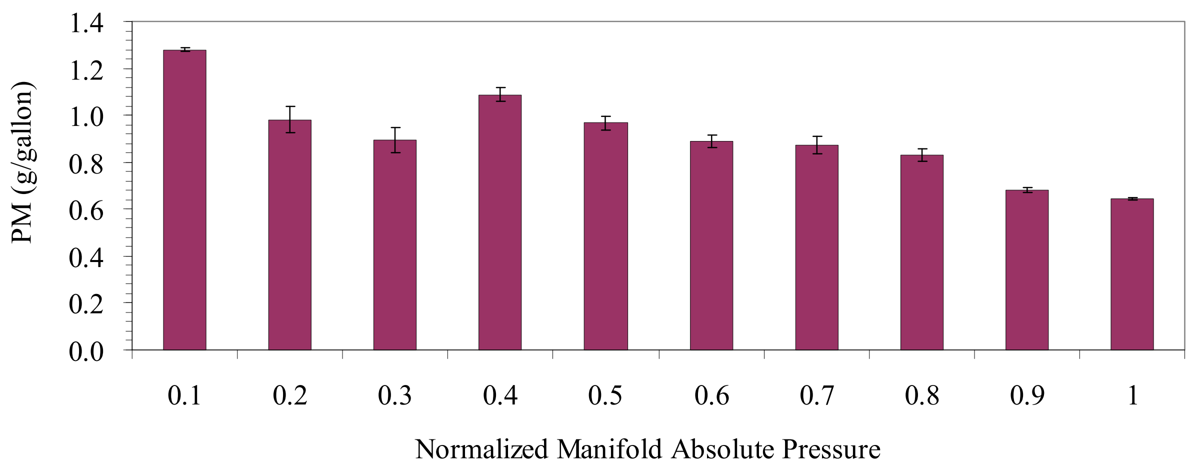
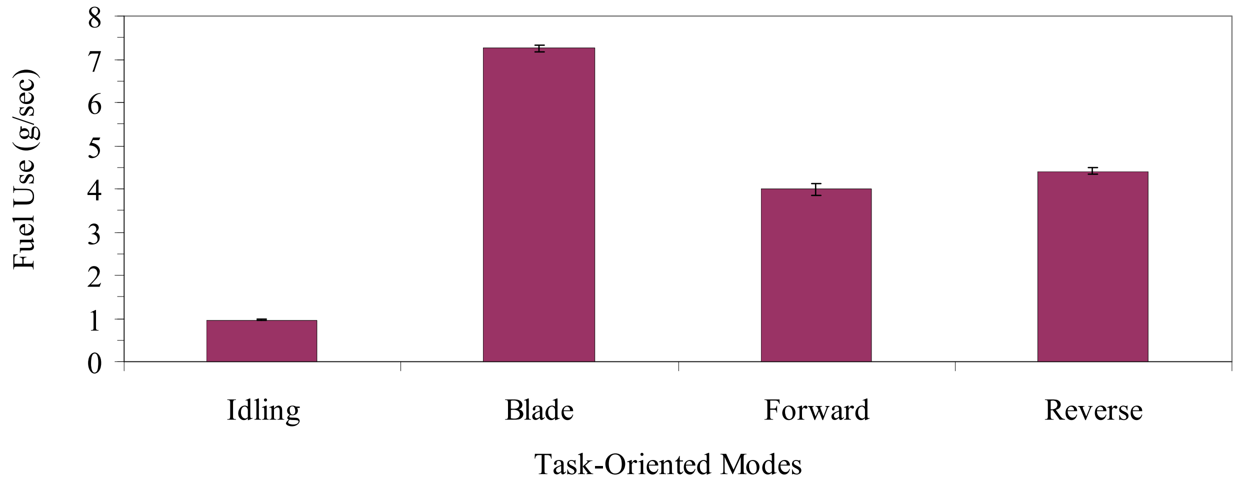
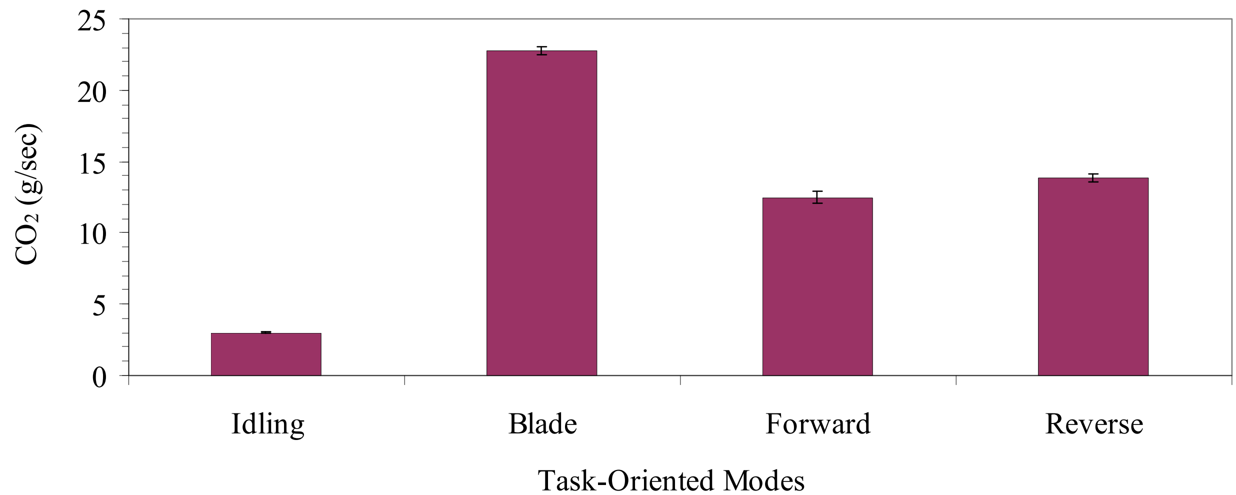


Figure A34. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 75 ^{o}F and the relative humidity was 54 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *forward*: forward movement of the dozer when the bucket is not in contact with the ground; *reverse*: reverse movement of the dozer when the bucket is not in contact with the ground; *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A35. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Dozer 4 (continued on next page)

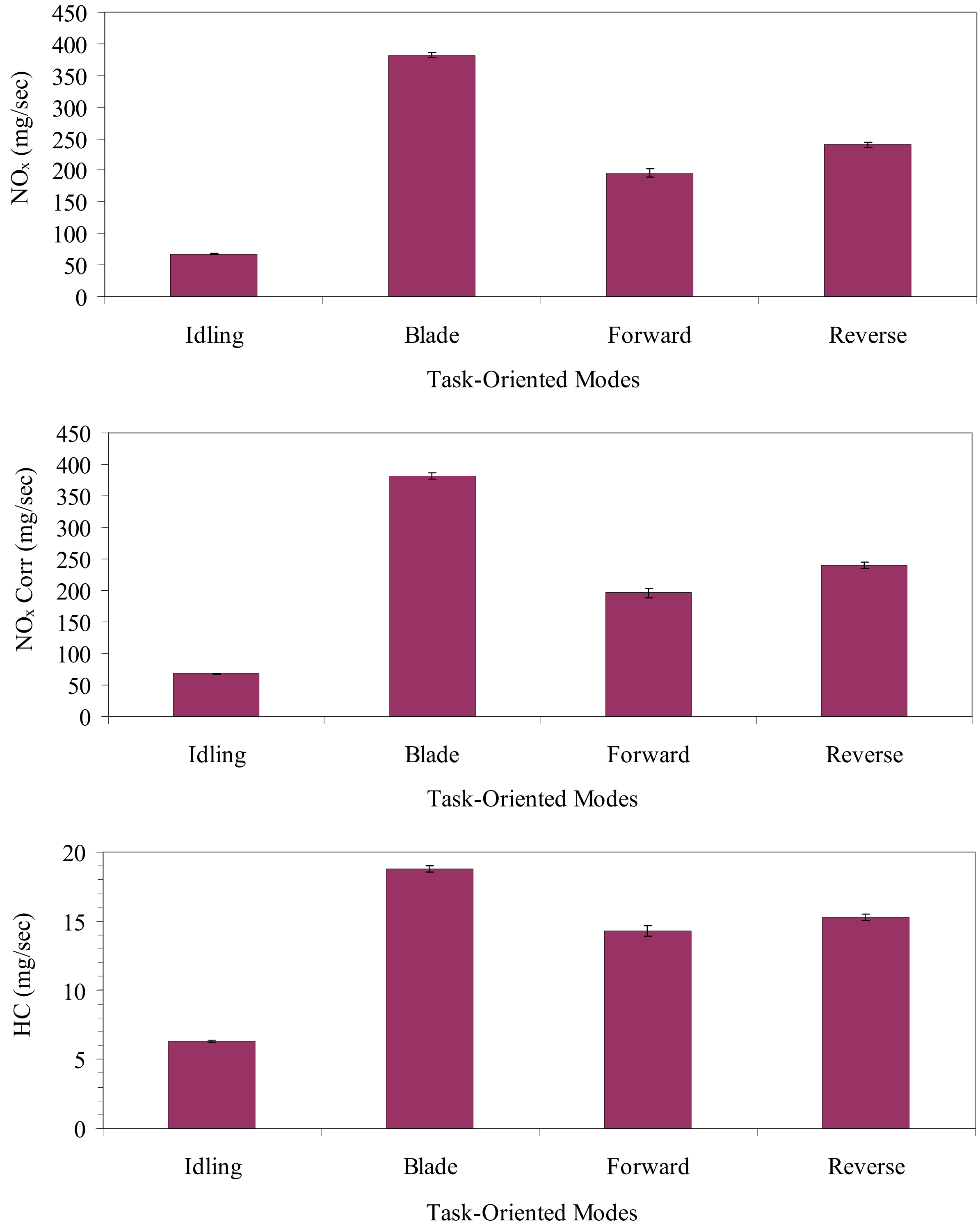


Figure A35. Continued

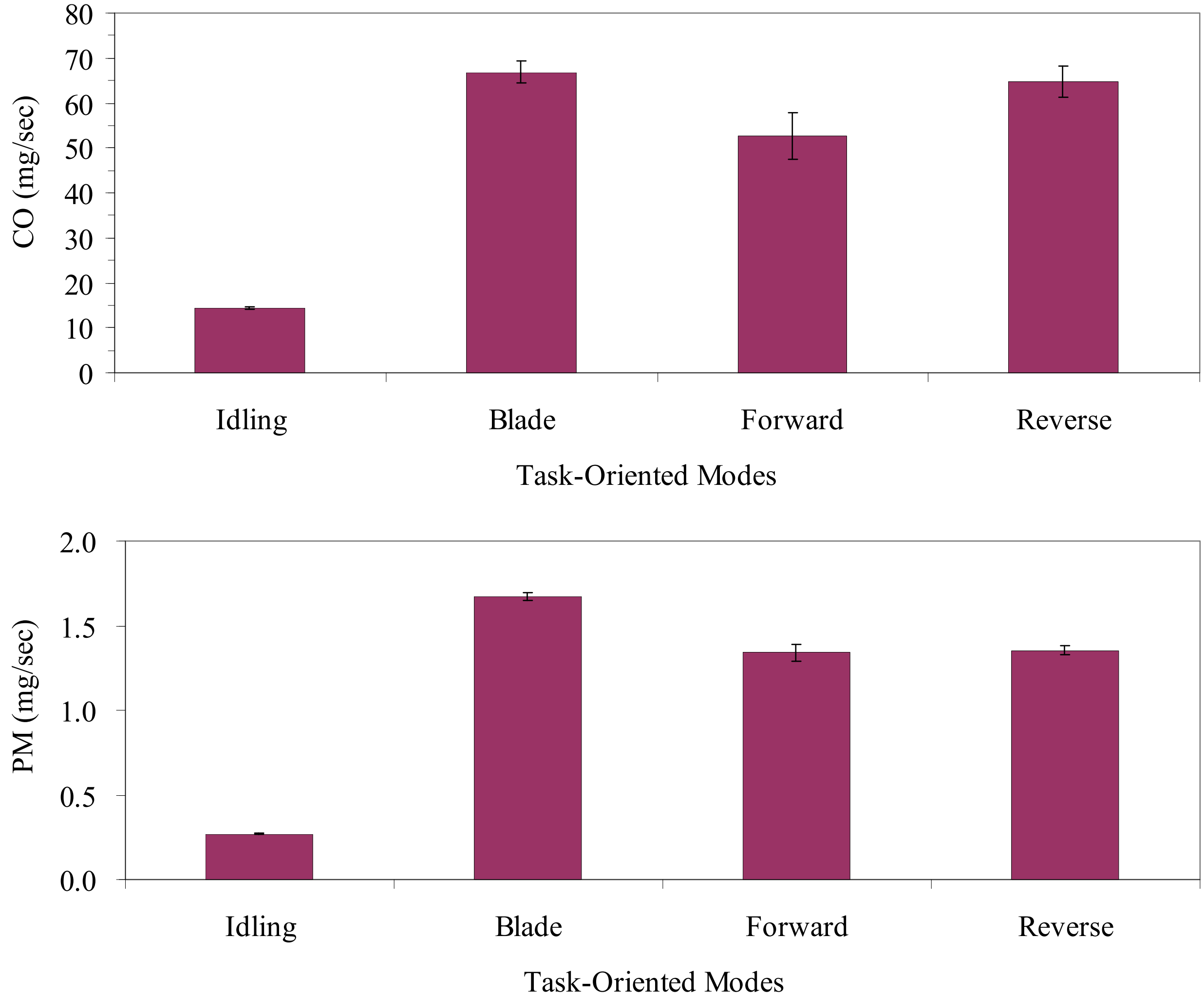
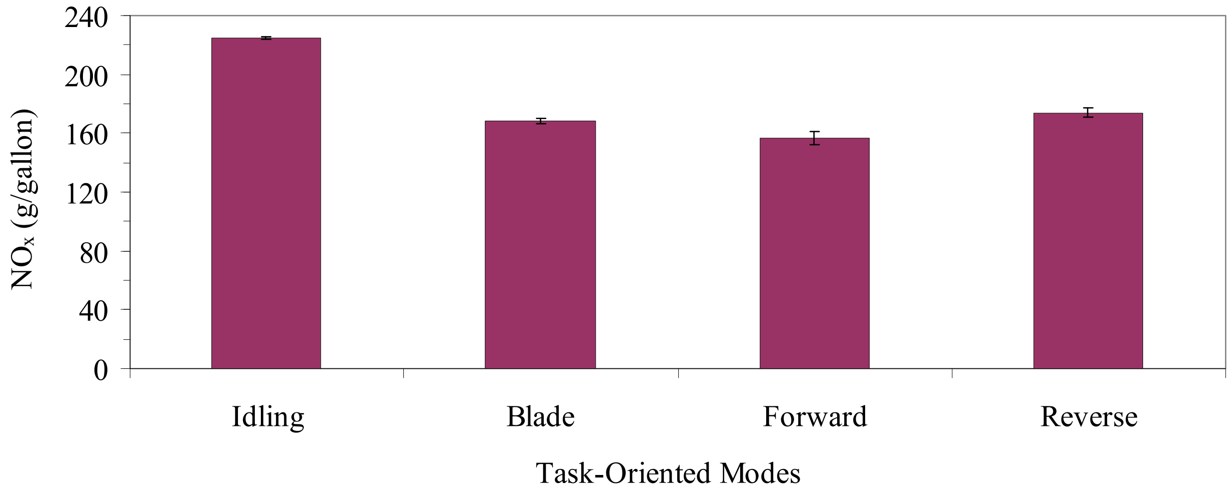
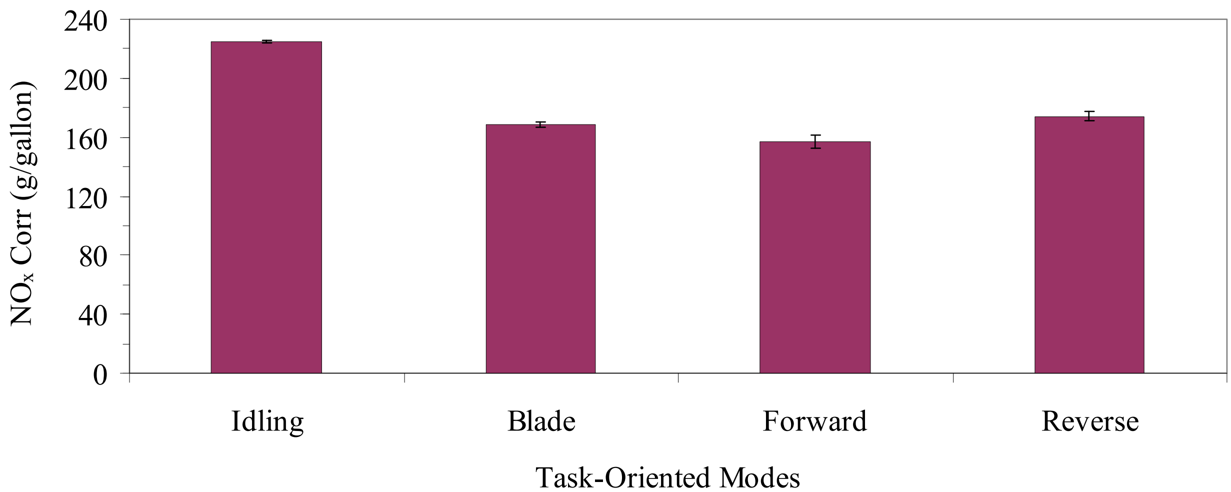


Figure A35. Continued

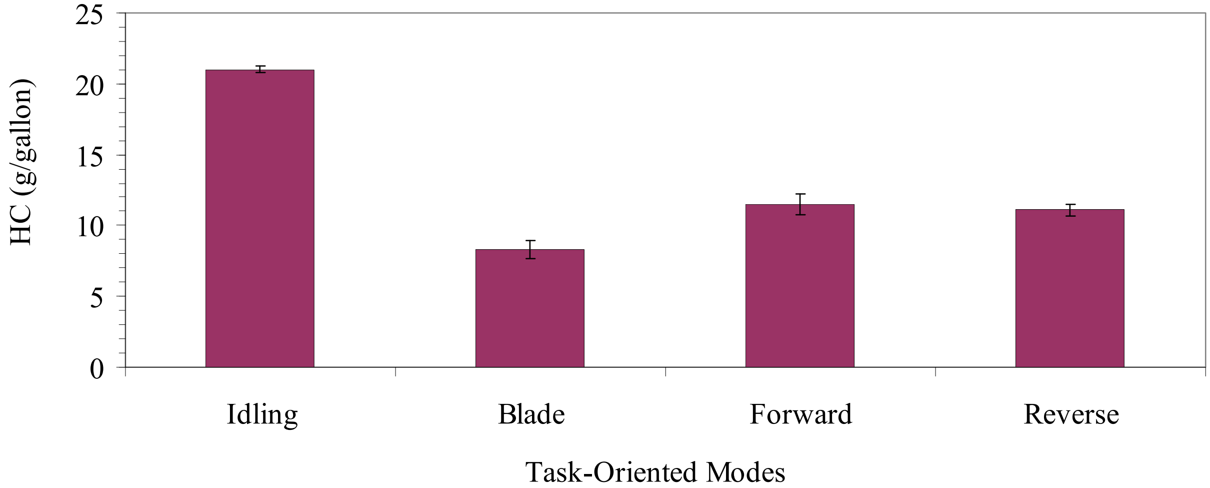


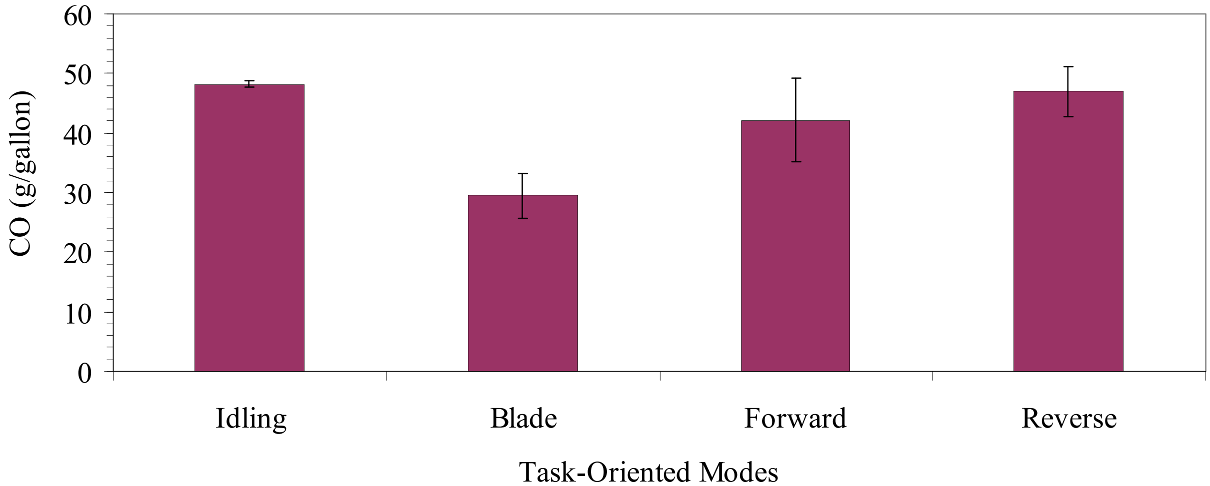


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 75 ^{o}F and the relative humidity was 54 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *forward*: forward movement of the dozer when the bucket is not in contact with the ground; *reverse*: reverse movement of the dozer when the bucket is not in contact with the ground; *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A36. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Dozer 4 (continued on next page)





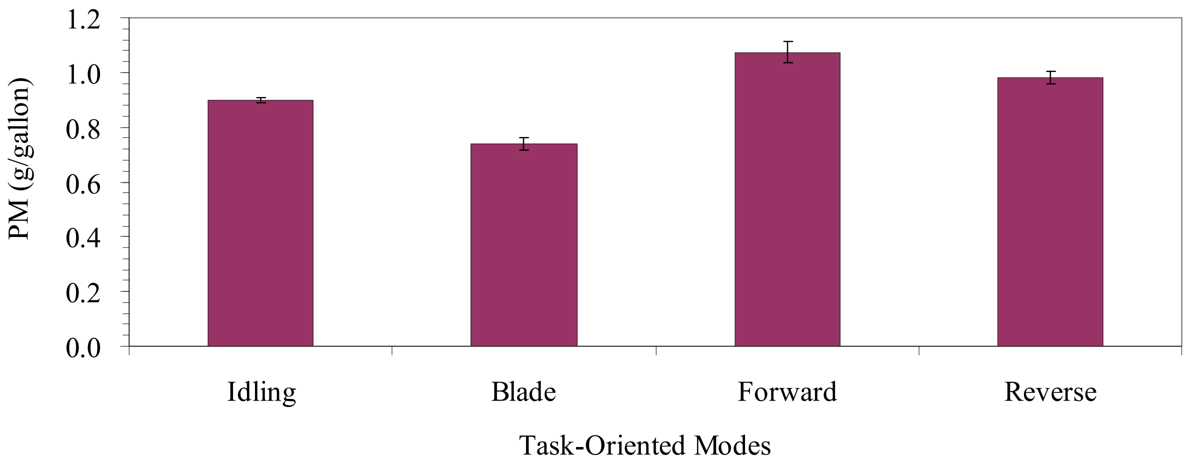
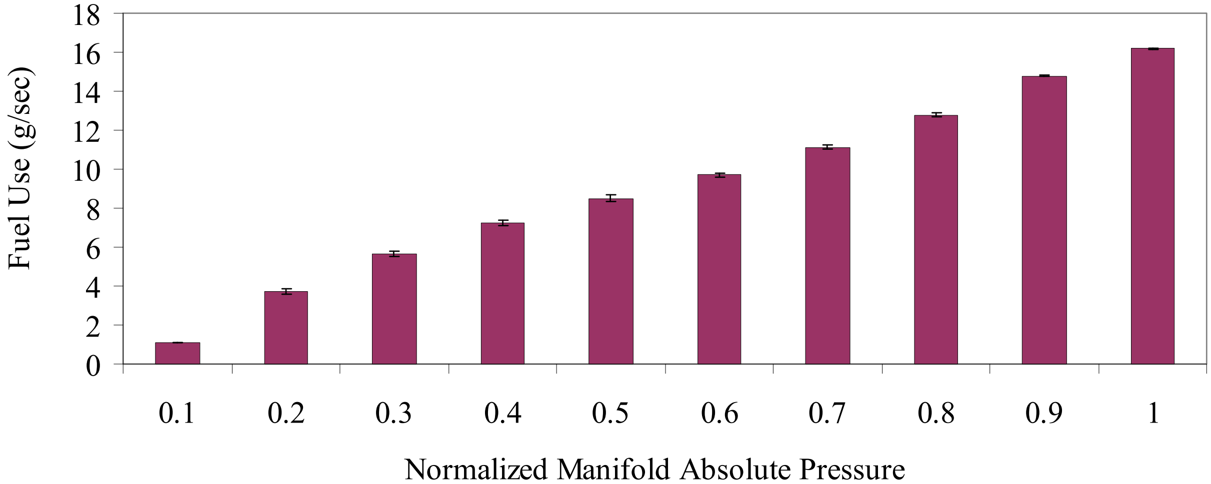
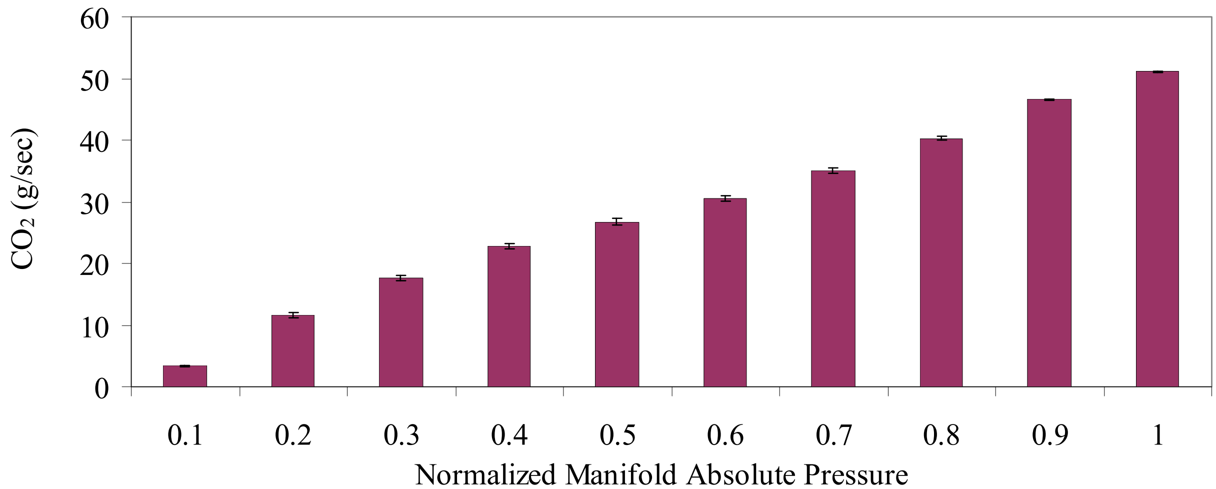


Figure A36. Continued

Dozer 5





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 56 ^{o}F and the relative humidity was 70 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A37. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Dozer 5 (continued on next page)

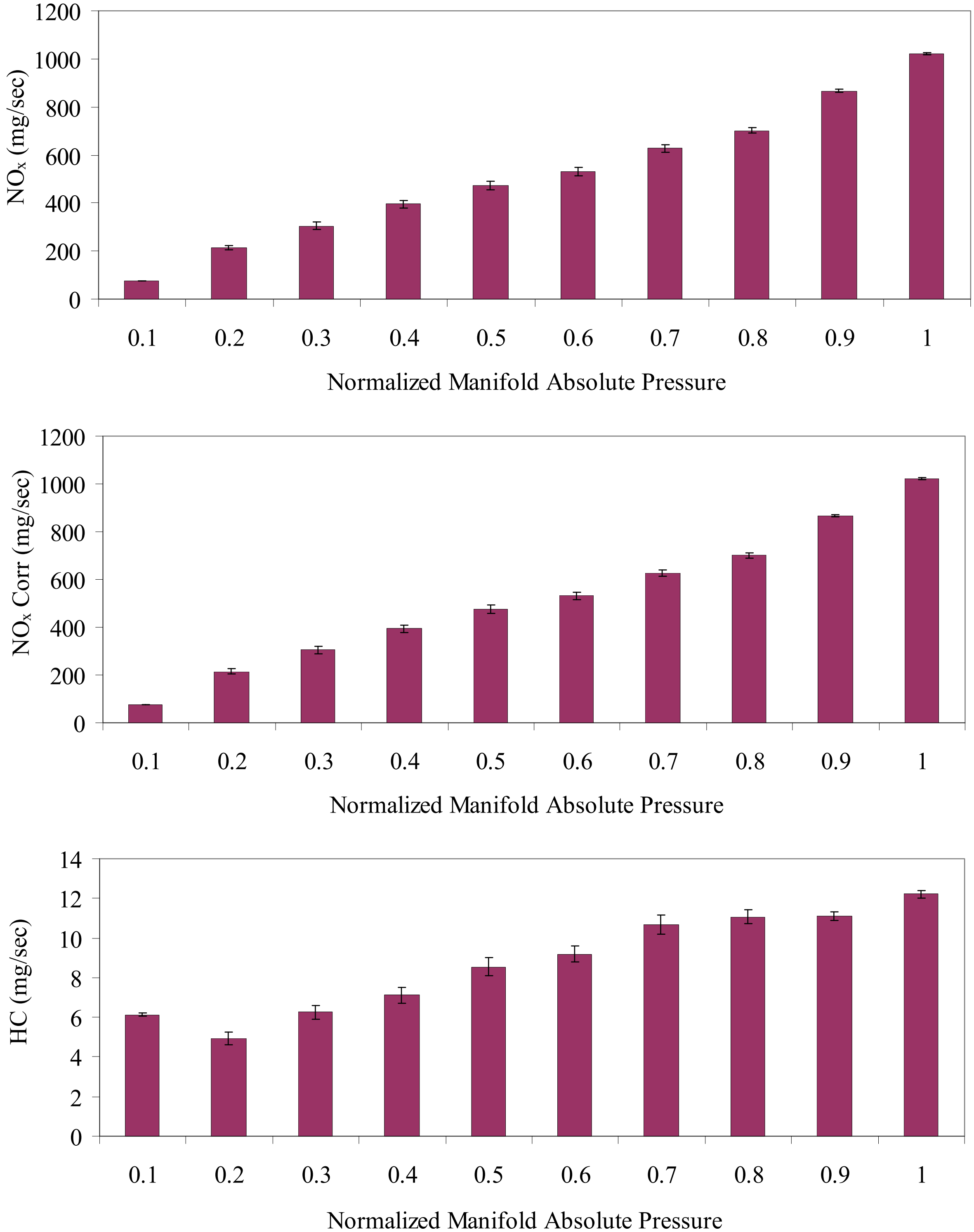


Figure A37. Continued

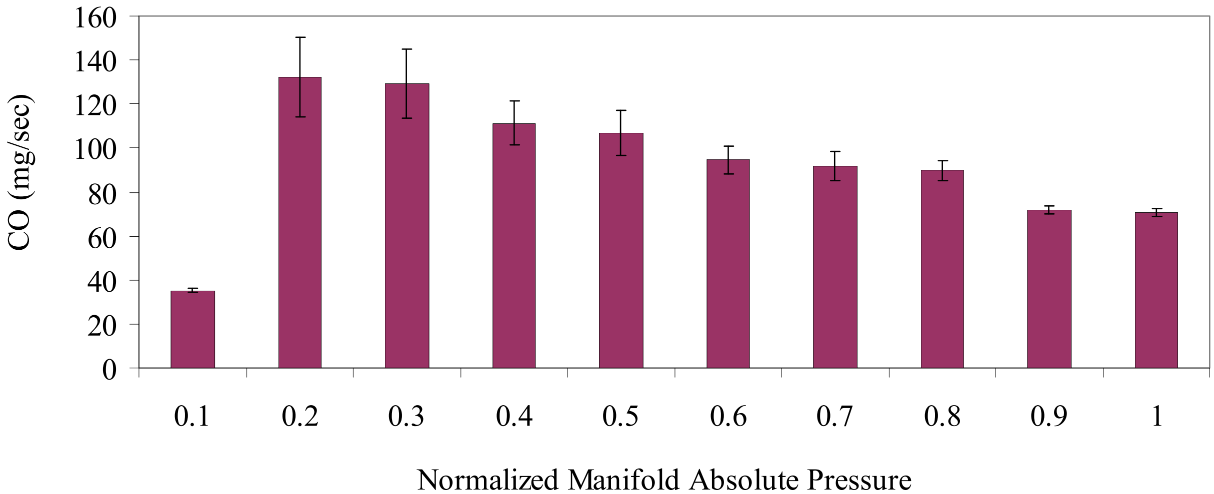
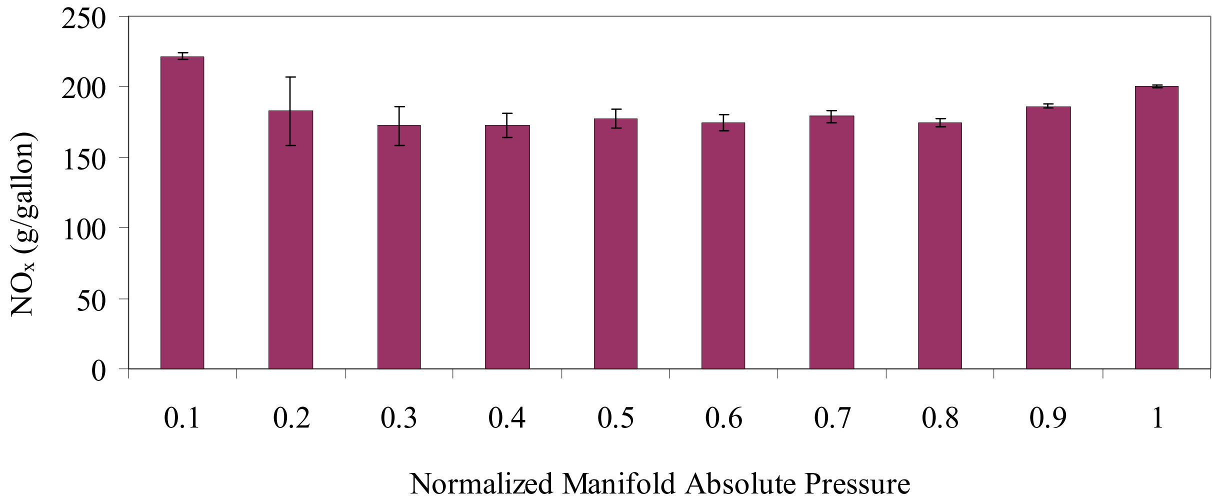
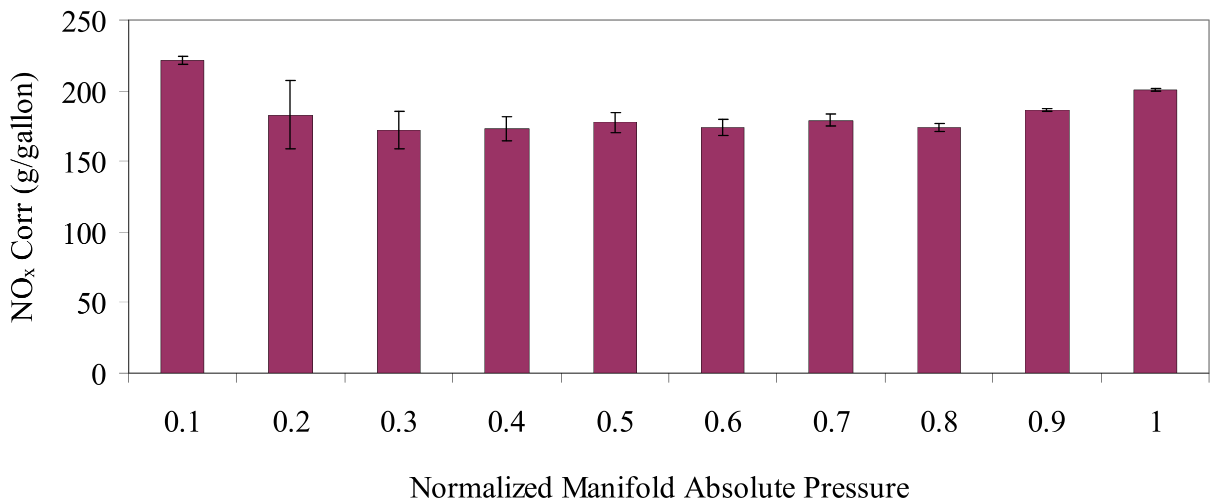


Figure A37. Continued

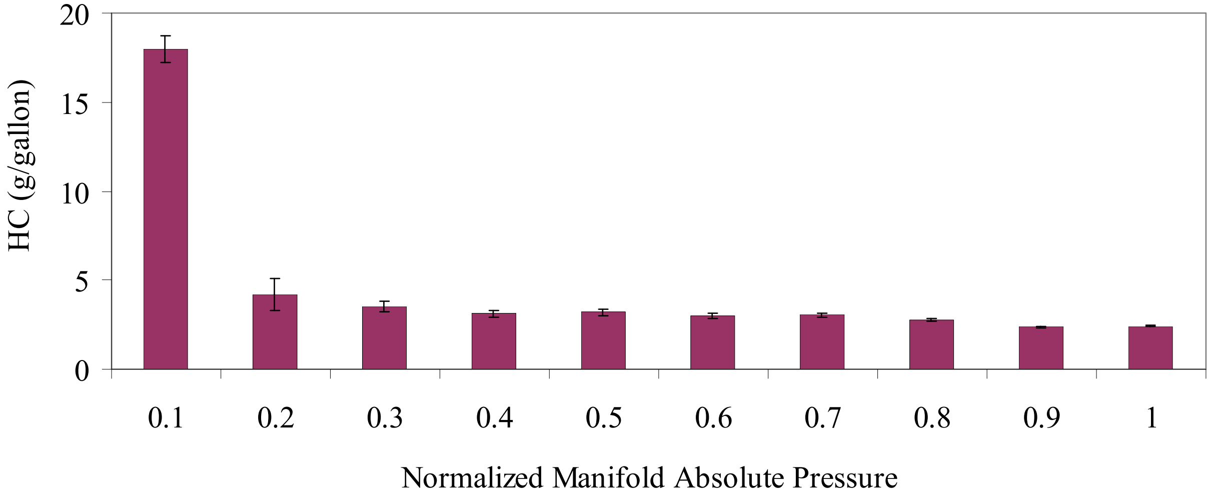




NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 56 ^{o}F and the relative humidity was 70 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A38. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Dozer 5 (continued on next page)



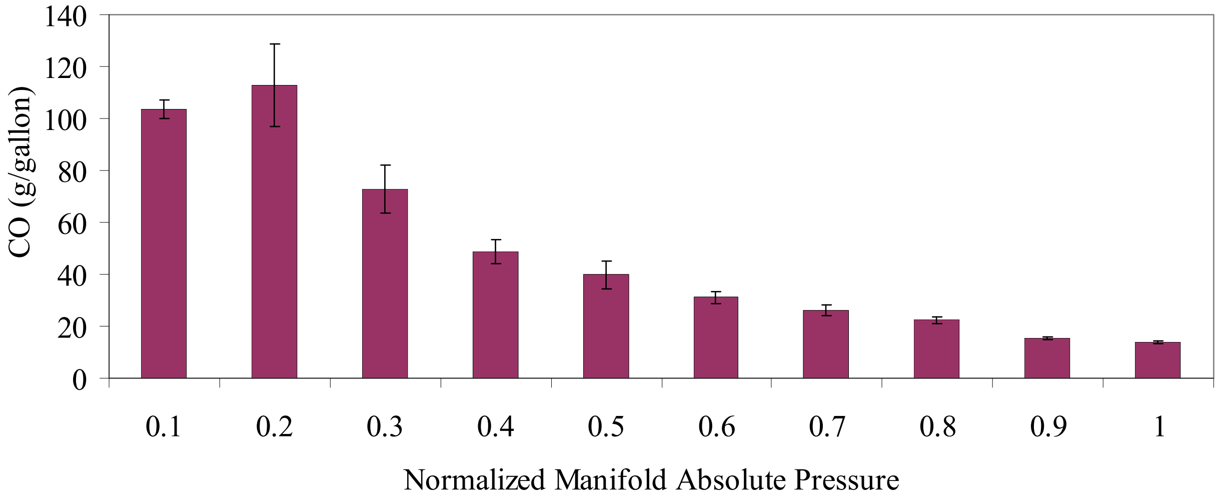
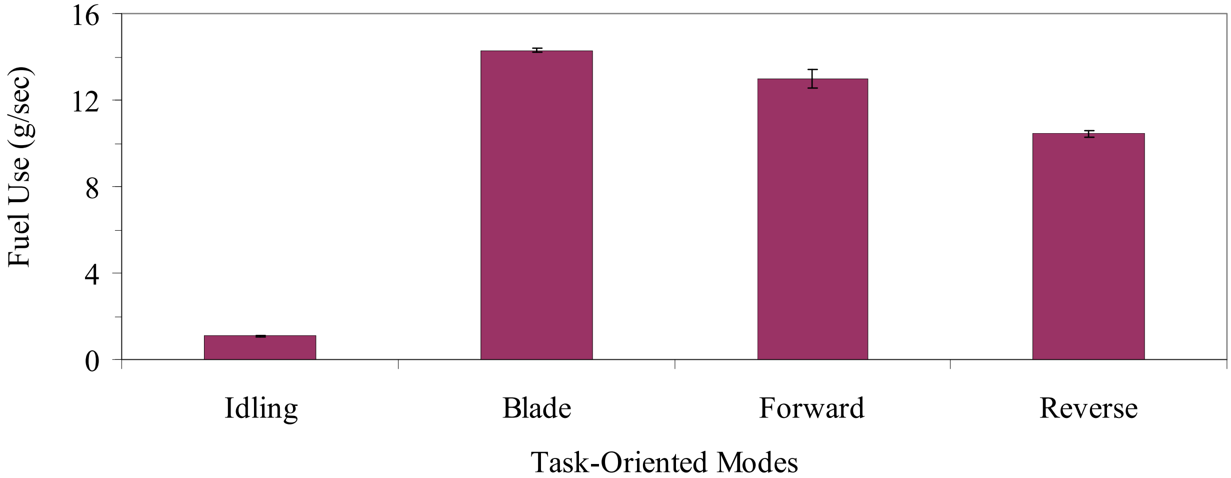
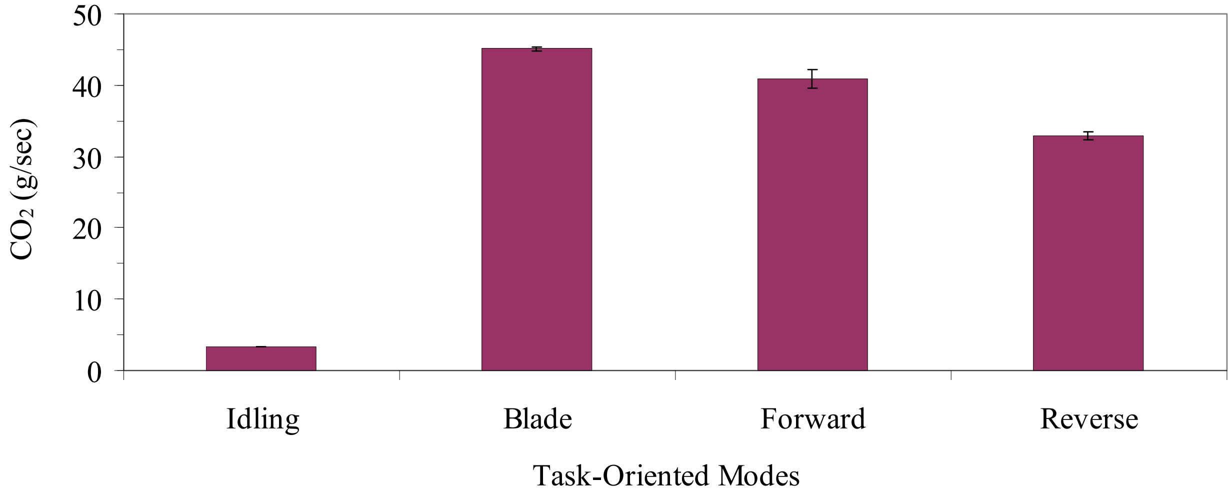


Figure A38. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 56 ^{o}F and the relative humidity was 70 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *forward*: forward movement of the dozer when the bucket is not in contact with the ground; *reverse*: reverse movement of the dozer when the bucket is not in contact with the ground; *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A39. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Dozer 5 (continued on next page)

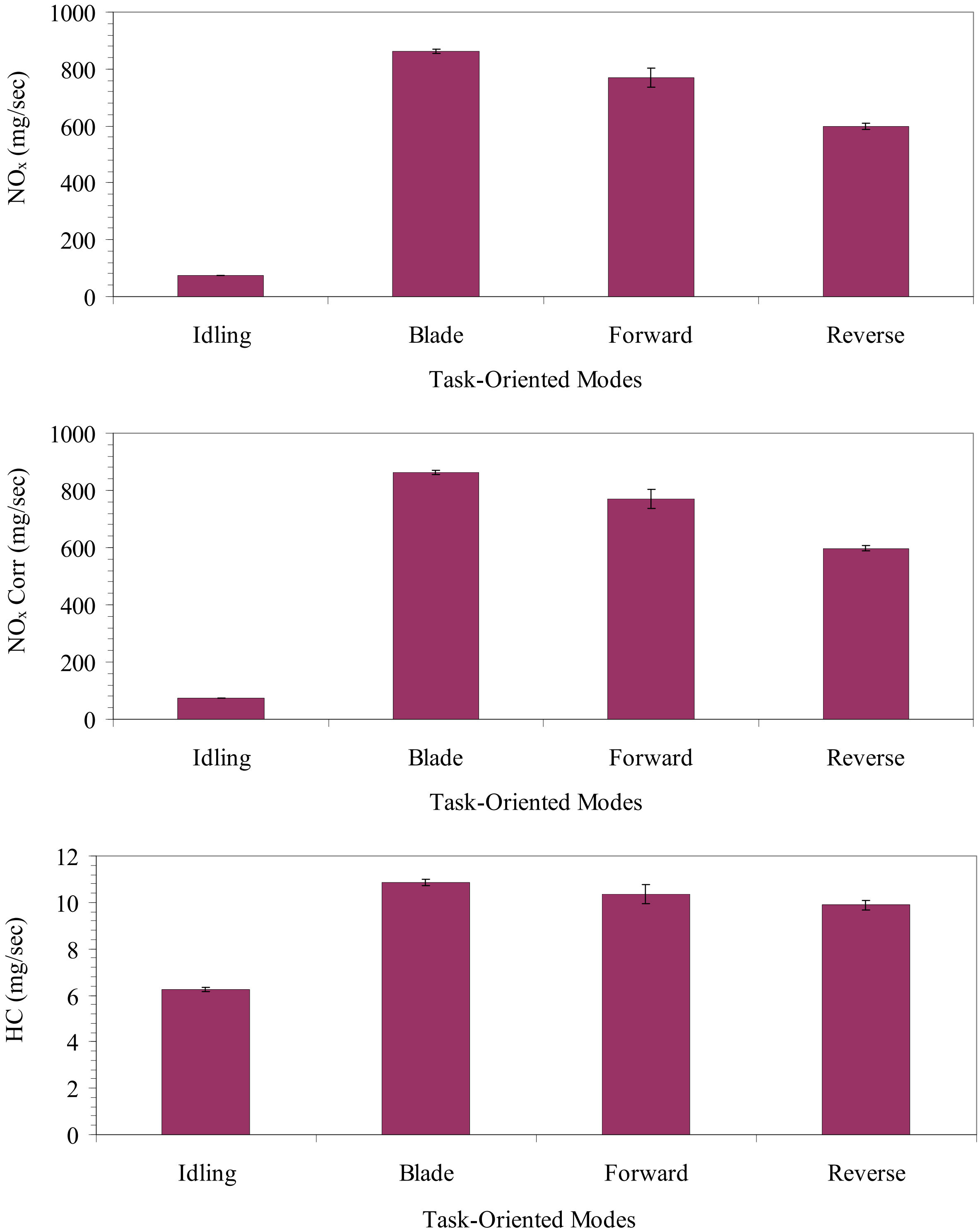


Figure A39. Continued

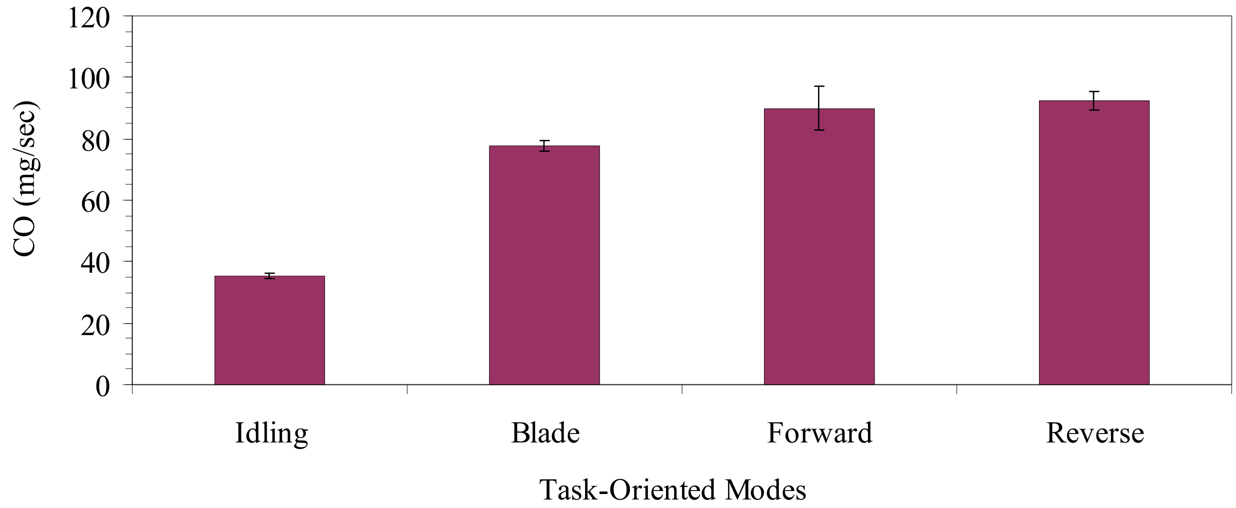
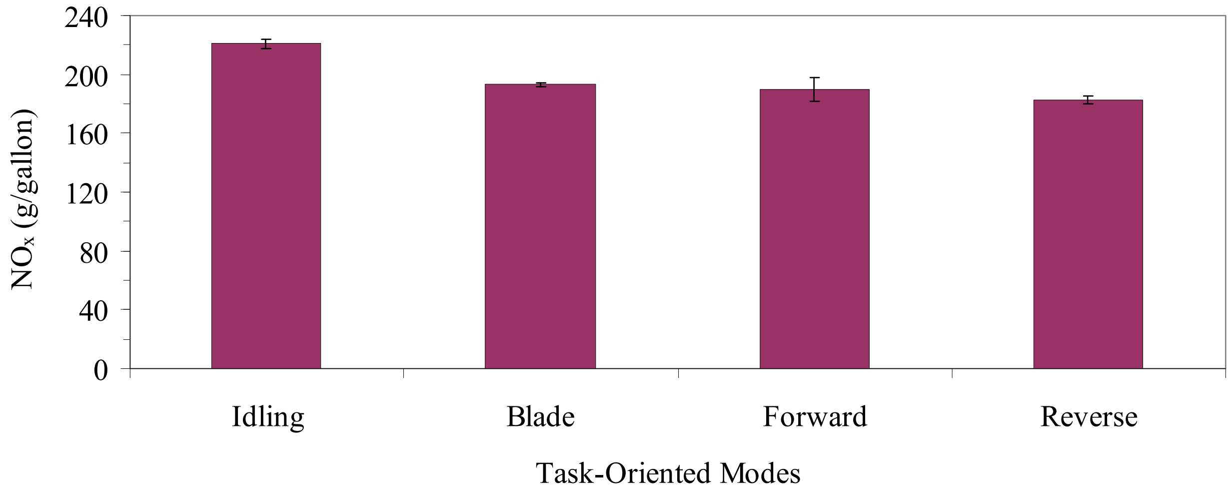
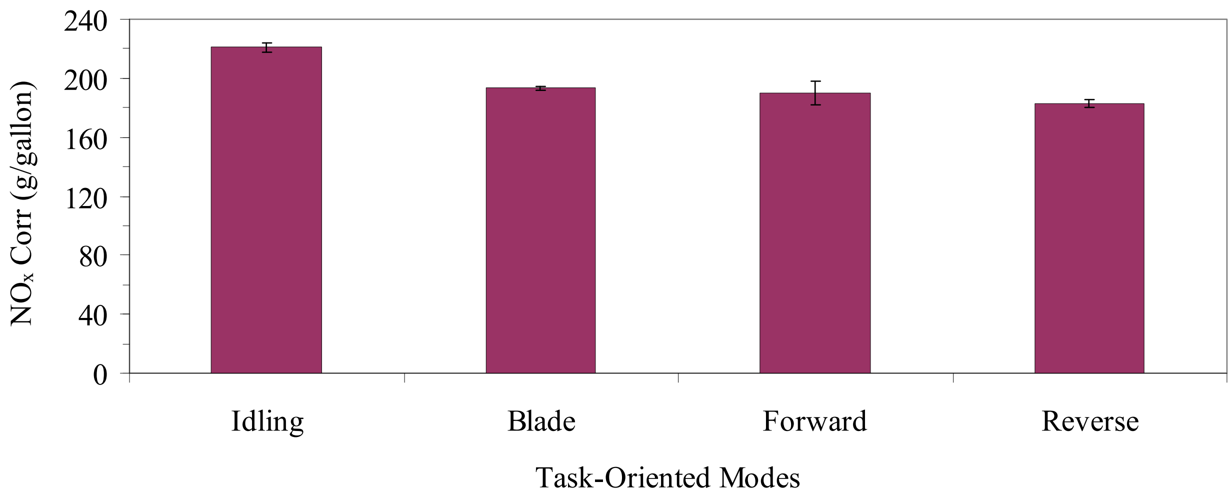


Figure A39. Continued

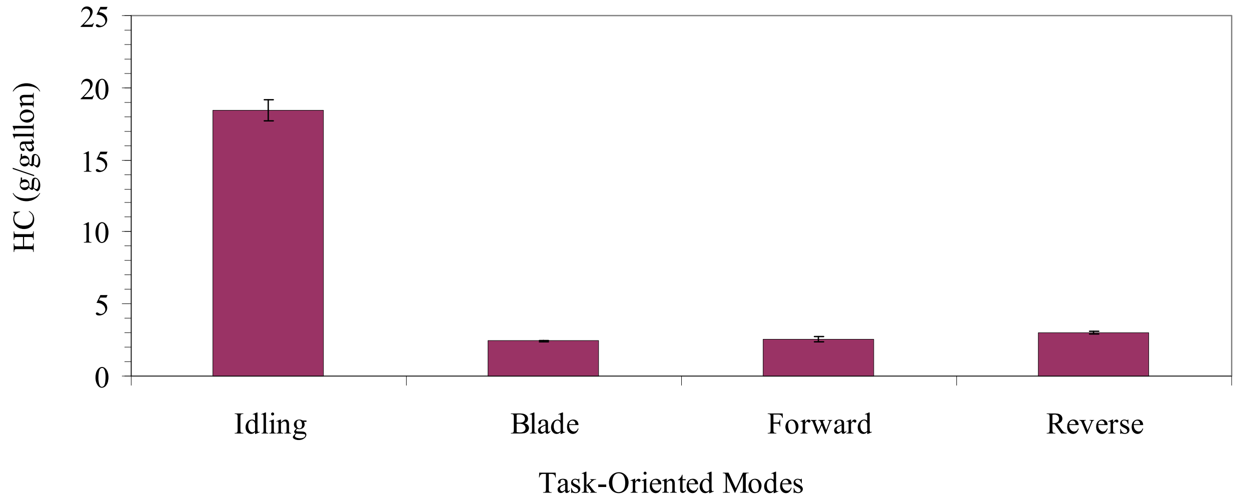




NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 56 ^{o}F and the relative humidity was 70 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *forward*: forward movement of the dozer when the bucket is not in contact with the ground; *reverse*: reverse movement of the dozer when the bucket is not in contact with the ground; *pushing*: movement of the dozer when the bucket is in contact with the ground.

Figure A40. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Dozer 5 (continued on next page)



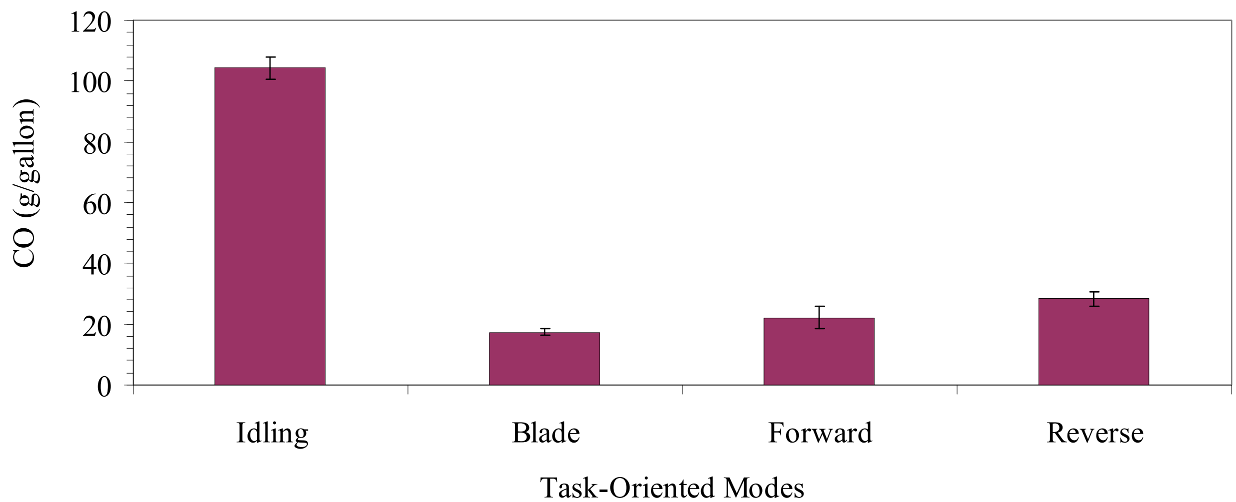
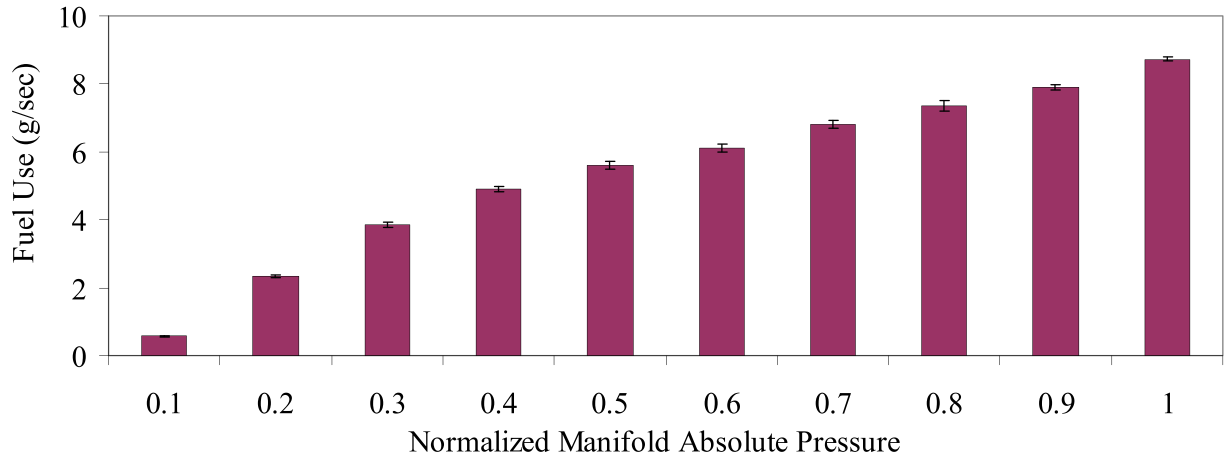
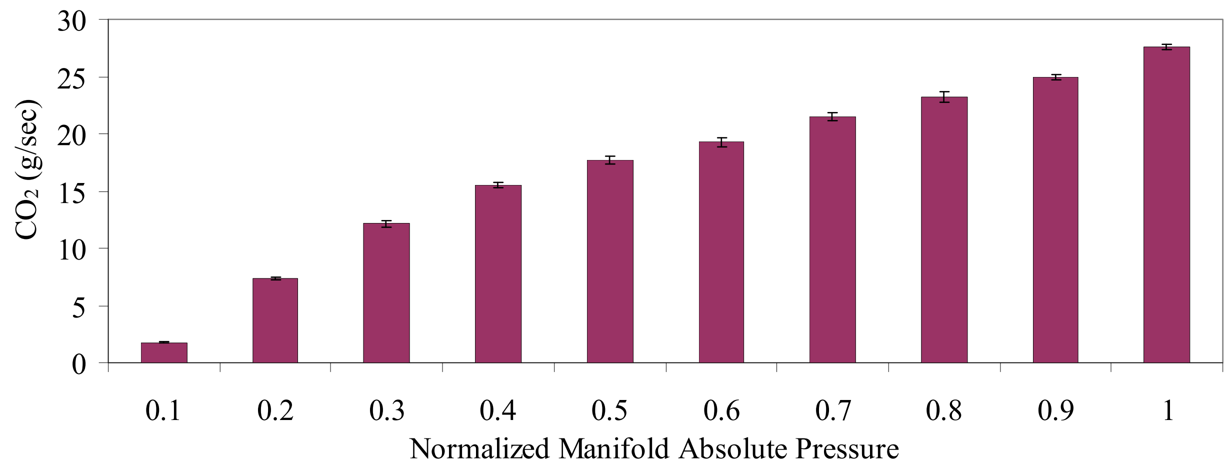


Figure A40. Continued

EXCAVATOR 1





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 78 ^oF and the relative humidity was 74 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A41. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Excavator 1 (continued on next page)

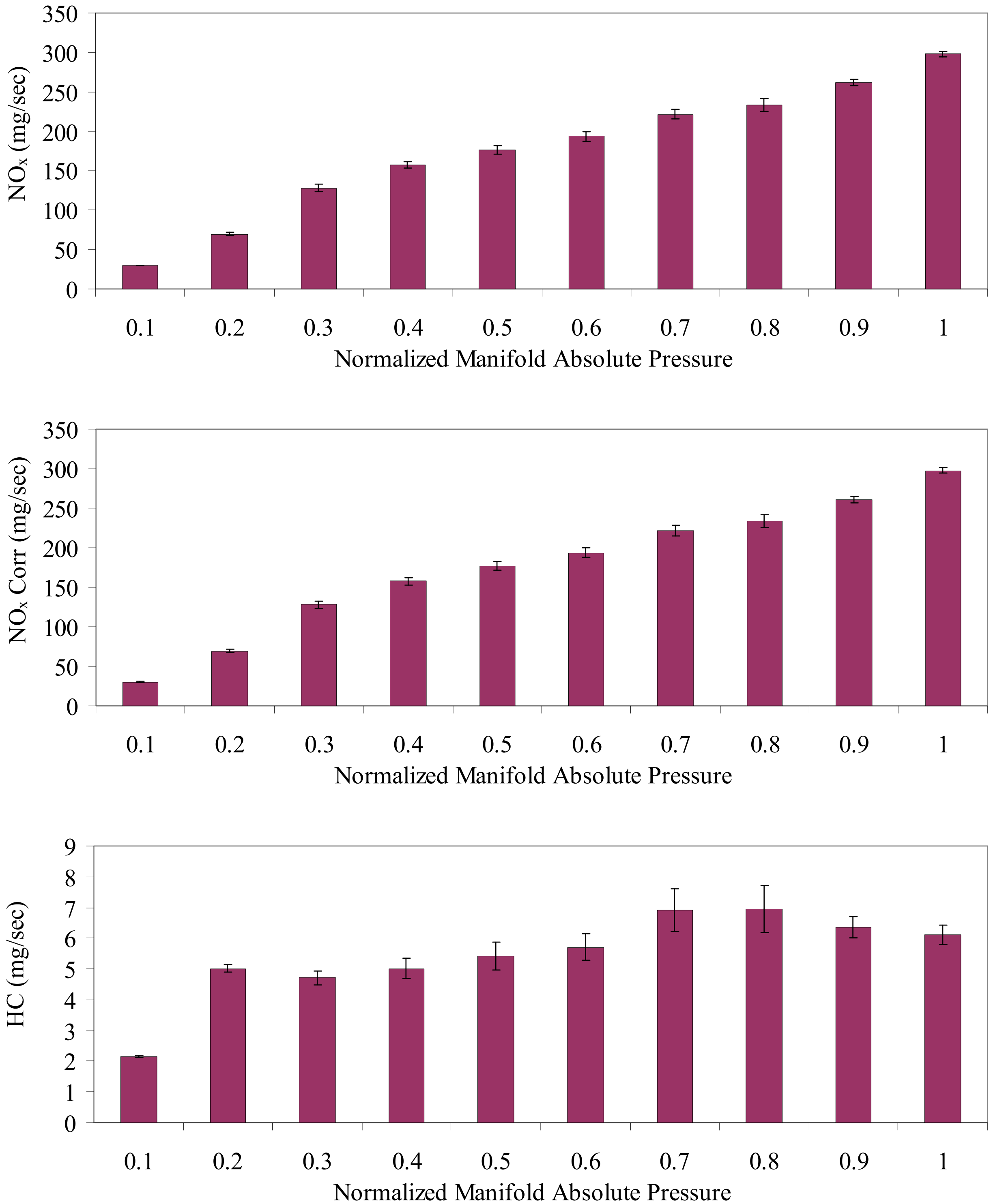
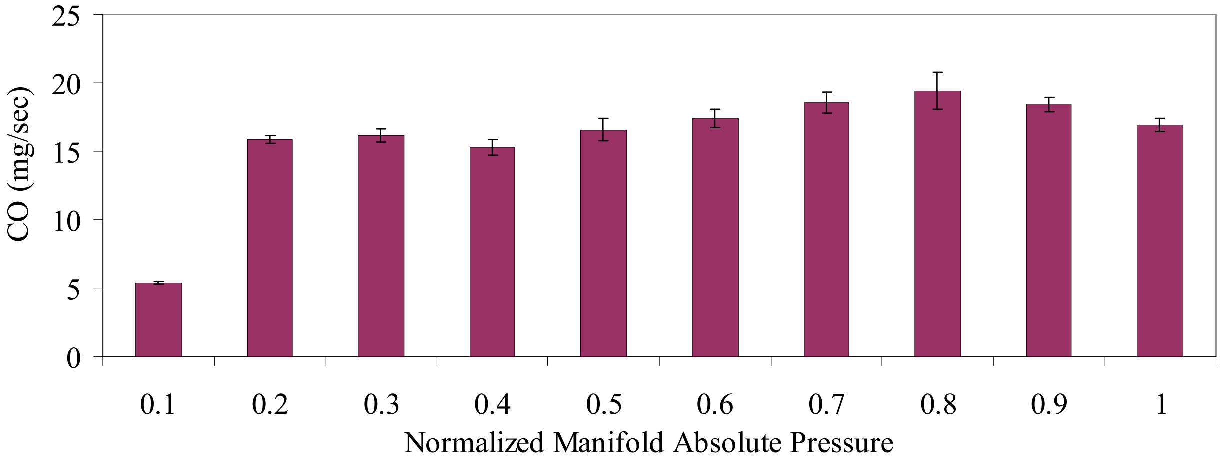


Figure A41. Continued



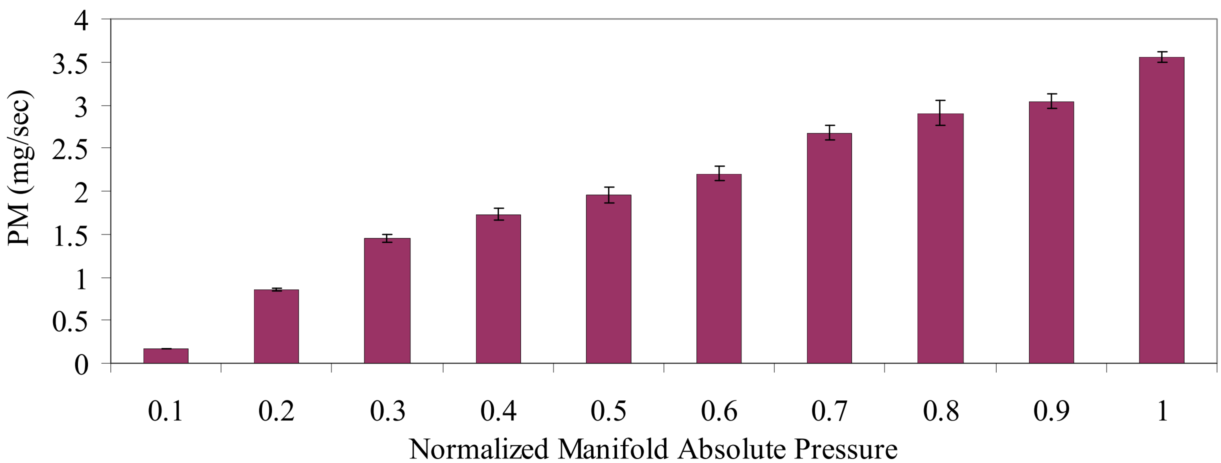
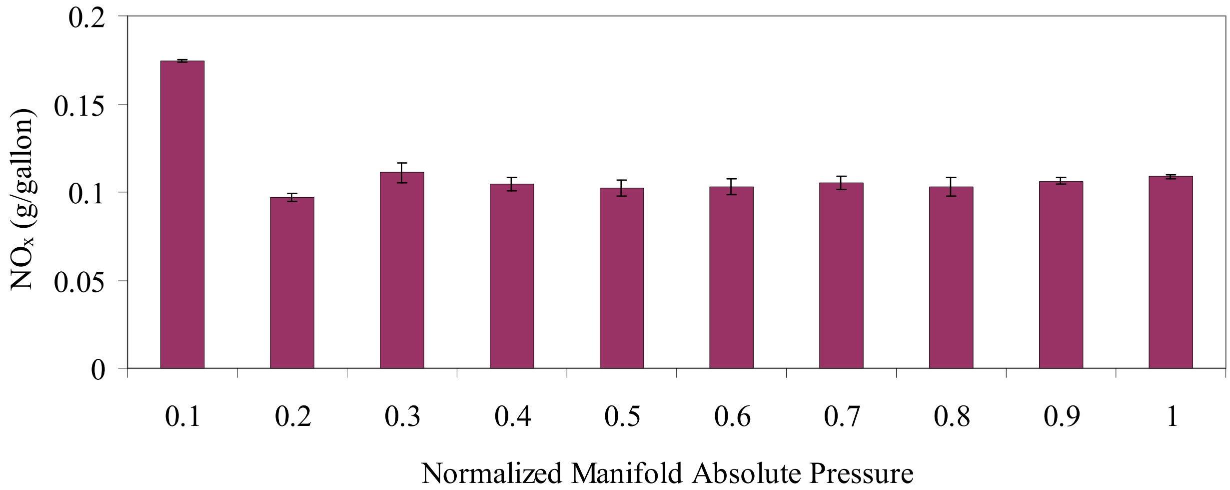
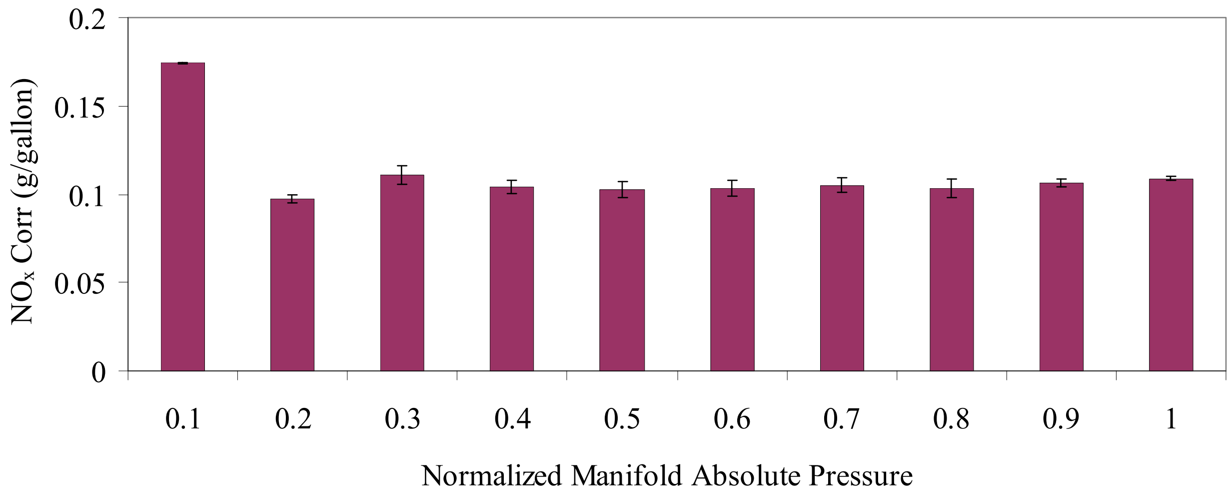


Figure A41. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 78 ^{o}F and the relative humidity was 74 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A42. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Excavator 1 (continued on next page)

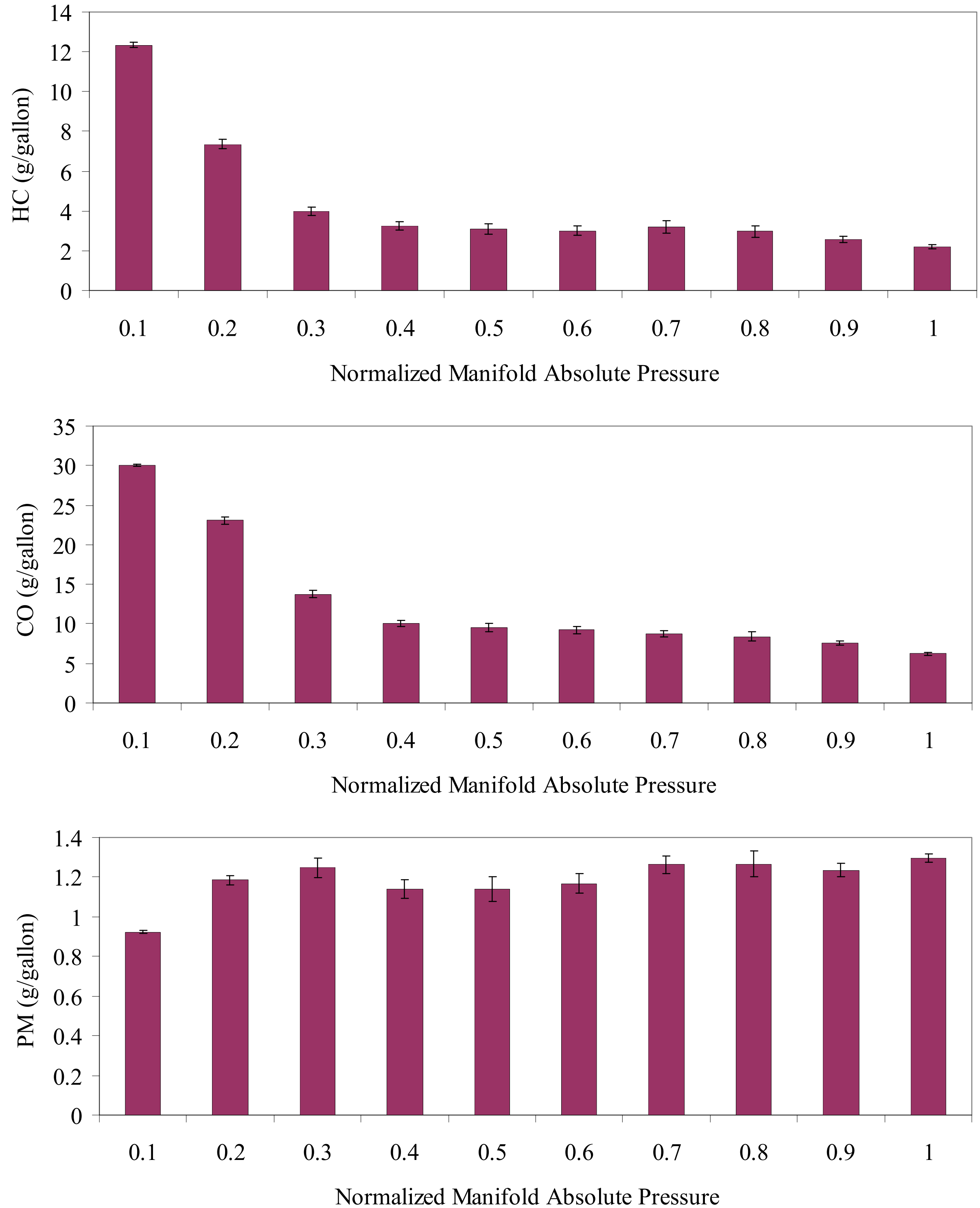
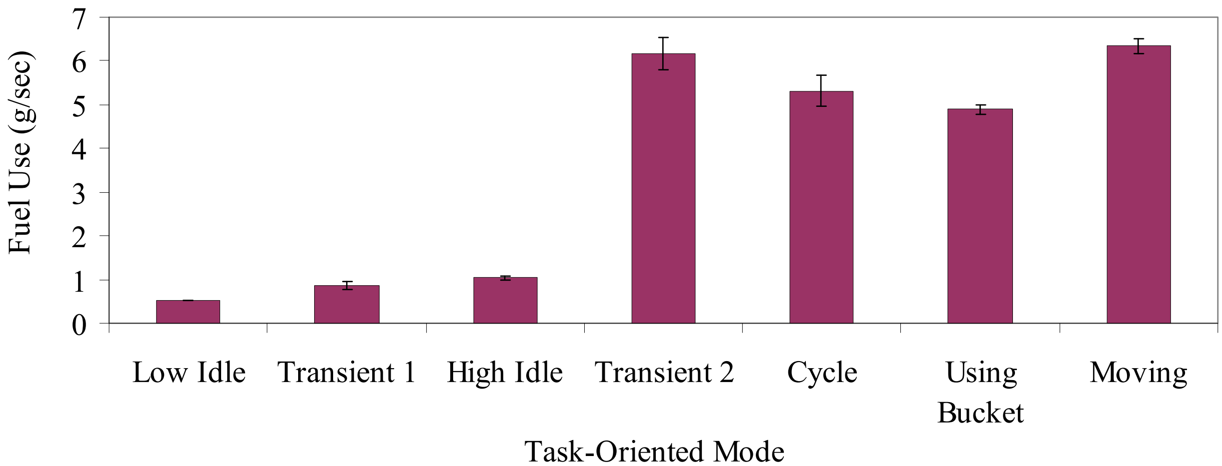
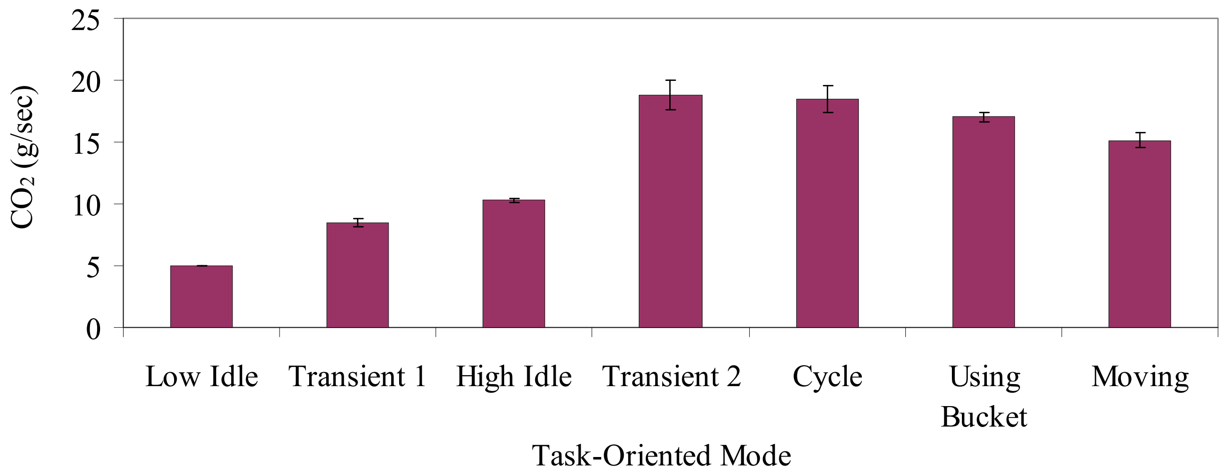


Figure A42. Continued

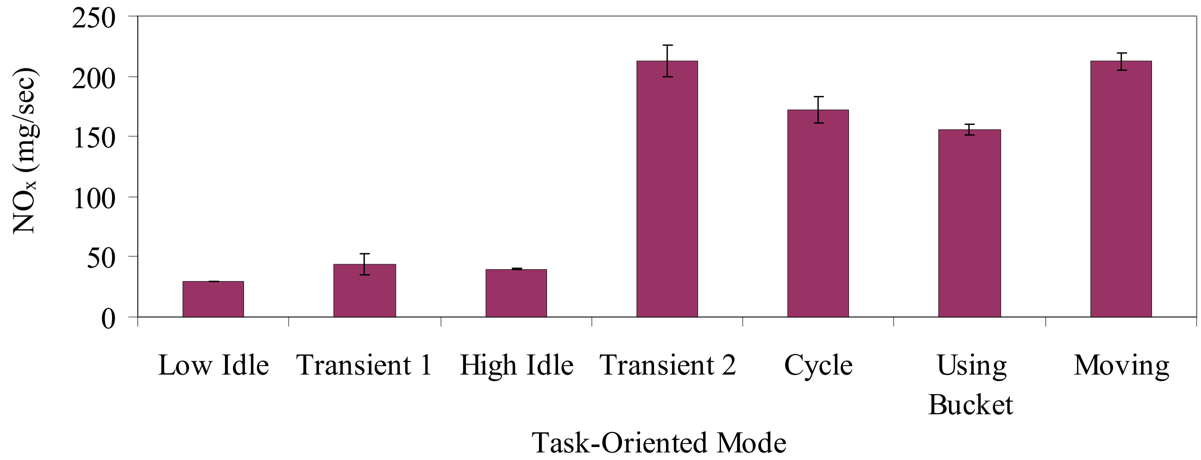


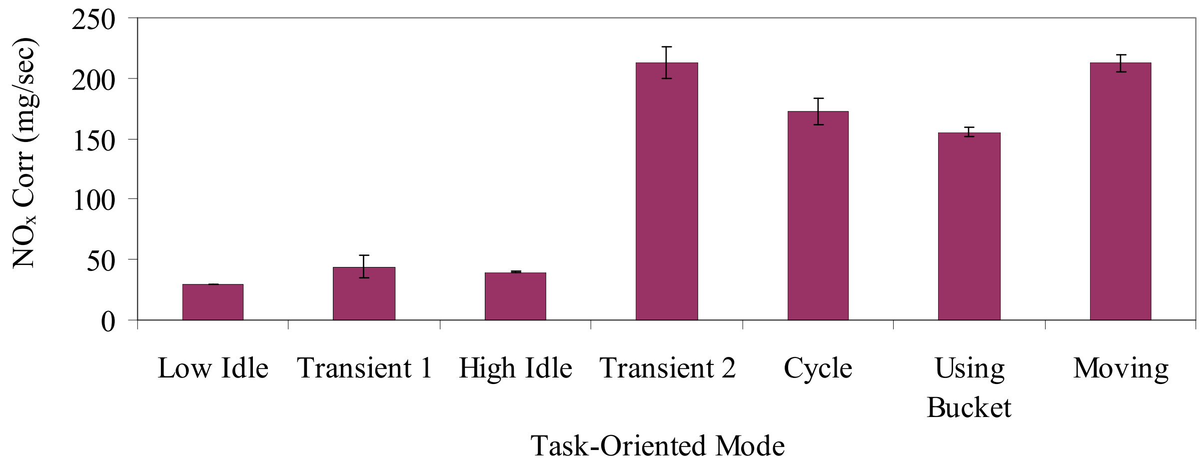


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 78 ^{o}F and the relative humidity was 74 %.

Task-oriented modes are: *low idle*: engine on, but the vehicle is not working or moving at low RPM; transient 1: engine RPM increases from low idle to high low; *high idle*: vehicle is not working or moving at high RPM; *transient 2*: vehicle from high idle to operation; *moving*: movement of the excavator; *bucket*: digging with excavator bucket; *cycle*: digging, swing, and dumping with the excavator bucket.

Figure A43. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Excavator 1 (continued on next page)





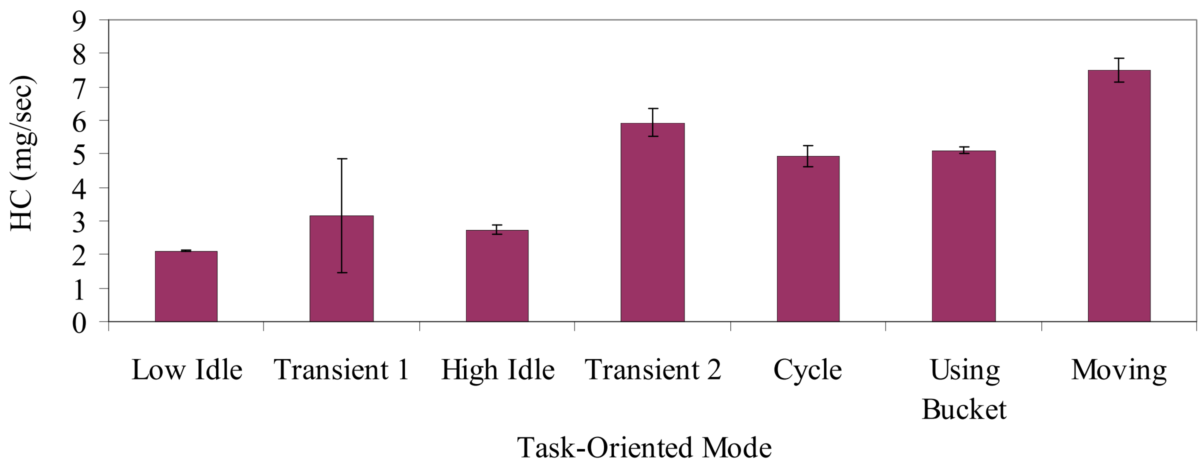
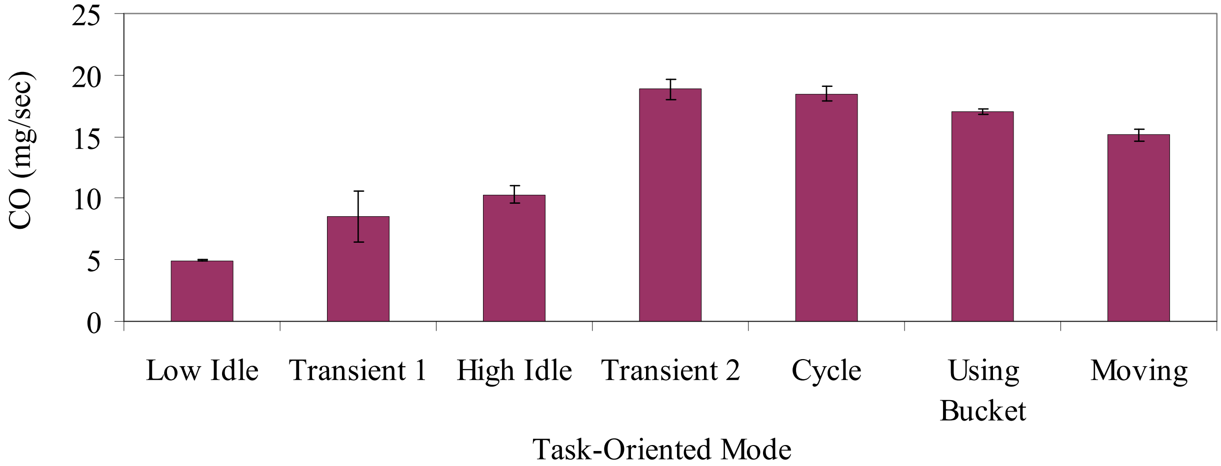


Figure A43. Continued



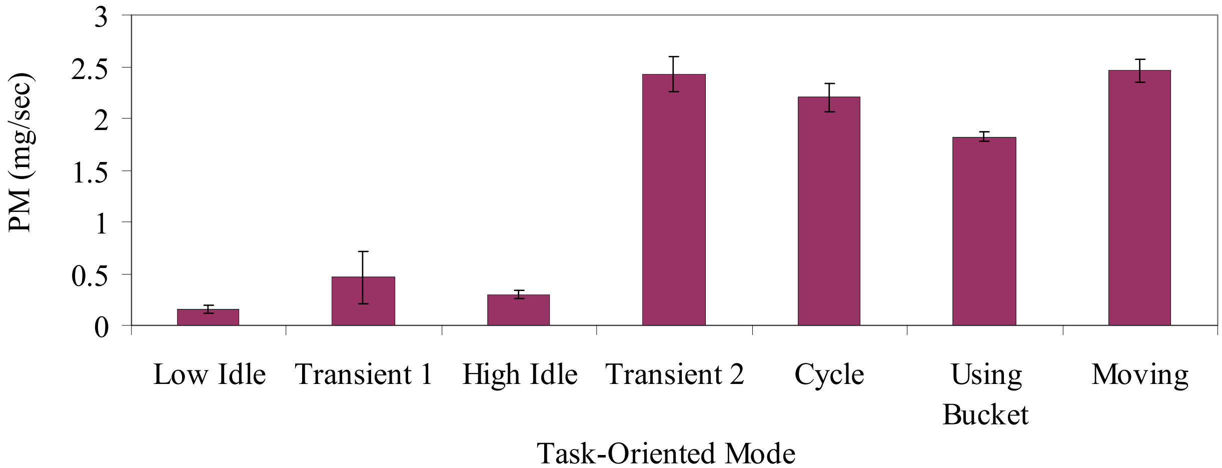
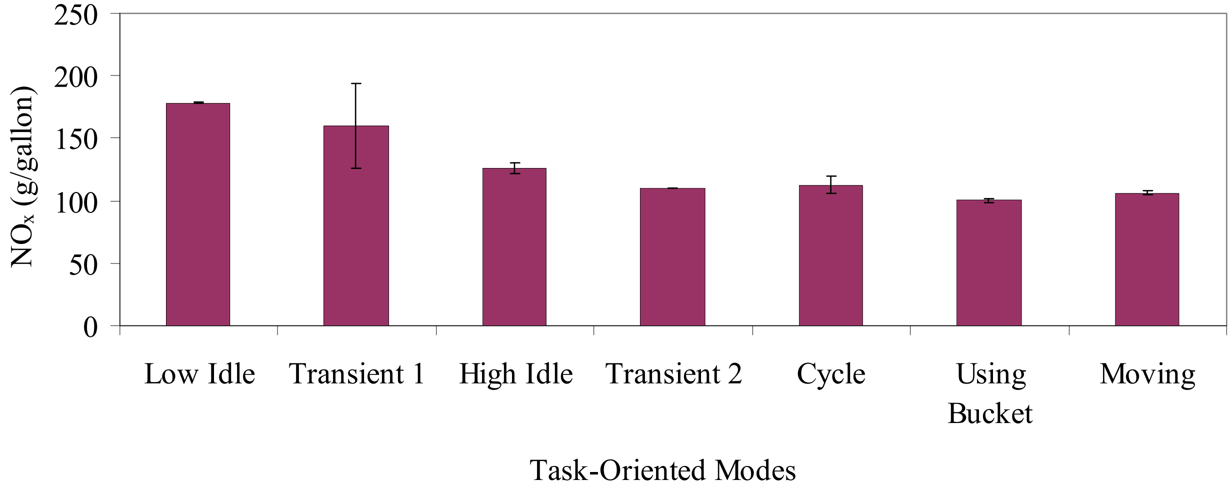
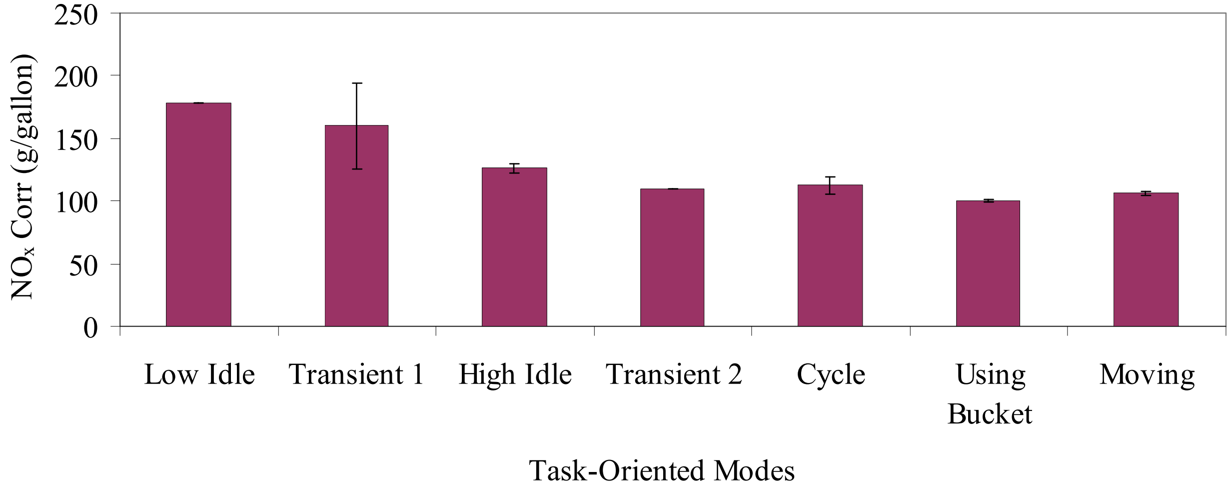


Figure A43. Continued

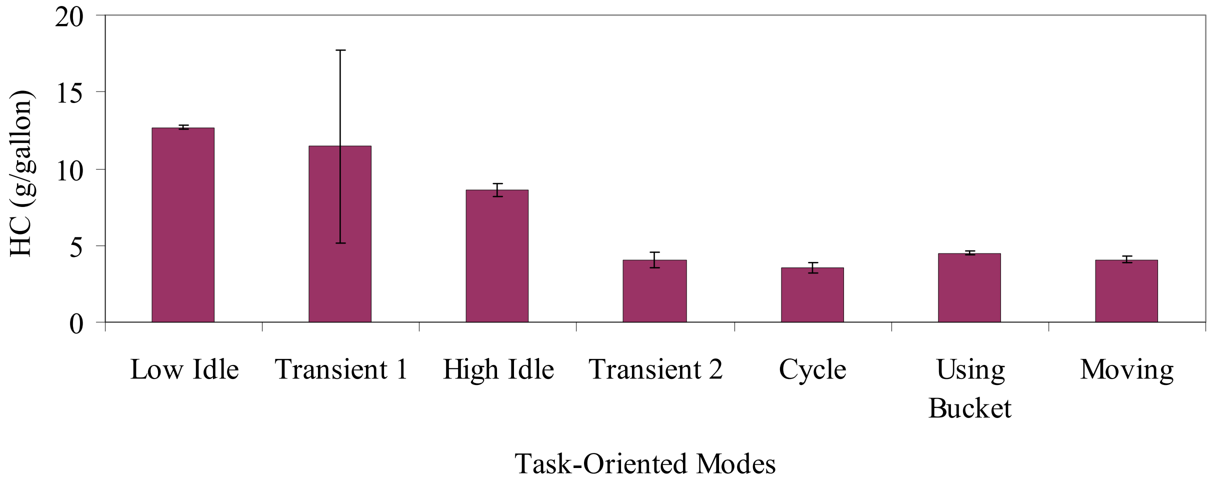


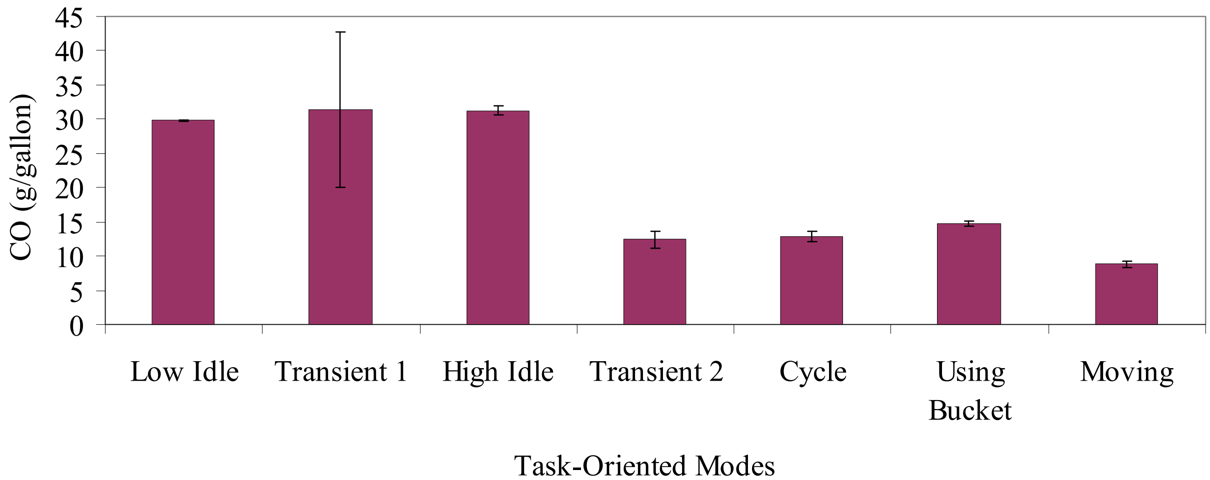


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 78 ^{o}F and the relative humidity was 74 %.

Task-oriented modes are: *low idle*: engine on, but the vehicle is not working or moving at low RPM; transient 1: engine RPM increases from low idle to high low; *high idle*: vehicle is not working or moving at high RPM; *transient 2*: vehicle from high idle to operation; *moving*: movement of the excavator; *bucket*: digging with excavator bucket; *cycle*: digging, swing, and dumping with the excavator bucket.

Figure A44. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Excavator 1 (continued on next page)





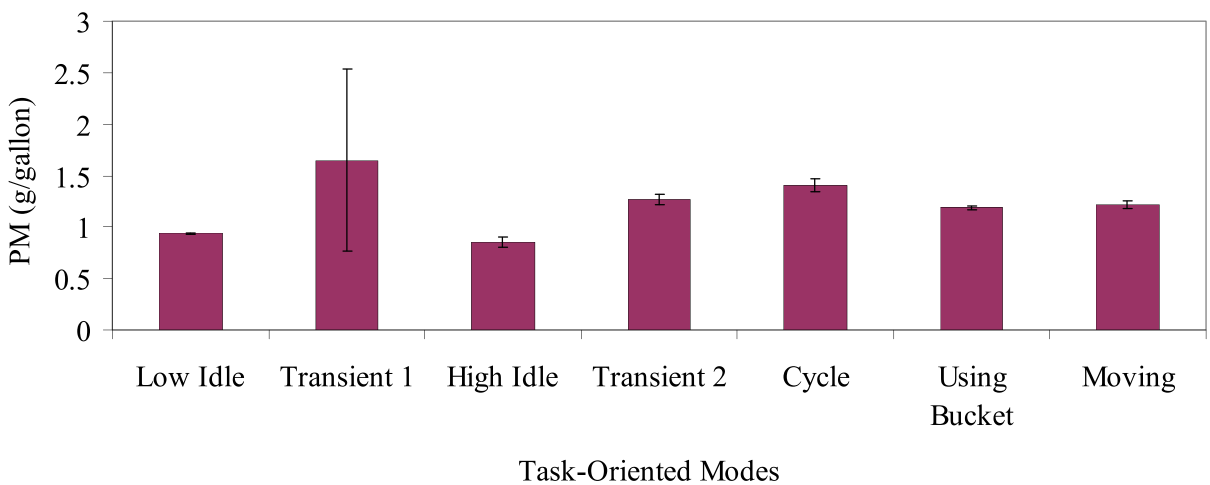
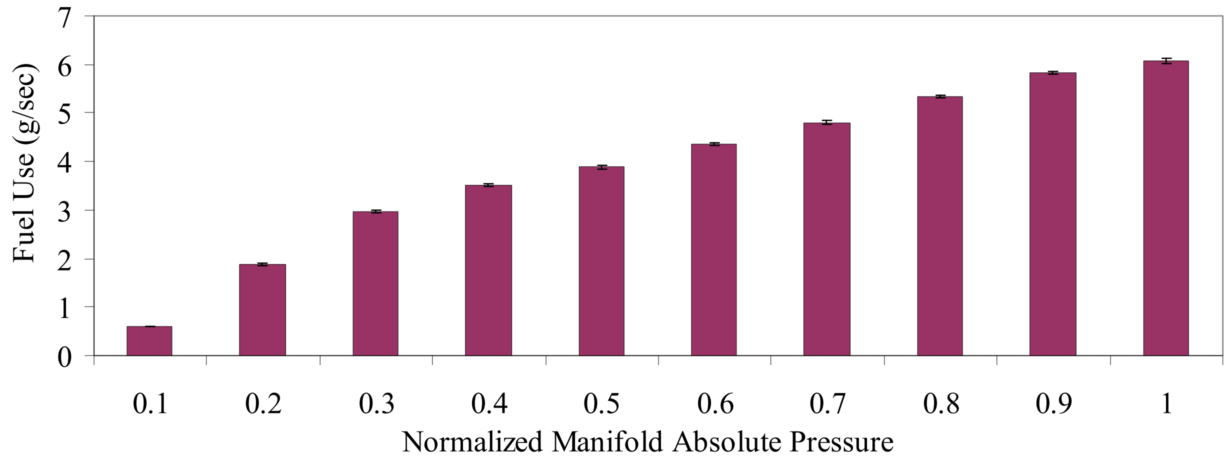
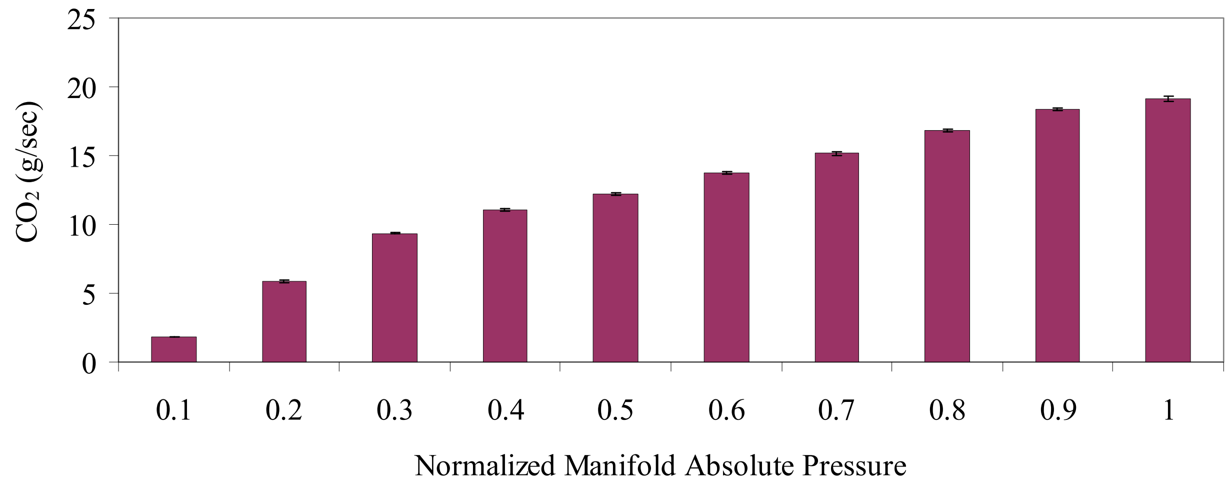


Figure A44. Continued

EXCAVATOR 2

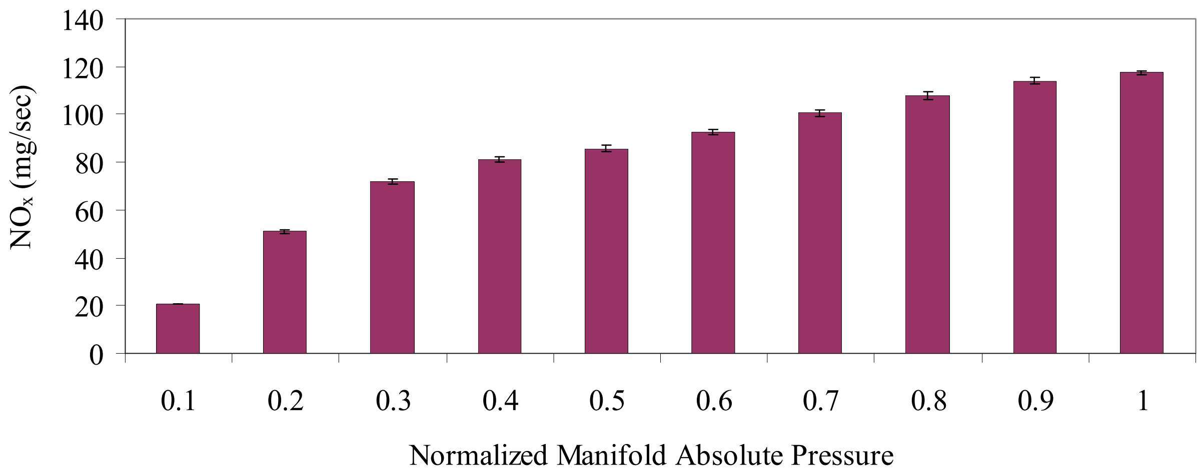


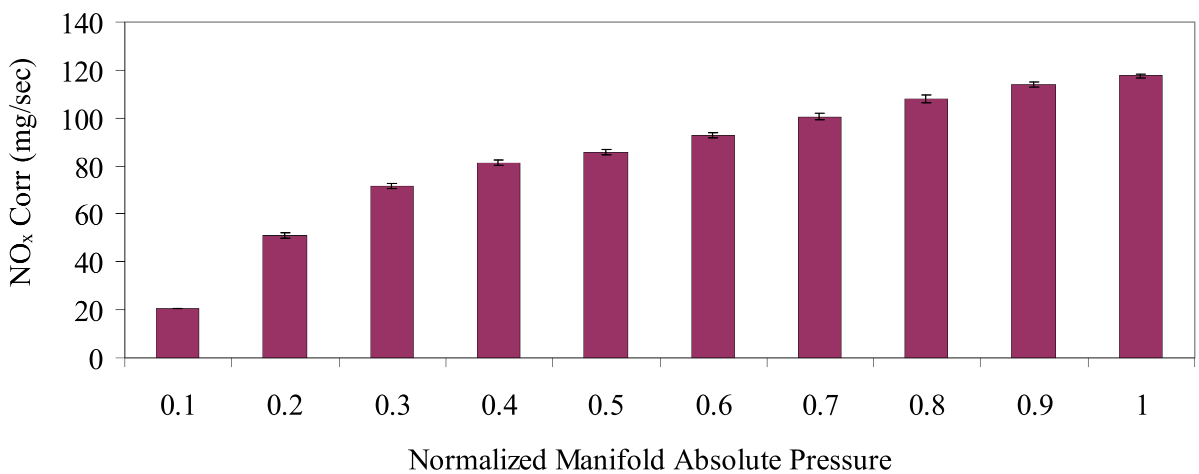


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 54 ^{o}F and the relative humidity was 61 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A45. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Excavator 2 (continued on next page)





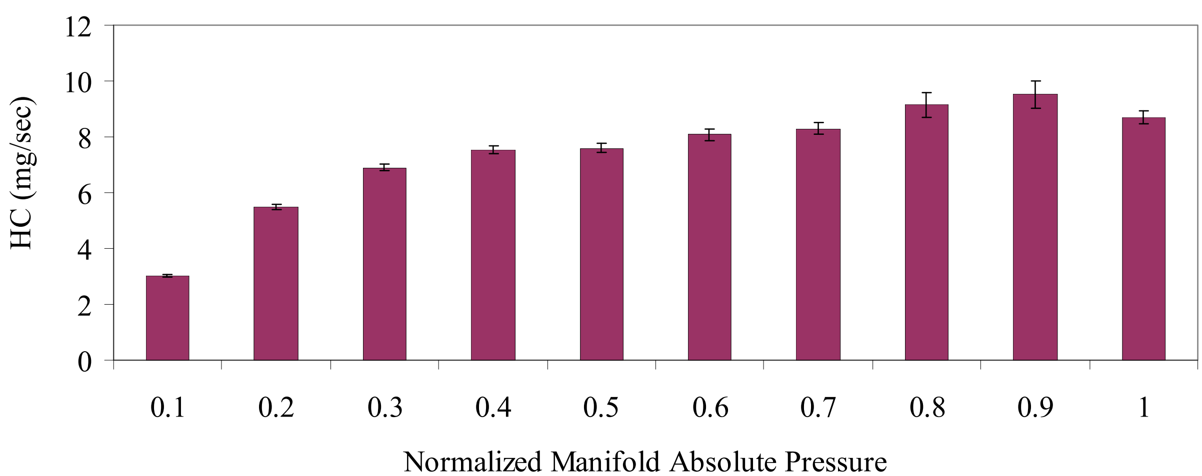
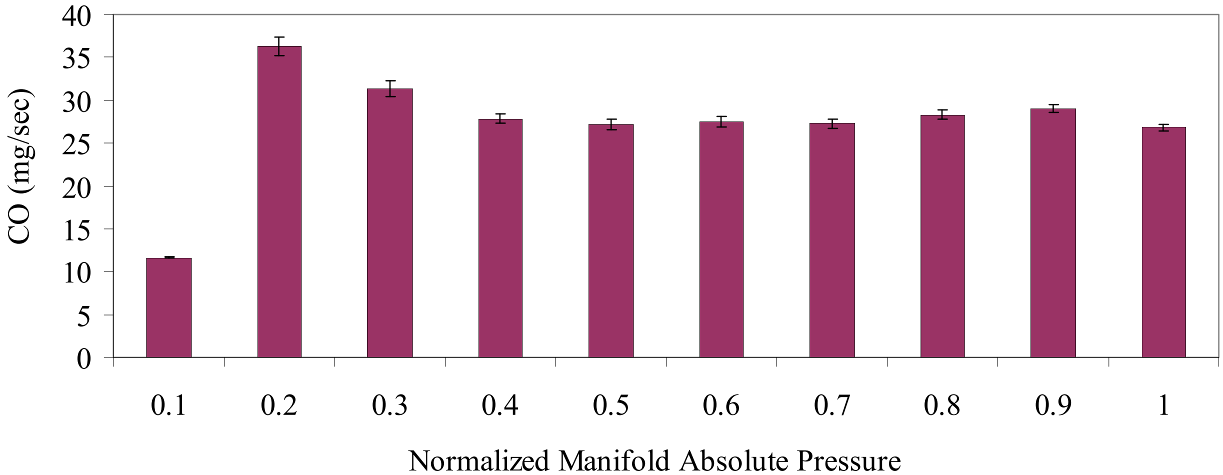


Figure A45. Continued



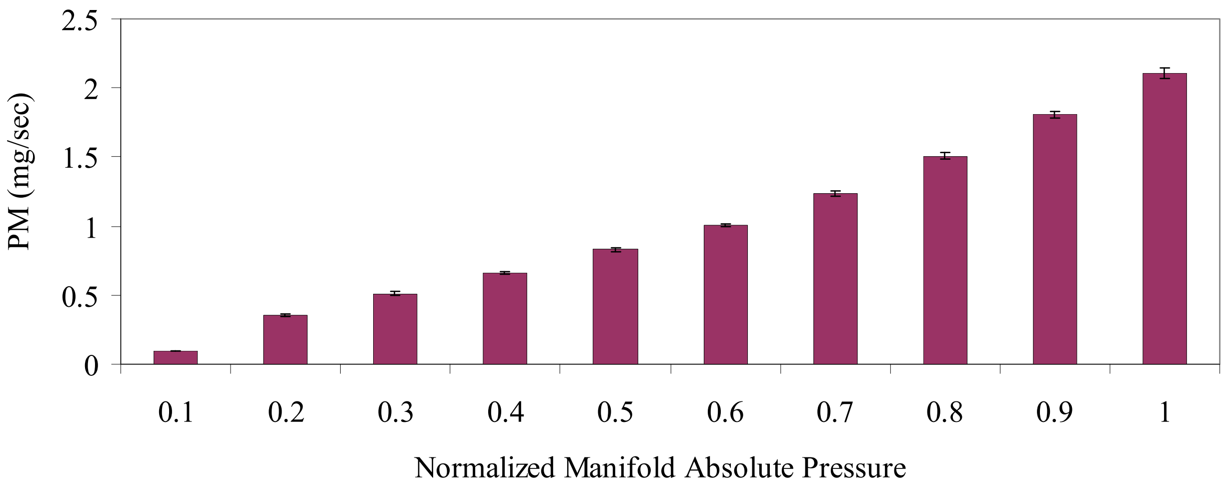
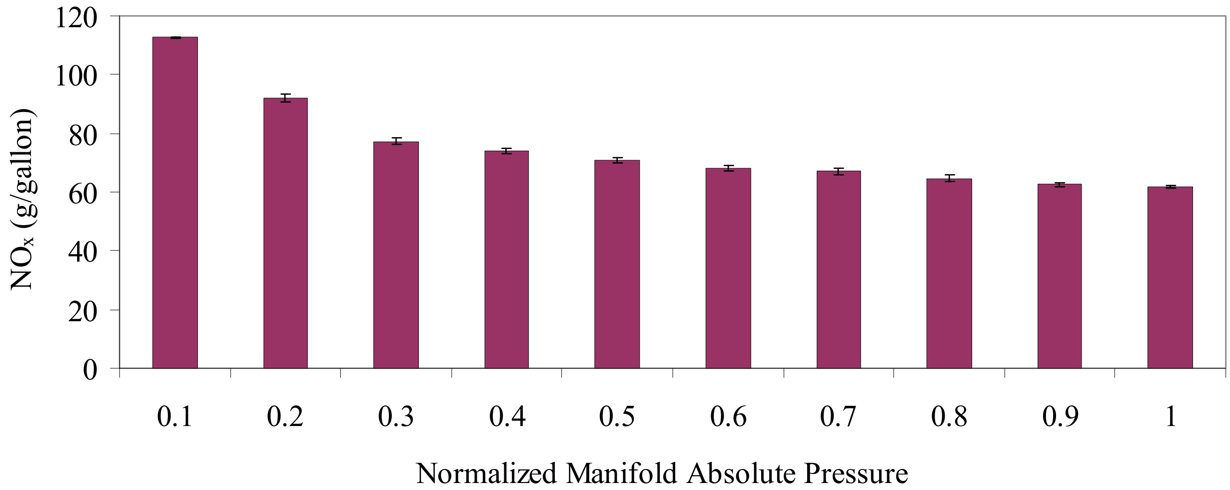
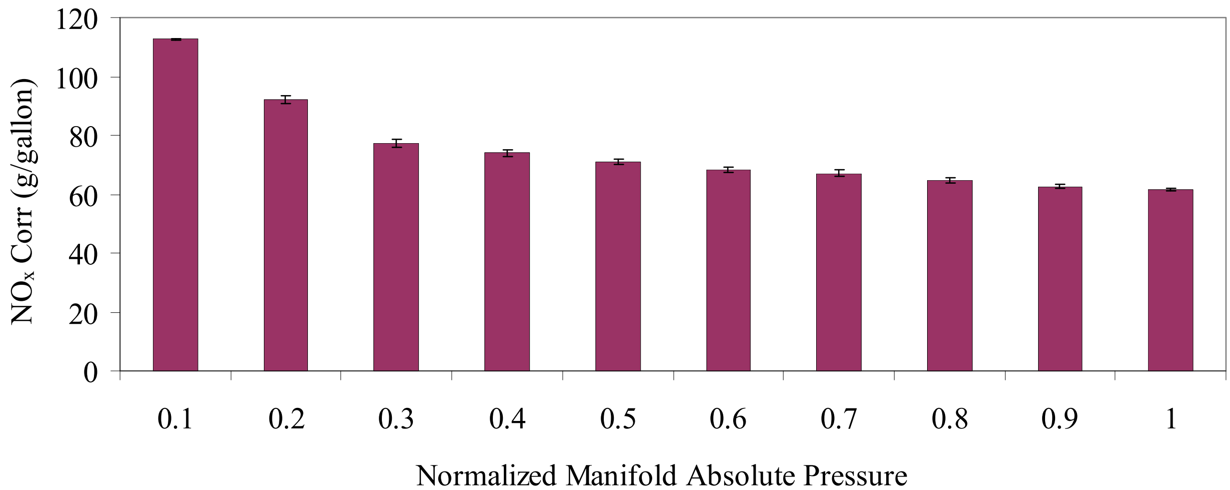


Figure A45. Continued

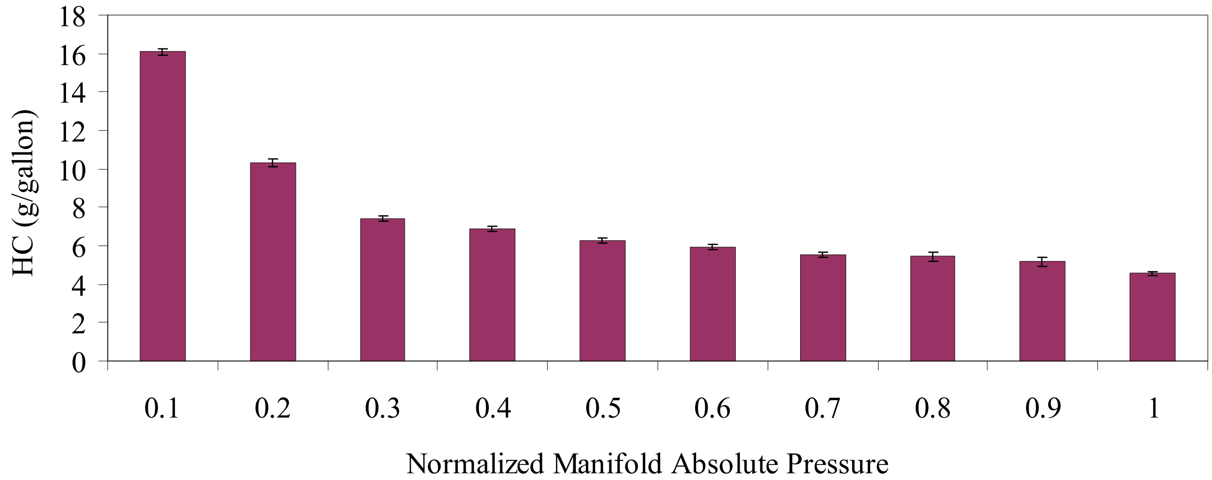


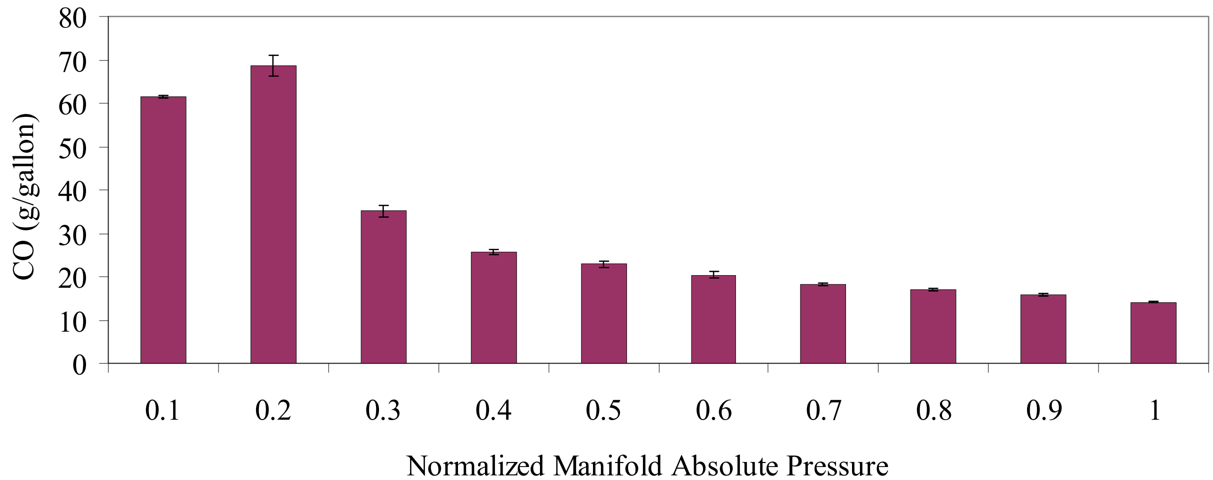


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 54 ^{o}F and the relative humidity was 61 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A46. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Excavator 2 (continued on next page)





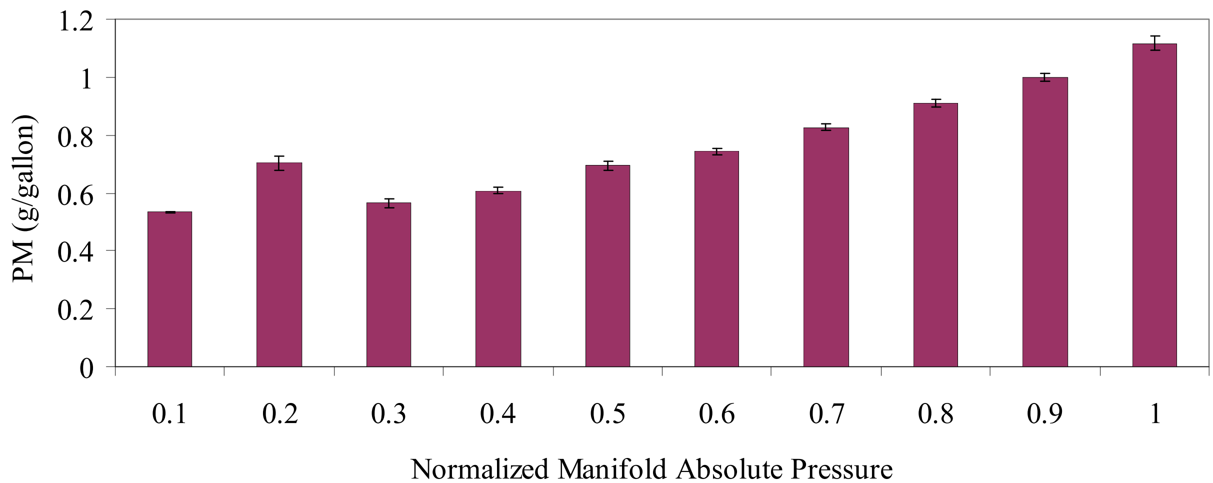
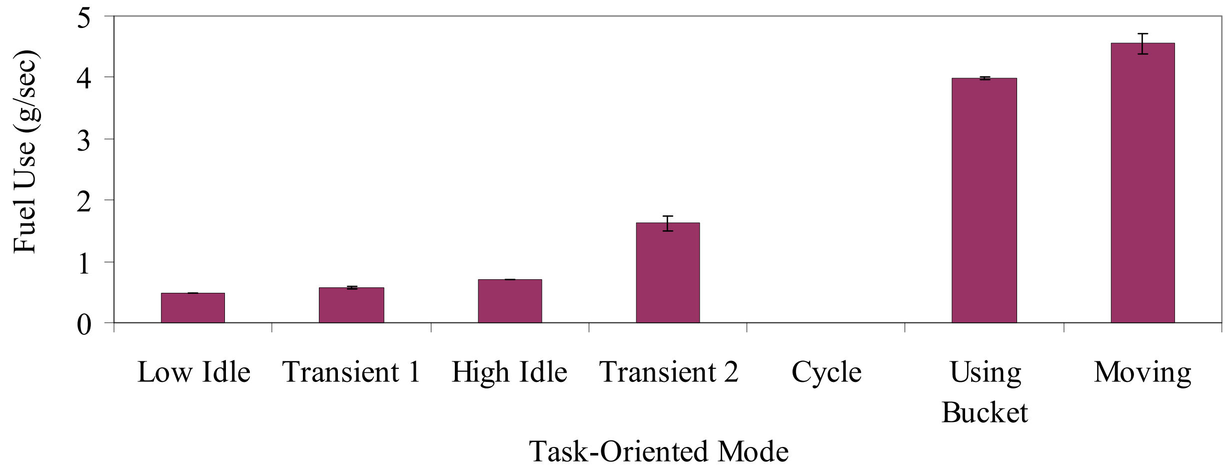
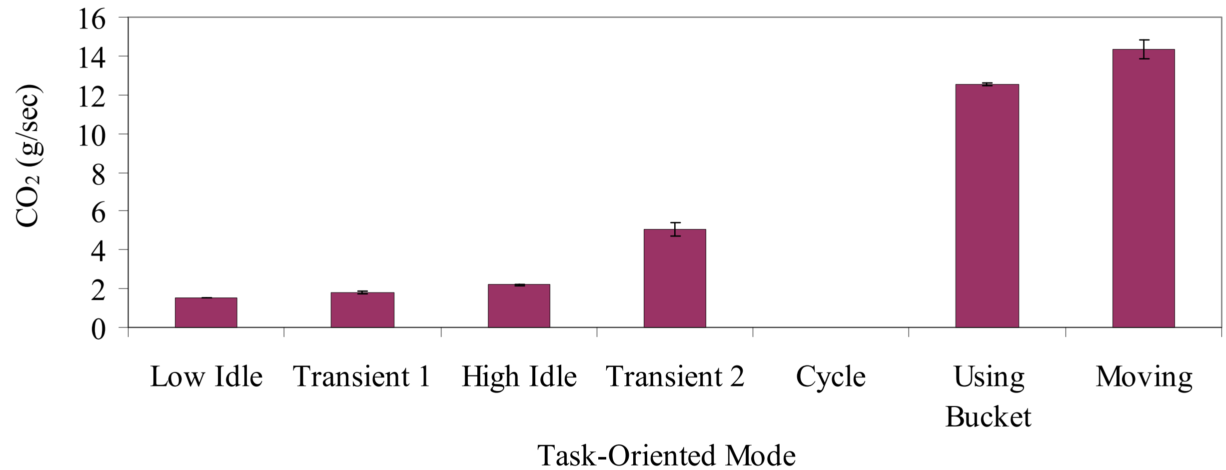


Figure A46. Continued

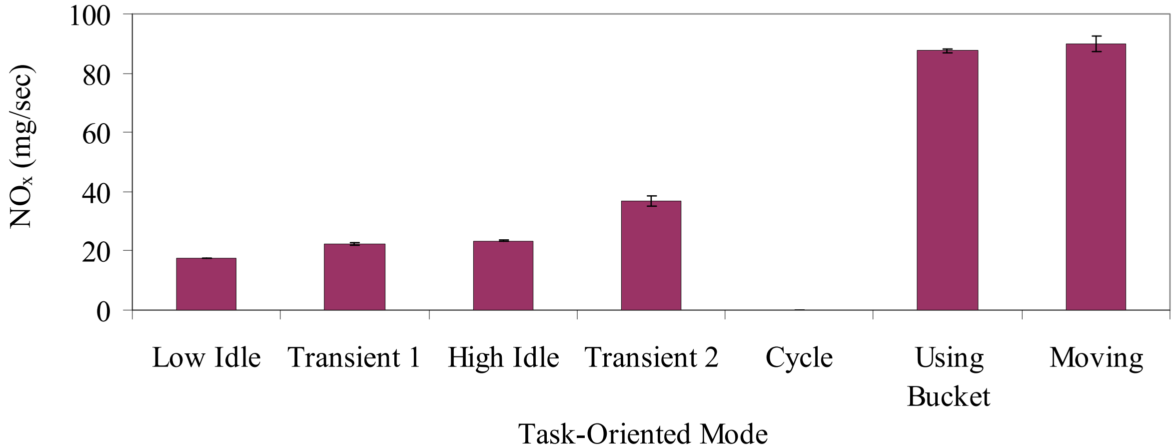


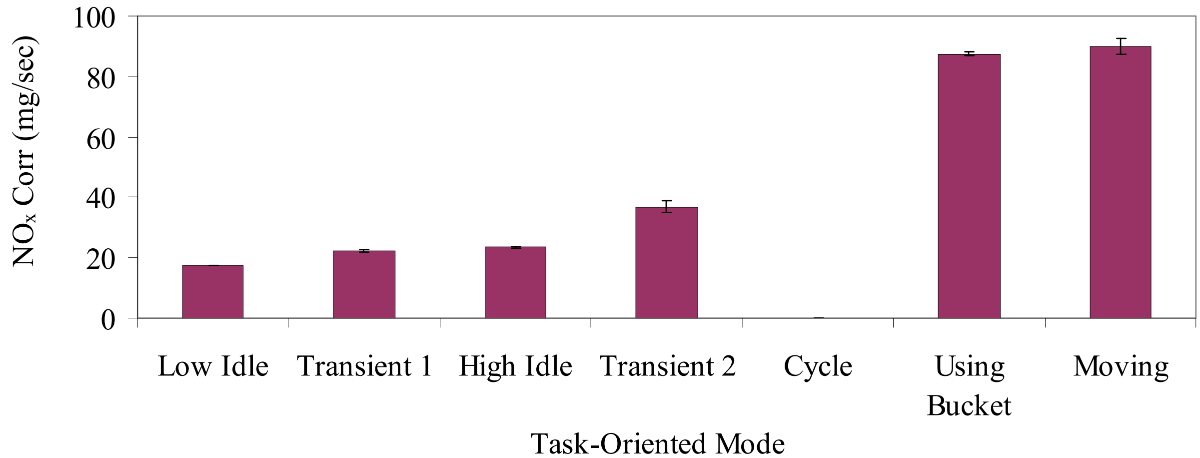


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 54 ^{o}F and the relative humidity was 61 %.

Task-oriented modes are: *low idle*: engine on, but the vehicle is not working or moving at low RPM; transient 1: engine RPM increases from low idle to high low; *high idle*: vehicle is not working or moving at high RPM; *transient 2*: vehicle from high idle to operation; *moving*: movement of the excavator; *bucket*: digging with excavator bucket; *cycle*: digging, swing, and dumping with the excavator bucket.

Figure A47. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Excavator 2 (continued on next page)





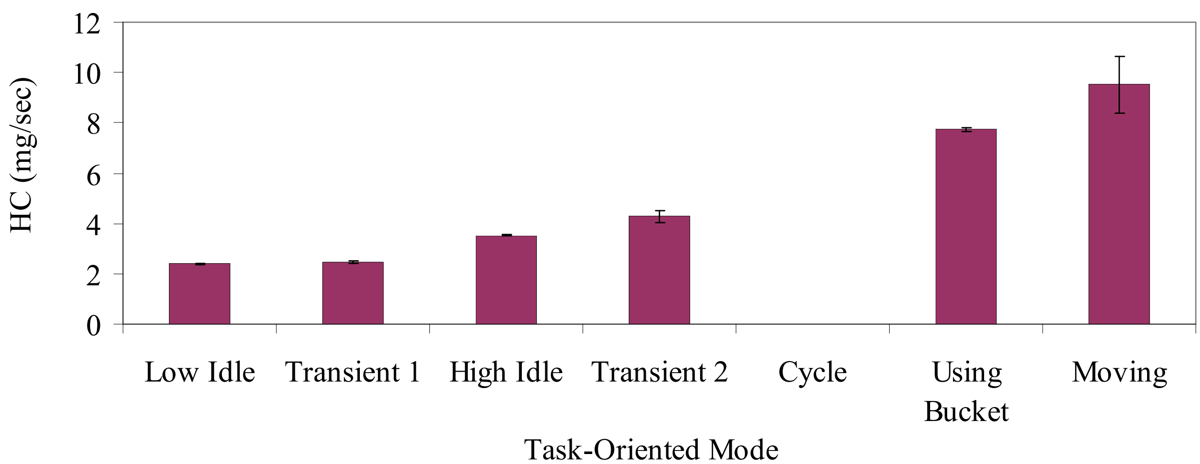
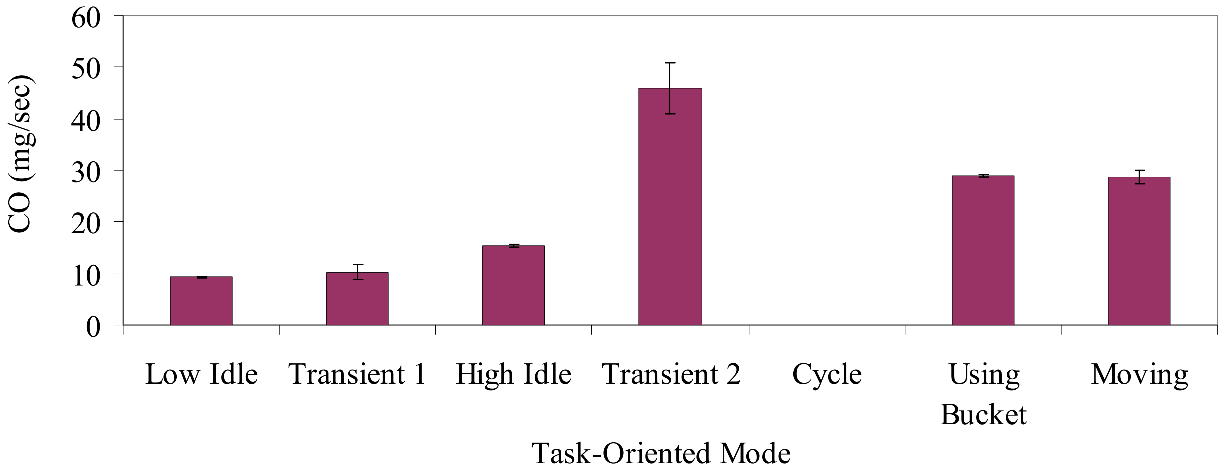


Figure A47. Continued



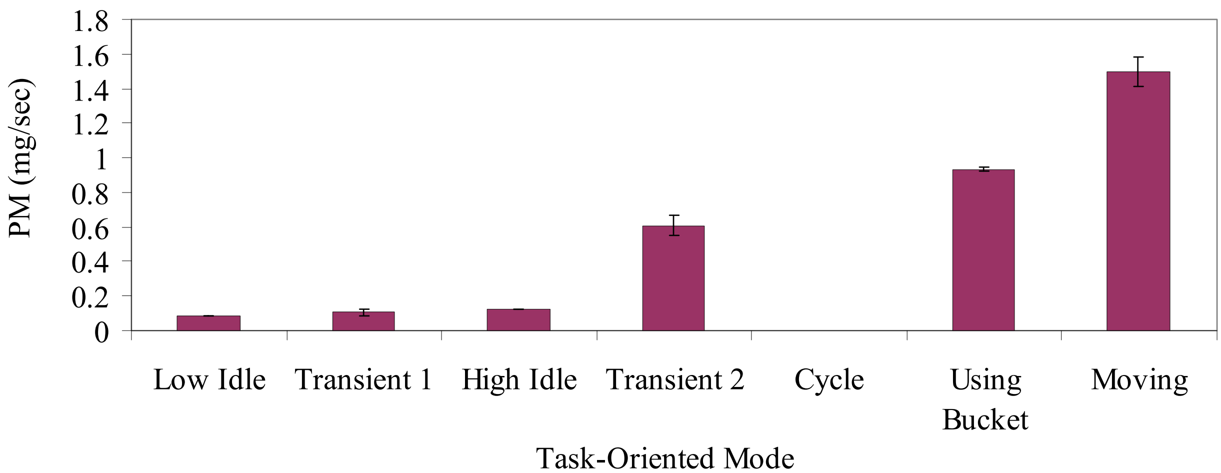
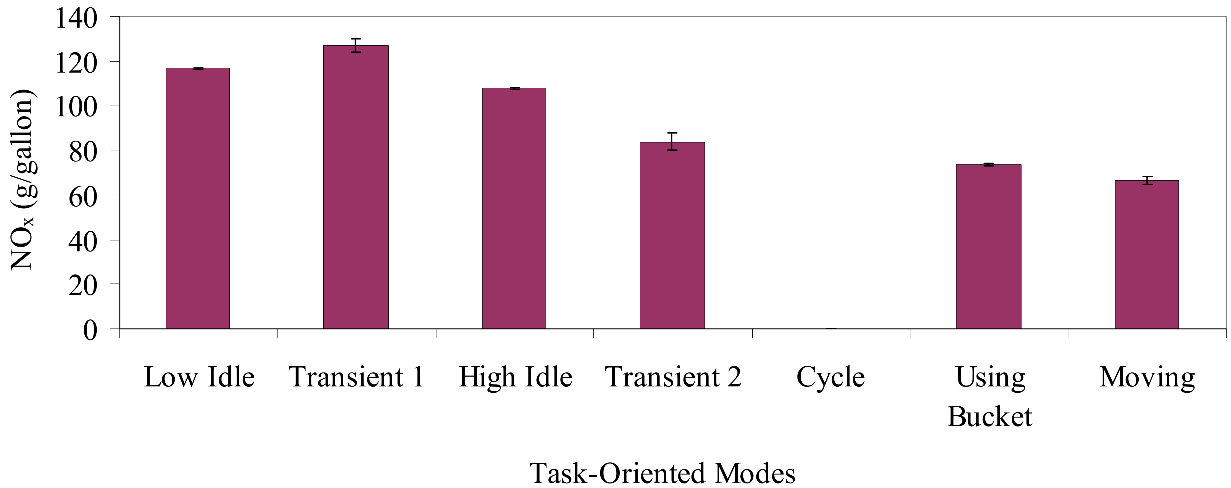
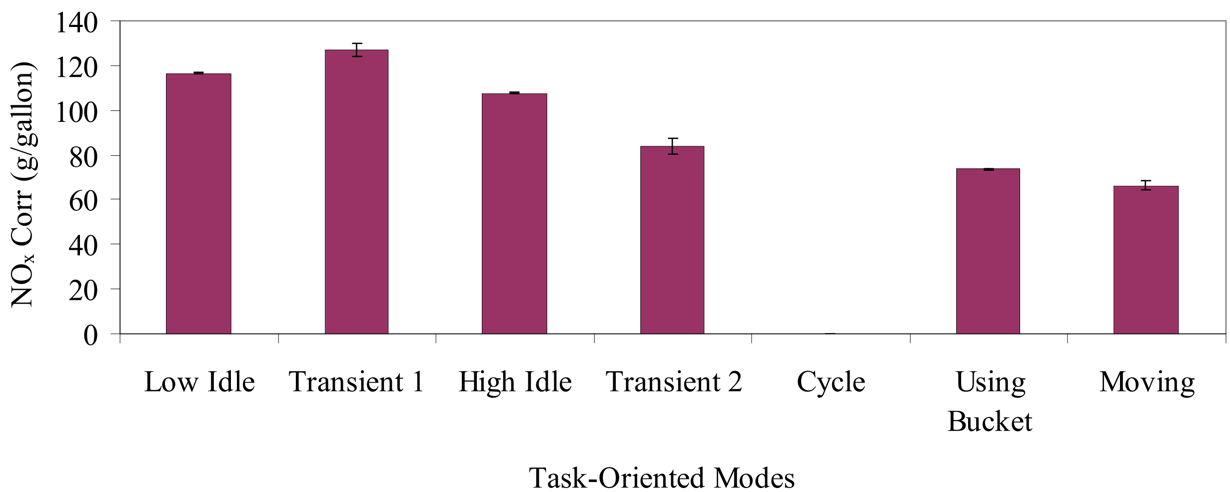


Figure A47. Continued

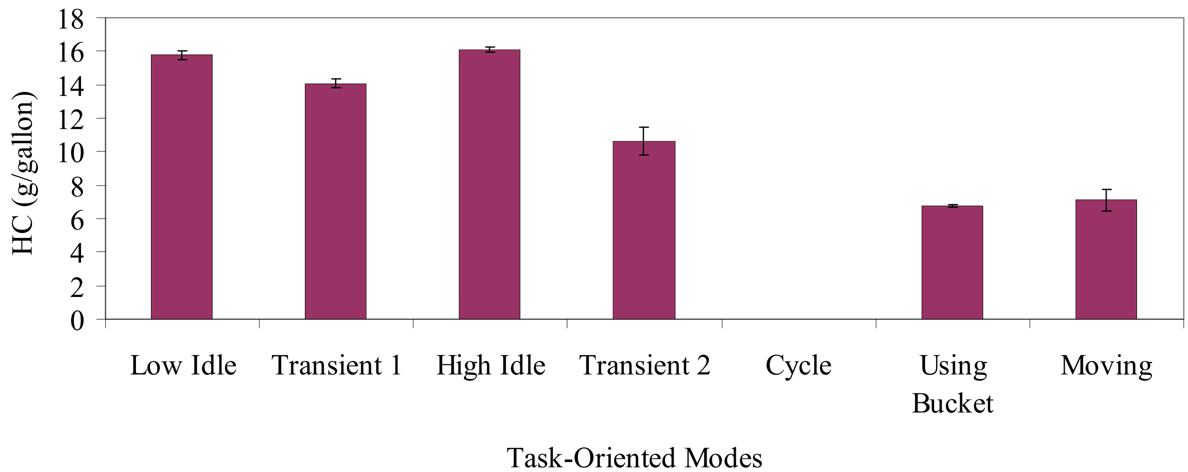


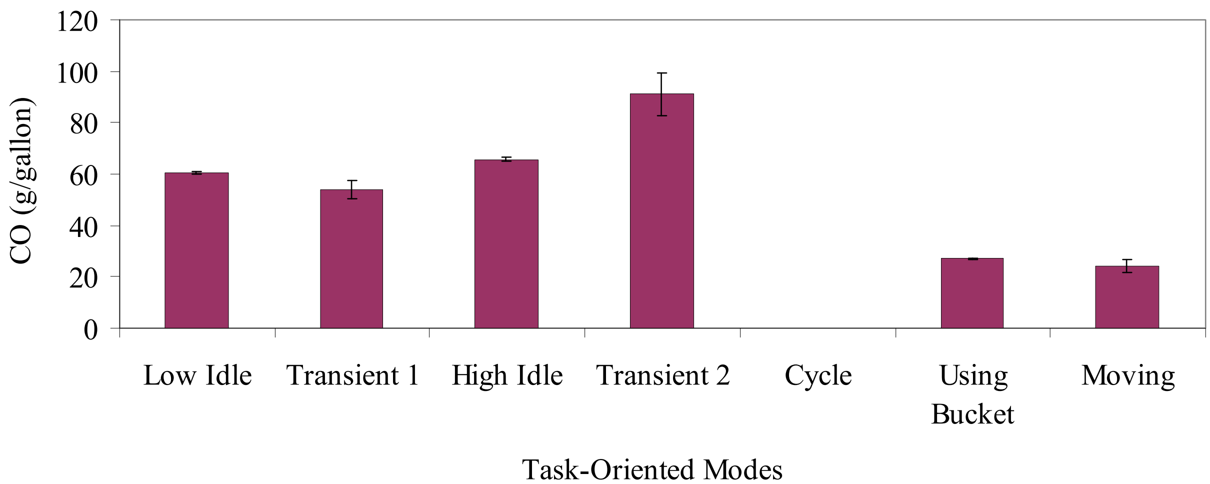


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 54 ^{o}F and the relative humidity was 61 %.

Task-oriented modes are: *low idle*: engine on, but the vehicle is not working or moving at low RPM; transient 1: engine RPM increases from low idle to high low; *high idle*: vehicle is not working or moving at high RPM; *transient 2*: vehicle from high idle to operation; *moving*: movement of the excavator; *bucket*: digging with excavator bucket; *cycle*: digging, swing, and dumping with the excavator bucket.

Figure A48. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Excavator 2 (continued on next page)





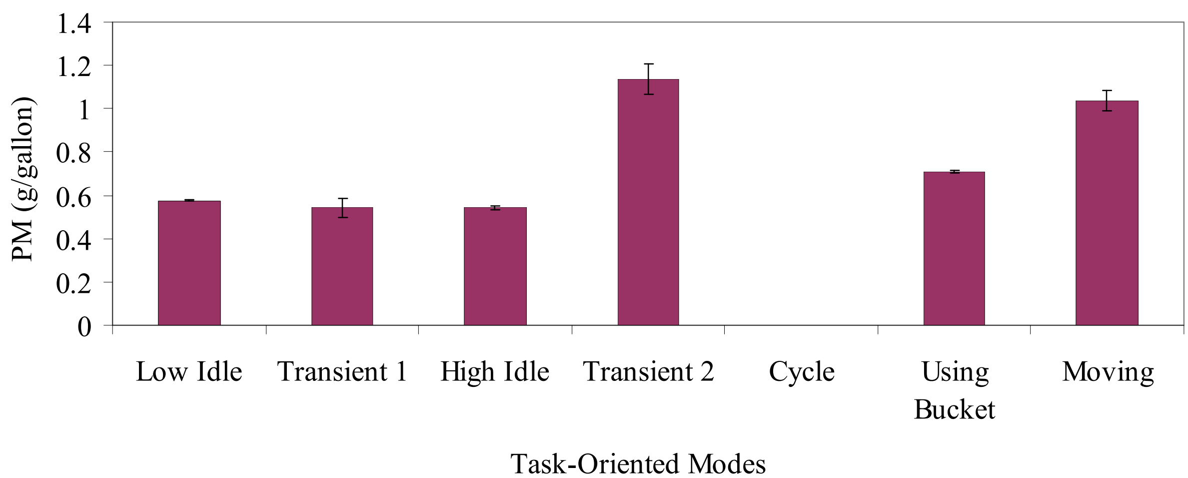
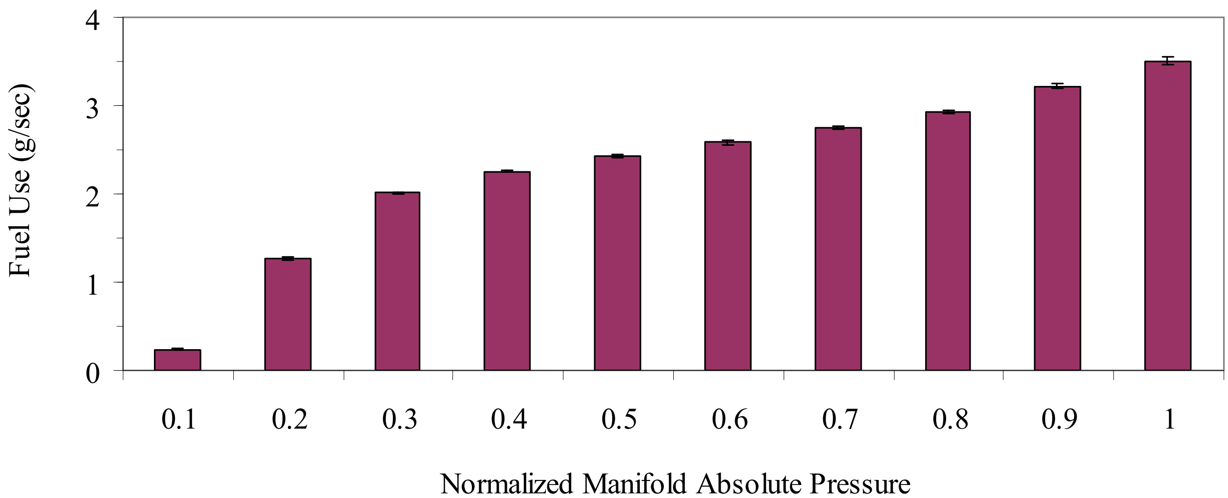
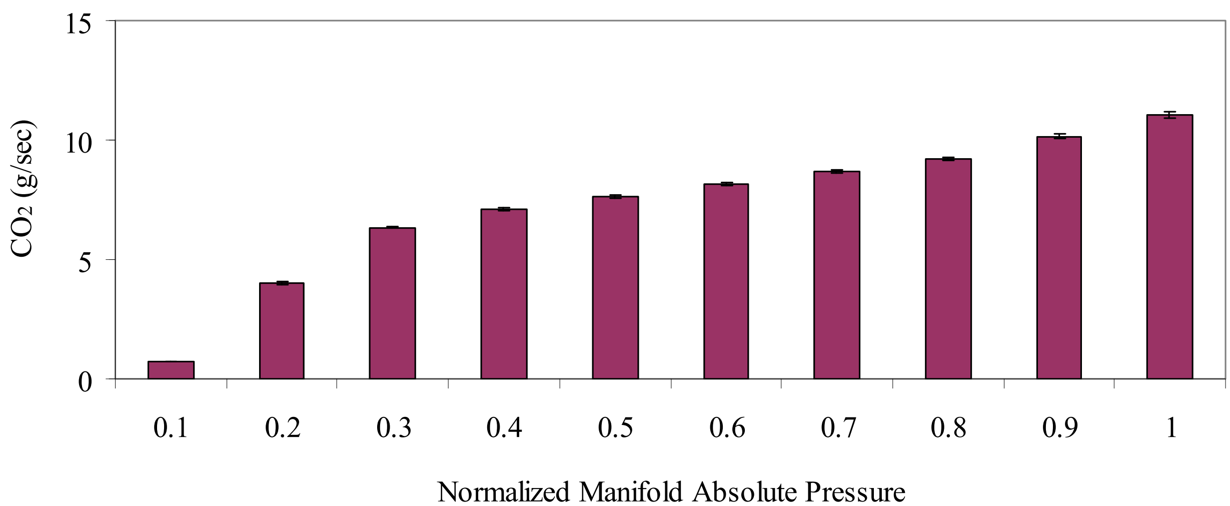


Figure A48. Continued

EXCAVATOR 3





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 47°F and the relative humidity was 46 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A49. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Excavator 3 (continued on next page)

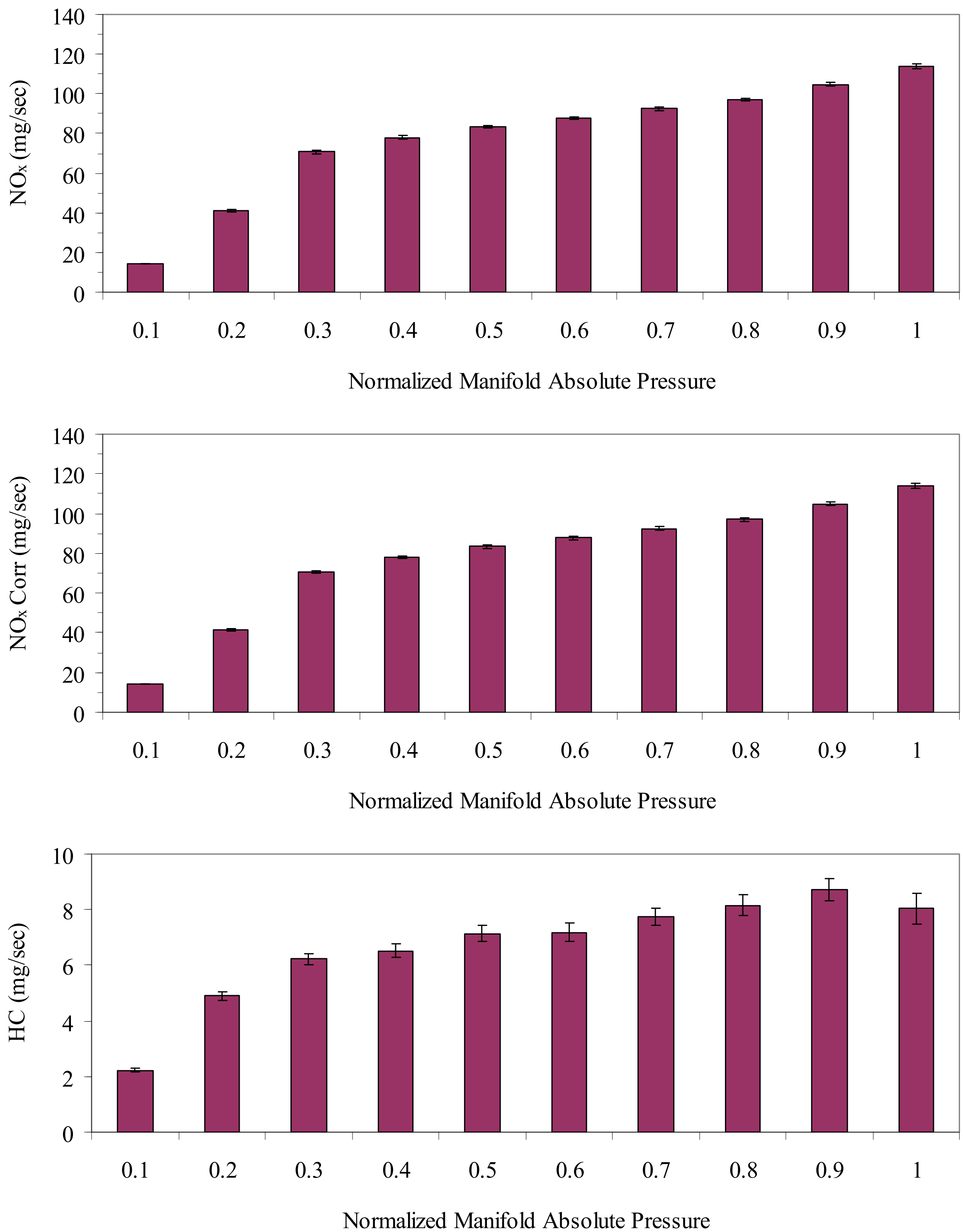
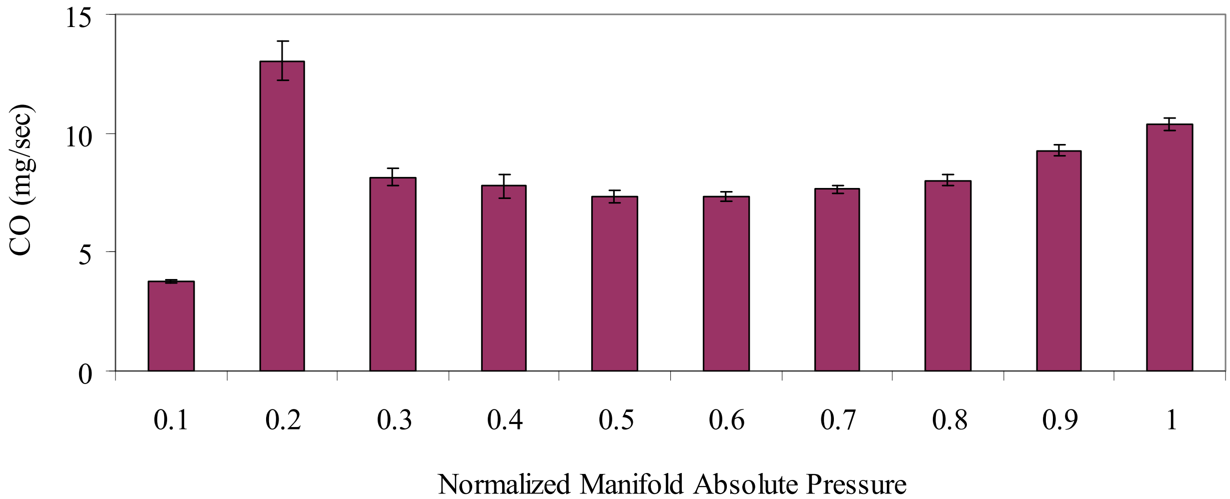


Figure A49. Continued



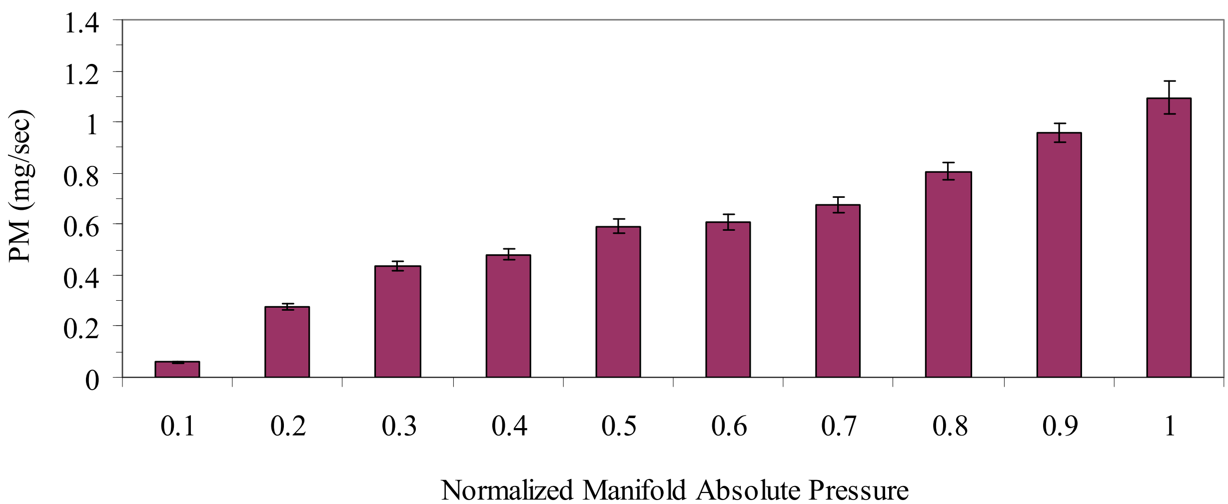
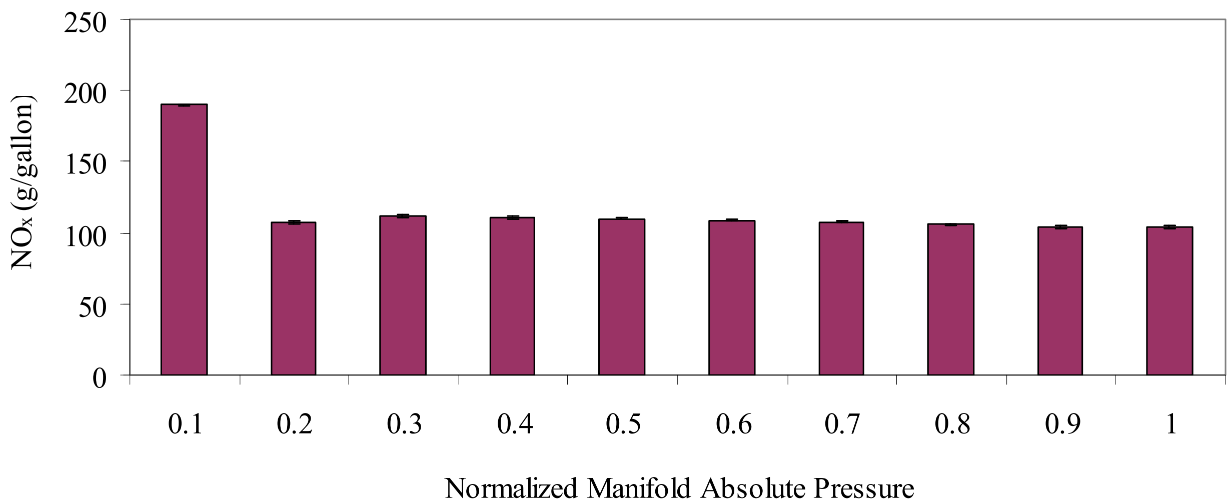
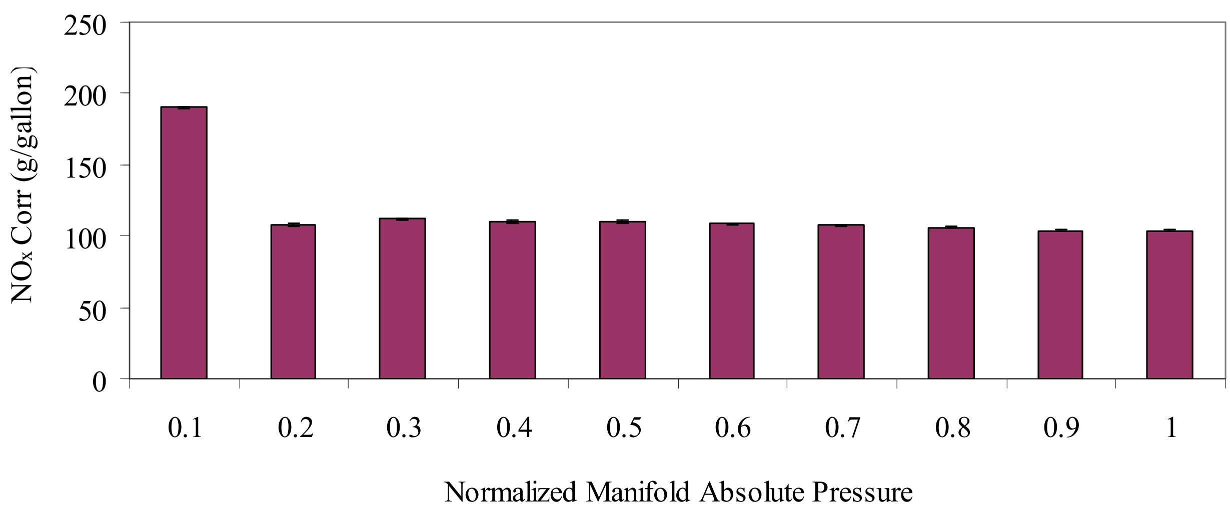


Figure A49. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 47^{o}F and the relative humidity was 46 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A50. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Excavator 3 (continued on next page)

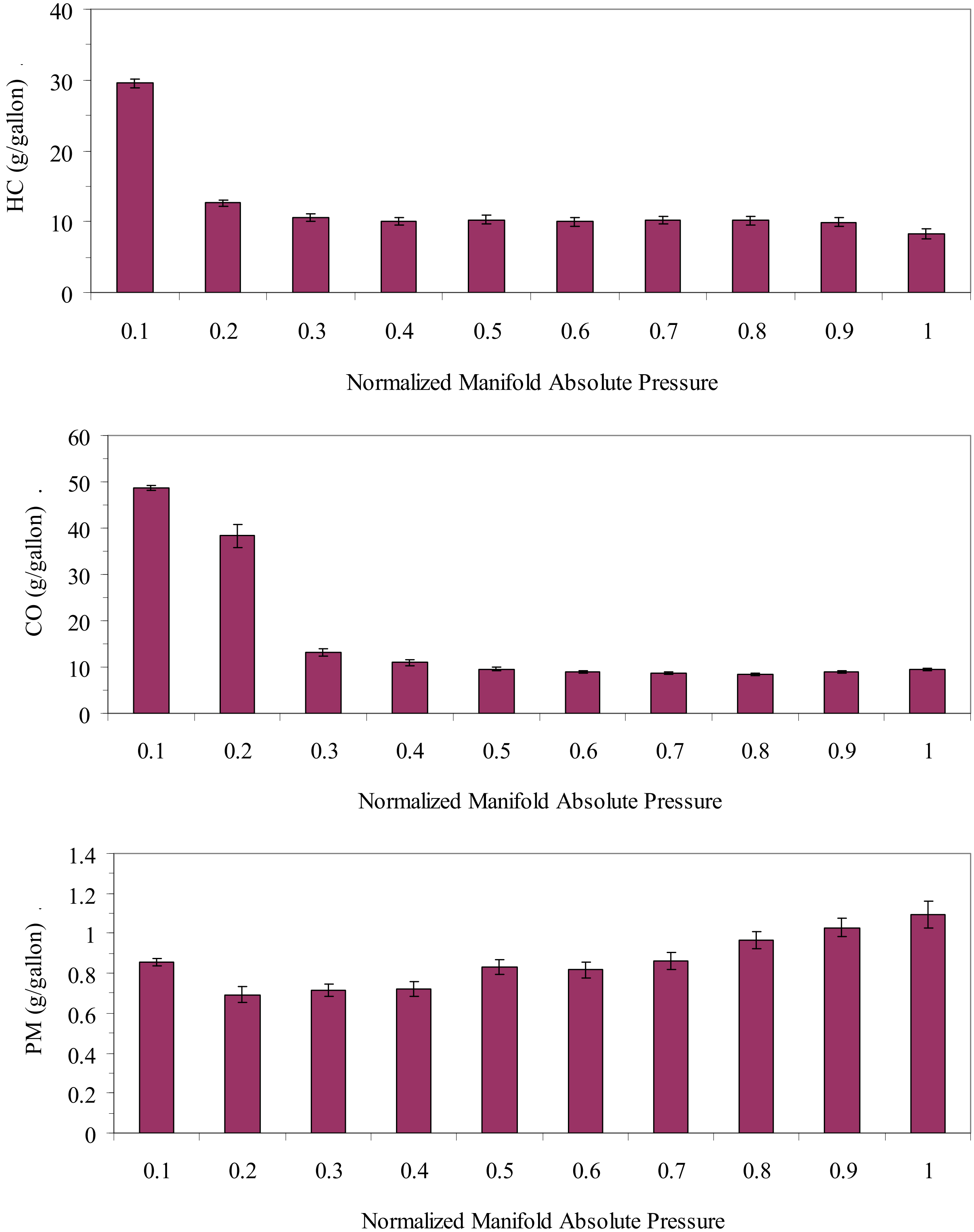
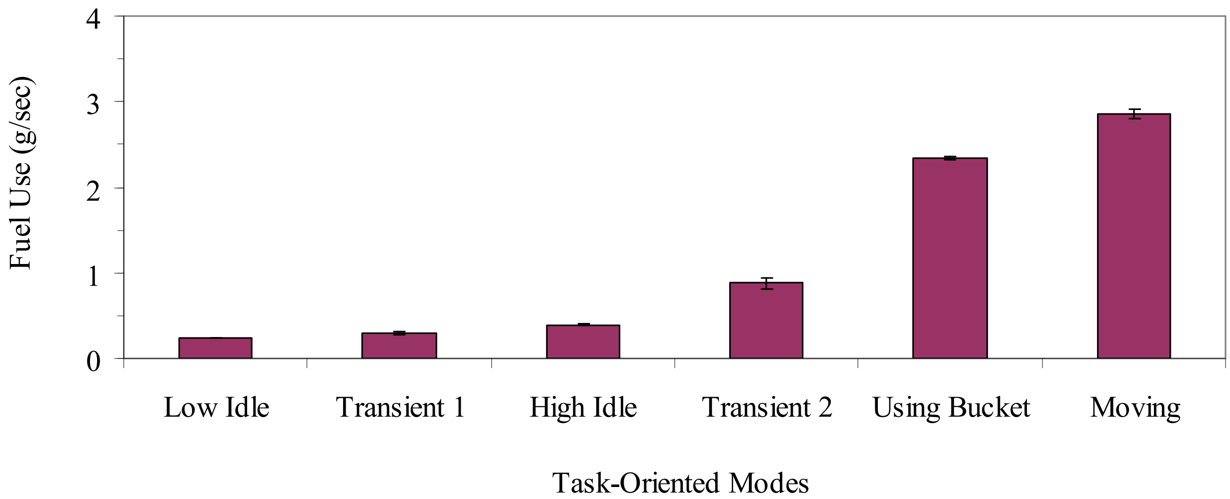
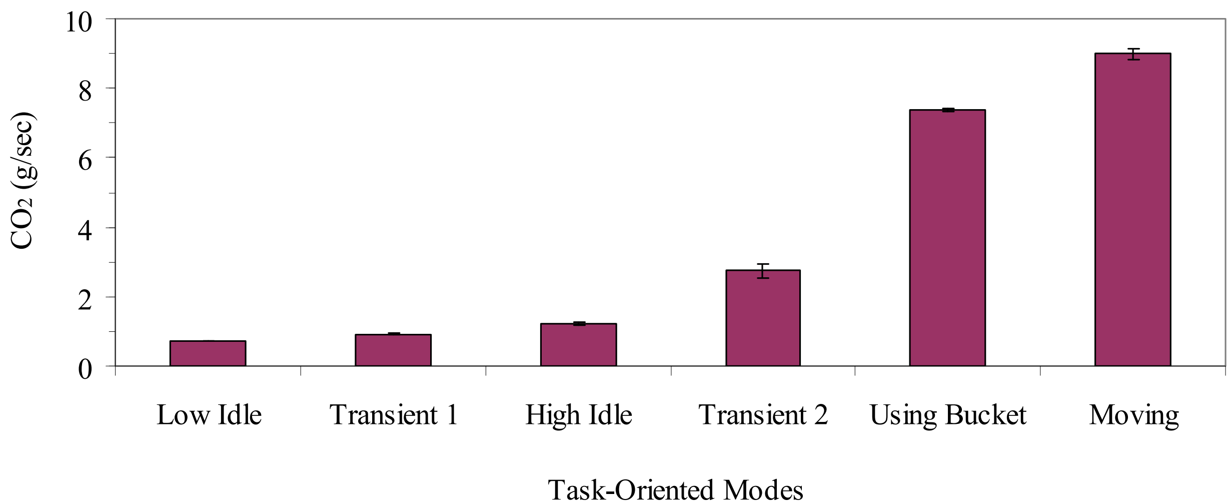


Figure A50. Continued

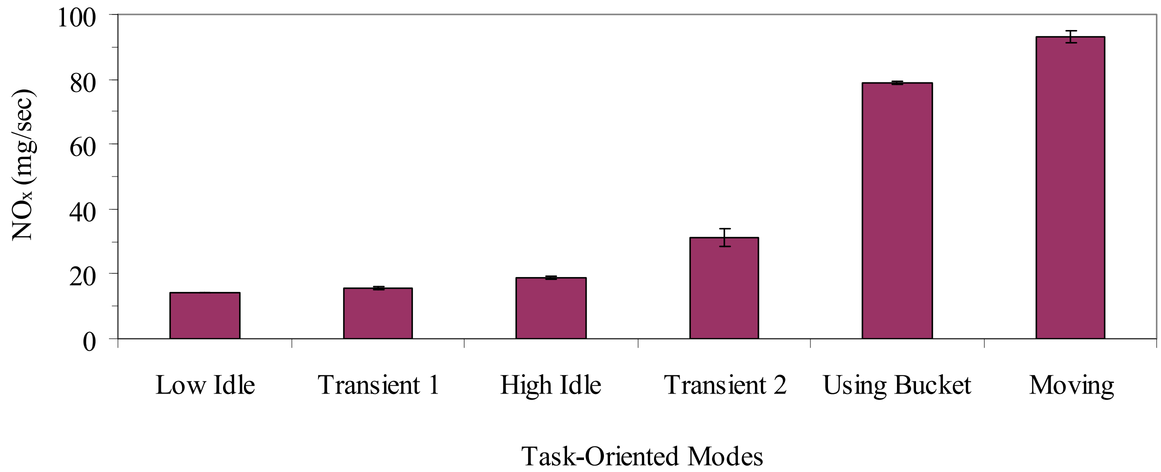


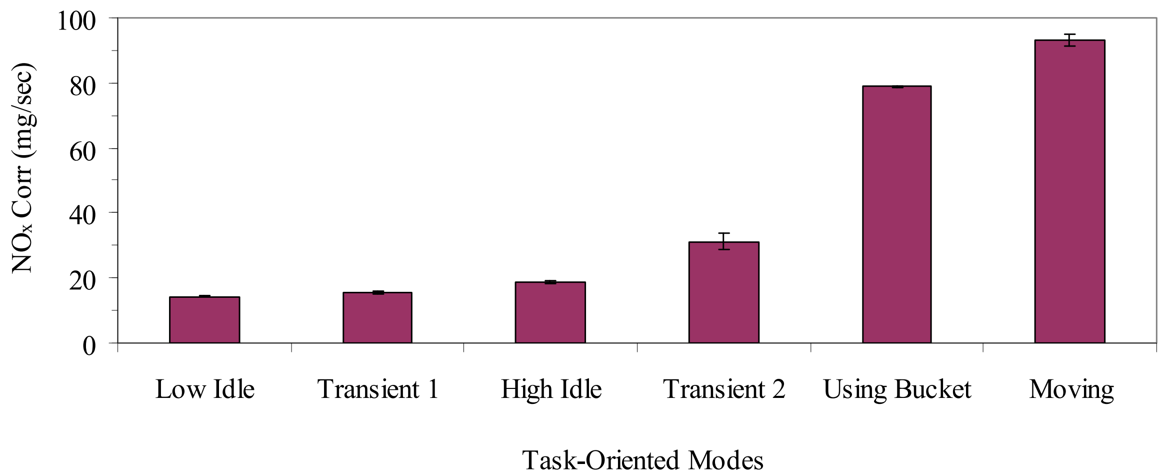


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 47^{o}F and the relative humidity was 46 %.

Task-oriented modes are: *low idle*: engine on, but the vehicle is not working or moving at low RPM; transient 1: engine RPM increases from low idle to high low; *high idle*: vehicle is not working or moving at high RPM; *transient 2*: vehicle from high idle to operation; *moving*: movement of the excavator; *bucket*: digging, swing, and dumping with the excavator bucket.

Figure A51. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Excavator 3 (continued on next page)





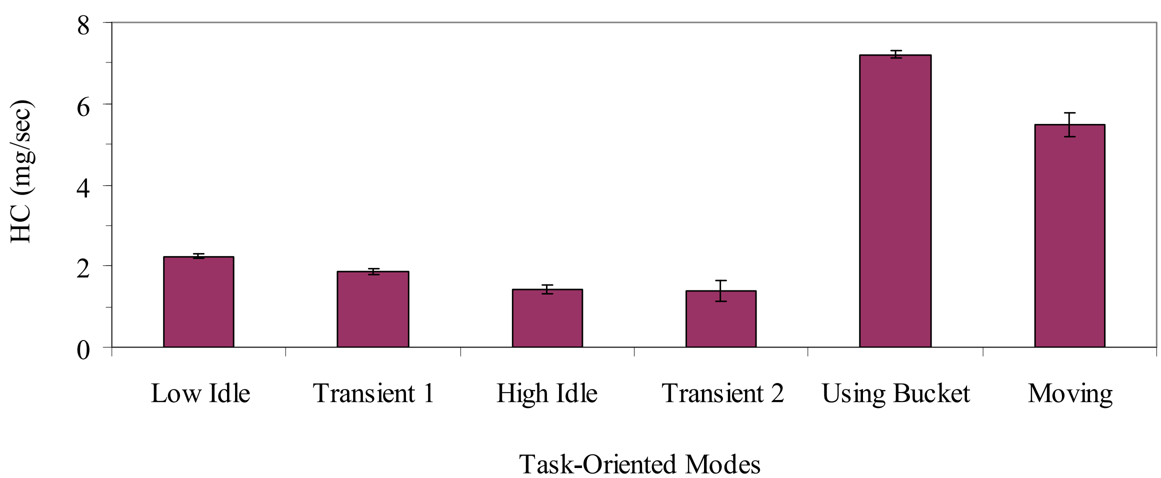
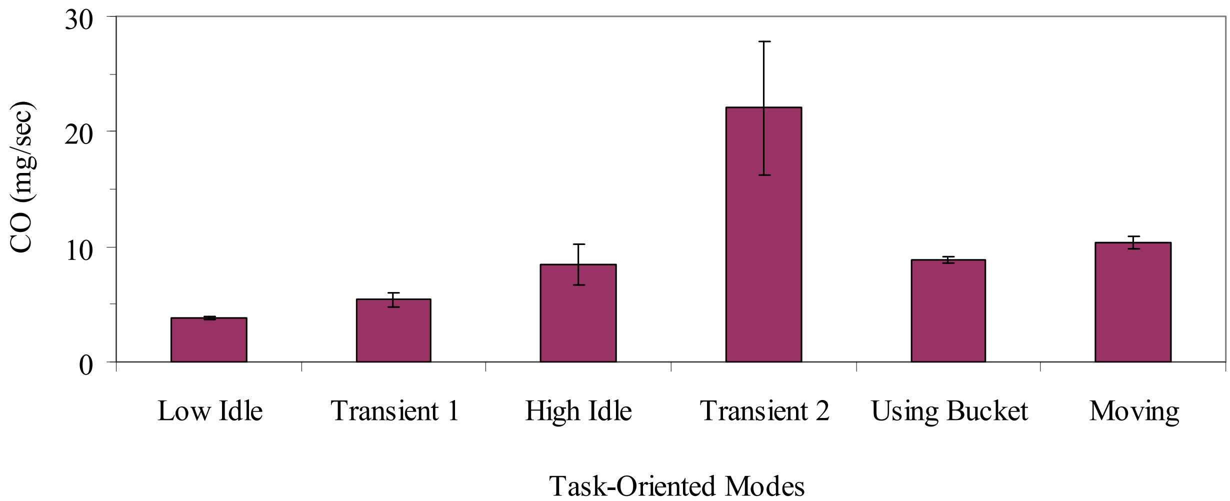


Figure A51. Continued



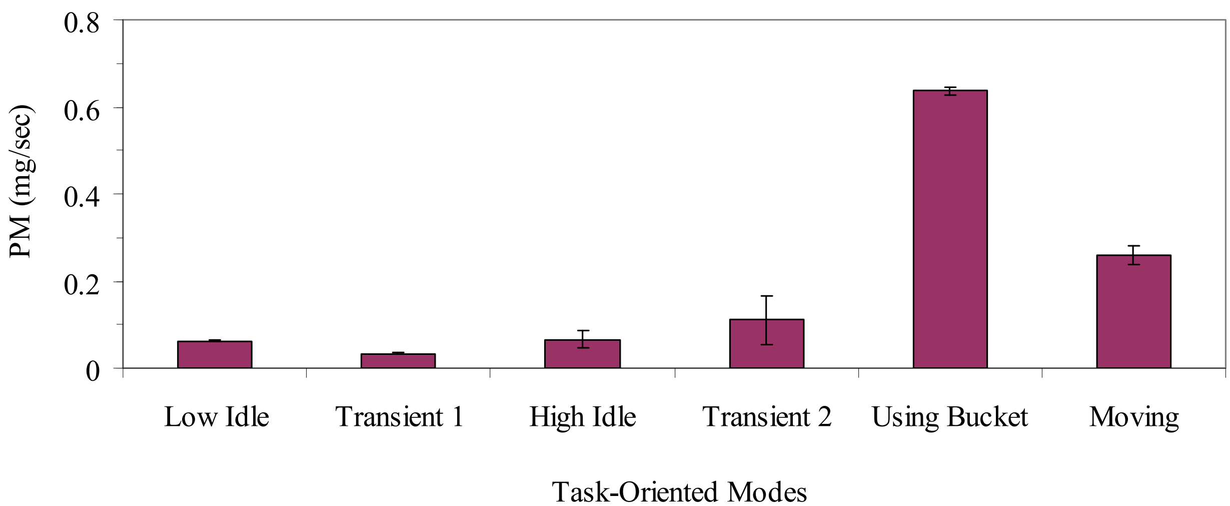
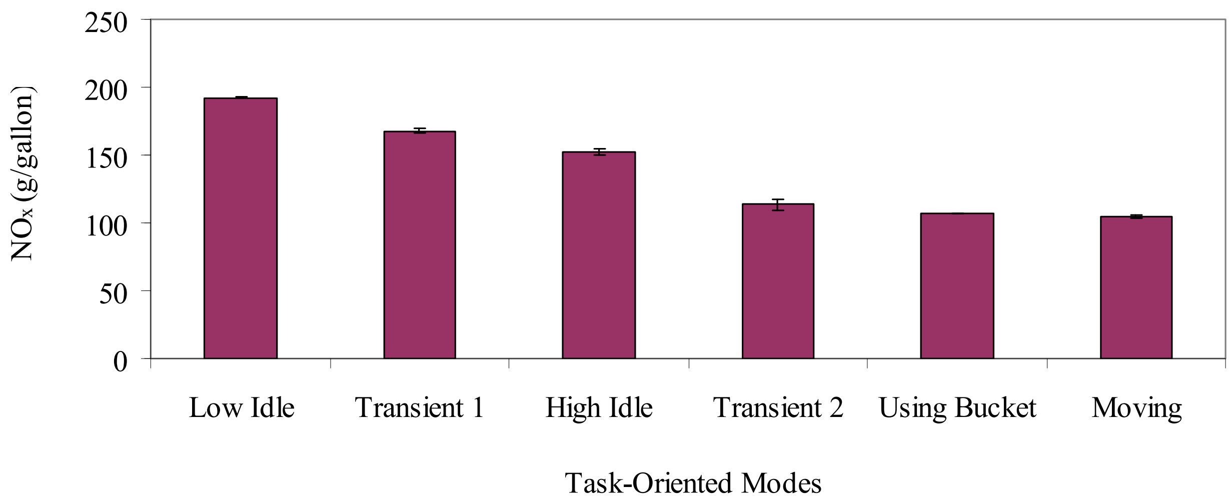
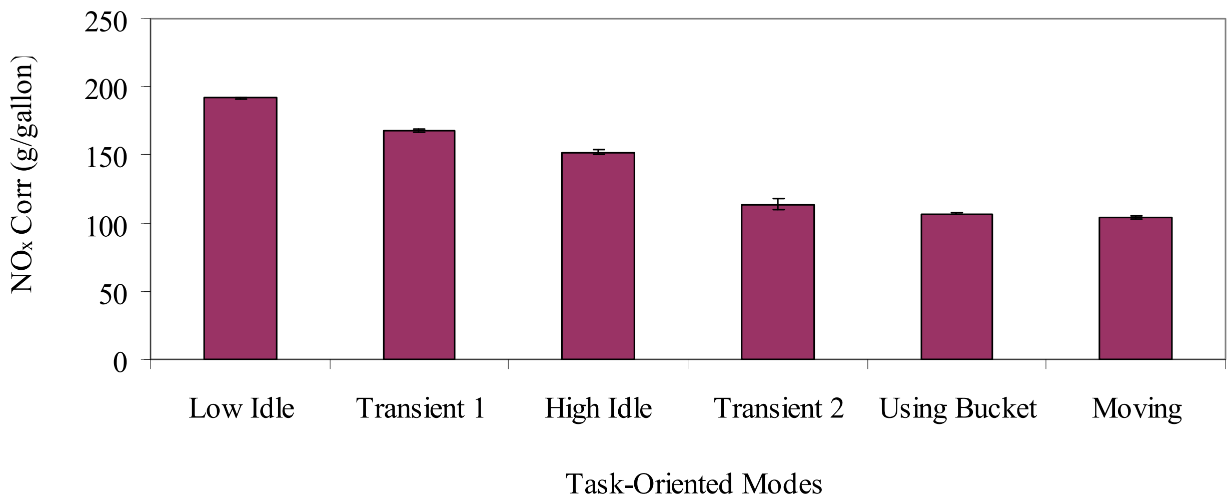


Figure A51. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 47°F and the relative humidity was 46 %.

Task-oriented modes are: *low idle*: engine on, but the vehicle is not working or moving at low RPM; transient 1: engine RPM increases from low idle to high low; *high idle*: vehicle is not working or moving at high RPM; *transient 2*: vehicle from high idle to operation; *moving*: movement of the excavator; *bucket*: digging, swing, and dumping with the excavator bucket.

Figure A52. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Excavator 3 (continued on next page)

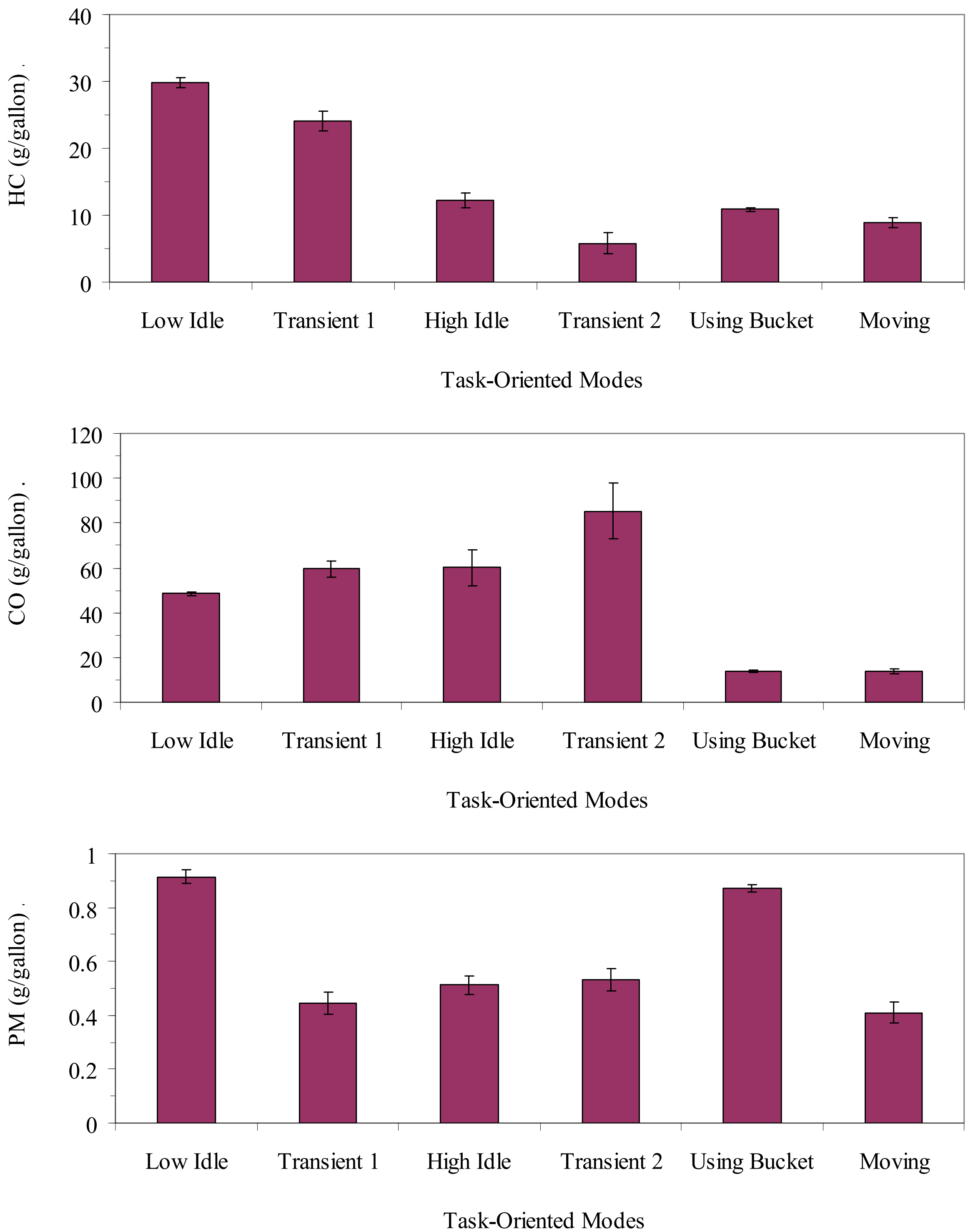
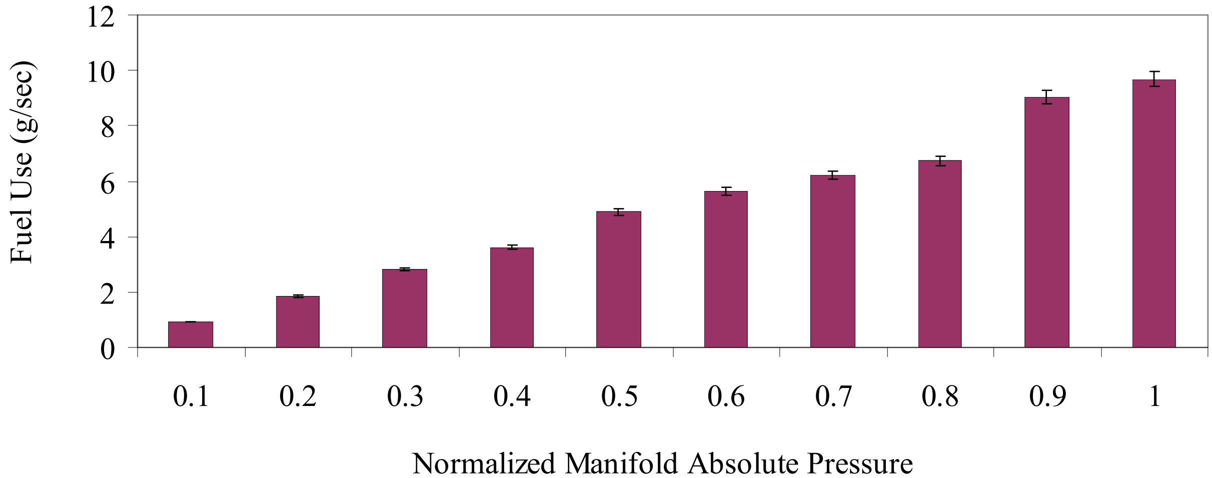
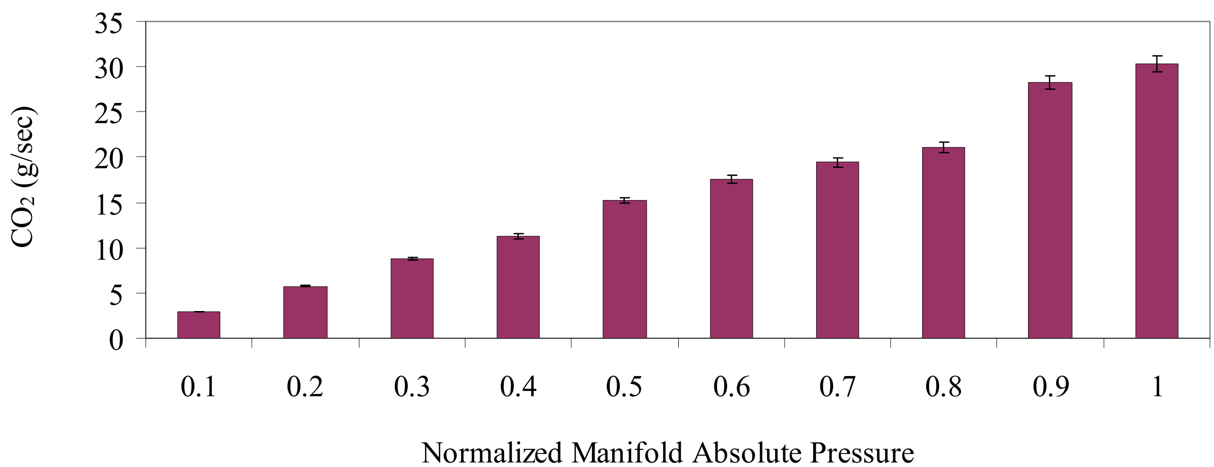


Figure A52. Continued

OFF-HIGHWAY TRUCK 1

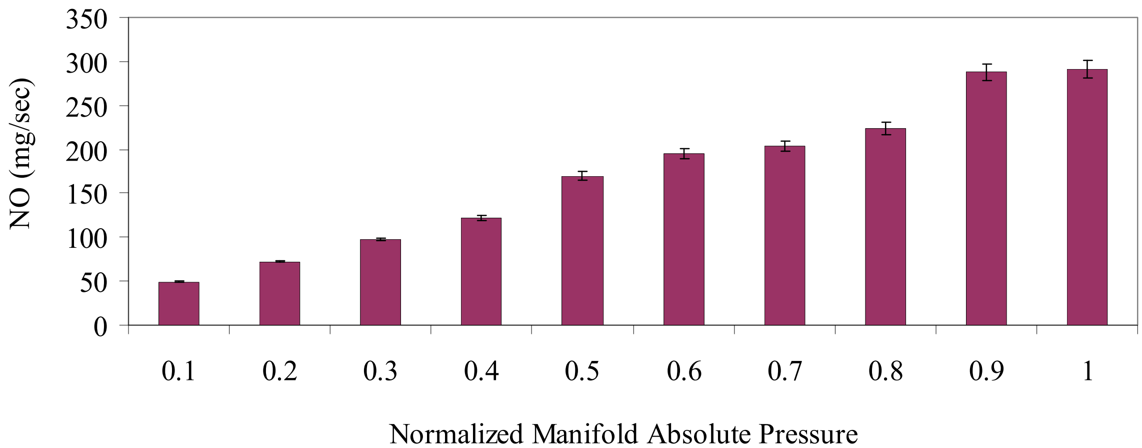


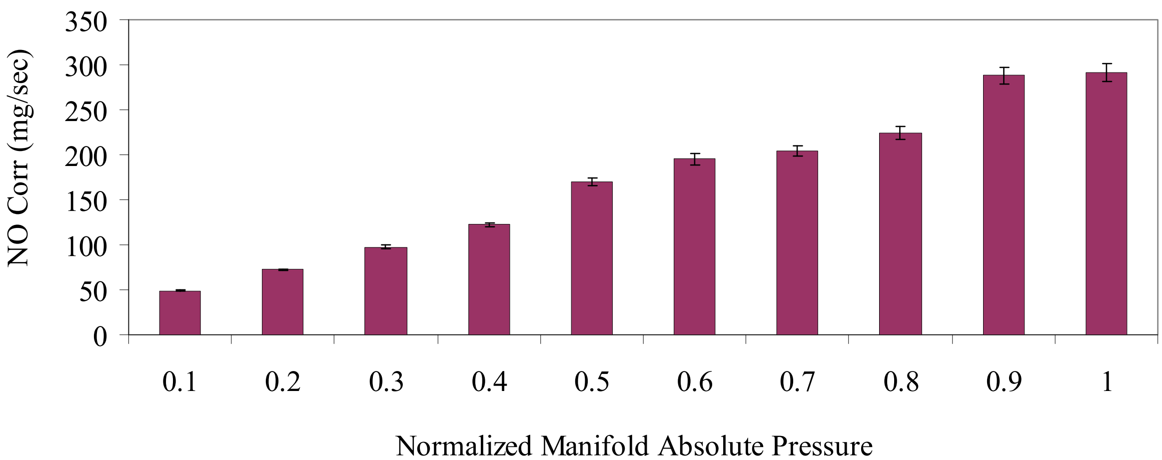


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 35 ^{o}F and the relative humidity was 42 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A53. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Off-Highway Truck 1 (continued on next page)





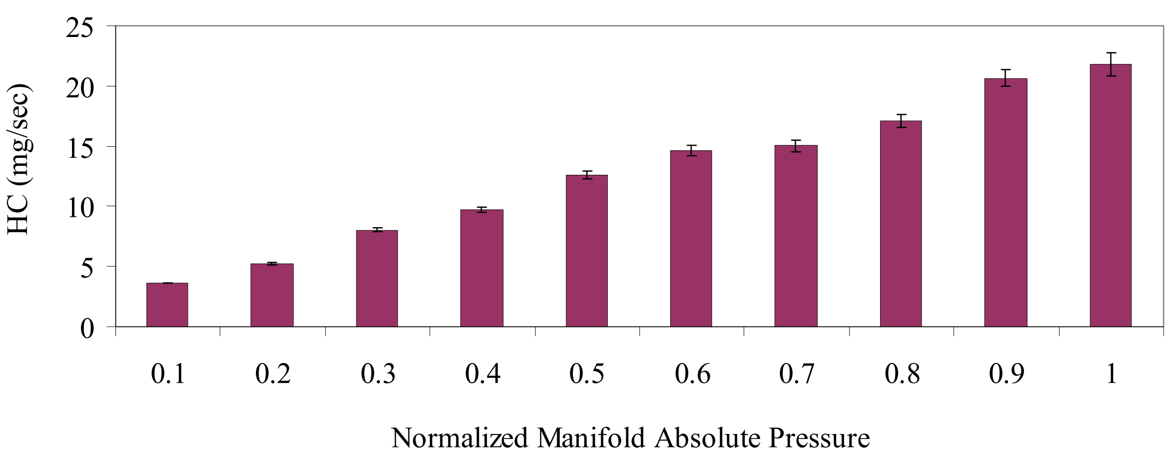
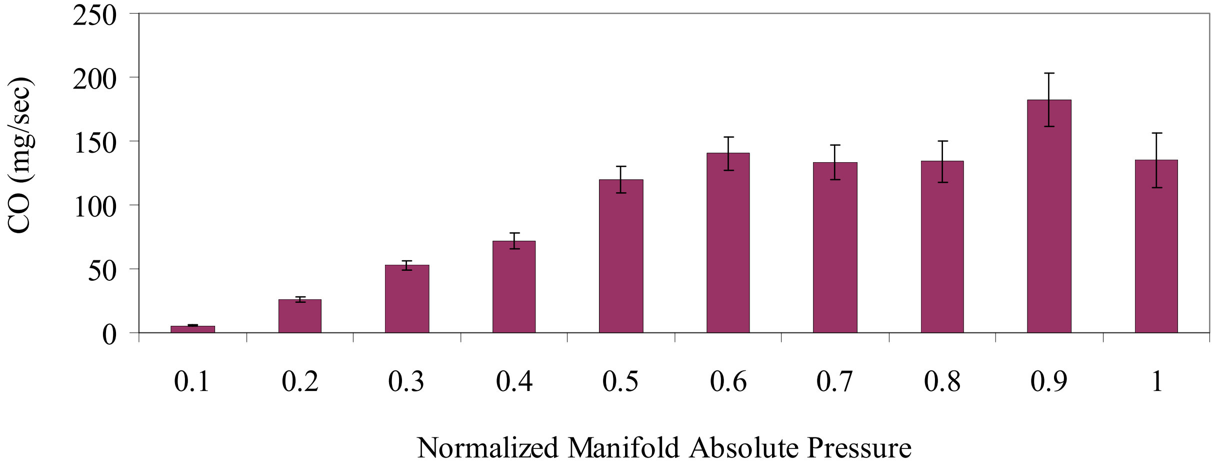


Figure A53. Continued



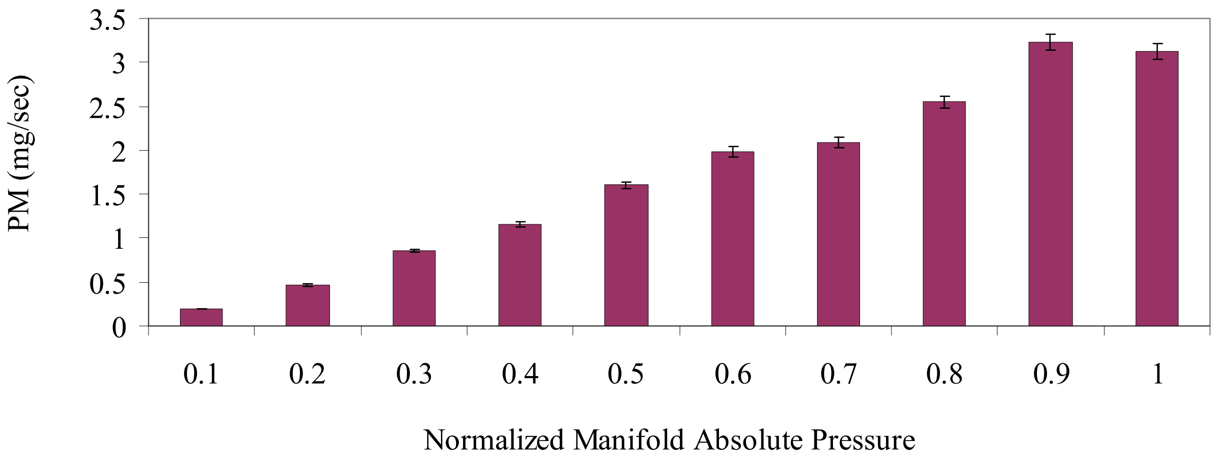
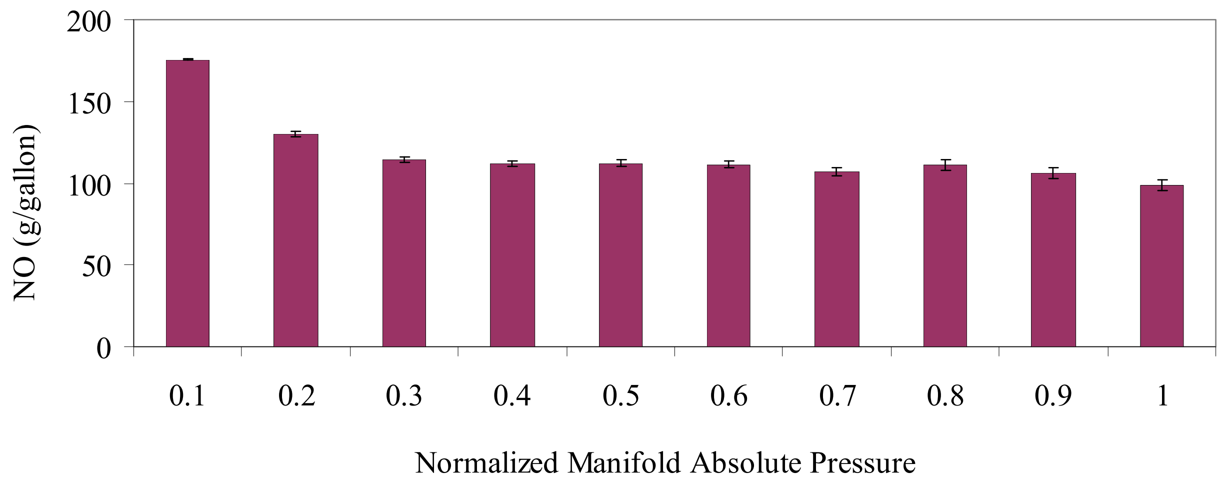
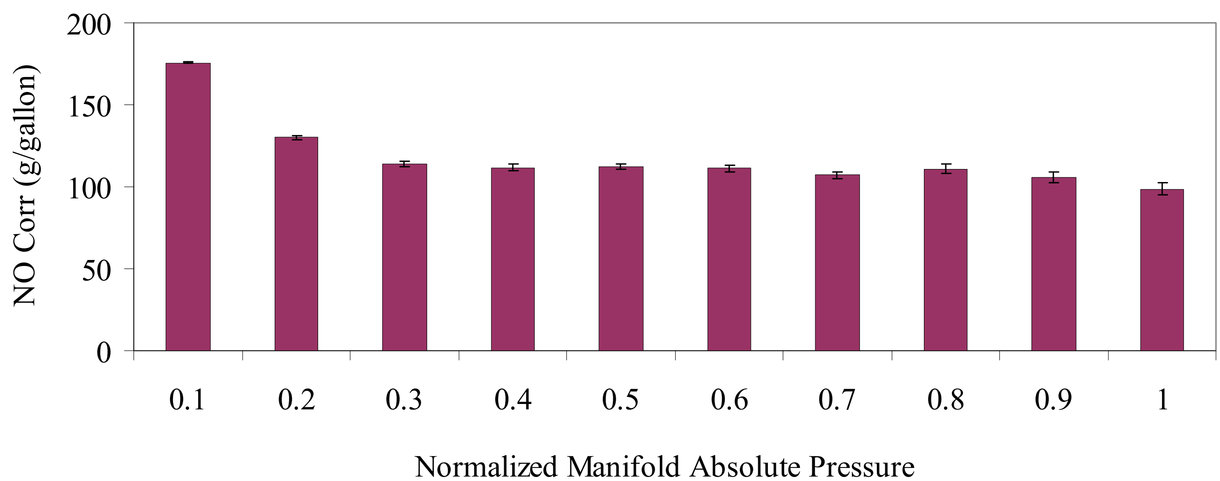


Figure A53. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 35 ^{o}F and the relative humidity was 42 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A54. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Off-Highway Truck 1 (continued on next page)

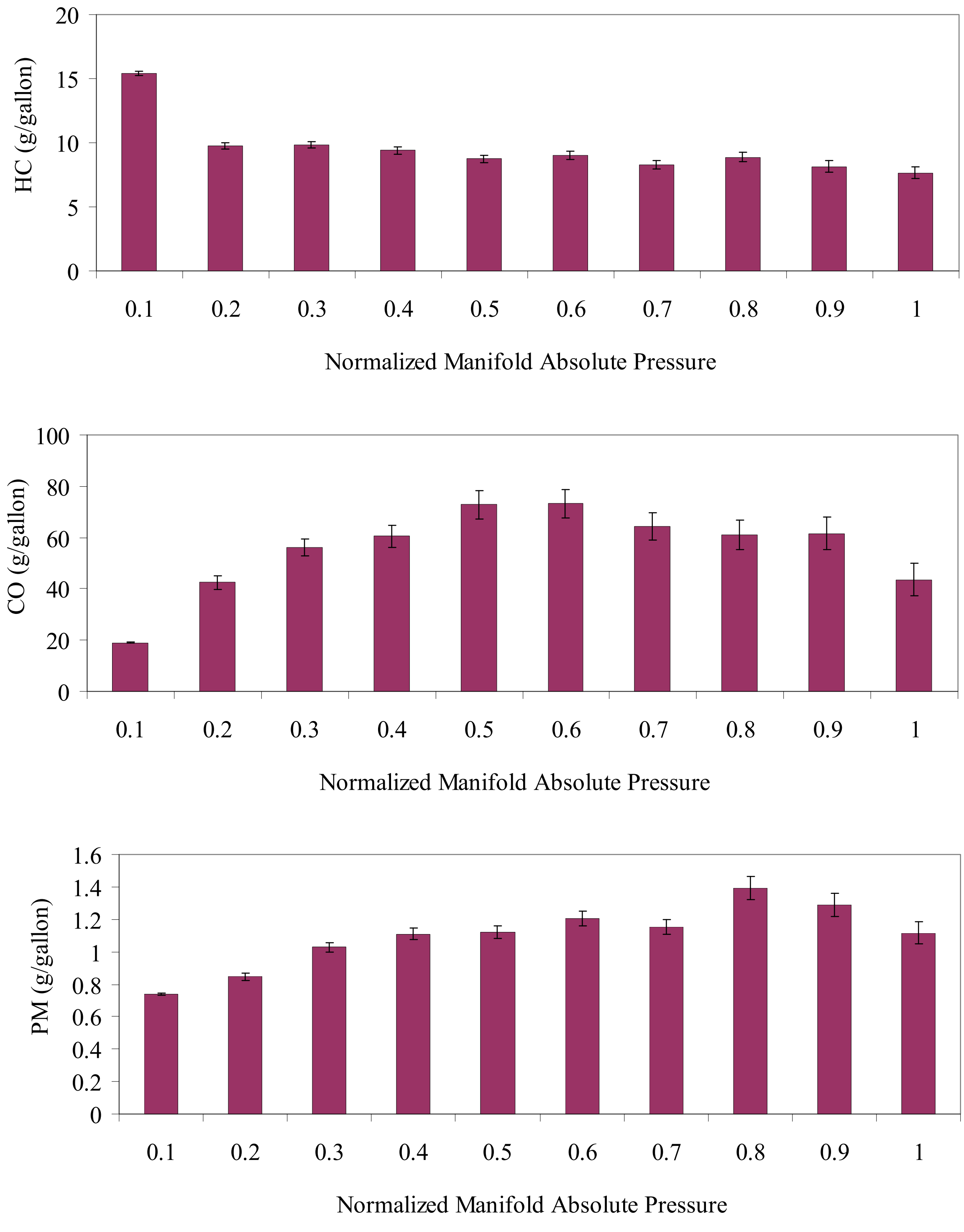
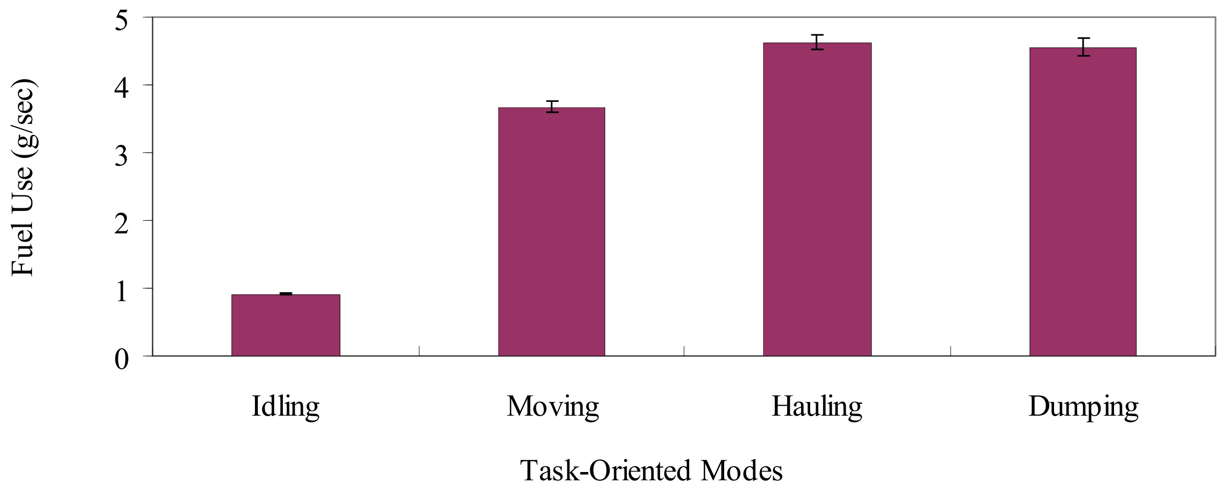
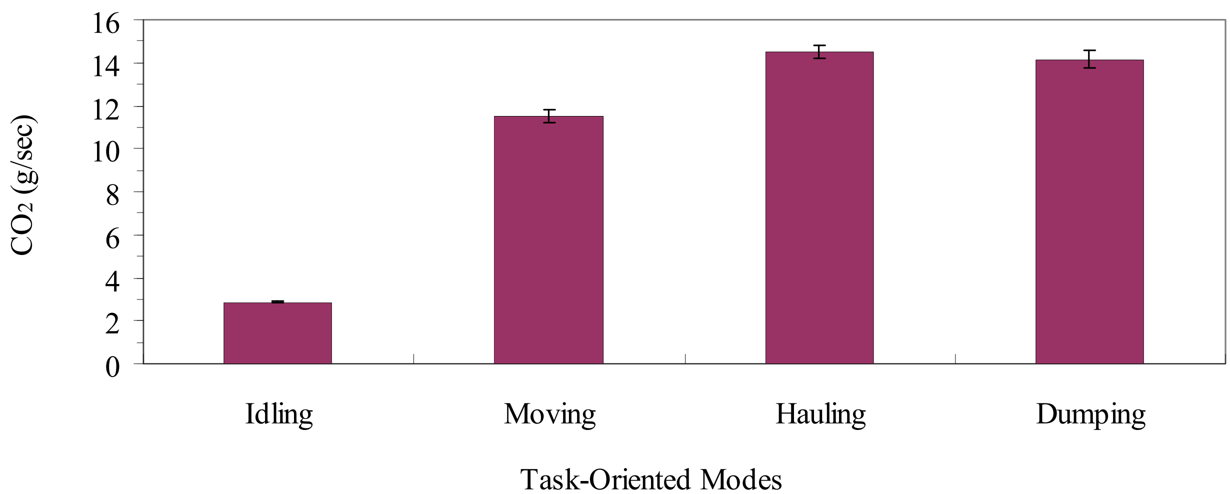


Figure A54. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 35 ^{o}F and the relative humidity was 42 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the off-highway truck (forward or backward); *hauling*: movement of the backhoe when the truck is hauling materials; *dumping*: dumping of the materials.

Figure A55. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Off-Highway Truck 1 (continued on next page)

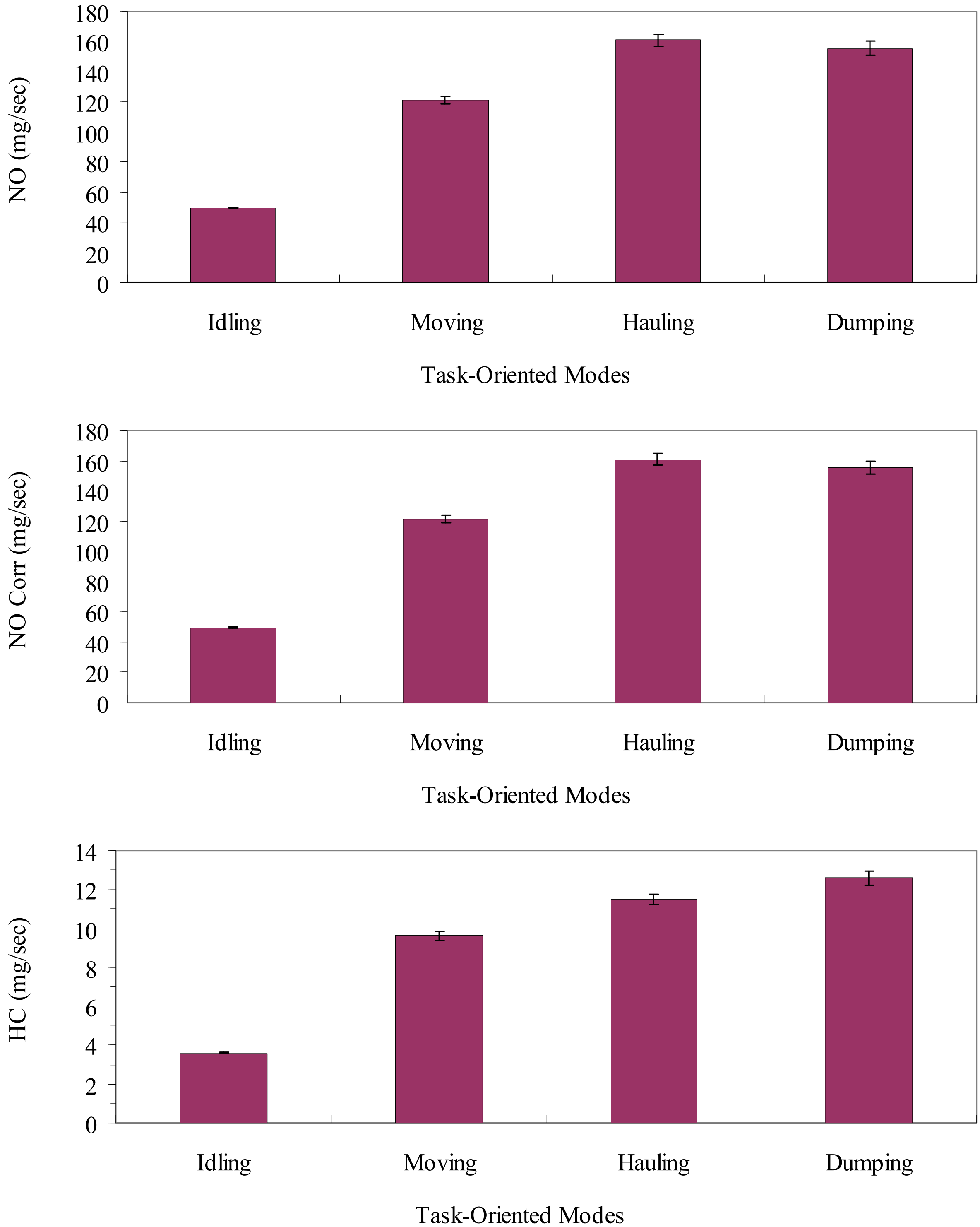
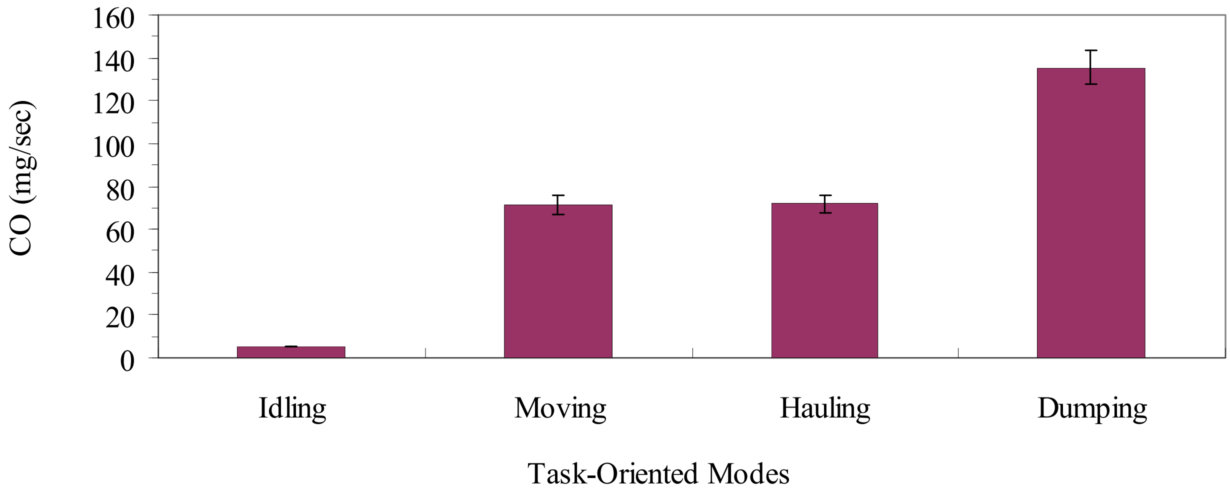


Figure A55. Continued



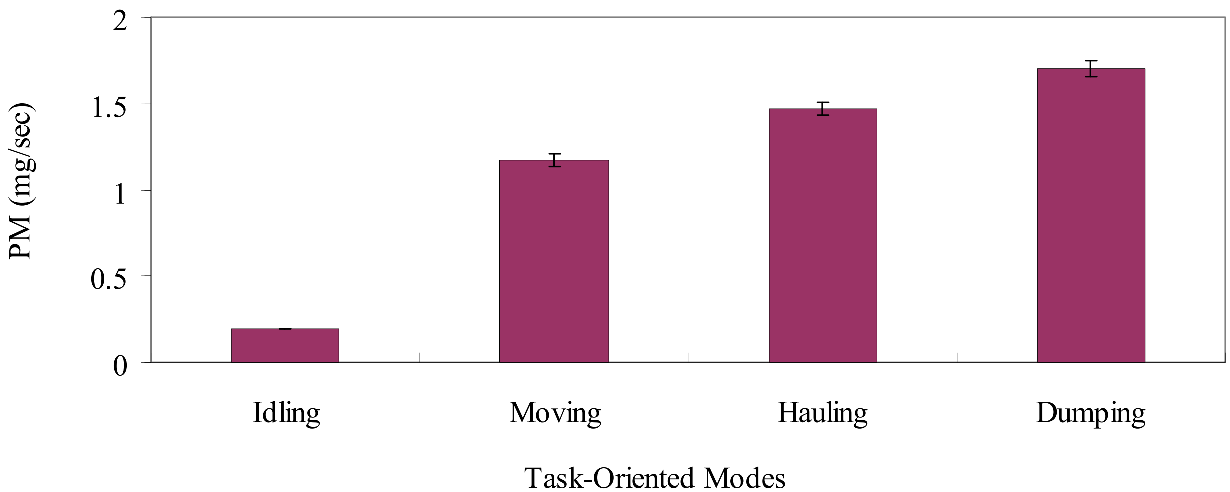
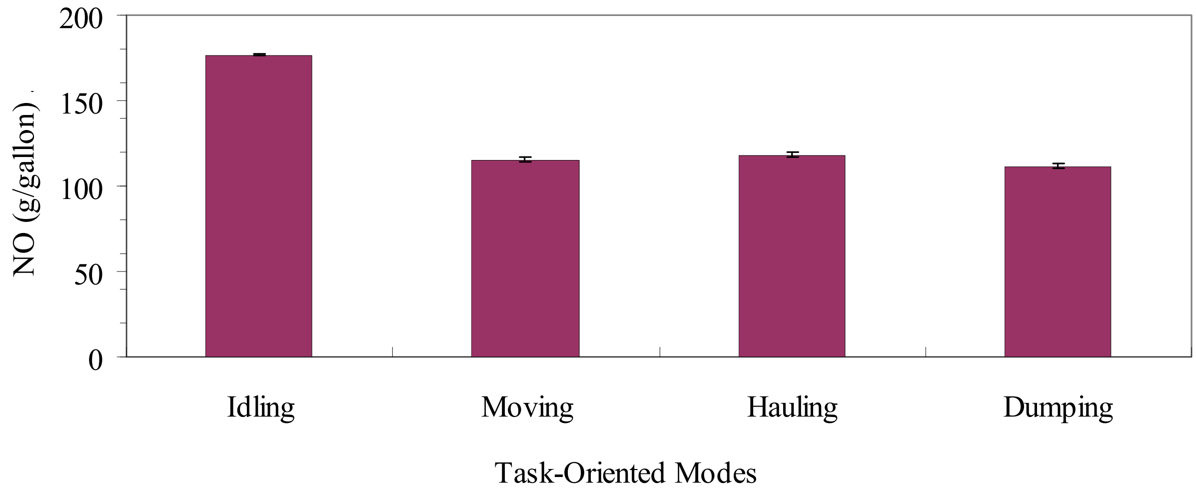
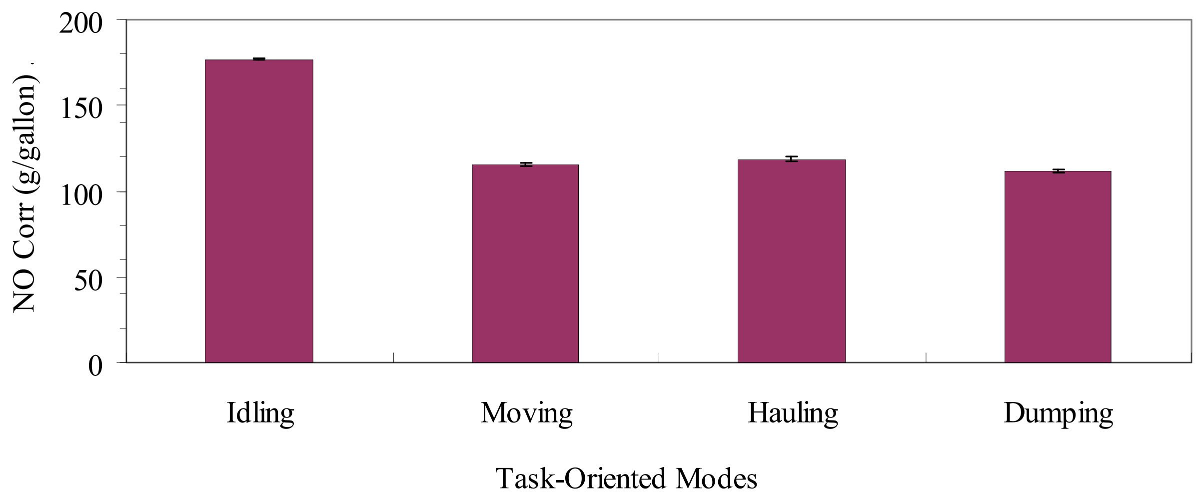


Figure A55. Continued

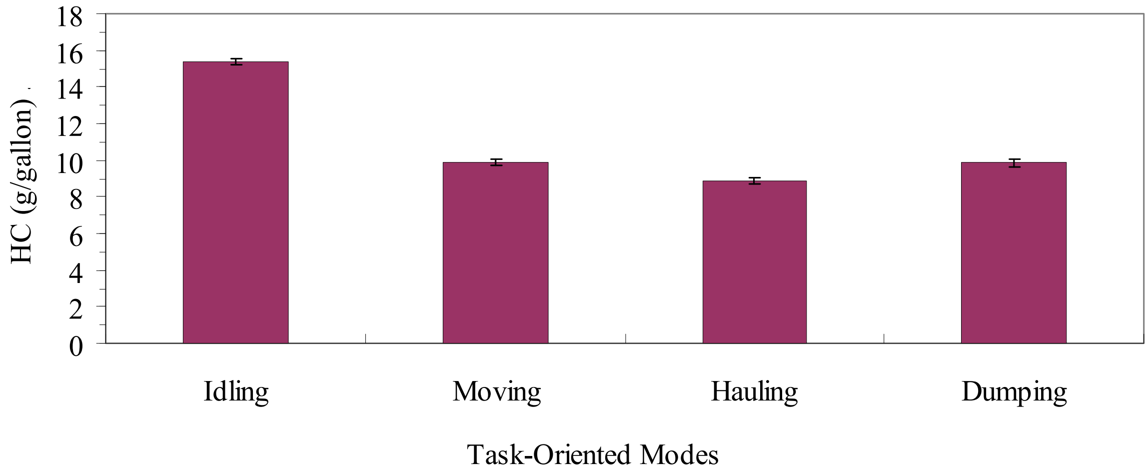


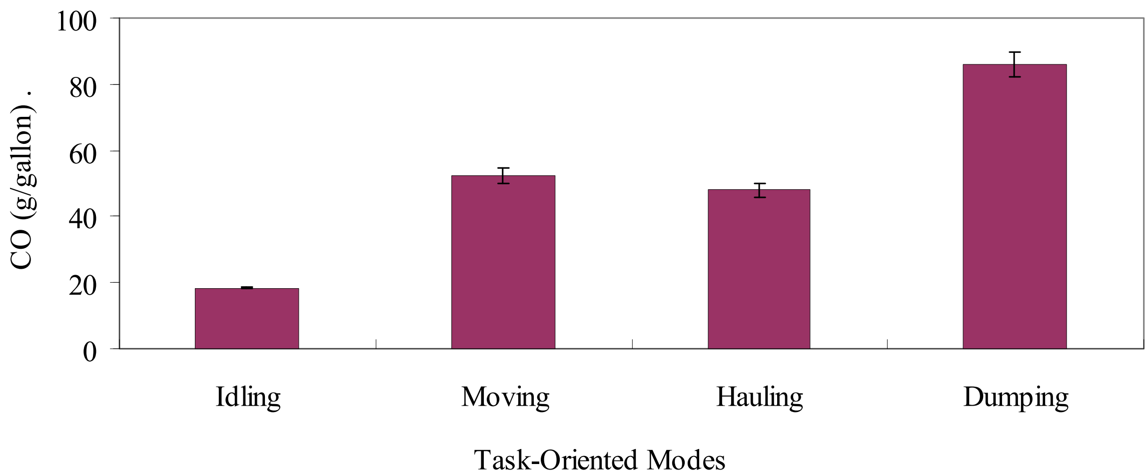


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 35 ^{o}F and the relative humidity was 42 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the off-highway truck (forward or backward); *hauling*: movement of the backhoe when the truck is hauling materials; *dumping*: dumping of the materials.

Figure A56. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Off-Highway Truck 1 (continued on next page)





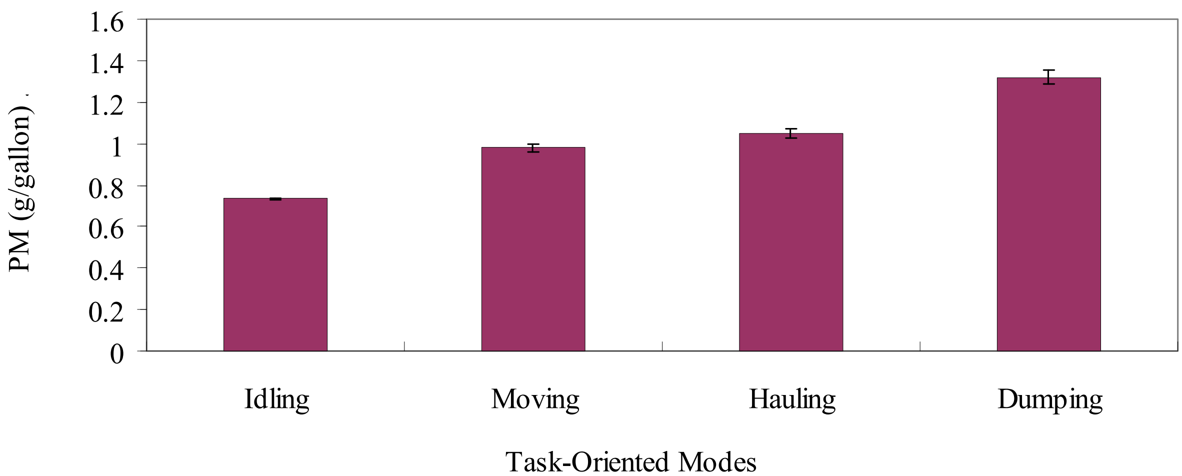
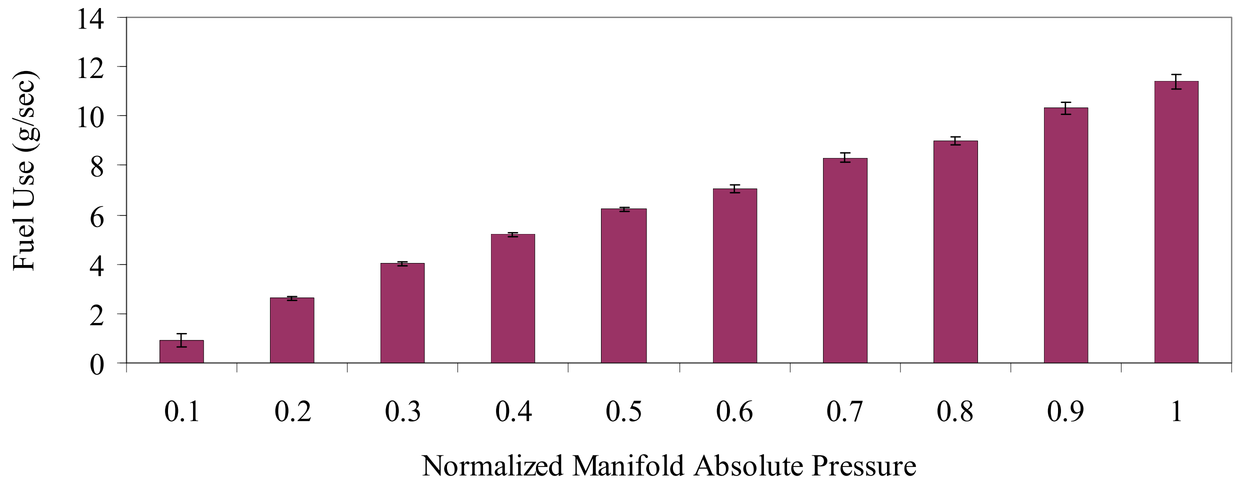
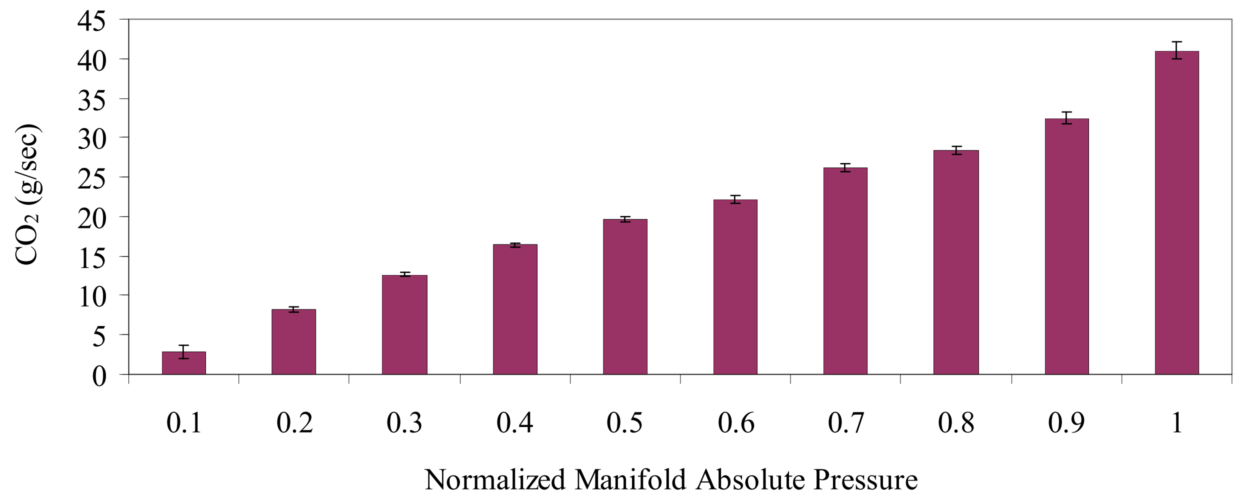


Figure A56. Continued

OFF-HIGHWAY TRUCK 2





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 74 ^oF and the relative humidity was 64 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A57. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Off-Highway Truck 2 (continued on next page)

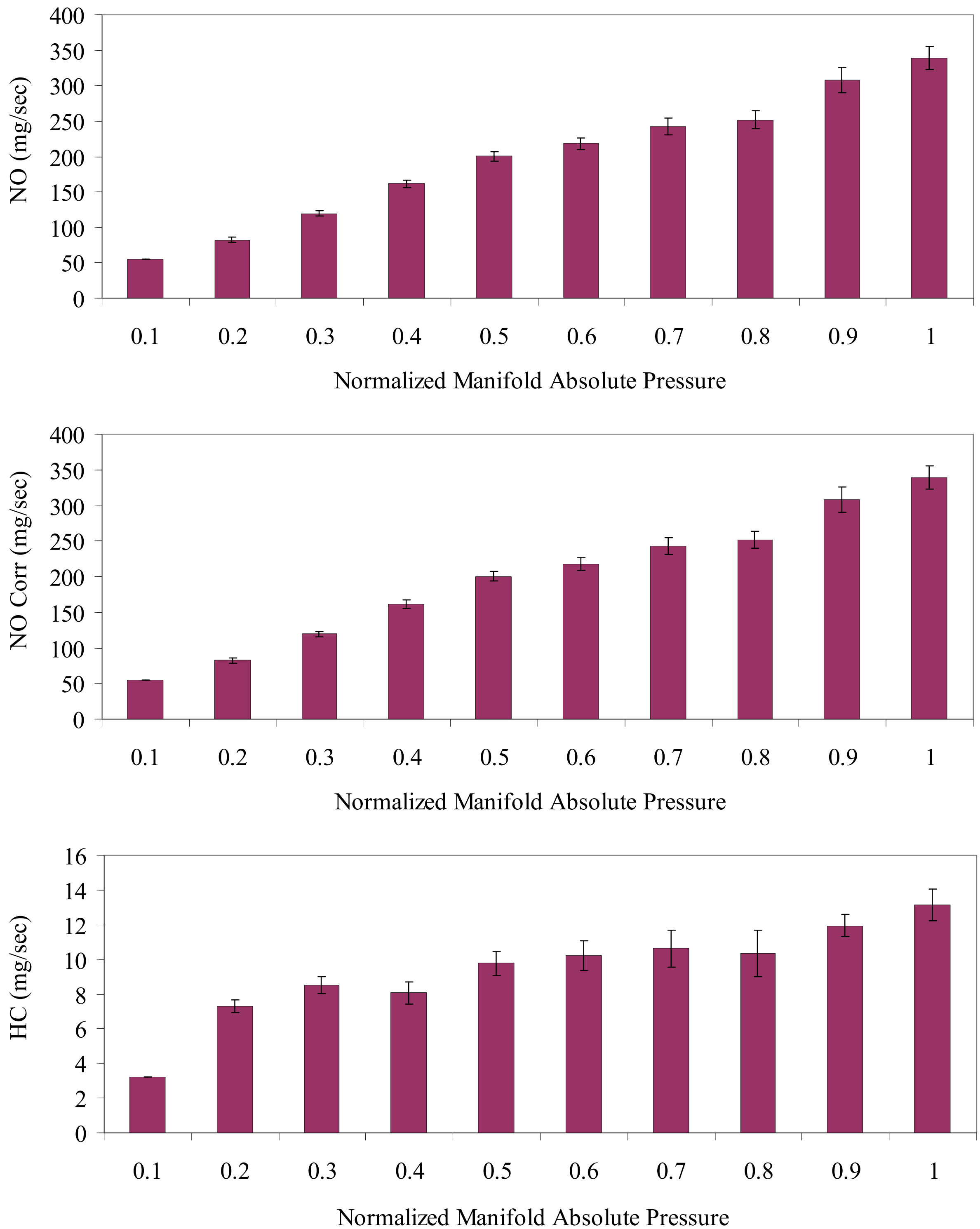


Figure A57. Continued

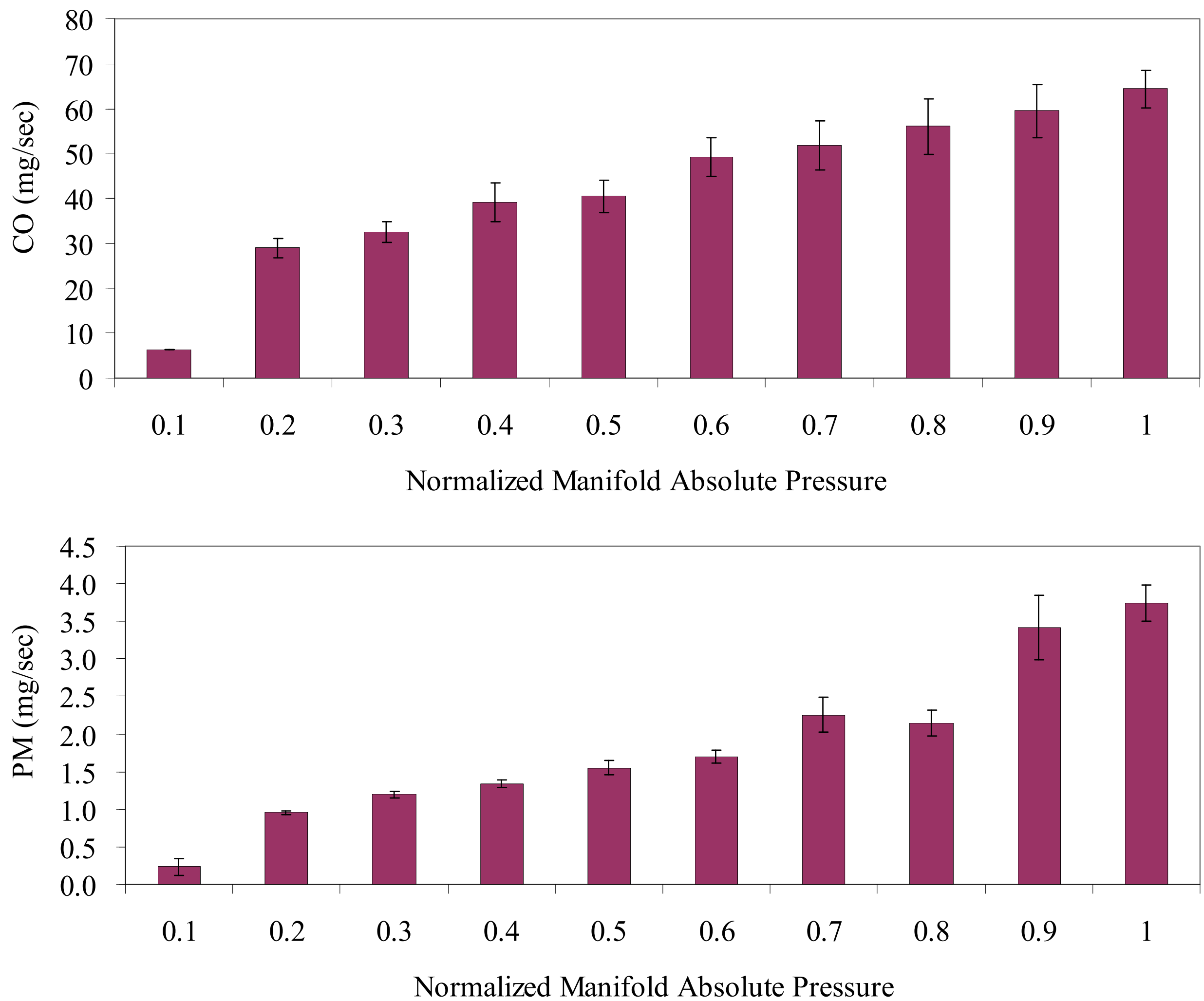
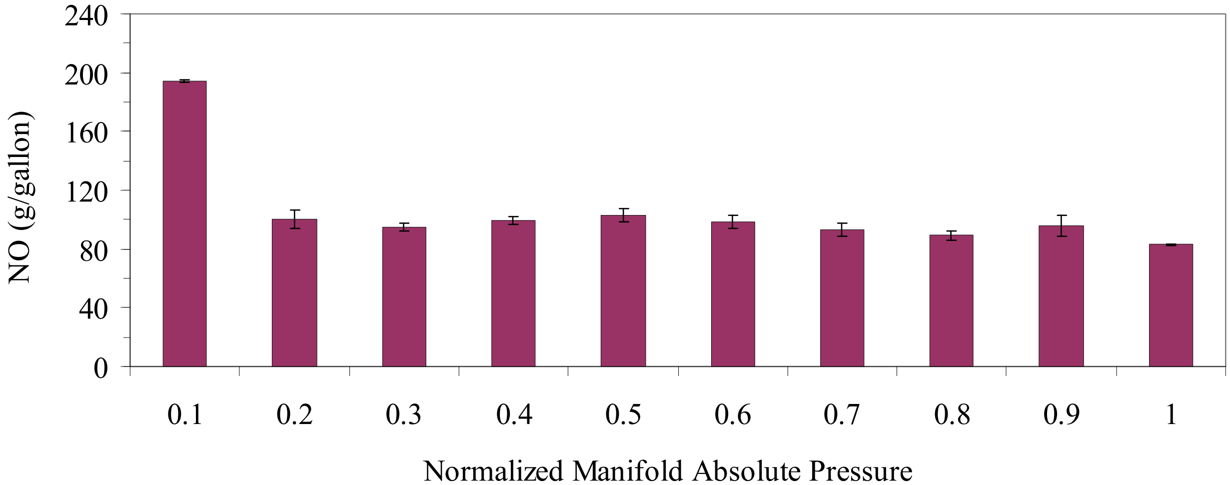
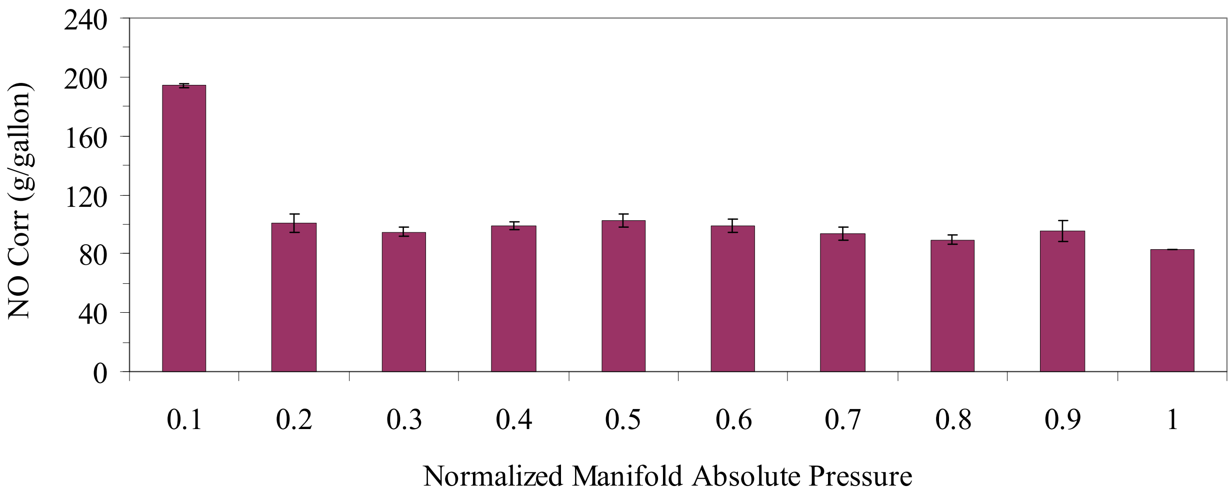


Figure A57. Continued

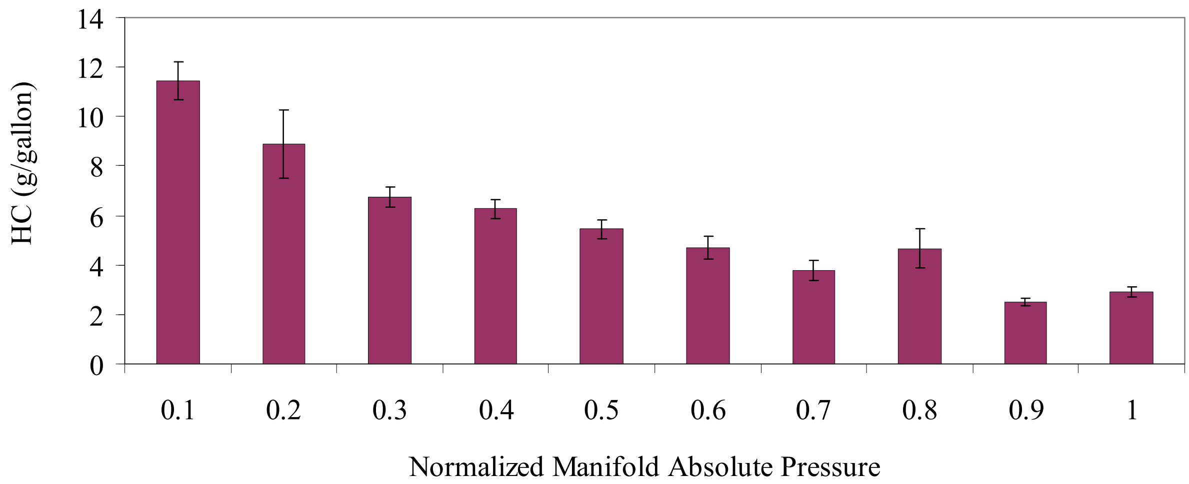


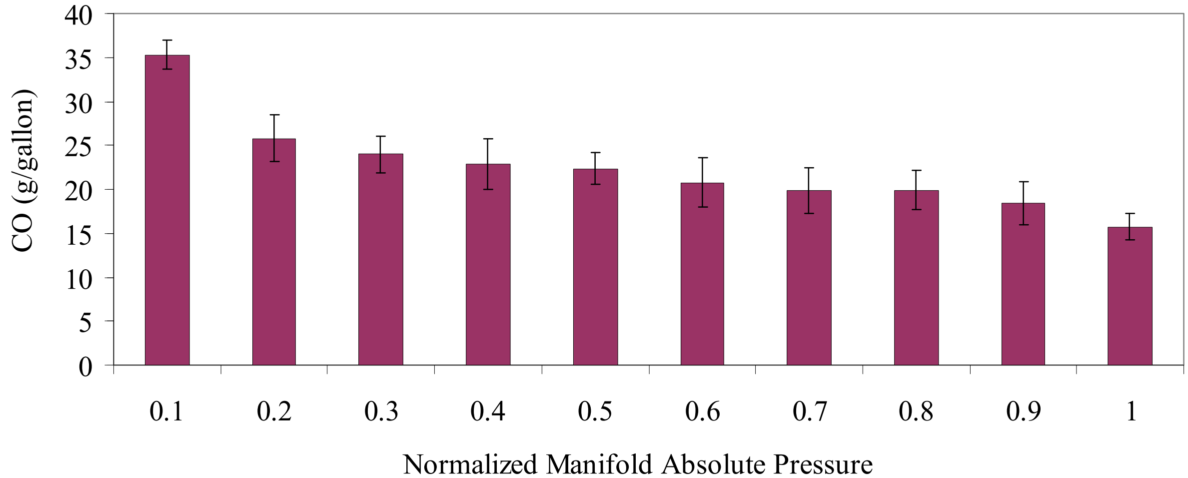


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 74 ^{o}F and the relative humidity was 64 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 $\leq$ Normalized MAP < 0.1; "0.2" = 0.1 $\leq$ Normalized MAP < 0.2, and so on.

Figure A58. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Off-Highway Truck 2 (continued on next page)





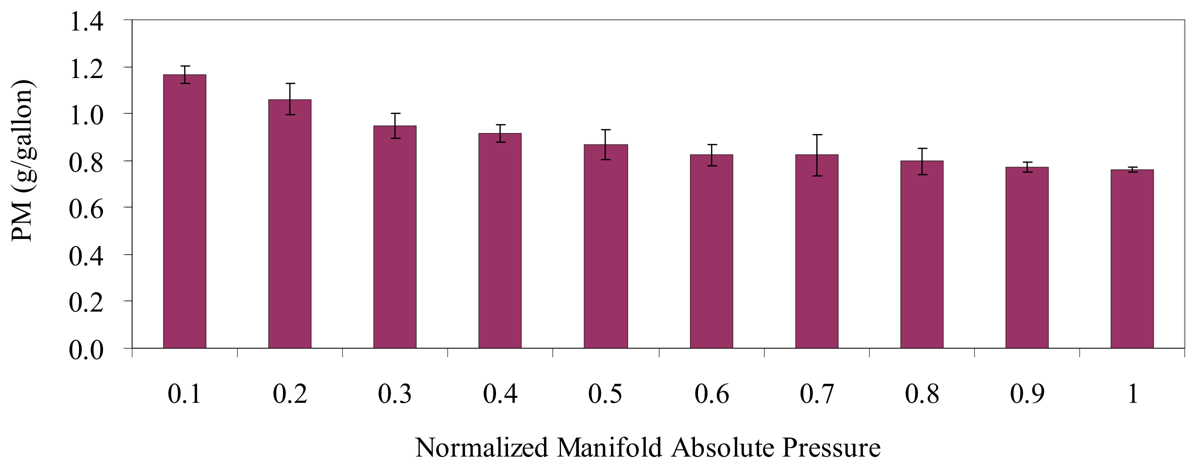
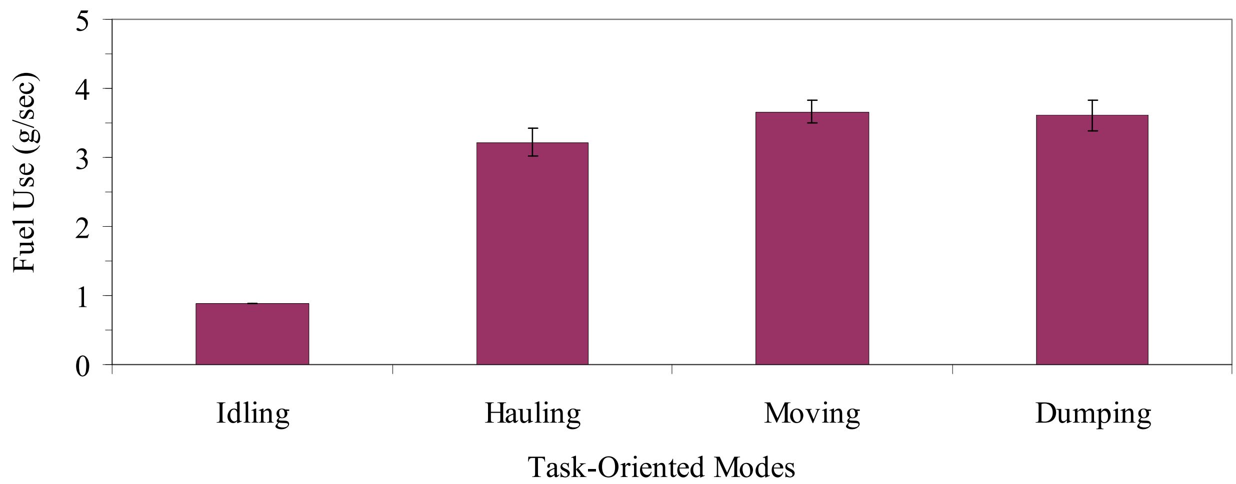
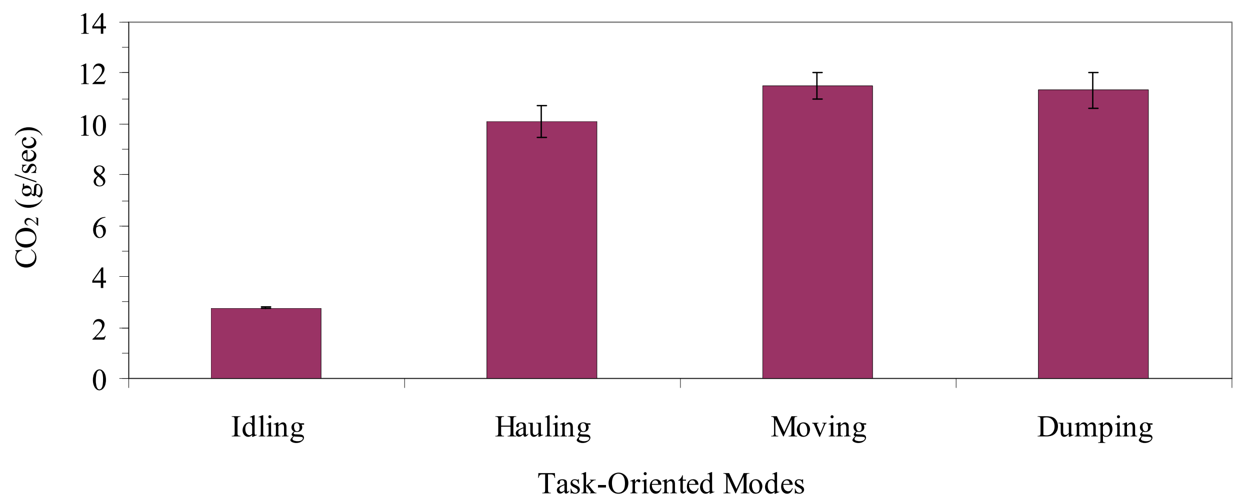


Figure A58. Continued

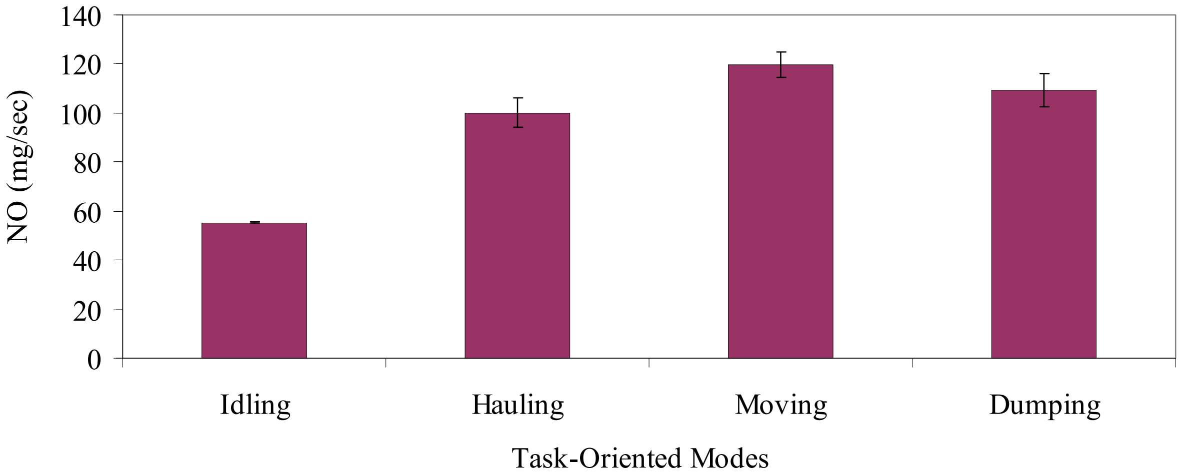


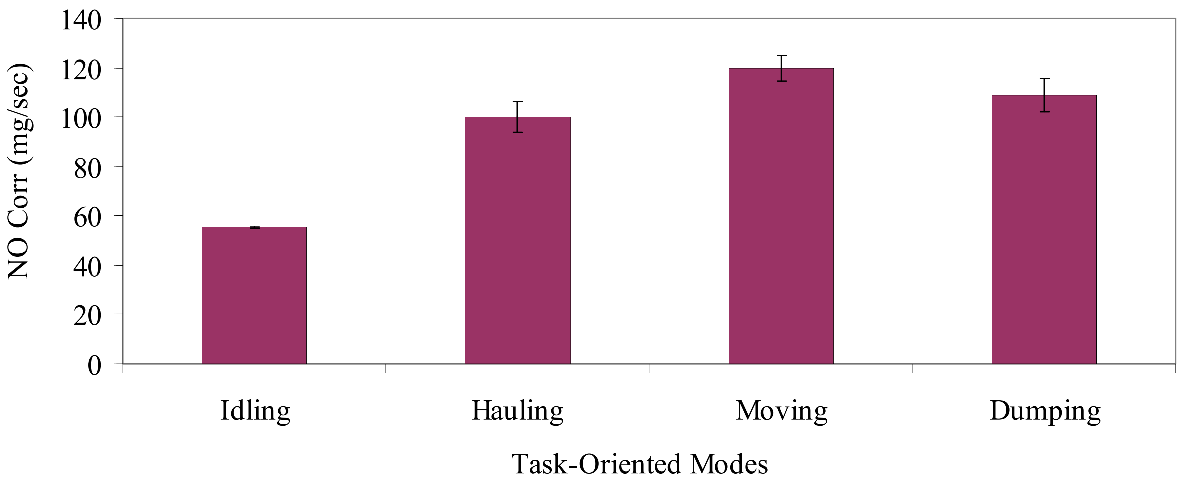


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 74 ^{o}F and the relative humidity was 64 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the off-highway truck (forward or backward); *hauling*: movement of the backhoe when the truck is hauling materials; *dumping*: dumping of the materials.

Figure A59. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Off-Highway Truck 2 (continued on next page)





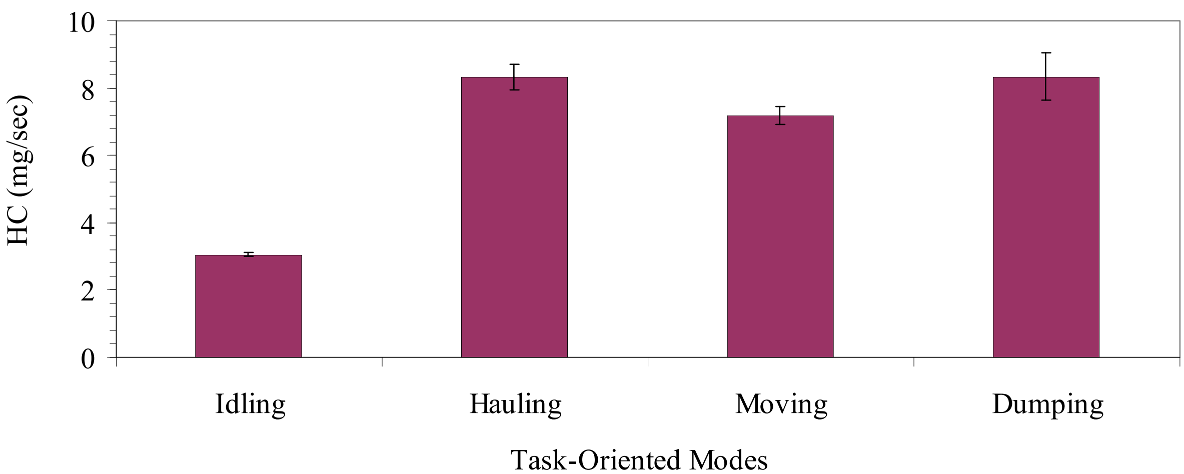
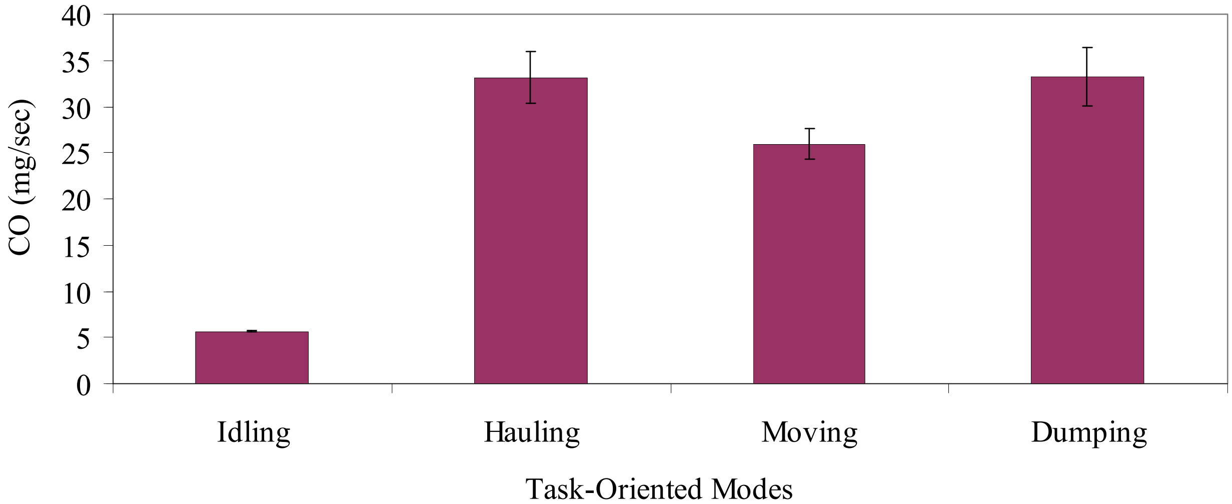


Figure A59. Continued



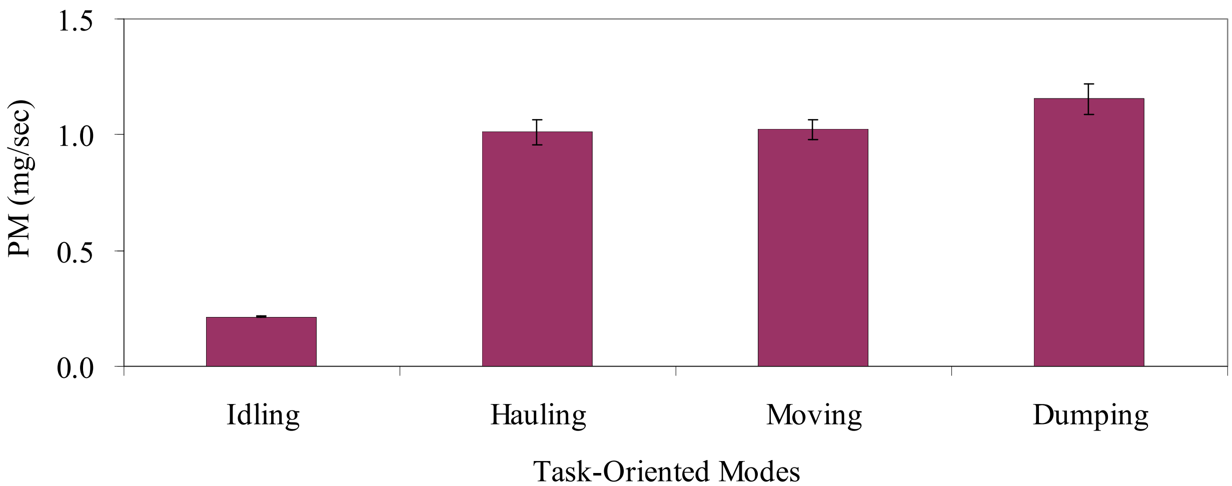
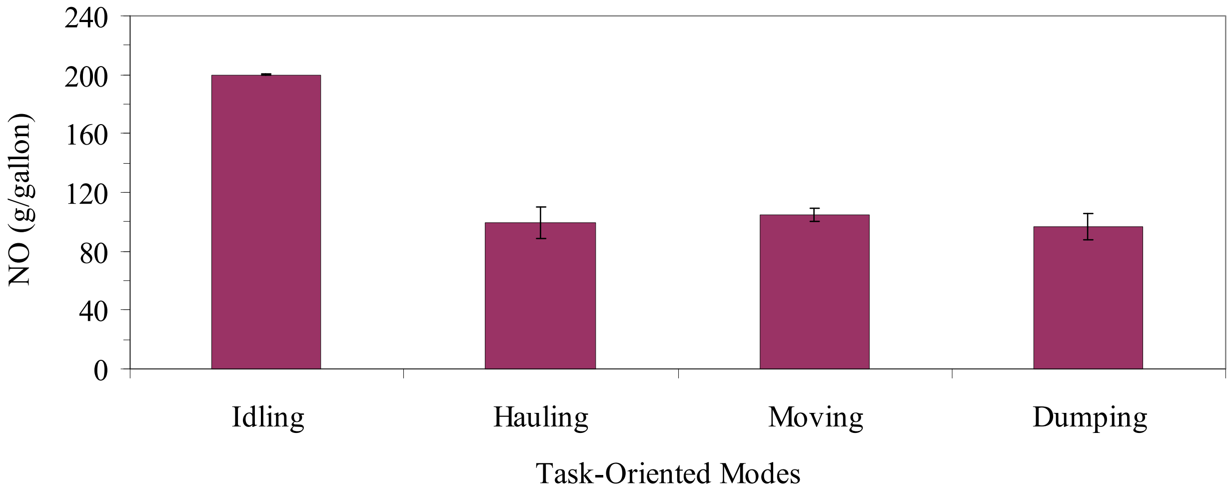
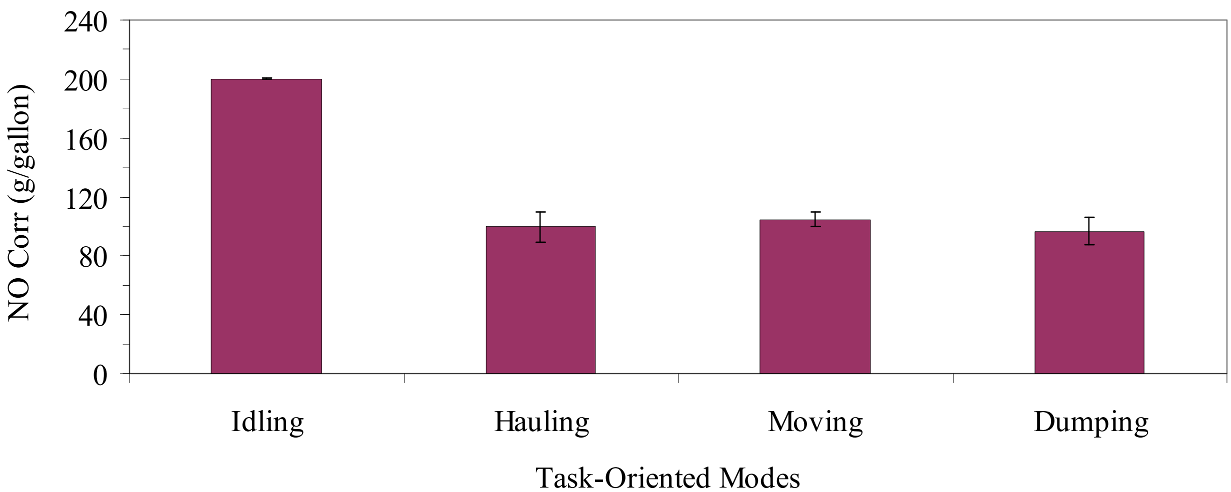


Figure A59. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 74 ^{o}F and the relative humidity was 64 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the off-highway truck (forward or backward); *hauling*: movement of the backhoe when the truck is hauling materials; *dumping*: dumping of the materials.

Figure A60. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Off-Highway Truck 2 (continued on next page)

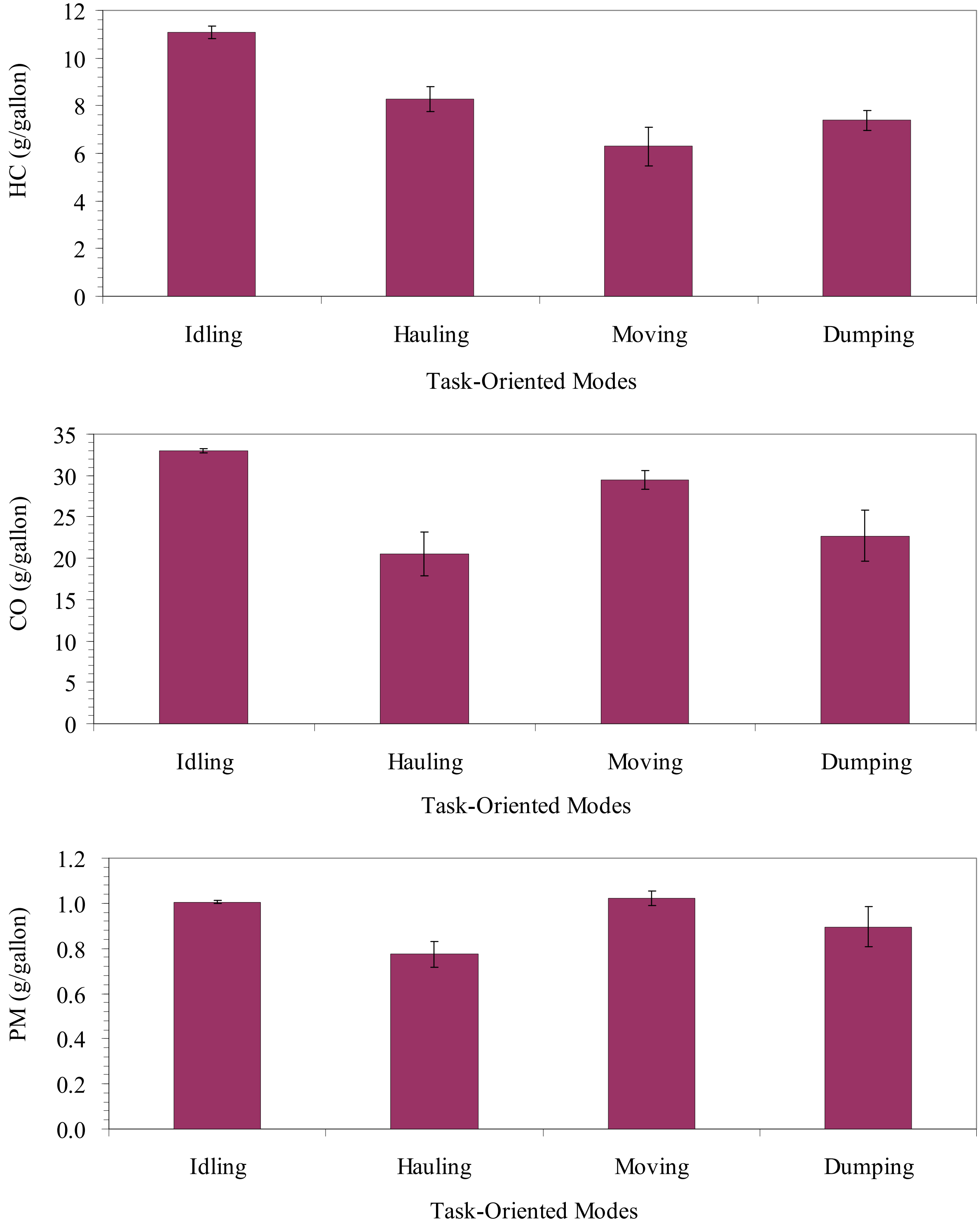
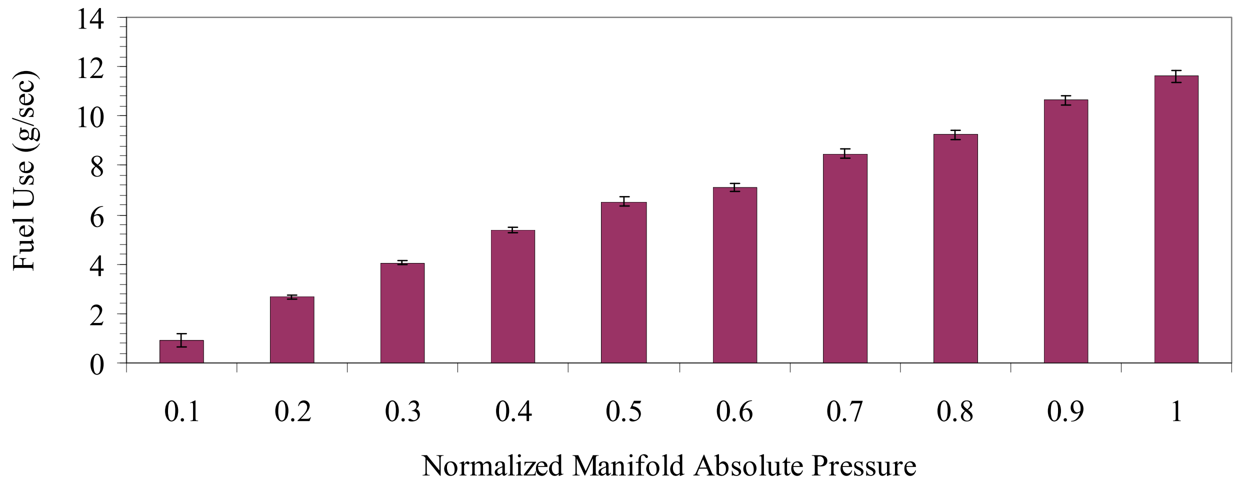
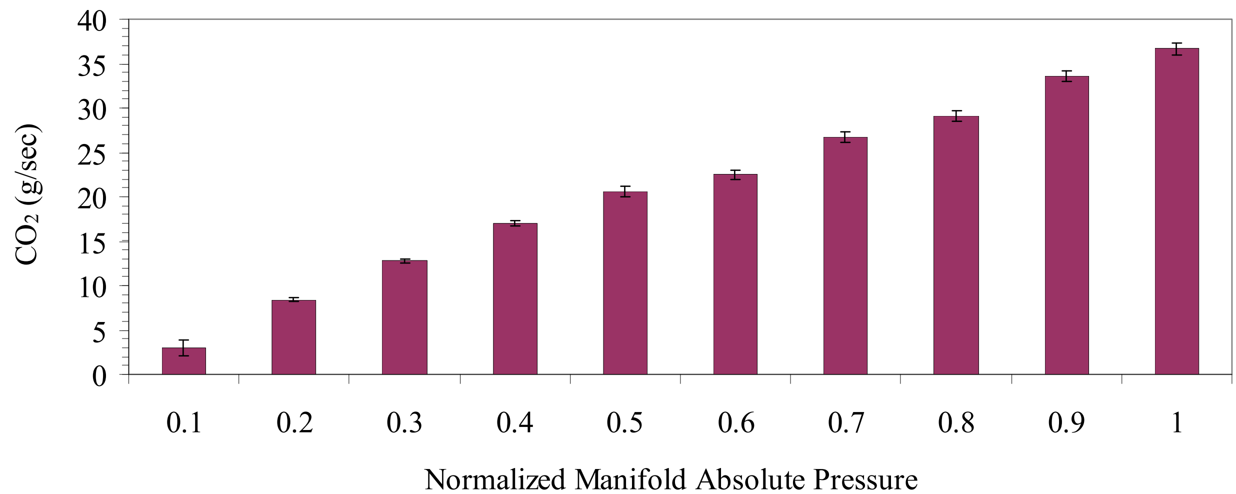


Figure A60. Continued

OFF-HIGHWAY TRUCK 3

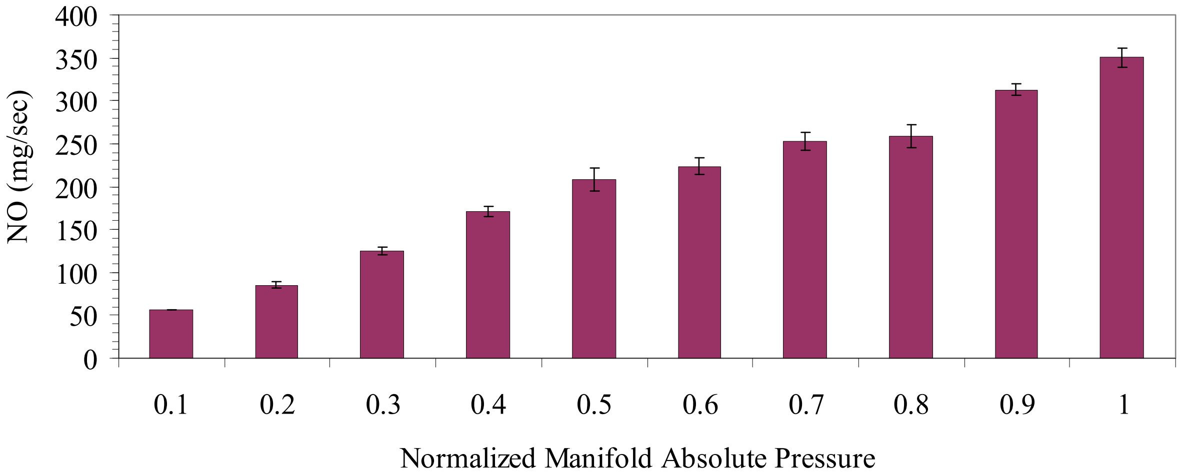


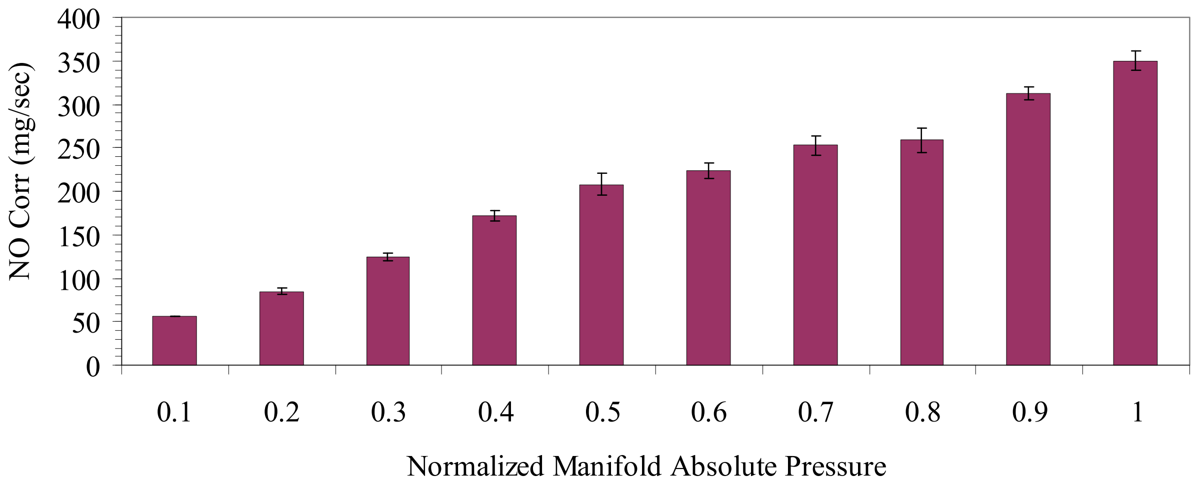


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 74 ^{o}F and the relative humidity was 64 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A61. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Off-Highway Truck 3 (continued on next page)





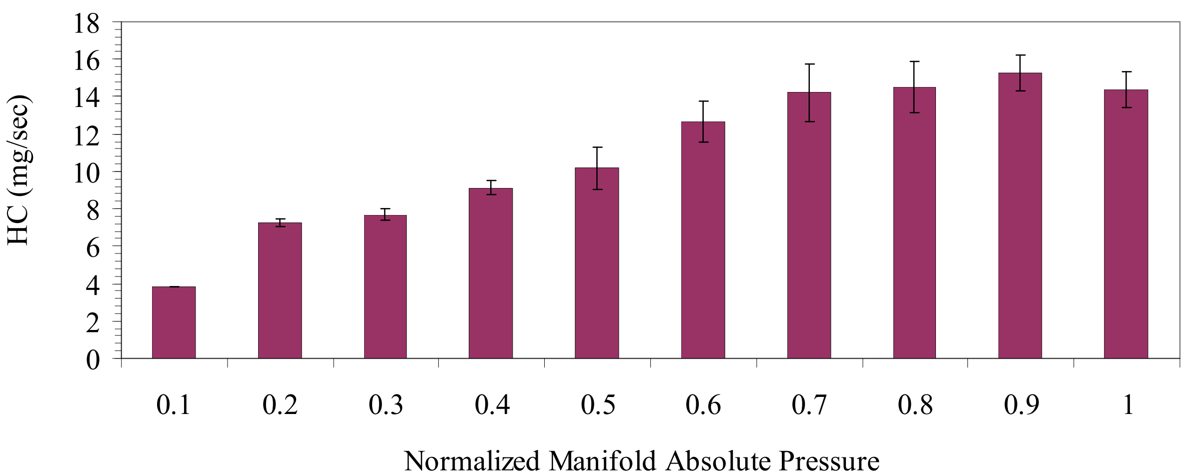
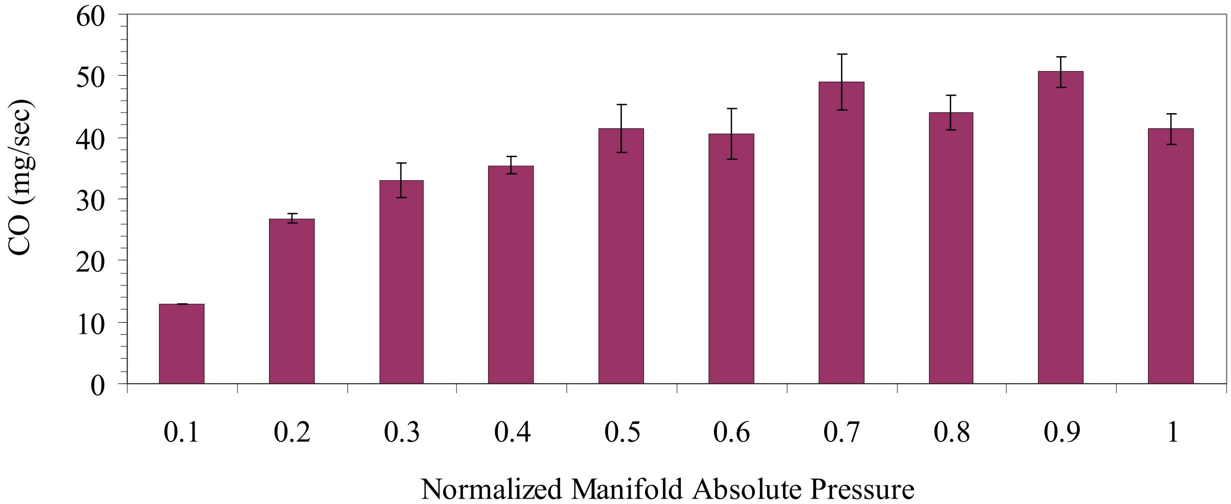


Figure A61. Continued



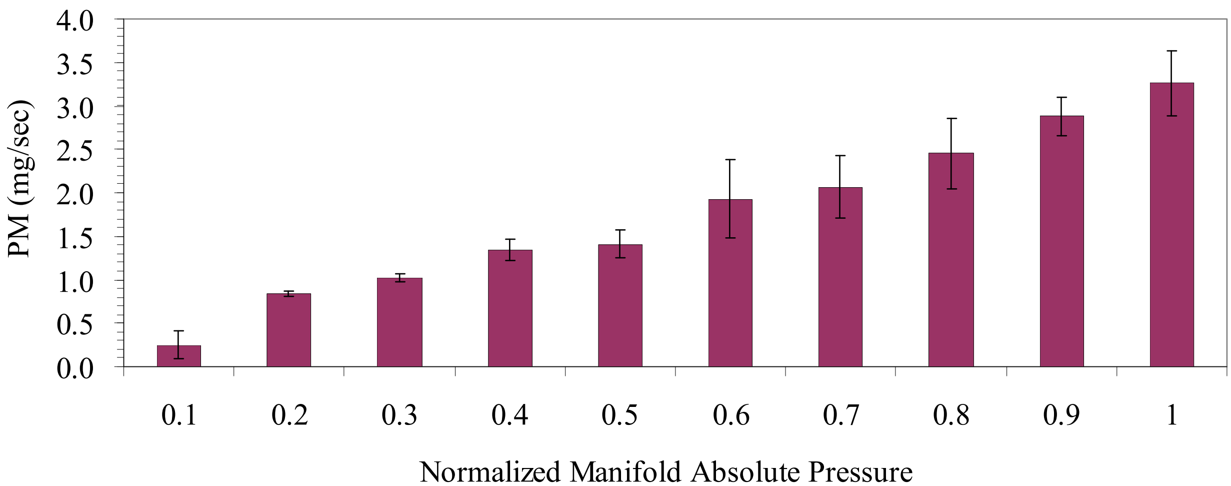
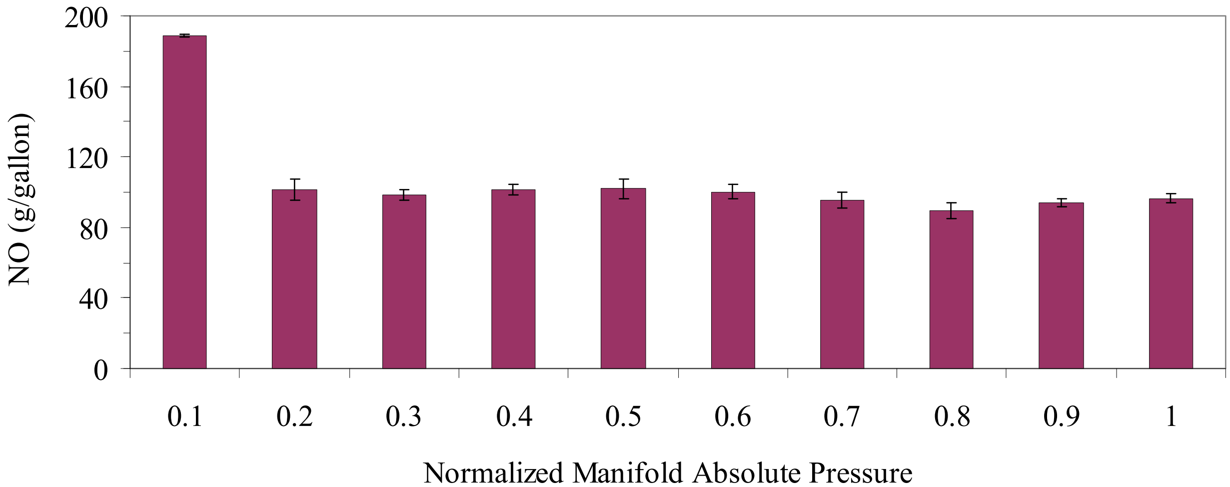
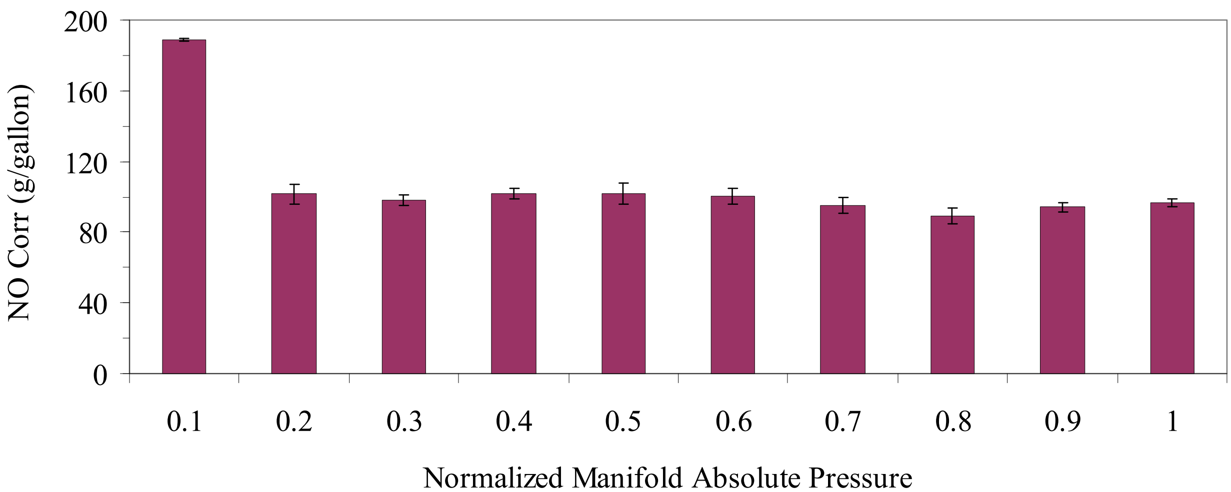


Figure A61. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 74 ^{o}F and the relative humidity was 64 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A62. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Off-Highway Truck 3 (continued on next page)

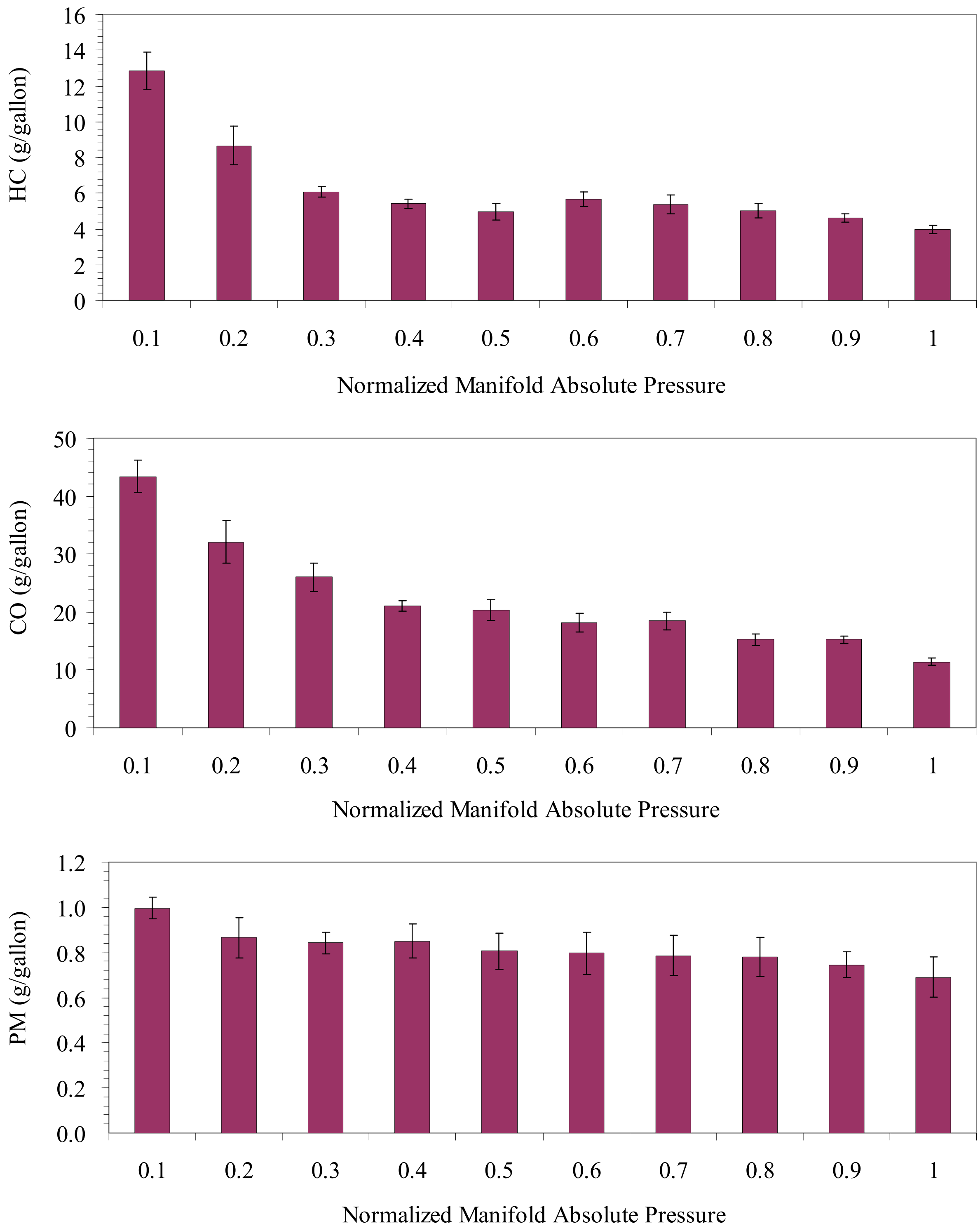
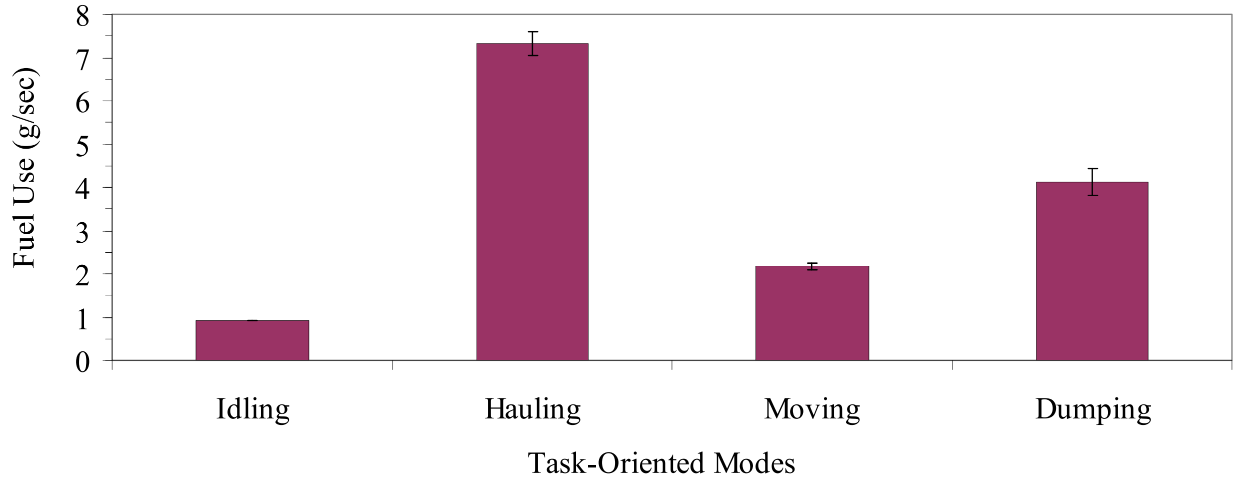
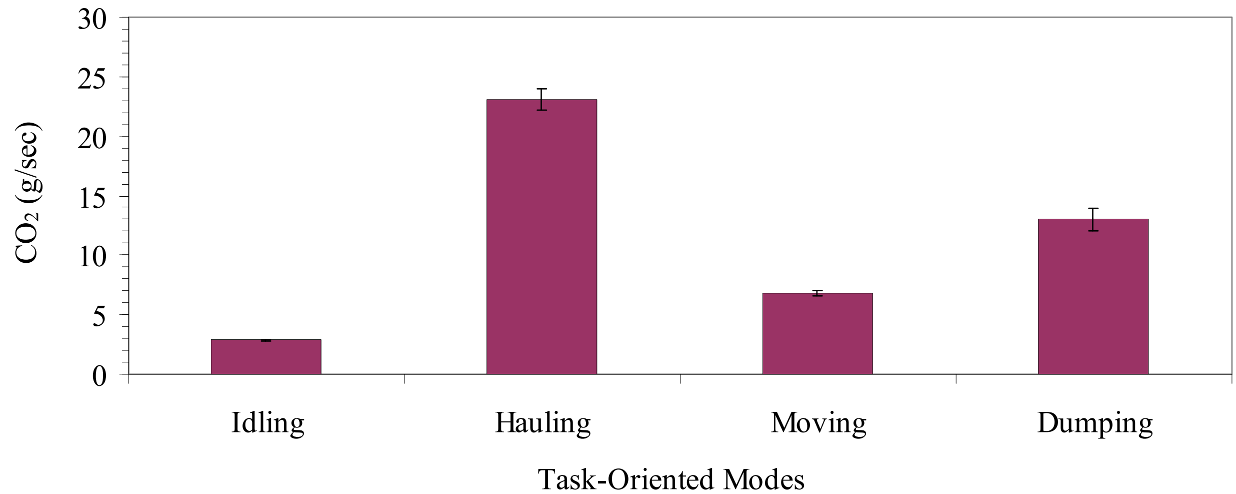


Figure A62. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 74 ^{o}F and the relative humidity was 64 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the off-highway truck (forward or backward); *hauling*: movement of the backhoe when the truck is hauling materials; *dumping*: dumping of the materials.

Figure A63. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Off-Highway Truck 3 (continued on next page)

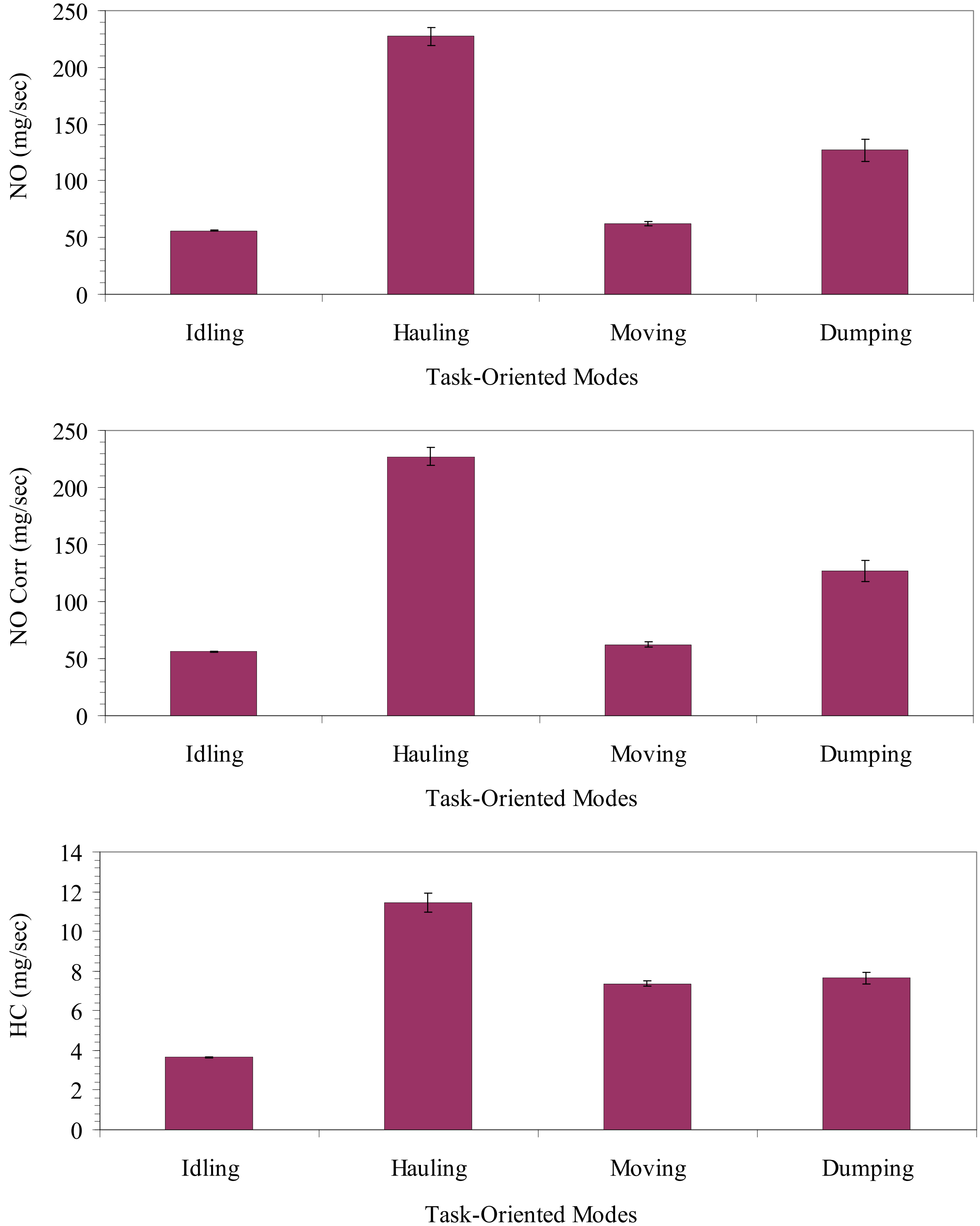


Figure A63. Continued

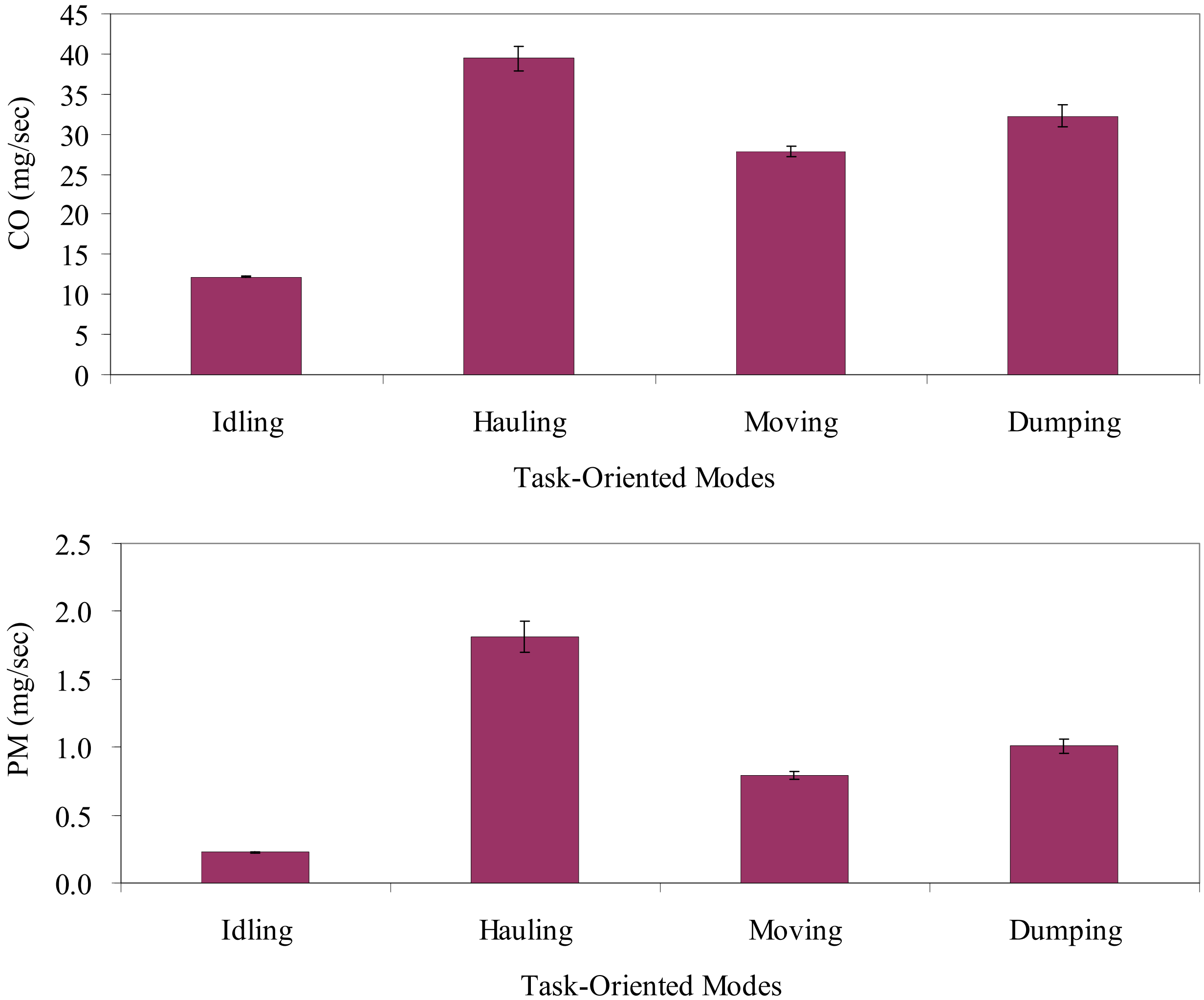
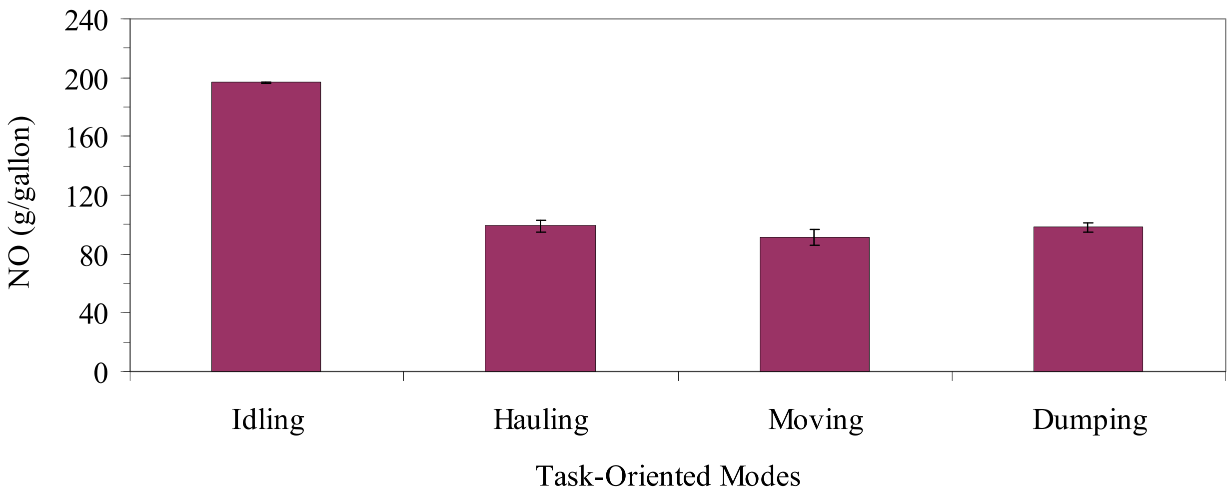
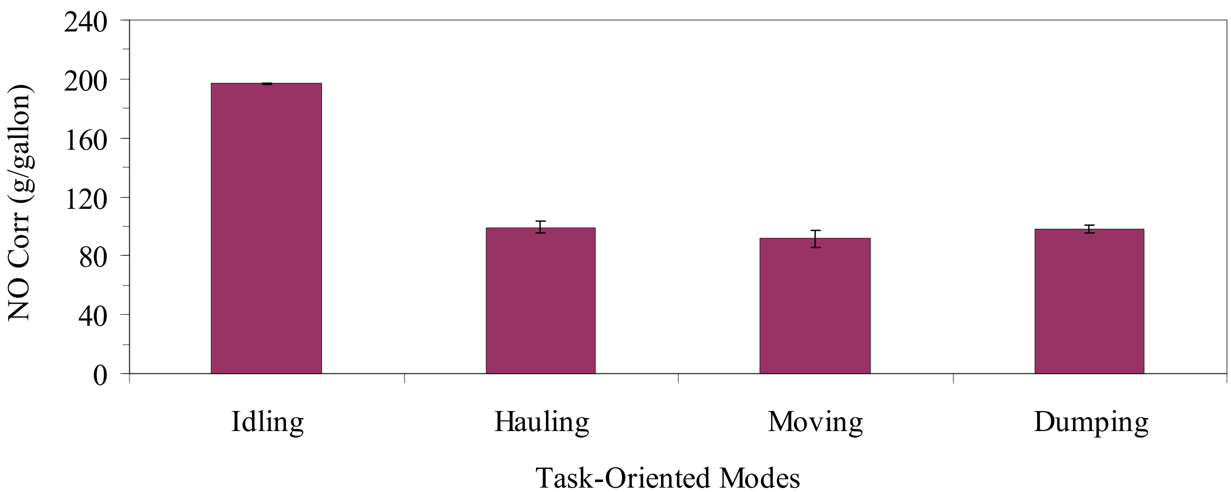


Figure A63. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 74 ^{o}F and the relative humidity was 64 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the off-highway truck (forward or backward); *hauling*: movement of the backhoe when the truck is hauling materials; *dumping*: dumping of the materials.

Figure A64. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Off-Highway Truck 3 (continued on next page)

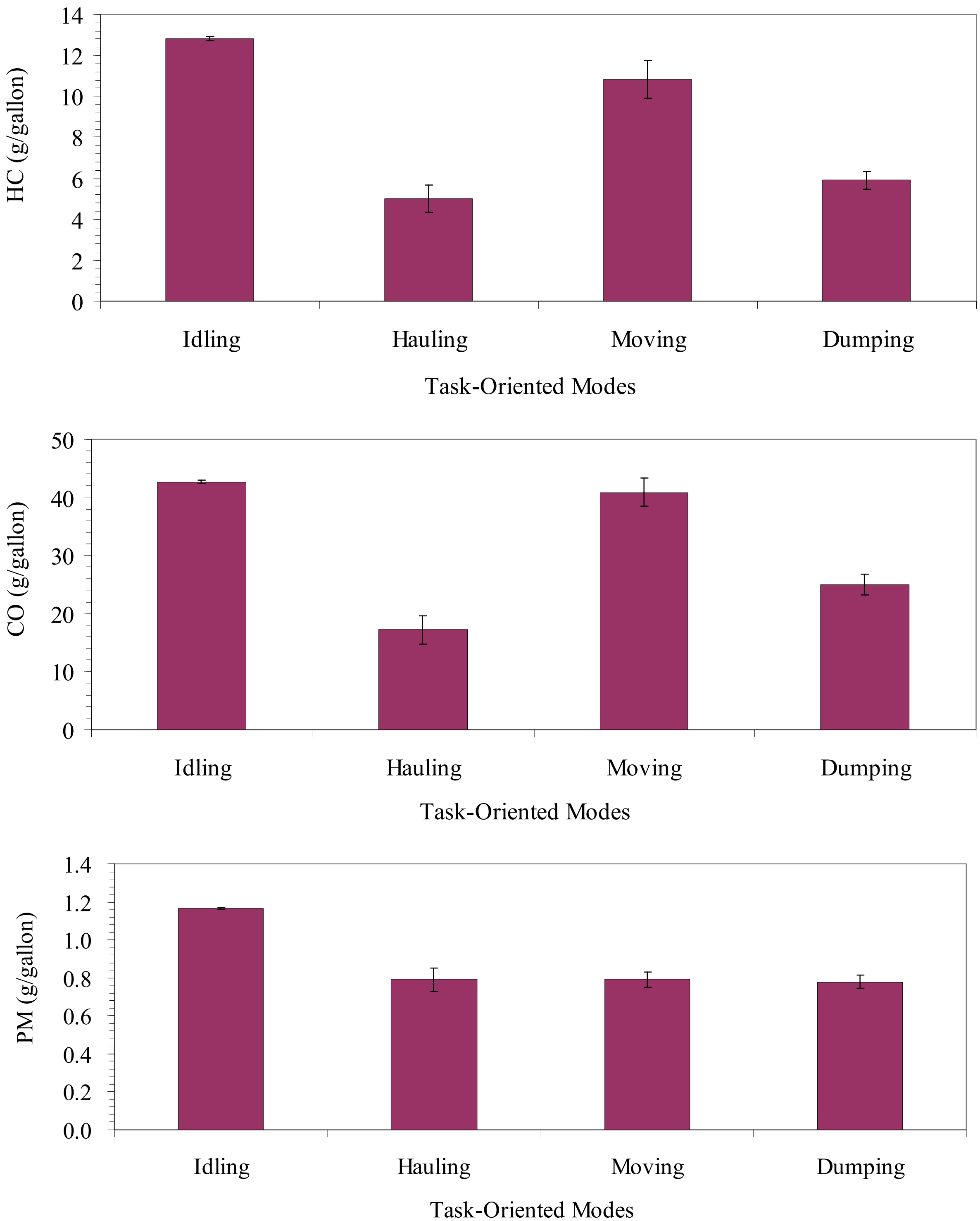
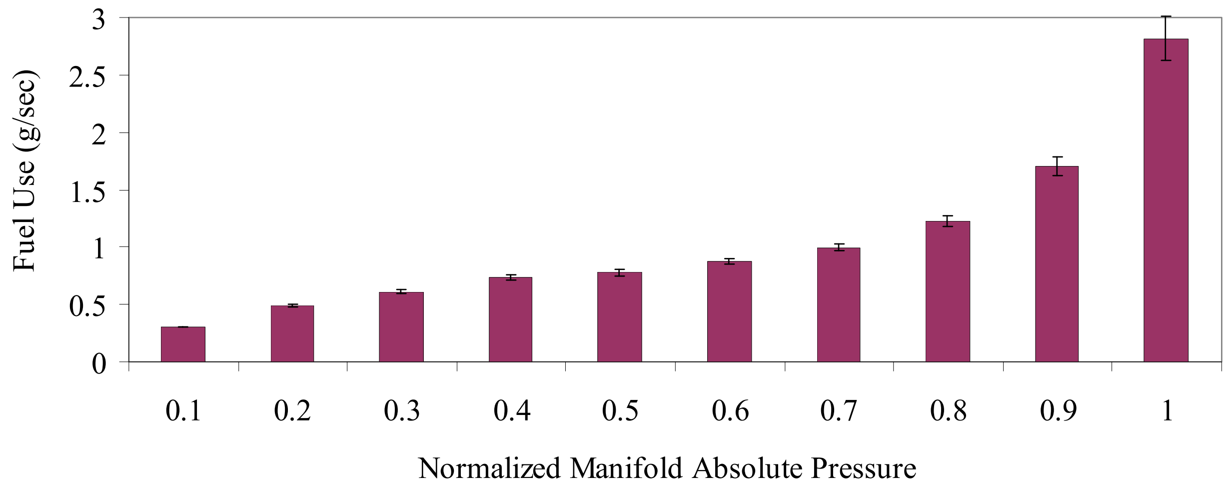
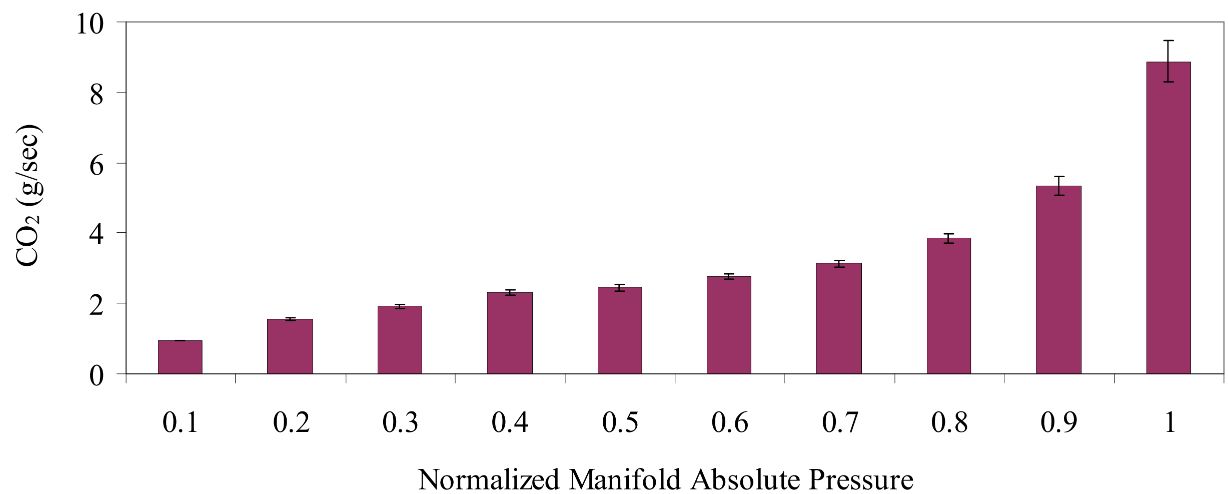


Figure A64. Continued

BACKHOE 1

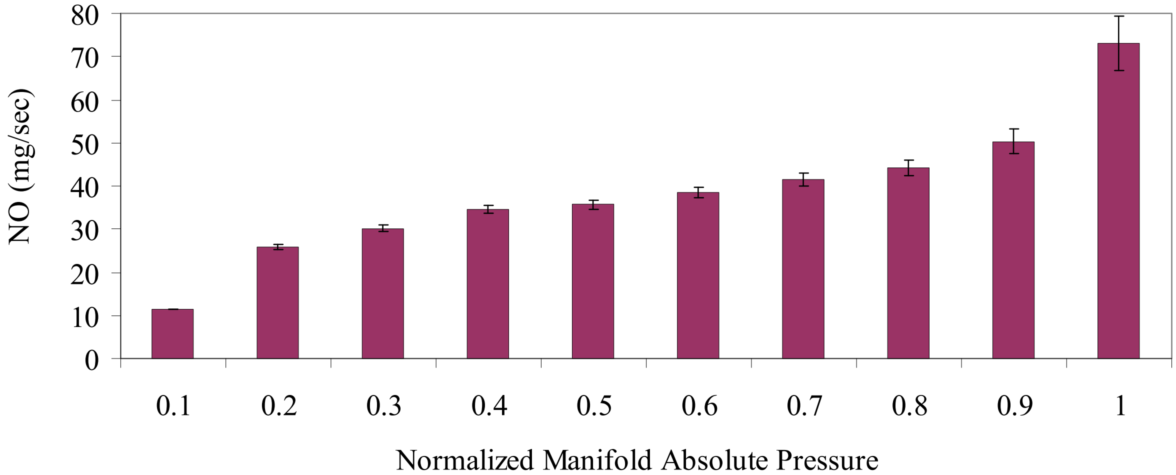


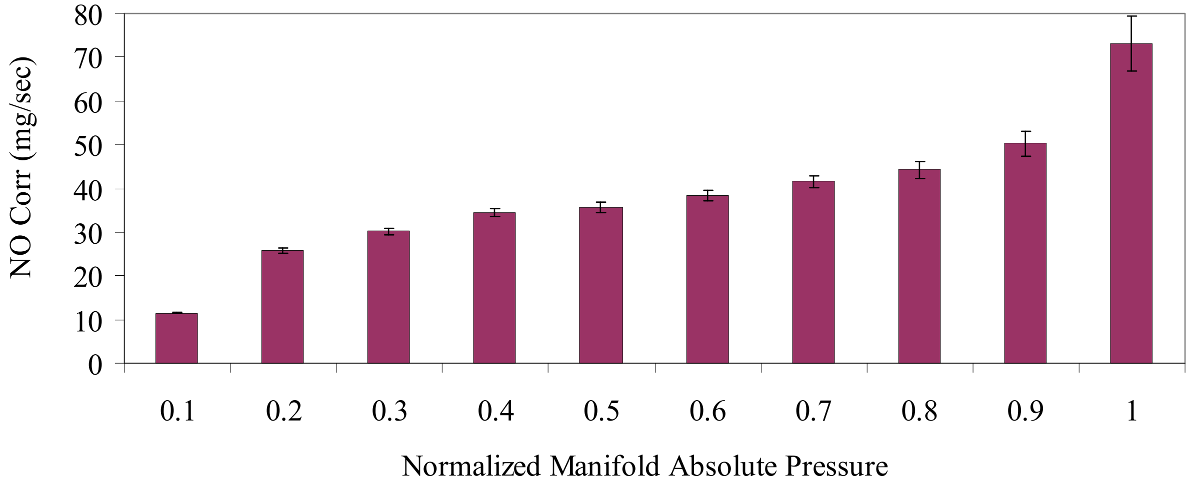


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 35 ^{o}F and the relative humidity was 48 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A65. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Backhoe 1 (continued on next page)





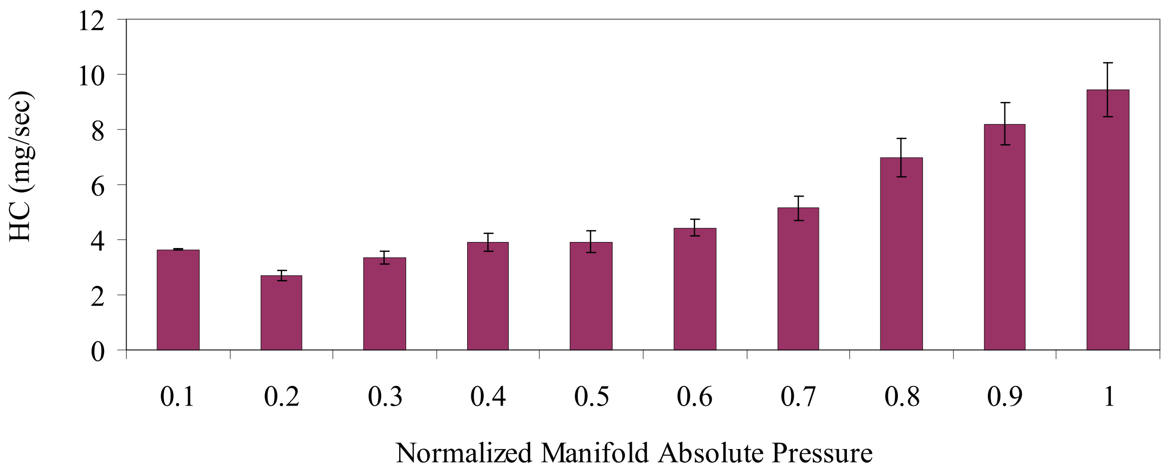
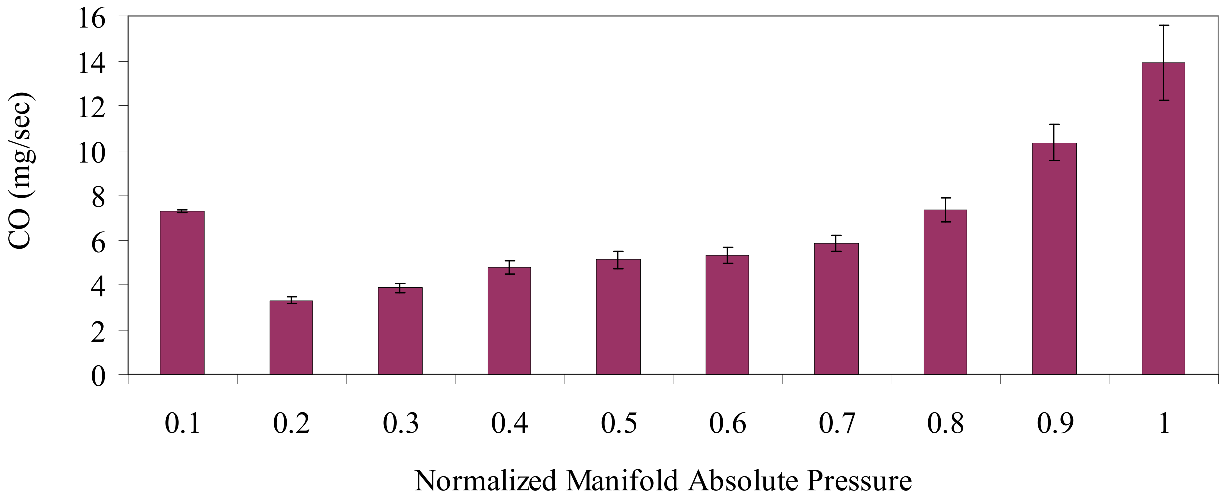


Figure A65. Continued



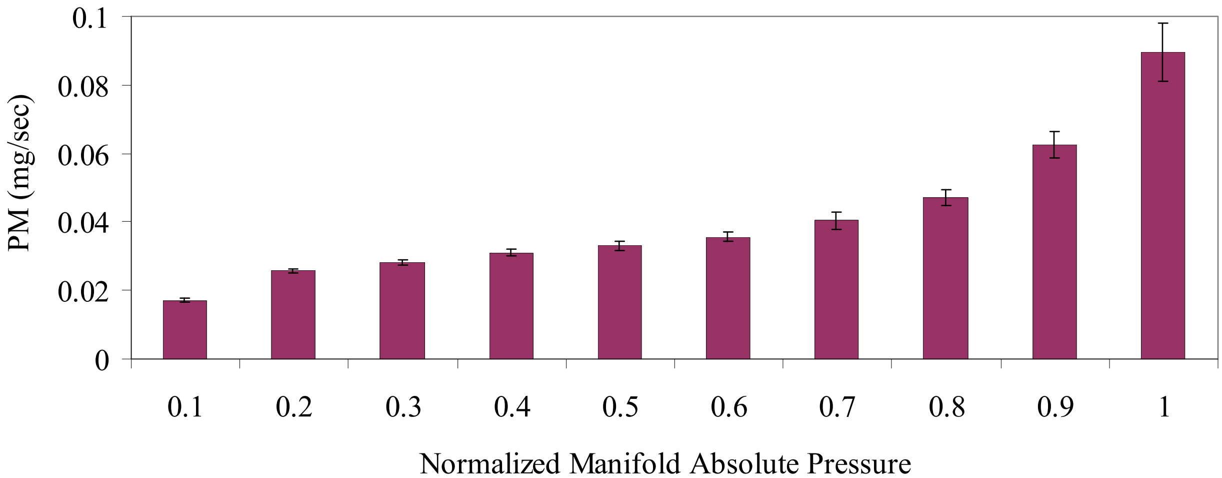
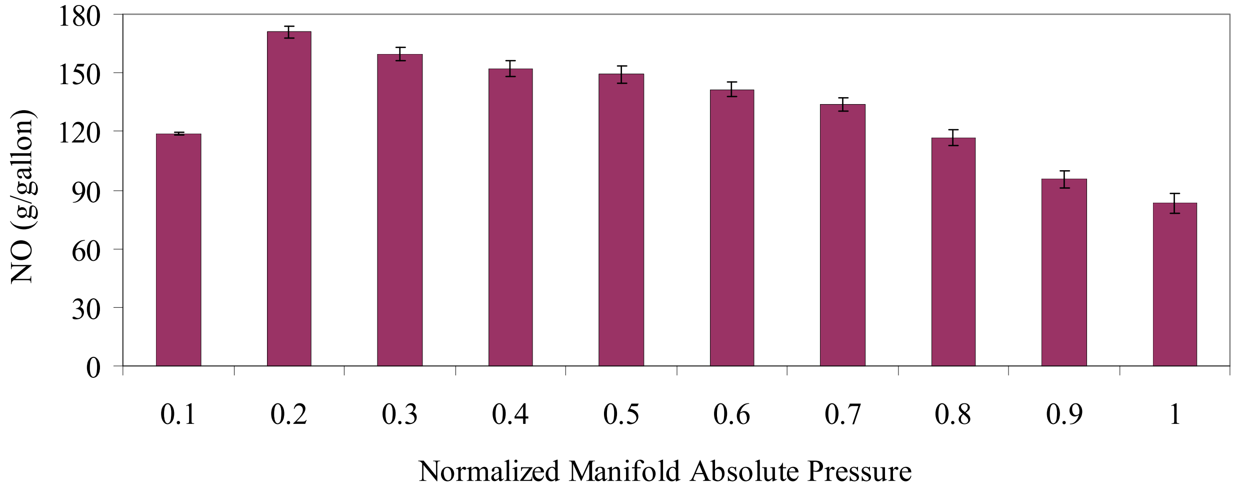
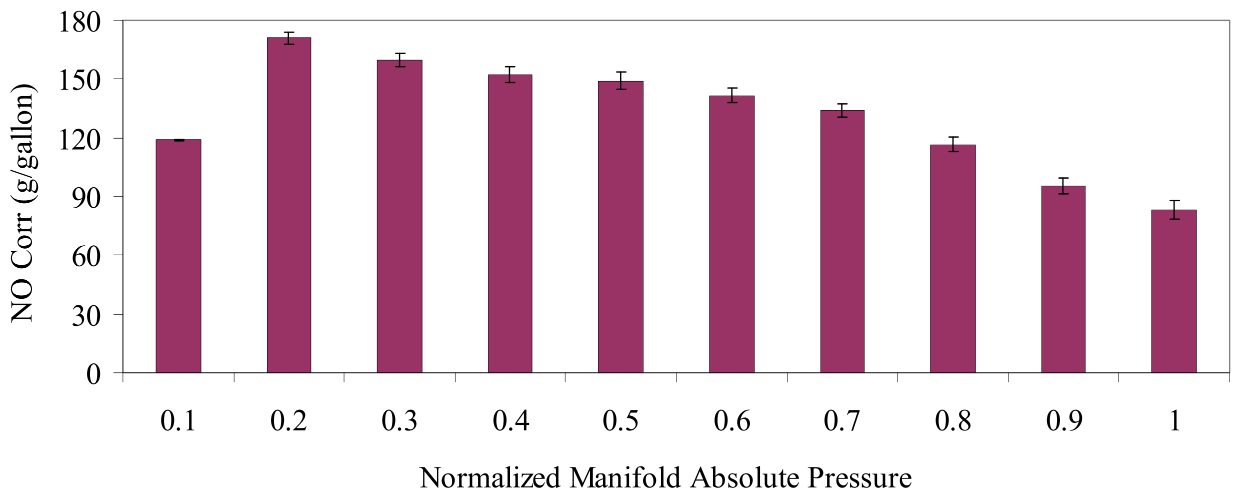


Figure A65. Continued

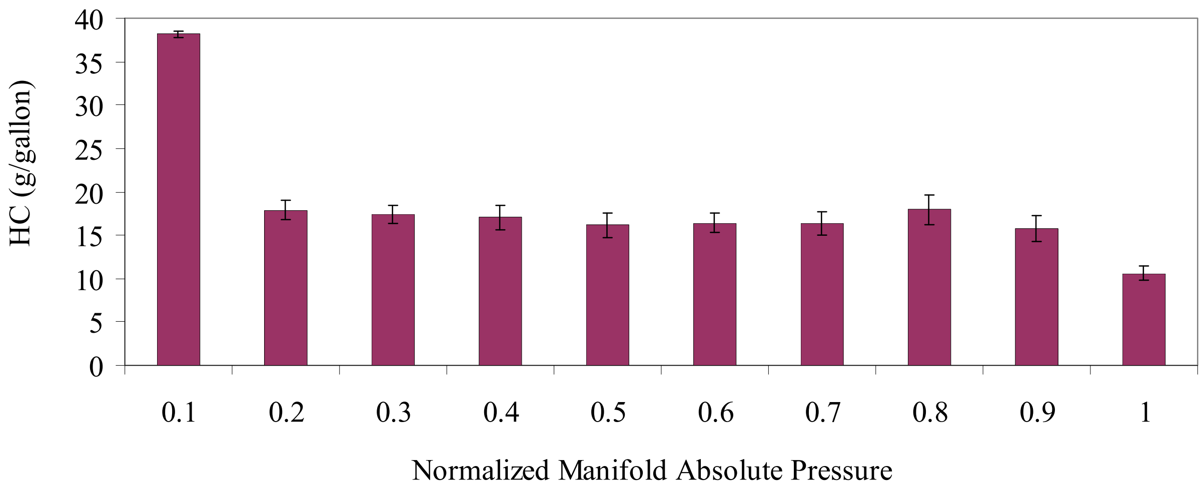


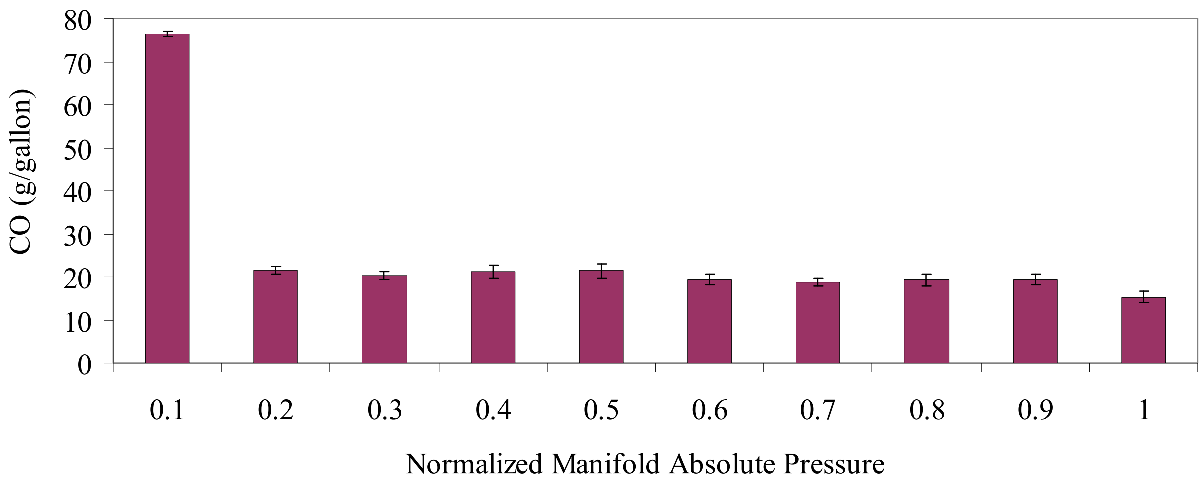


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 35 ^{o}F and the relative humidity was 48 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A66. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Backhoe 1 (continued on next page)





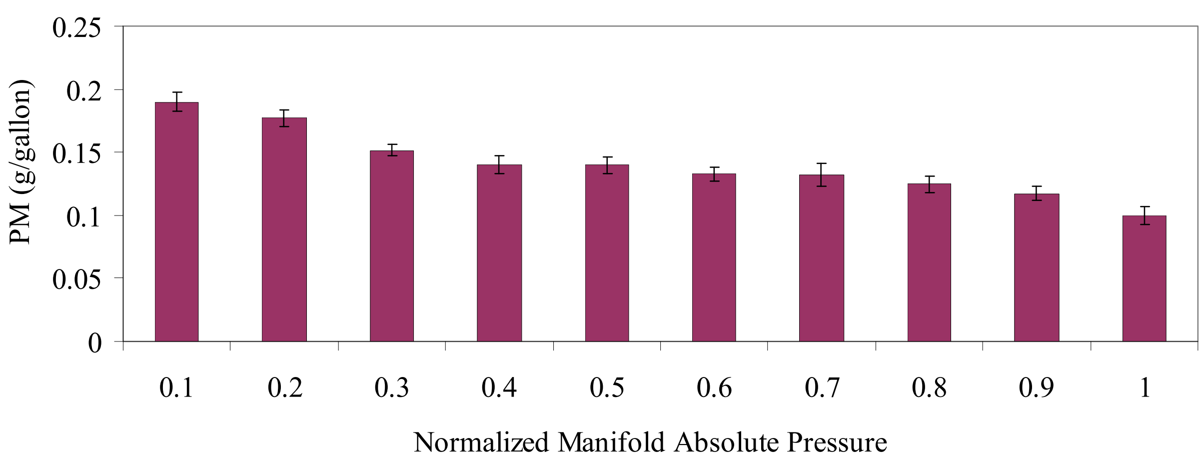
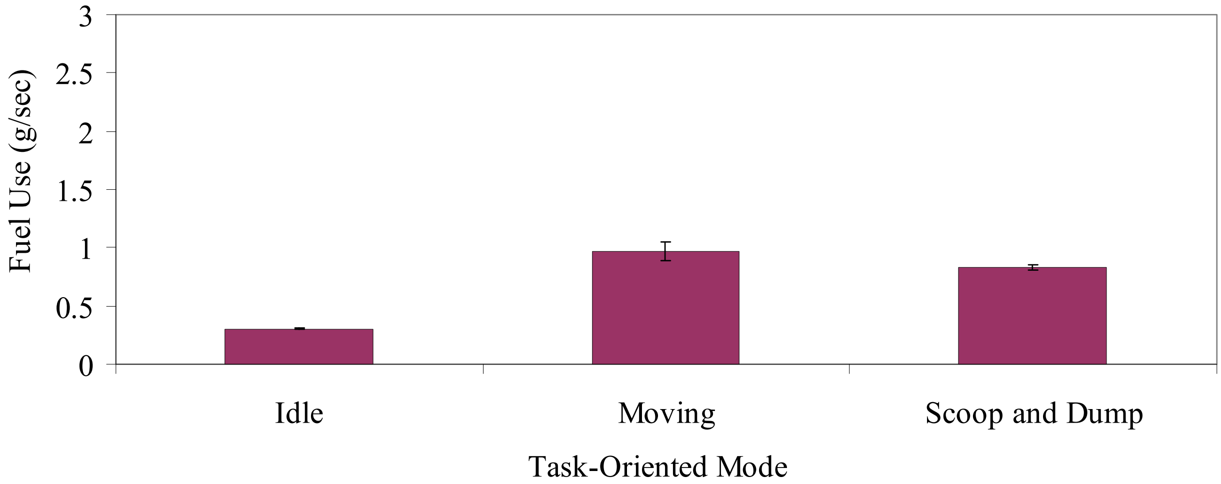
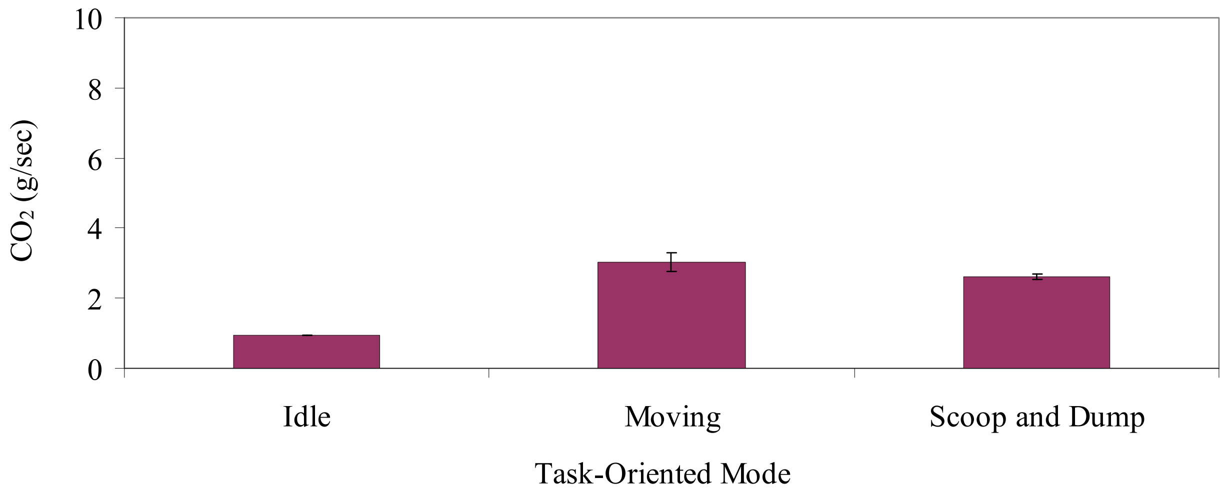


Figure A66. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 35 ^{o}F and the relative humidity was 48 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A67. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 1 (continued on next page)

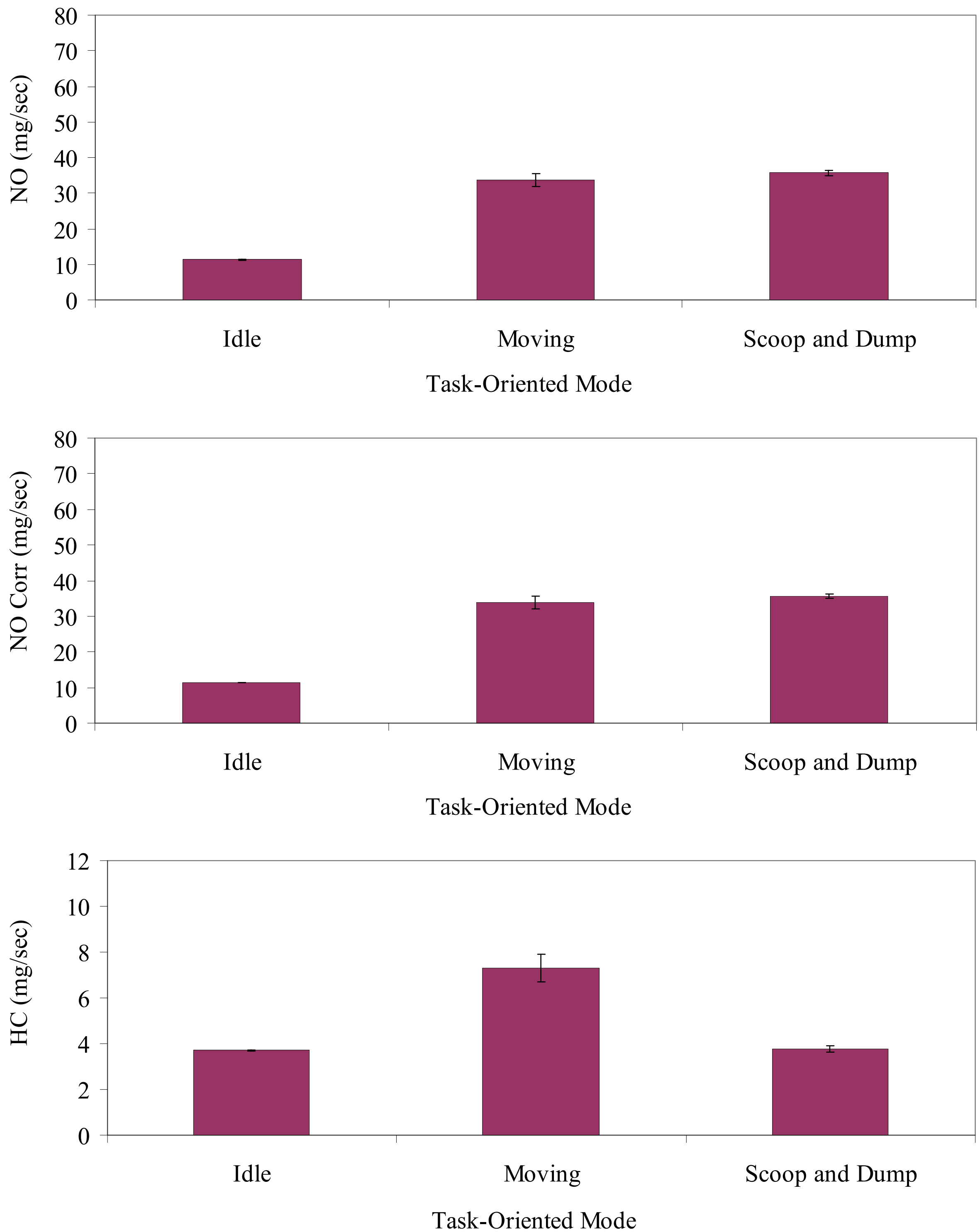
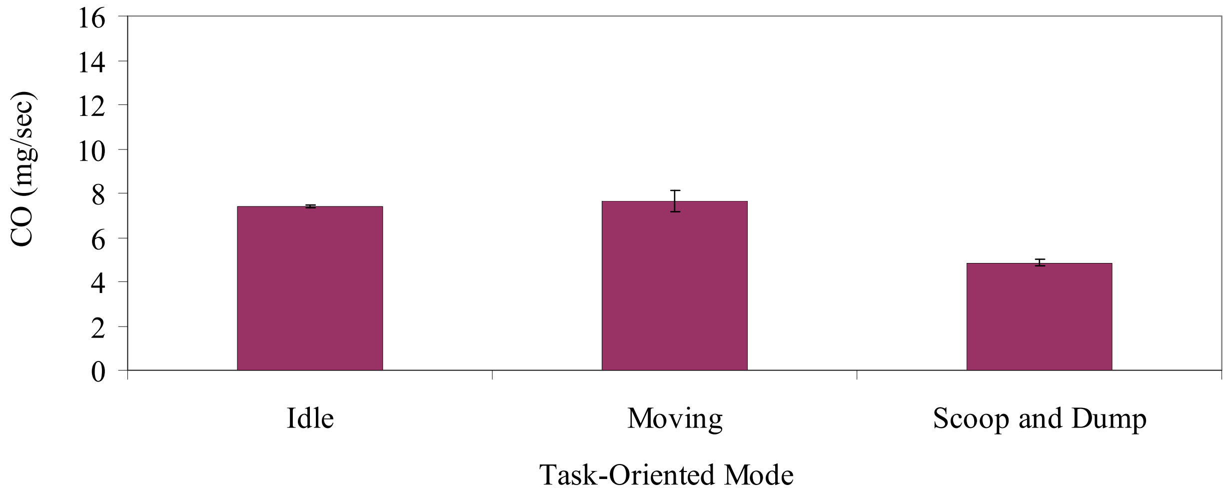


Figure A67. Continued



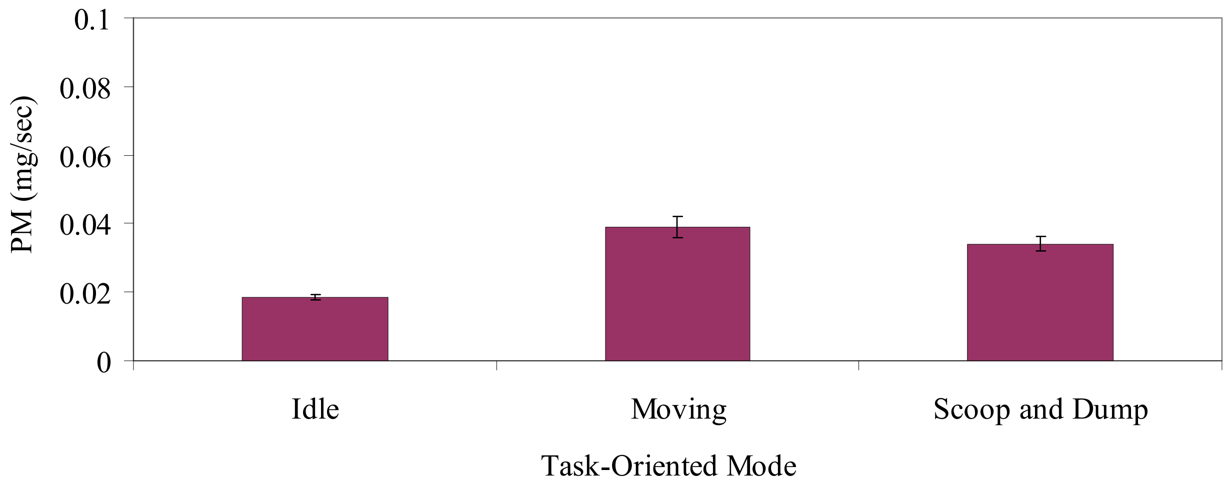
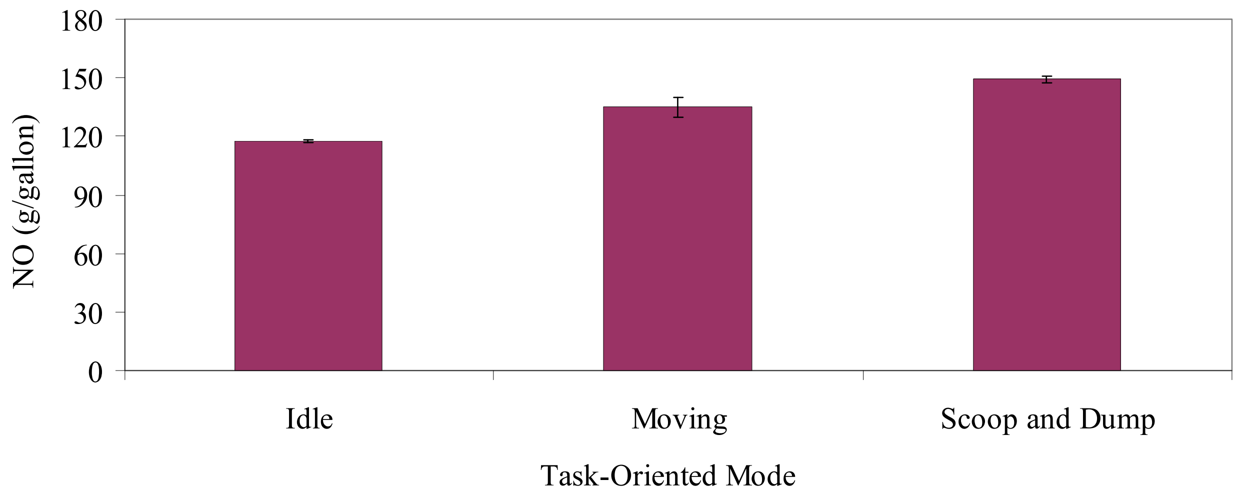
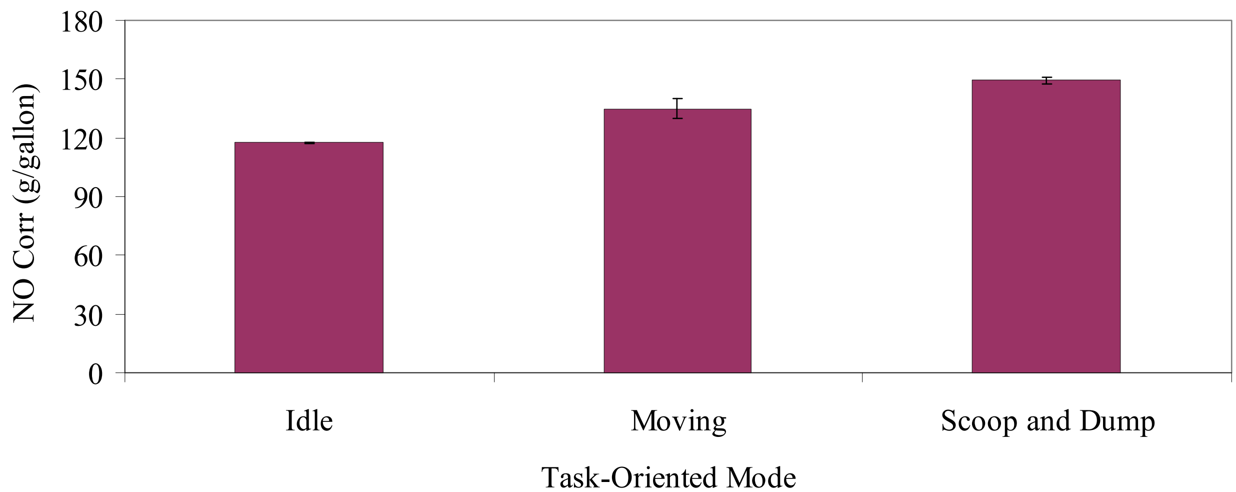


Figure A67. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 35 ^{o}F and the relative humidity was 48 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A68. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 1 (continued on next page)

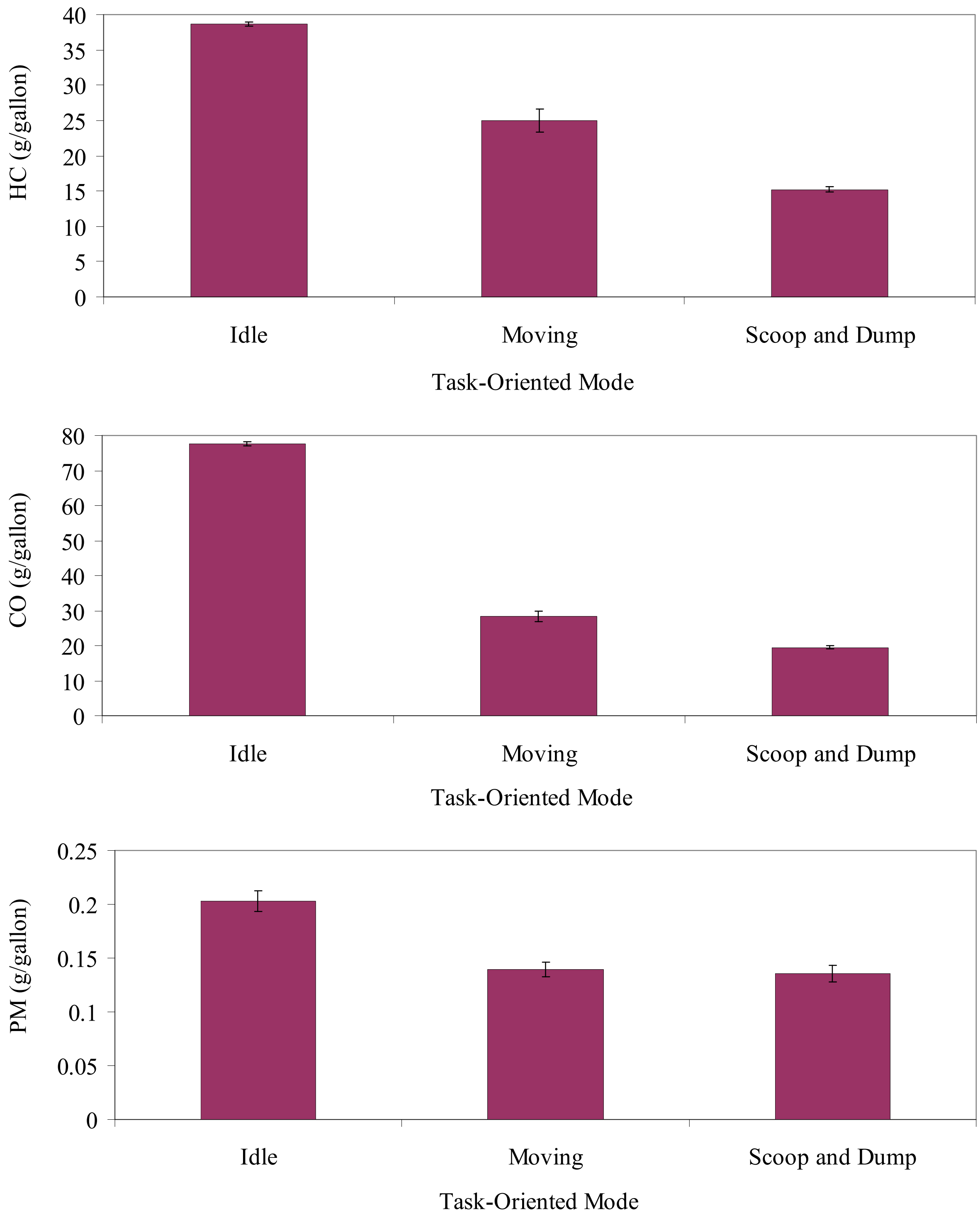
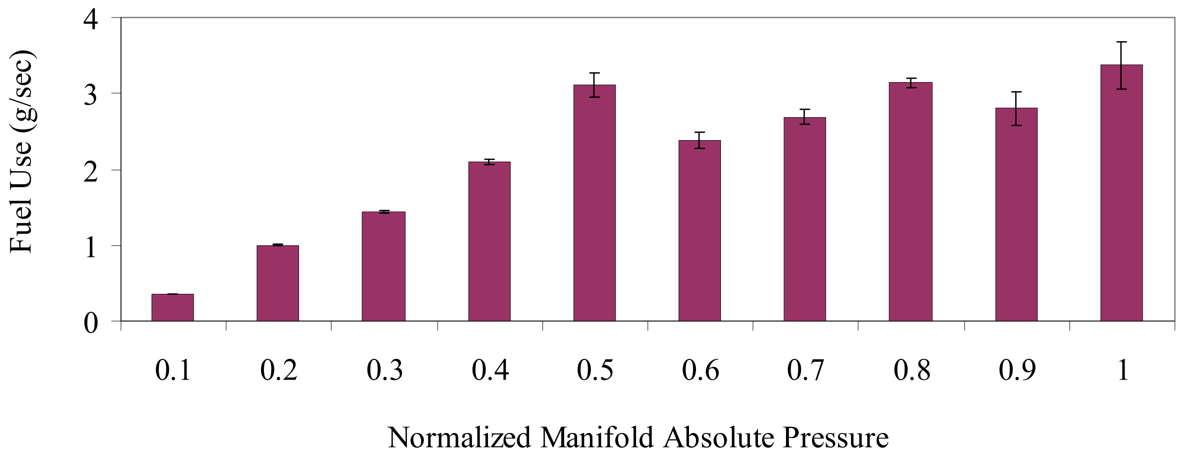
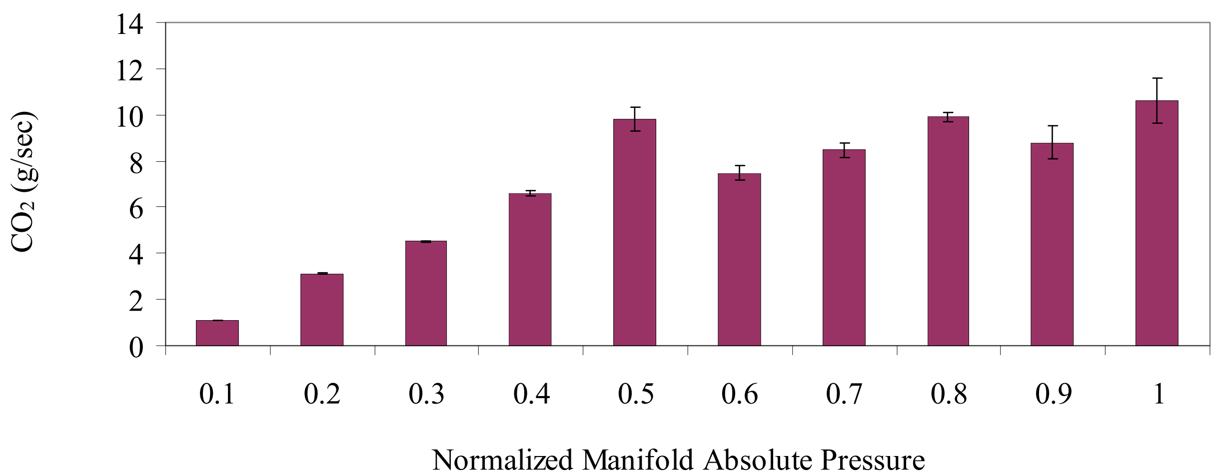


Figure A68. Continued

BACKHOE 2

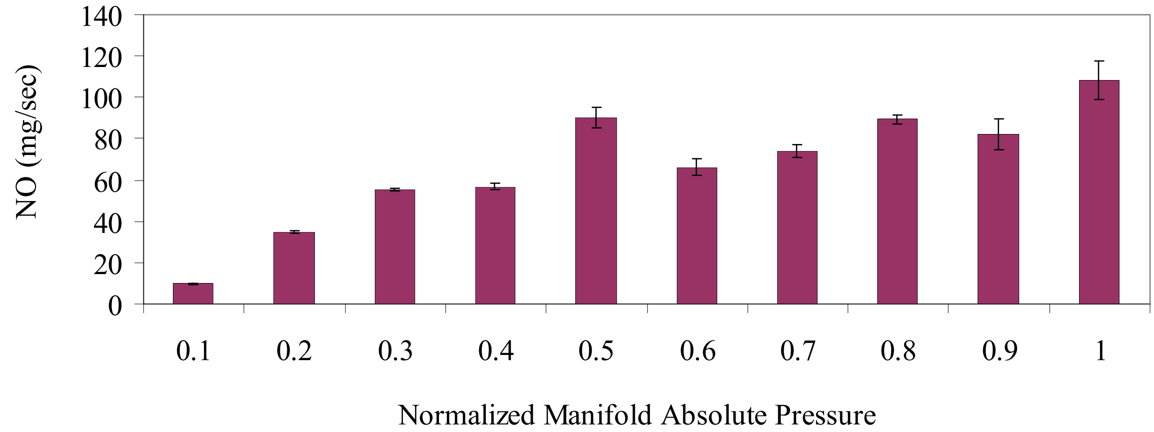


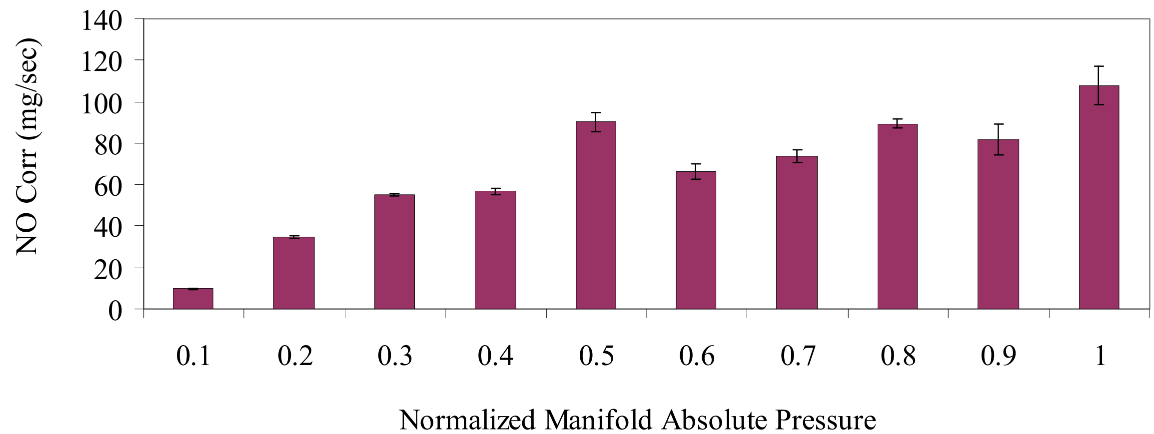


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 44 ^{o}F and the relative humidity was 69 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A69. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Backhoe 2 (continued on next page)





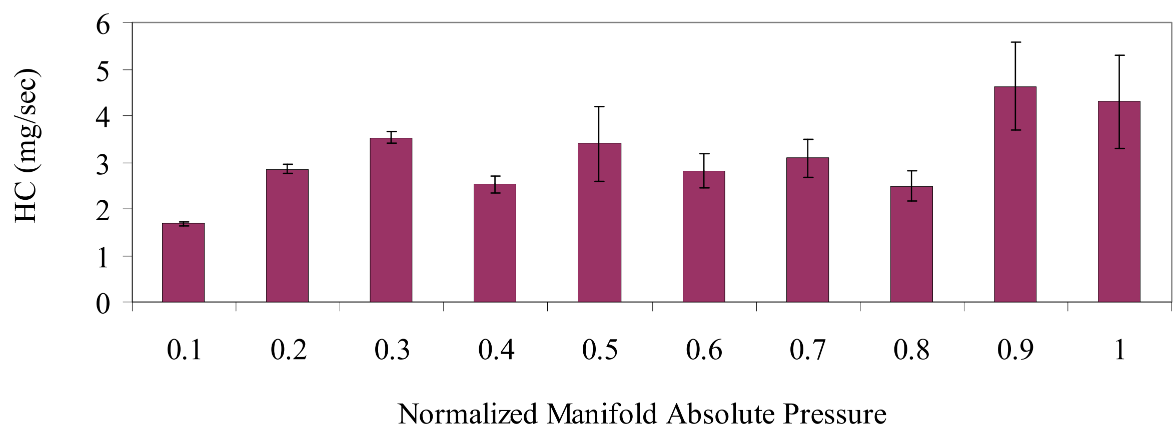
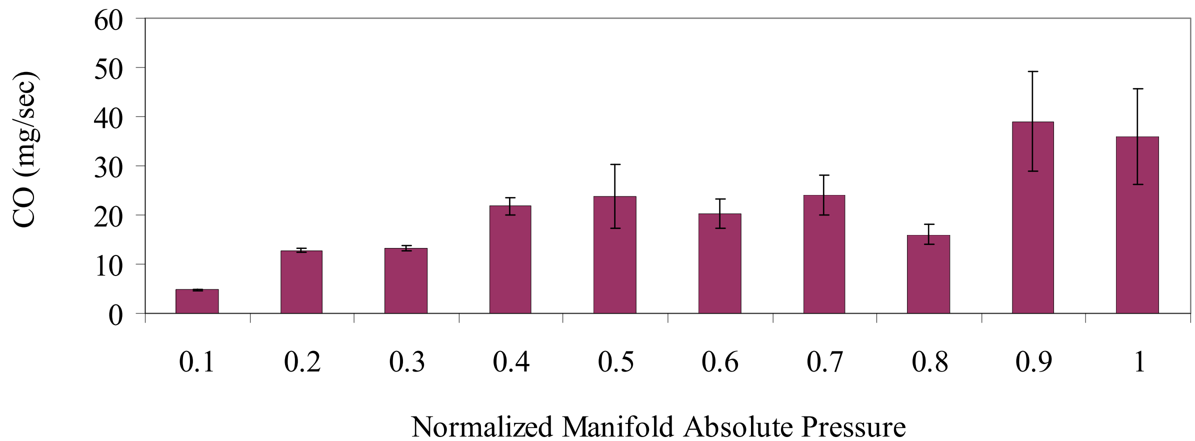


Figure A69. Continued



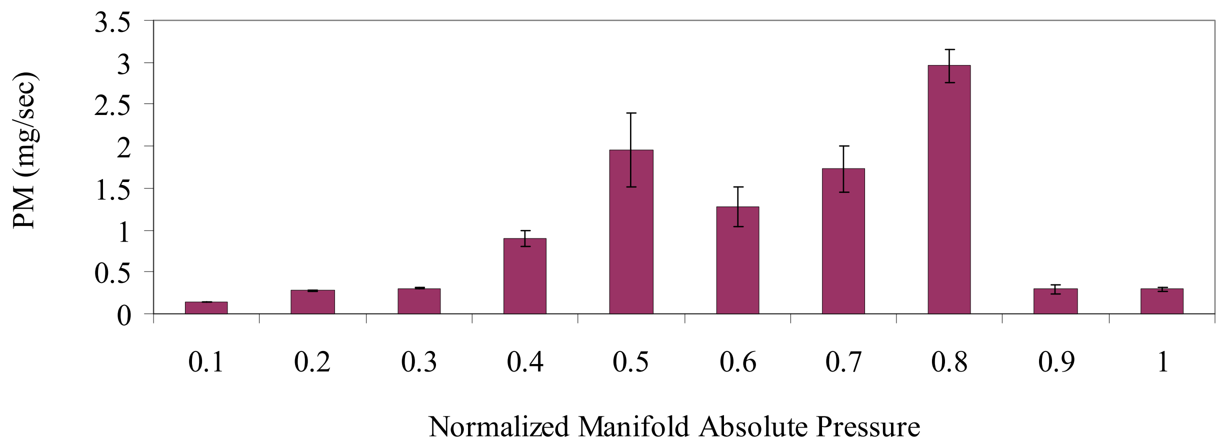
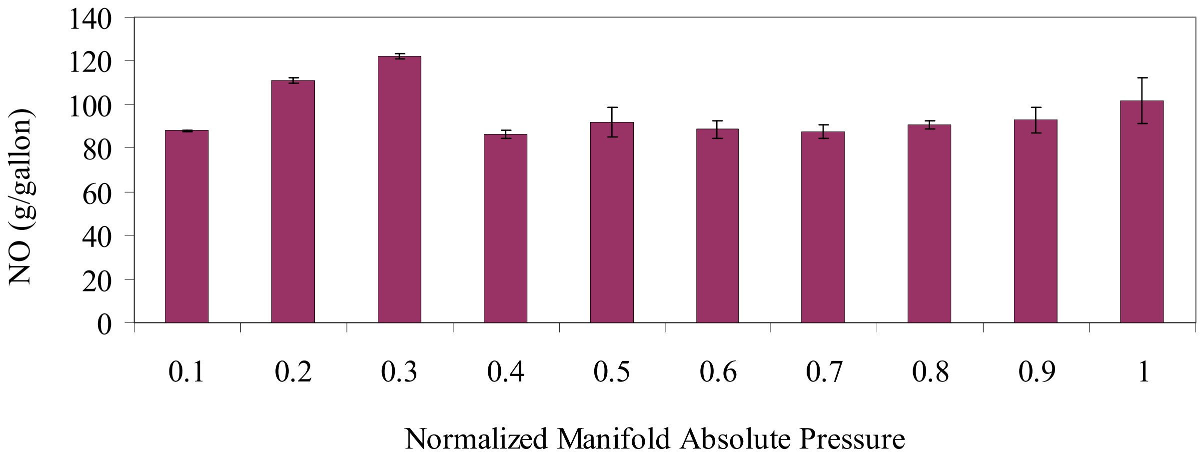
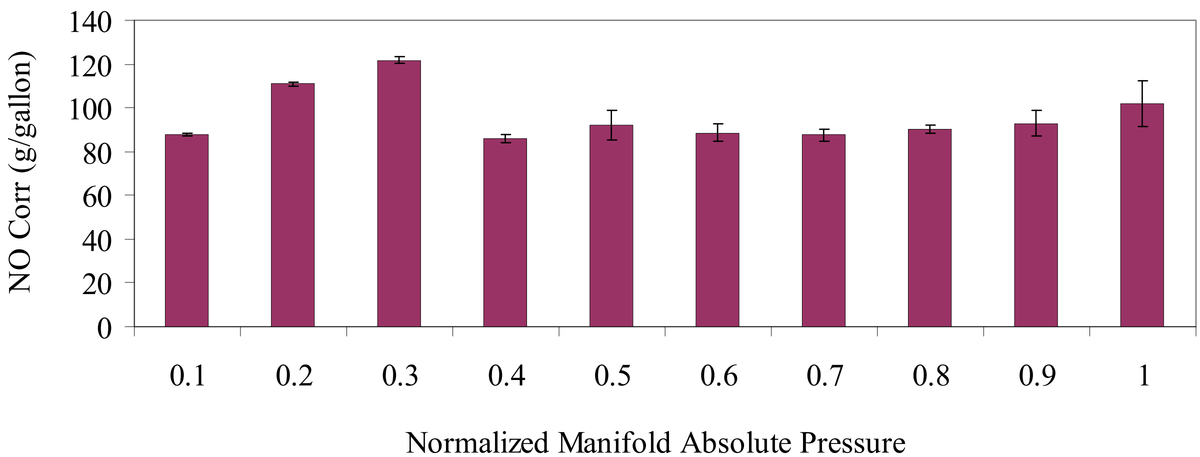


Figure A69. Continued

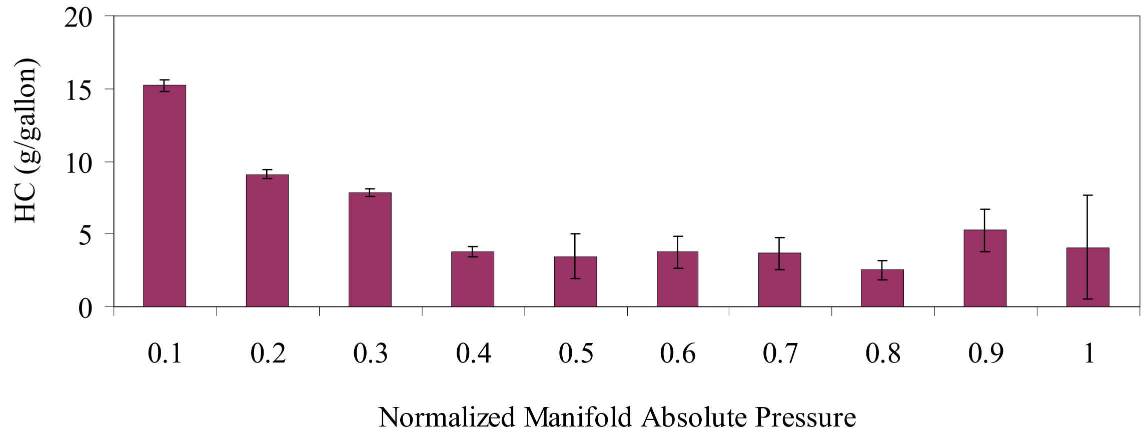


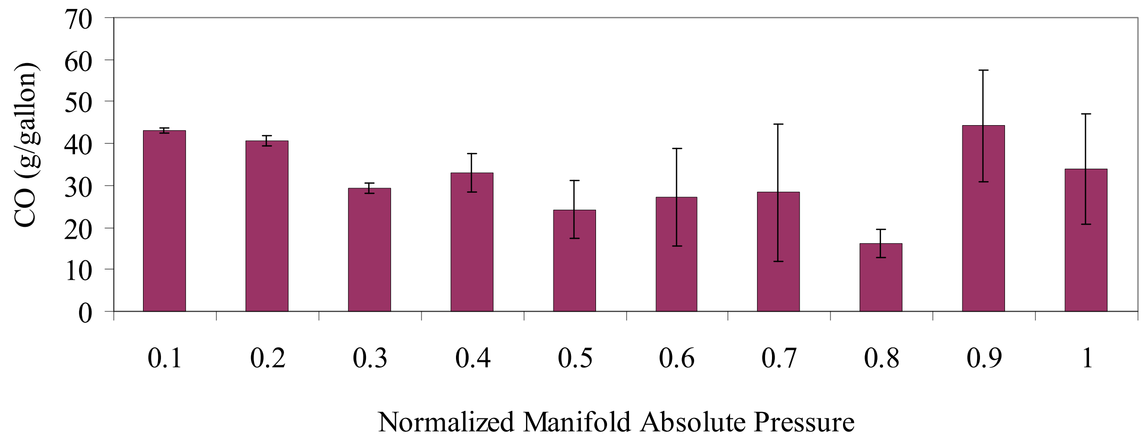


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 44 ^{o}F and the relative humidity was 69 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A70. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Backhoe 2 (continued on next page)





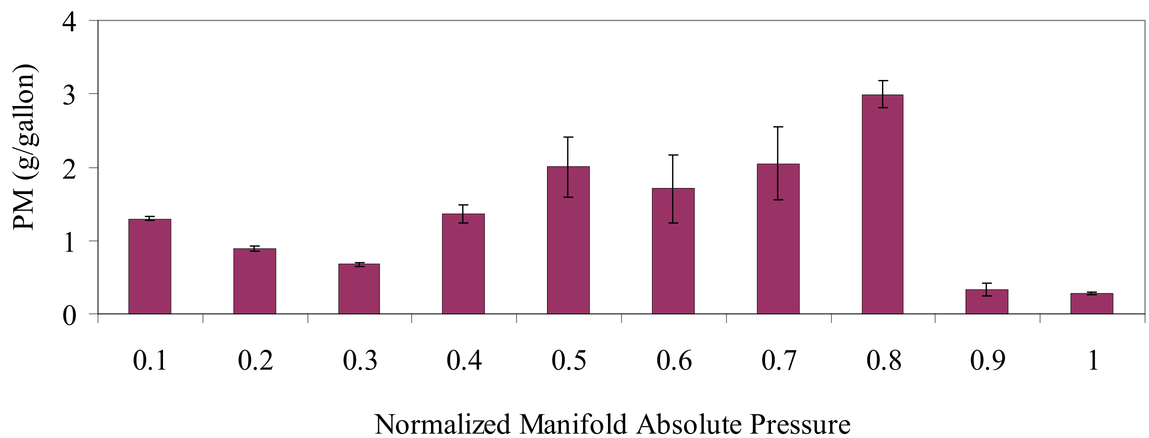
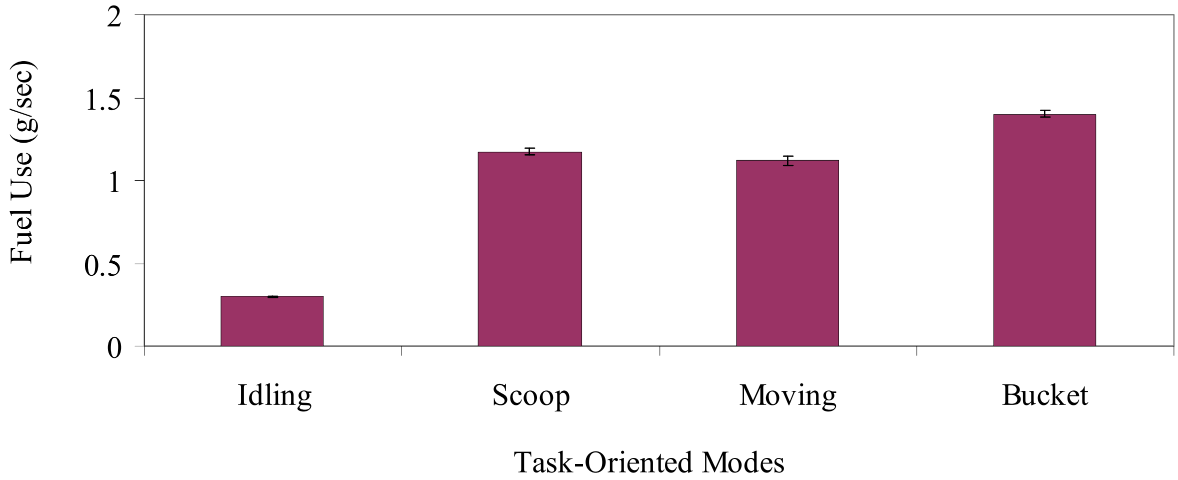
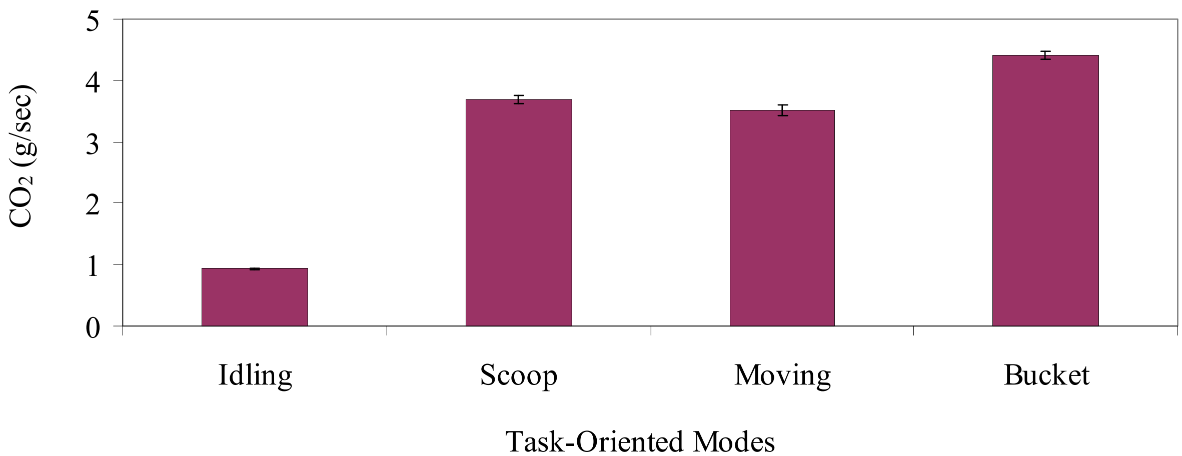


Figure A70. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 44 ^{o}F and the relative humidity was 69 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A71. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 2 (continued on next page)

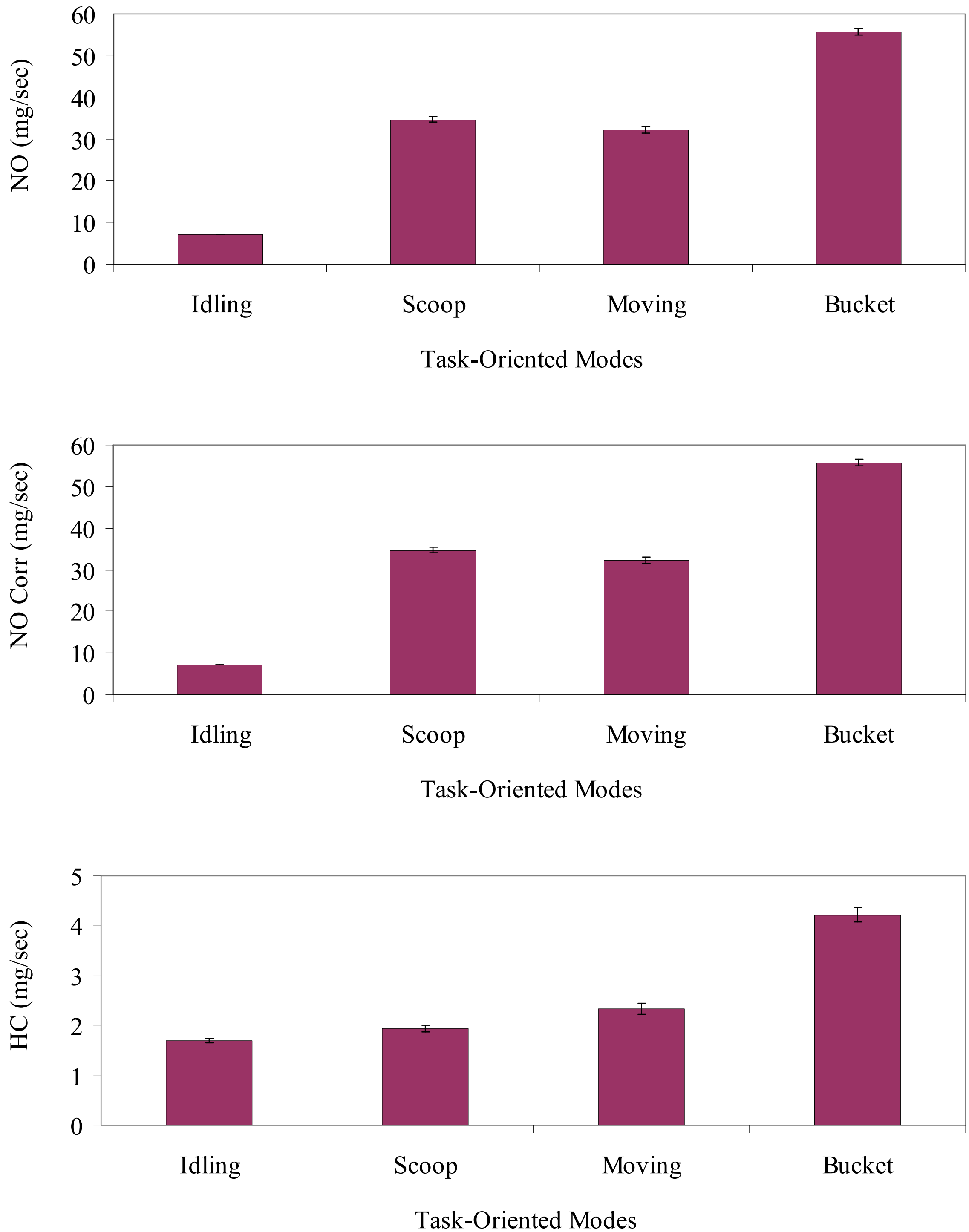
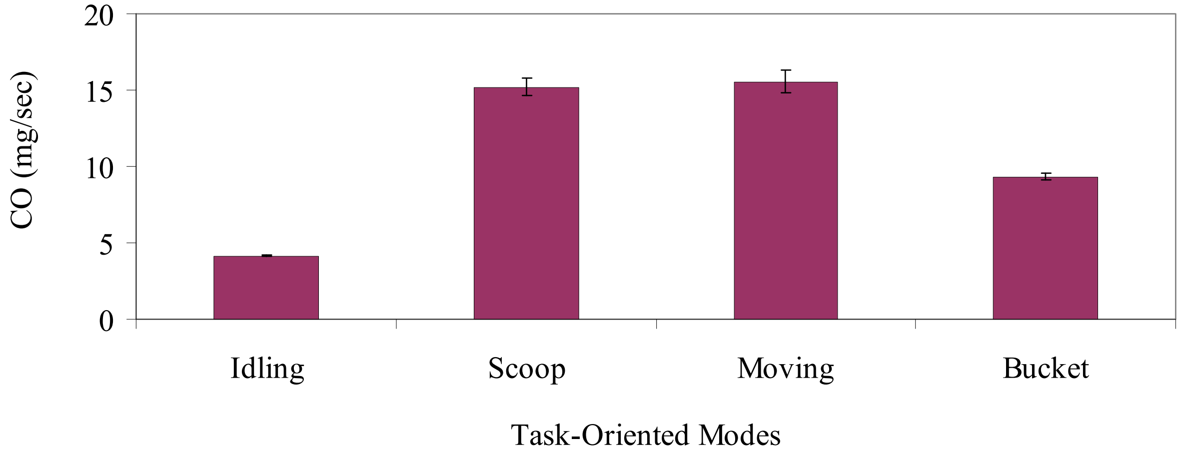


Figure A71. Continued



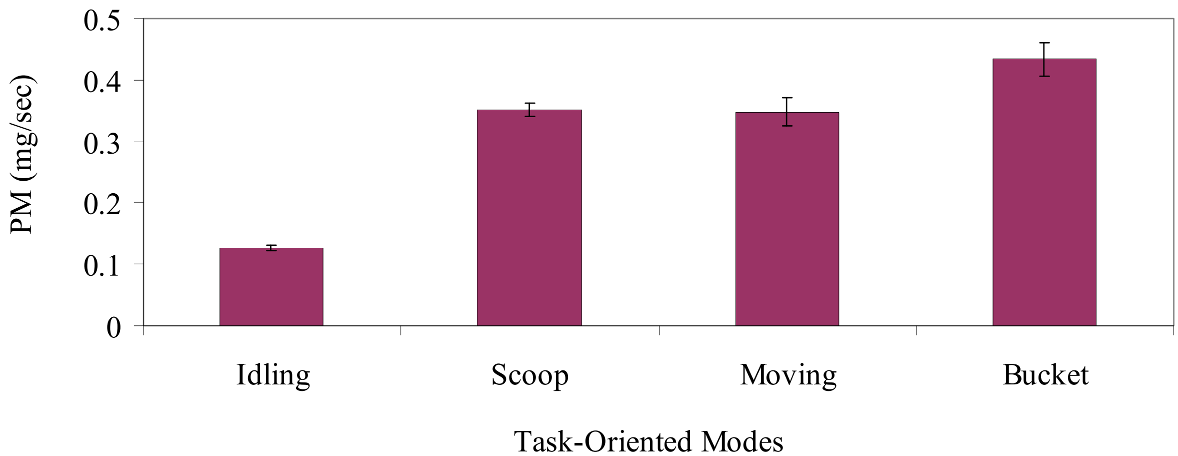
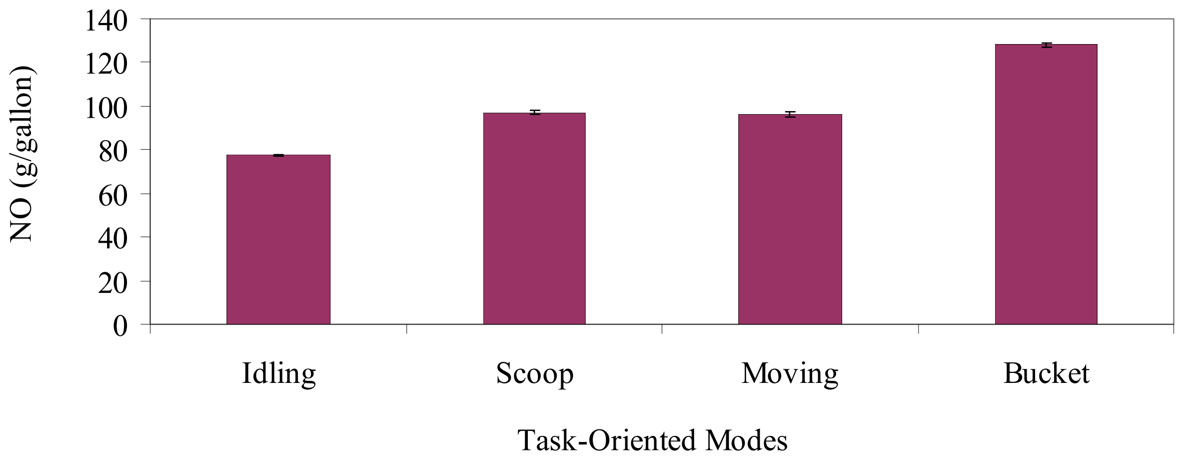
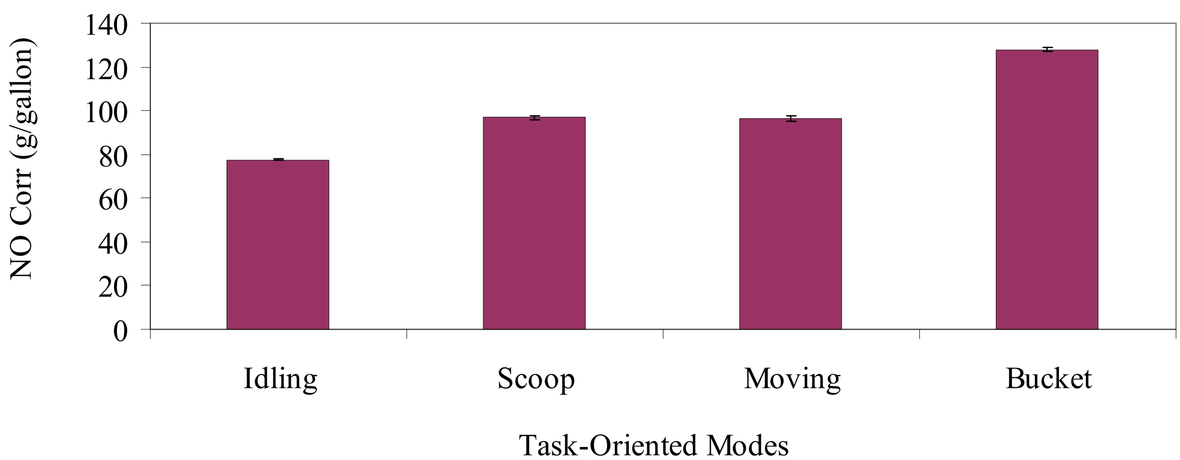


Figure A71. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 44 ^{o}F and the relative humidity was 69 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A72. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 2 (continued on next page)

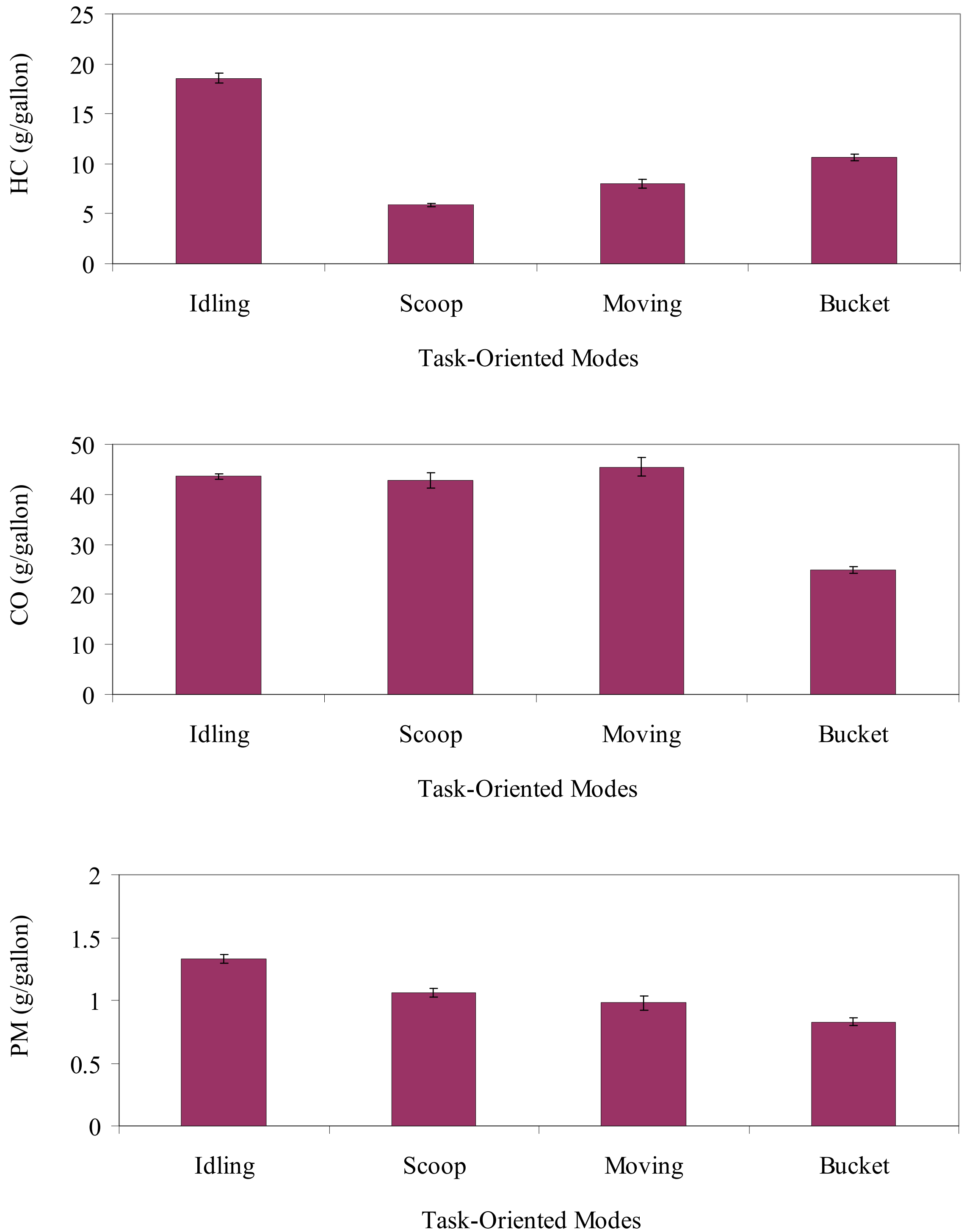
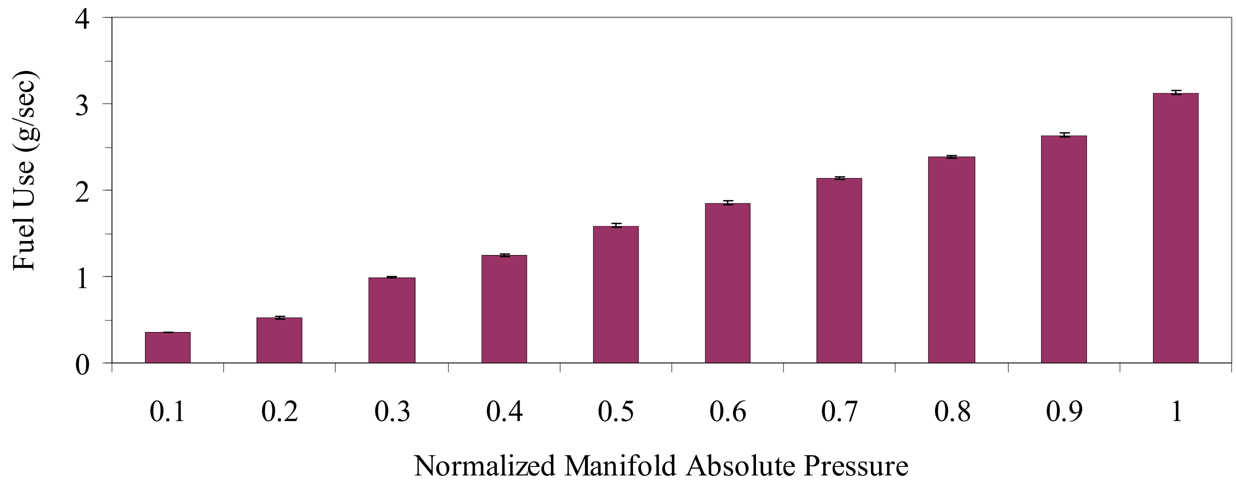
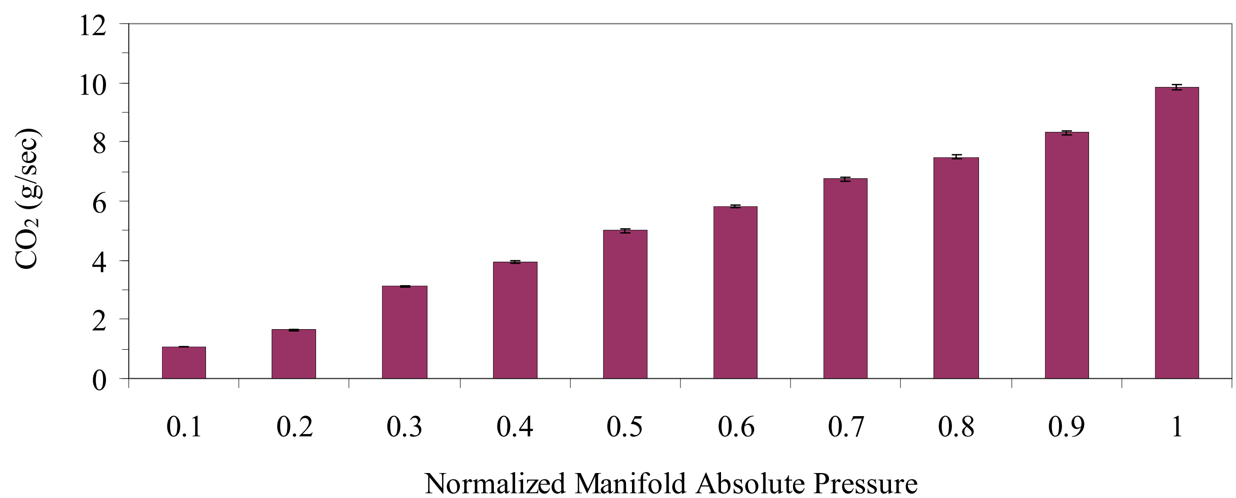


Figure A72. Continued

BACKHOE 3

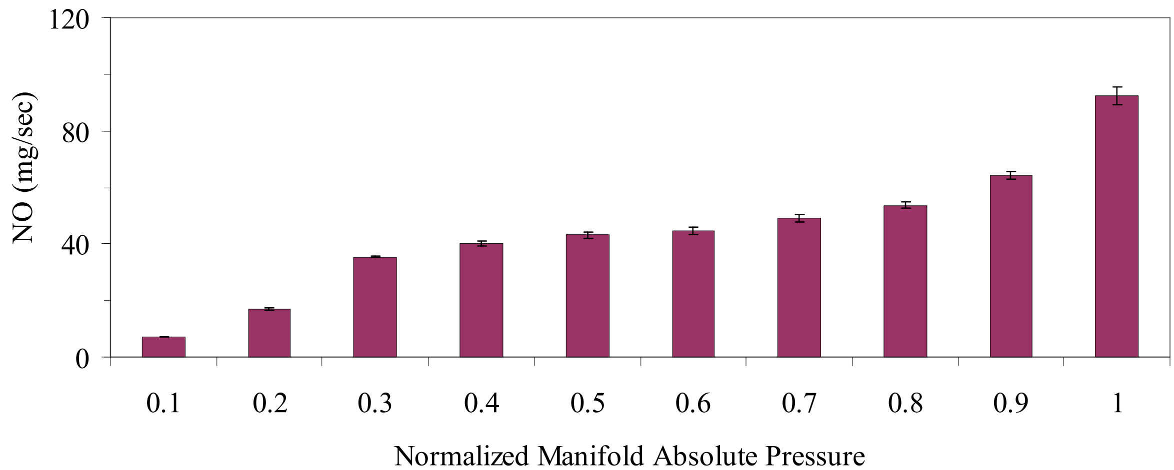


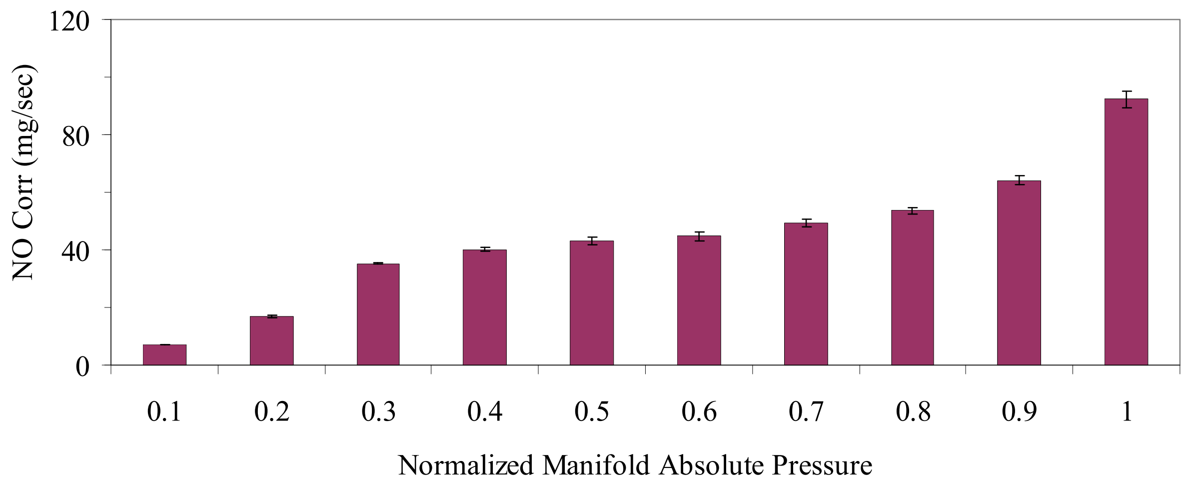


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 77 ^oF and the relative humidity was 79 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A73. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Backhoe 3 (continued on next page)





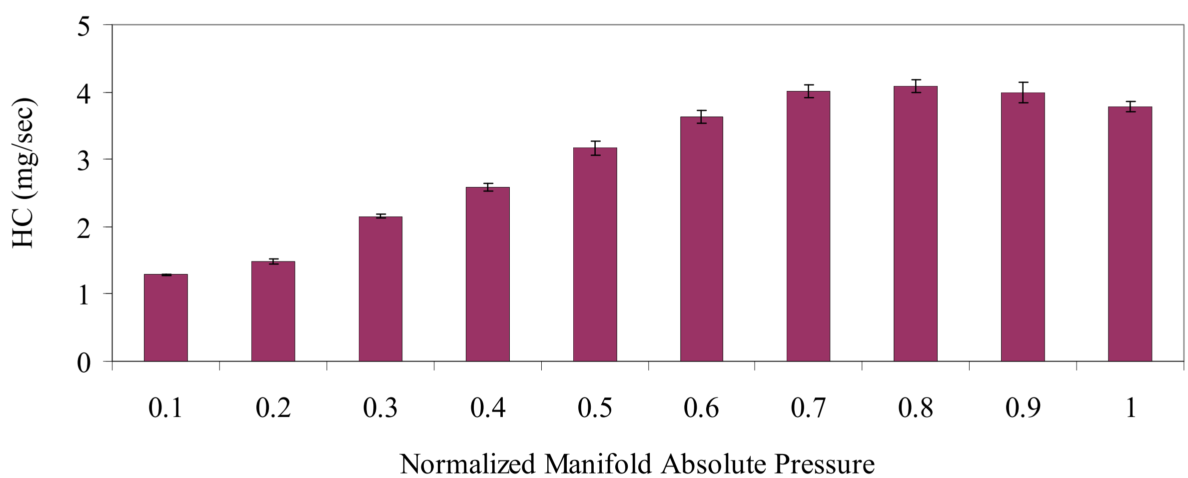


Figure A73. Continued

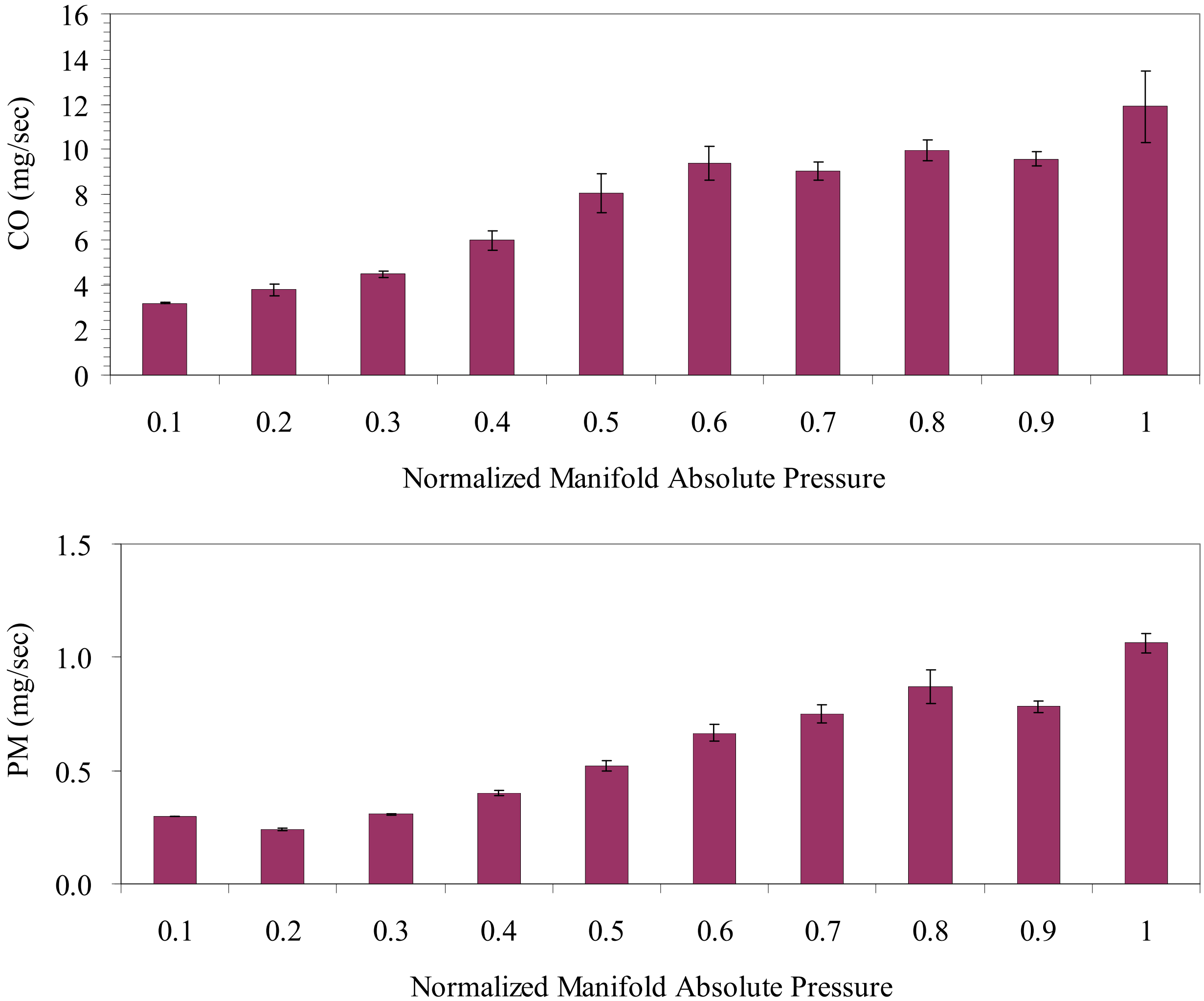
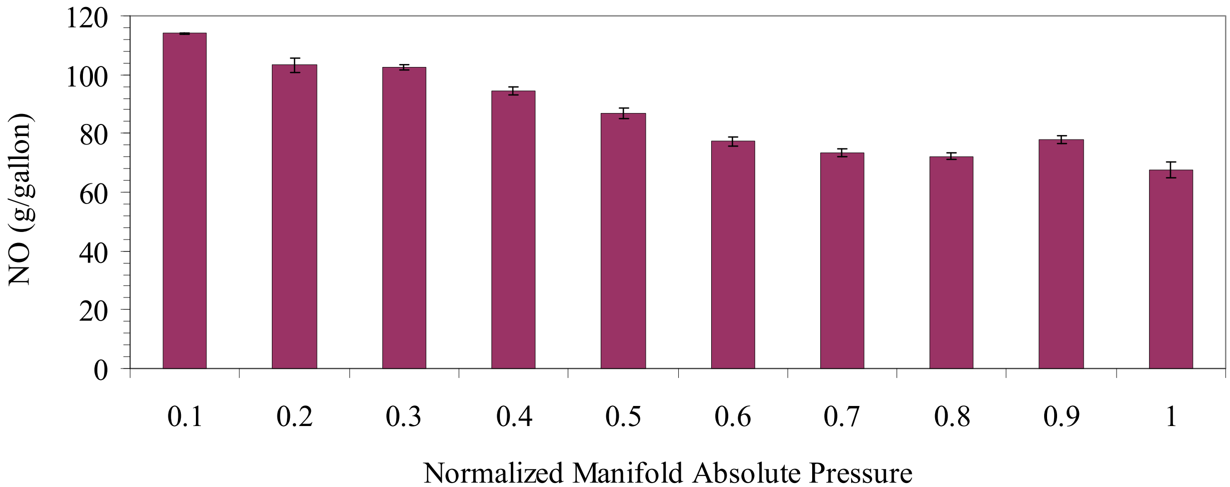
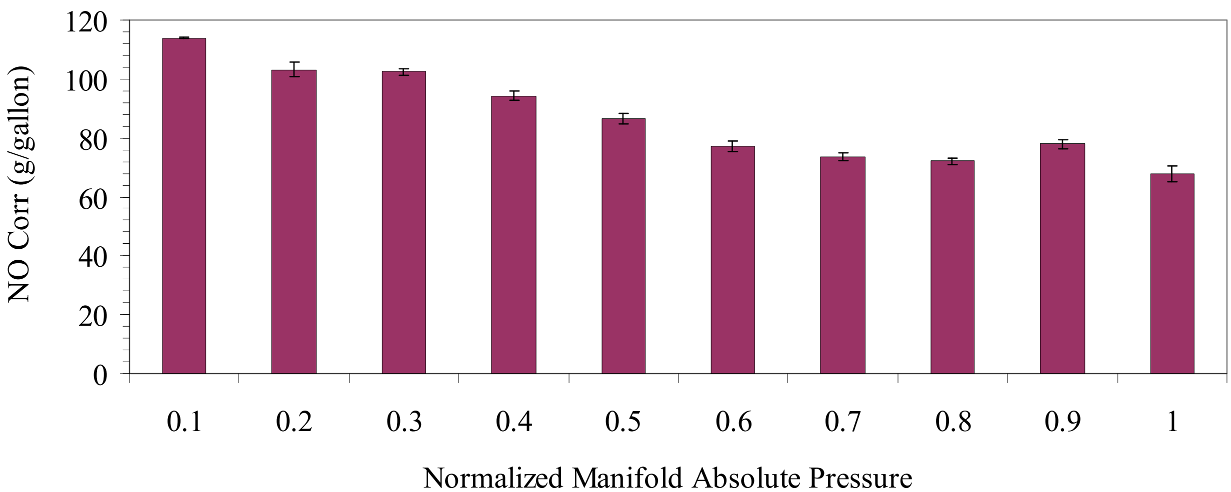


Figure A73. Continued

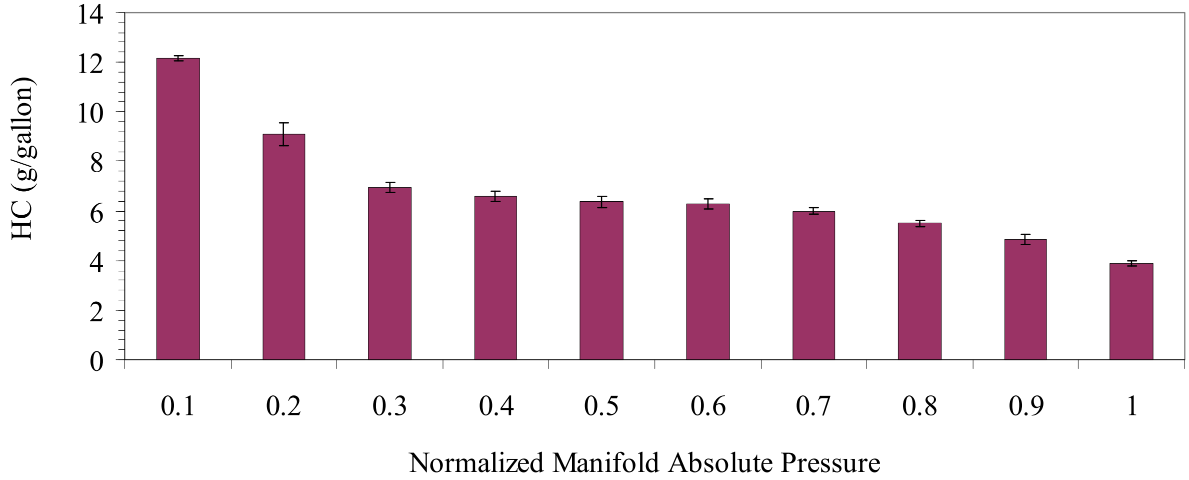


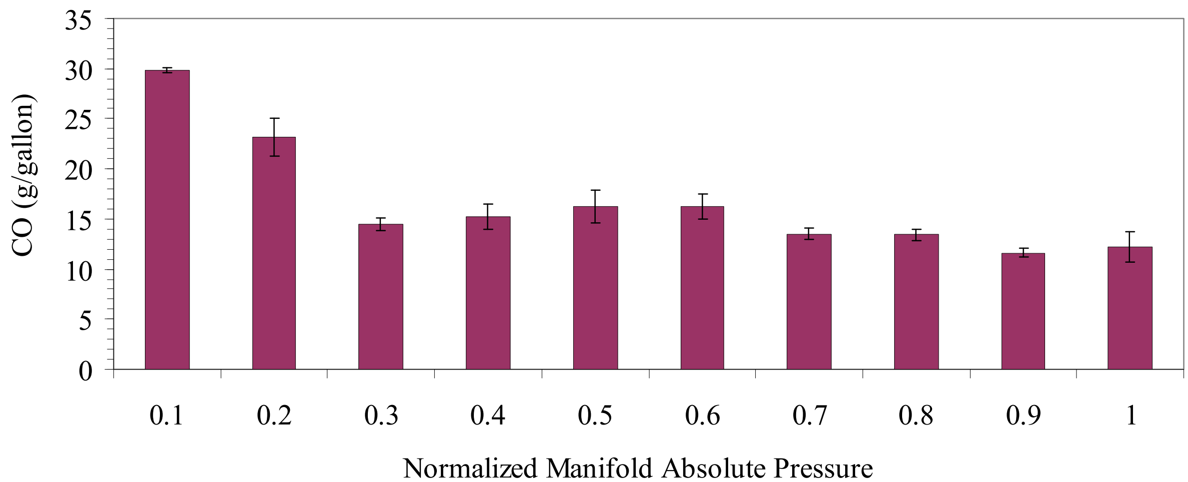


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 77 ^{o}F and the relative humidity was 79 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A74. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Backhoe 3 (continued on next page)





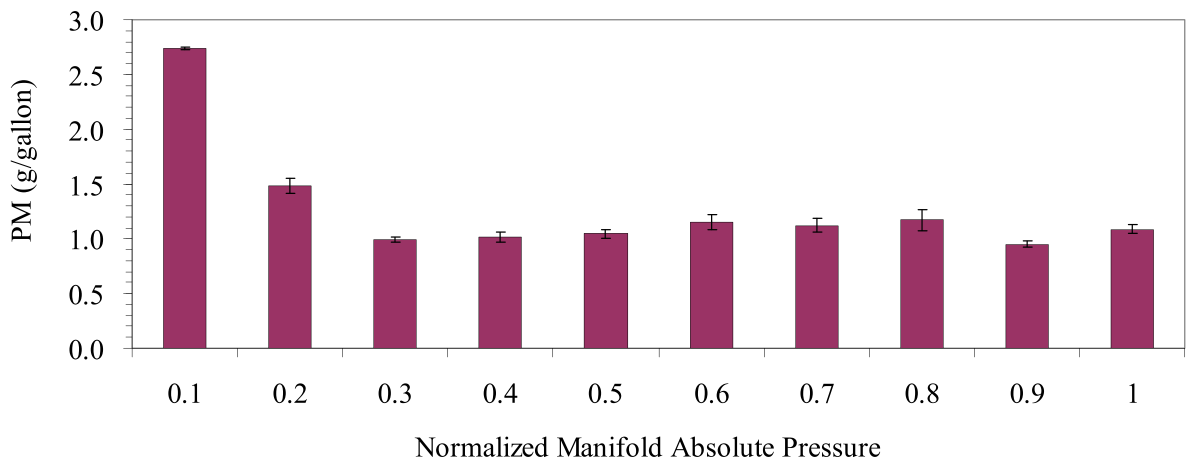
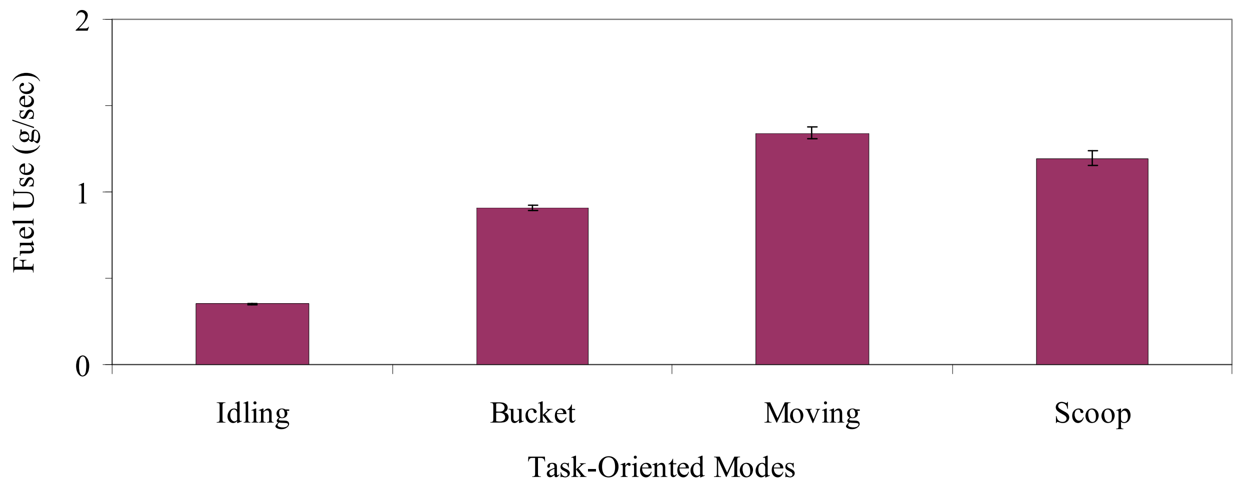
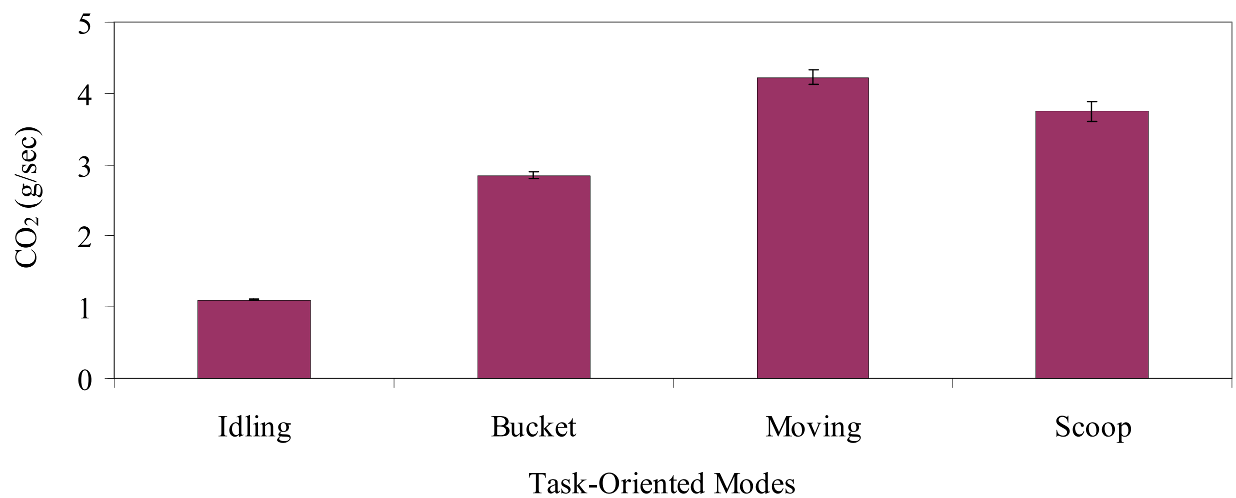


Figure A74. Continued

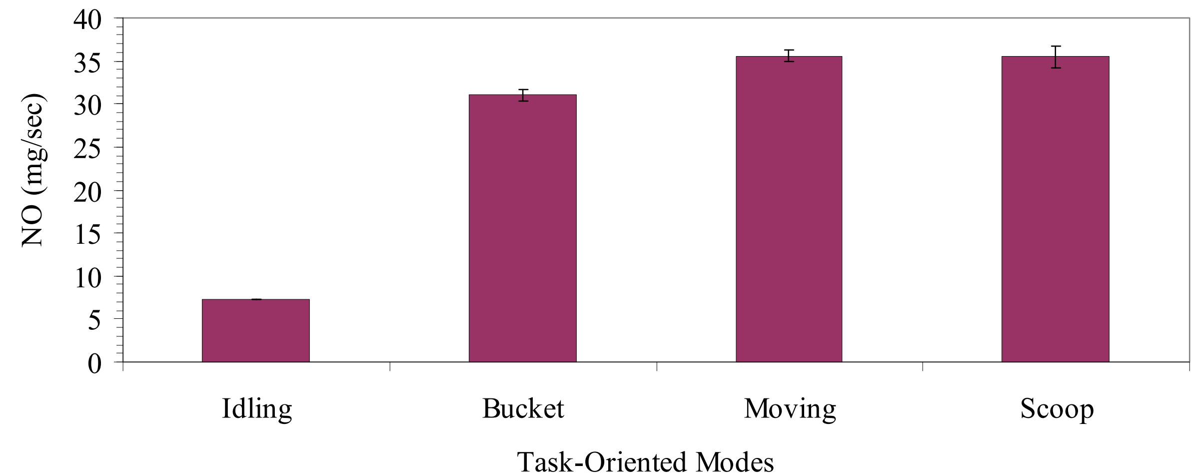


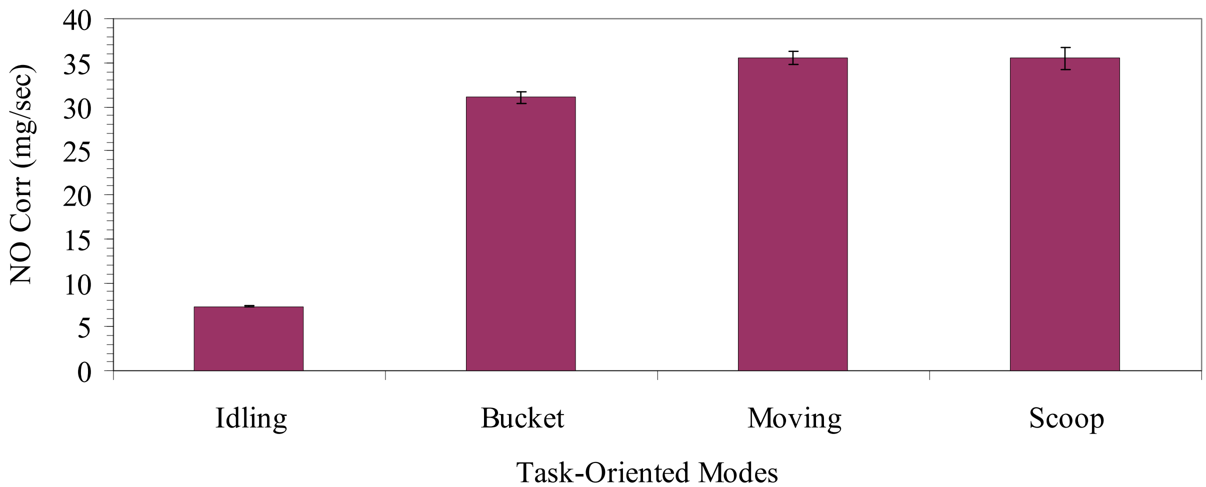


NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 77 ^{o}F and the relative humidity was 79 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A75. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 3 (continued on next page)





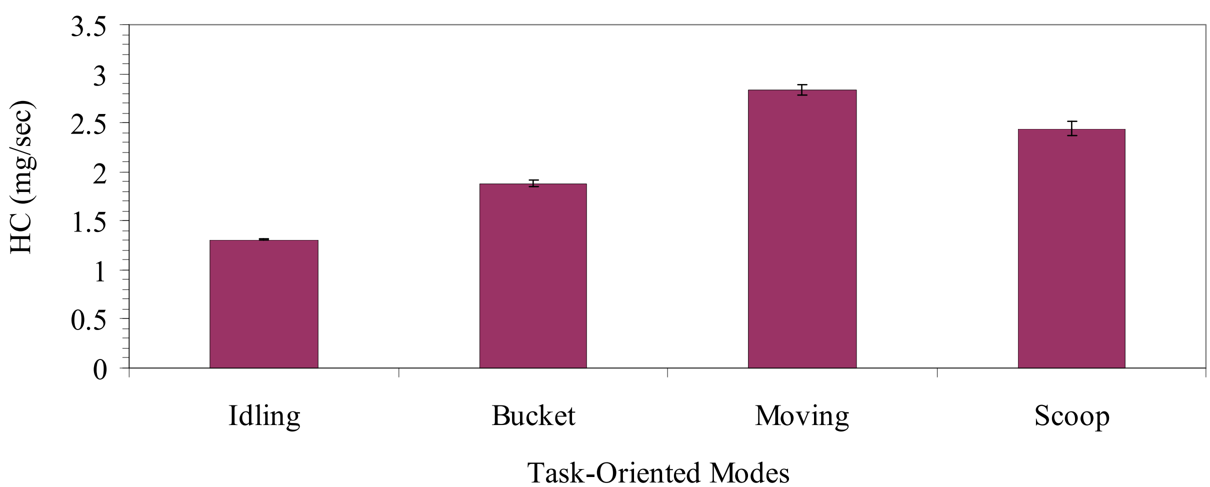


Figure A75. Continued

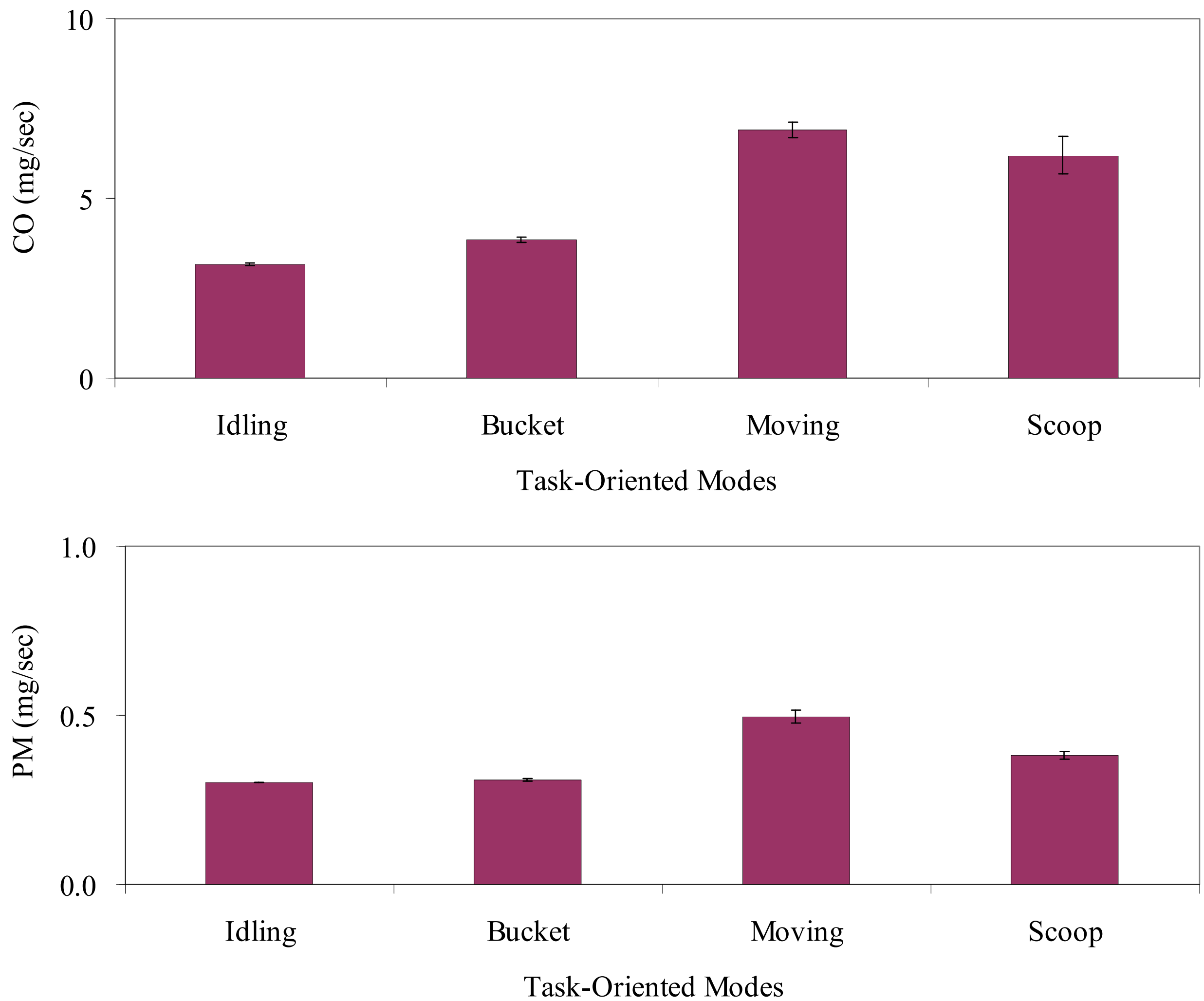
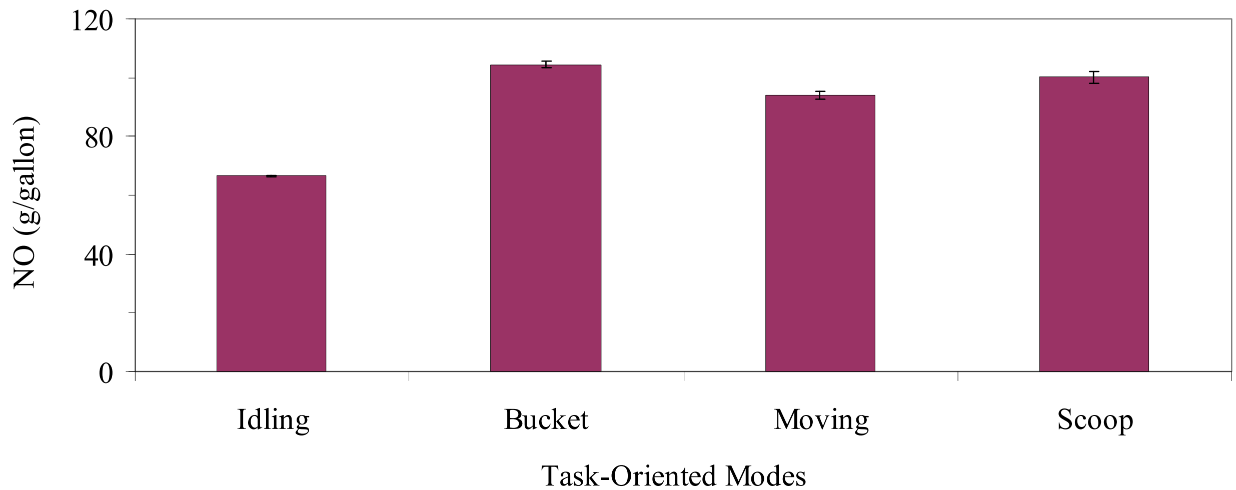
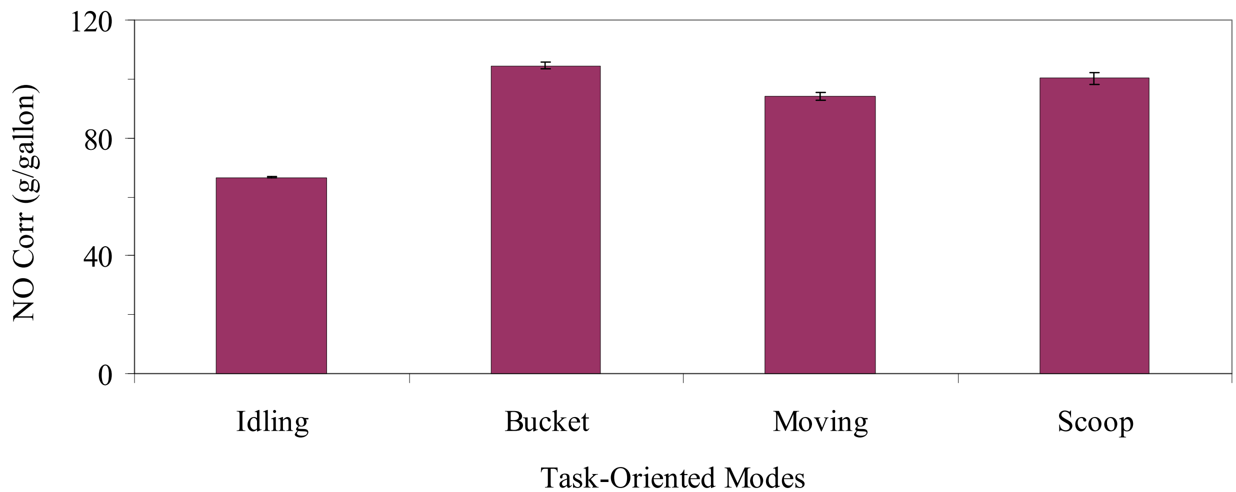


Figure A75. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. The ambient temperature was 77 ^{o}F and the relative humidity was 79 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A76. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 3 (continued on next page)

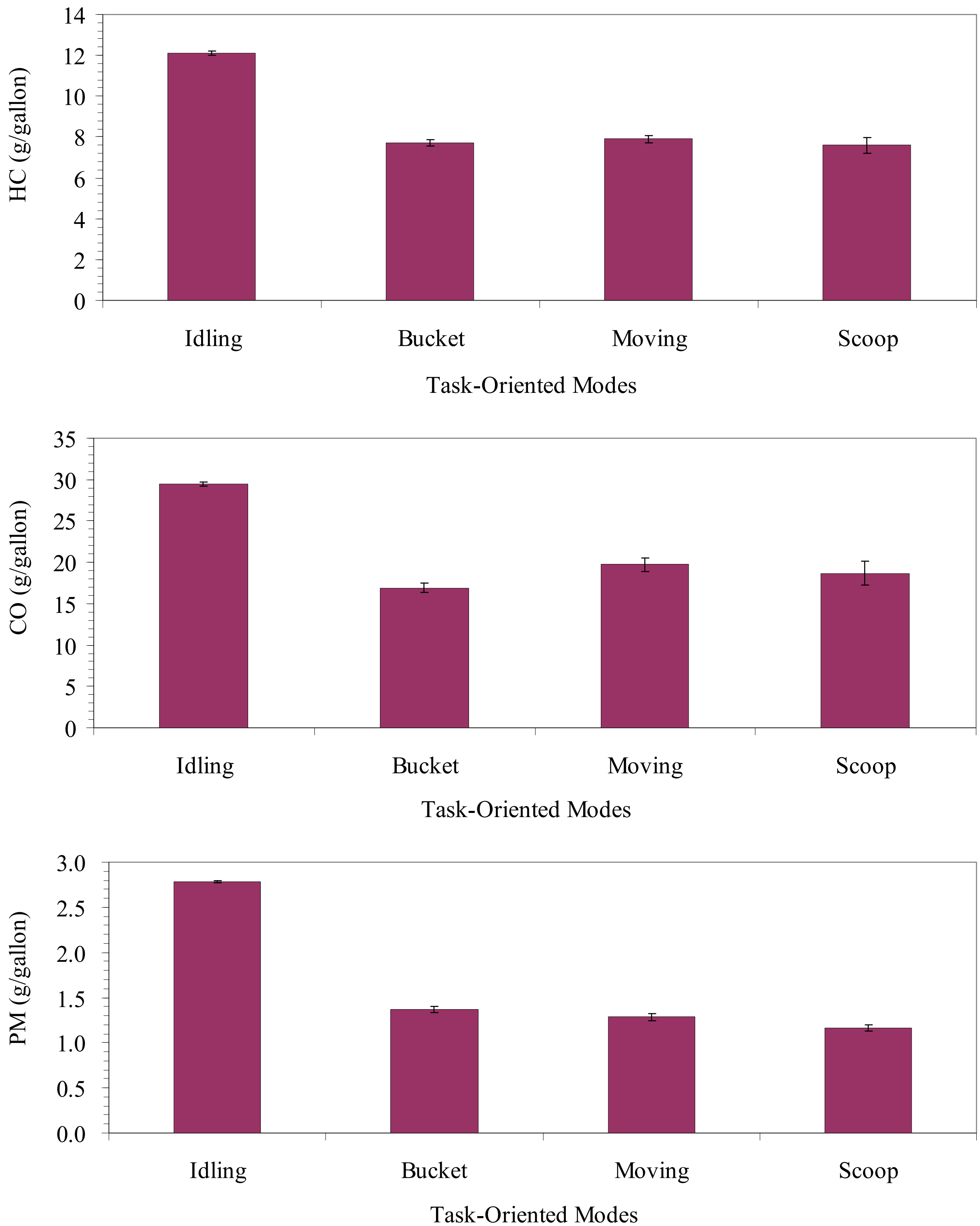
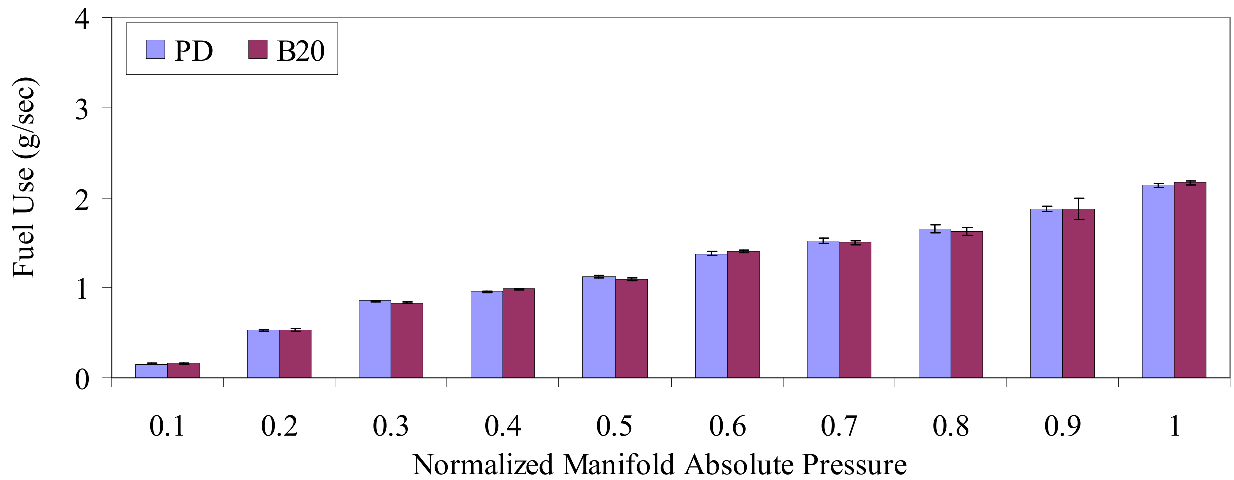
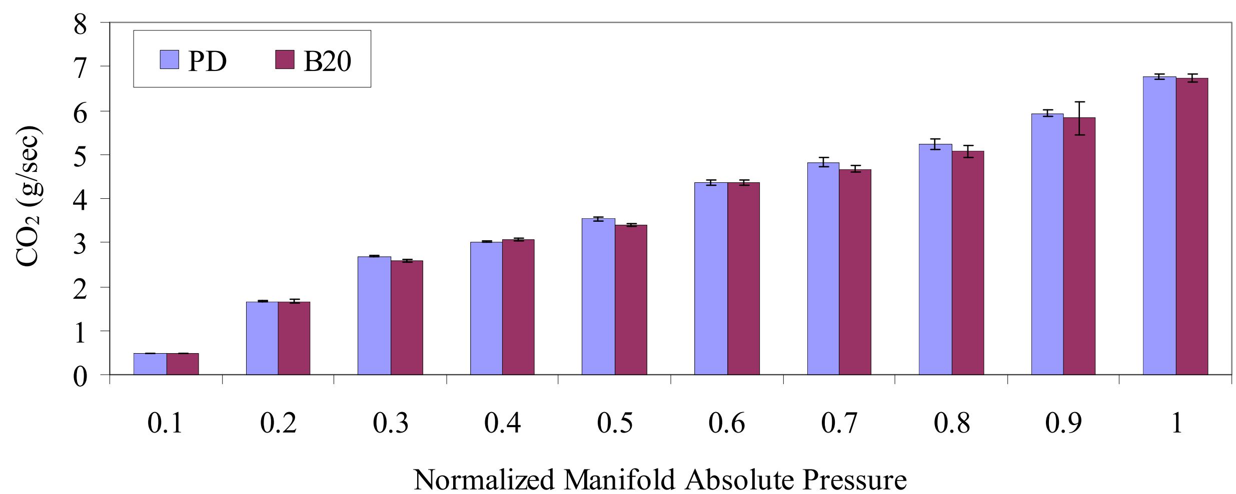


Figure A76. Continued

BACKHOE 4

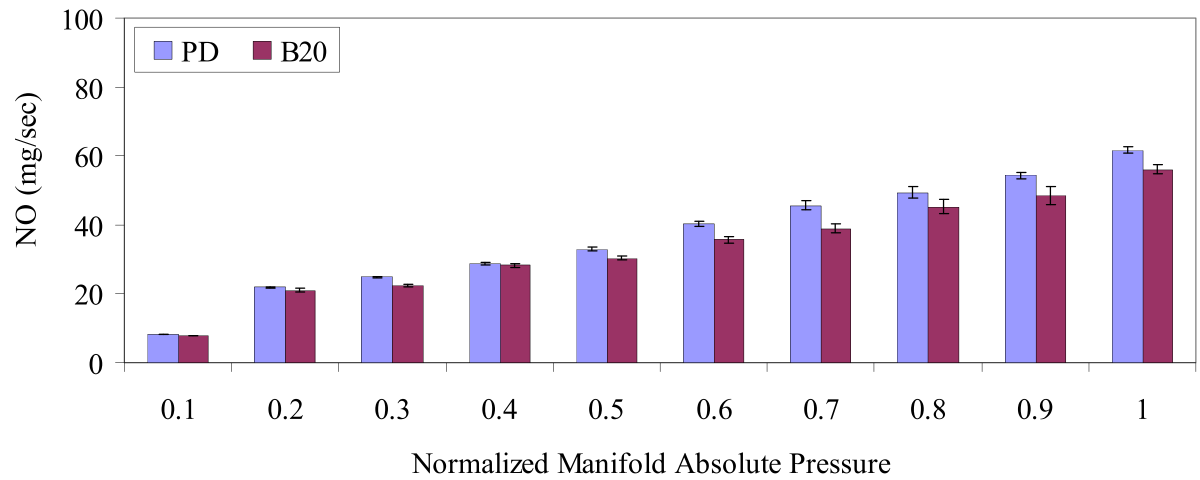


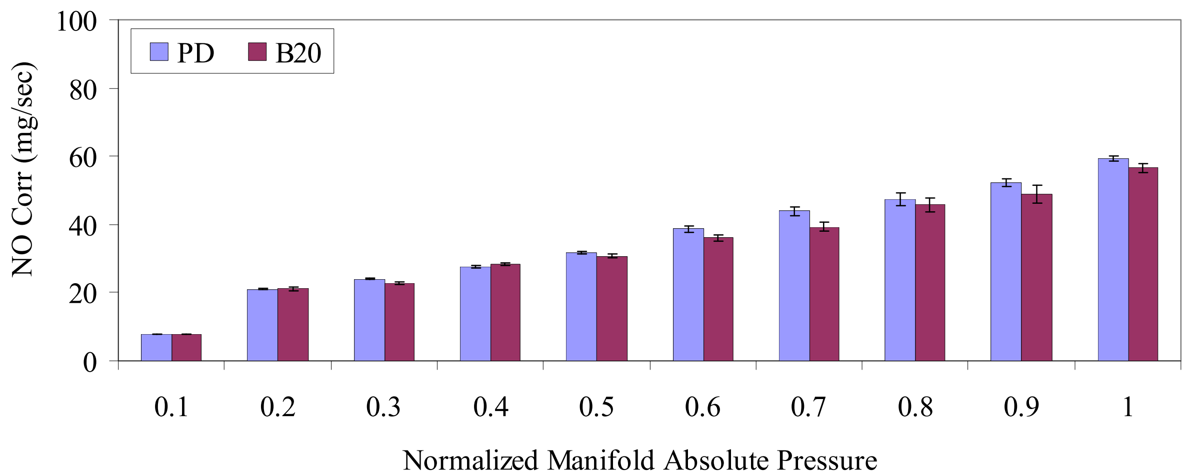


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 79 ^{o}F and the relative humidity was 52 %. For the B20 biodiesel test, the ambient temperature was 77 ^{o}F and the relative humidity was 60 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A77. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Backhoe 4 (continued on next page)





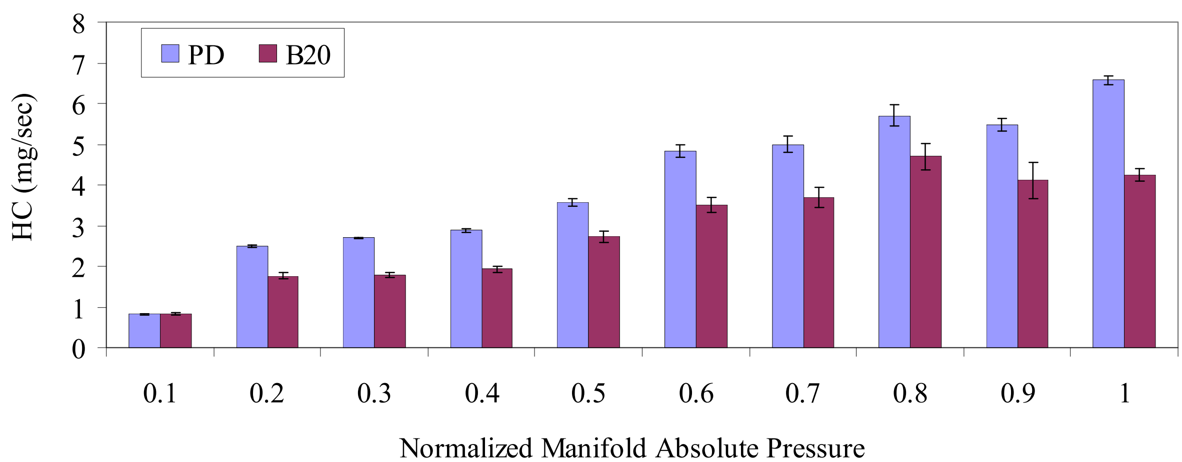
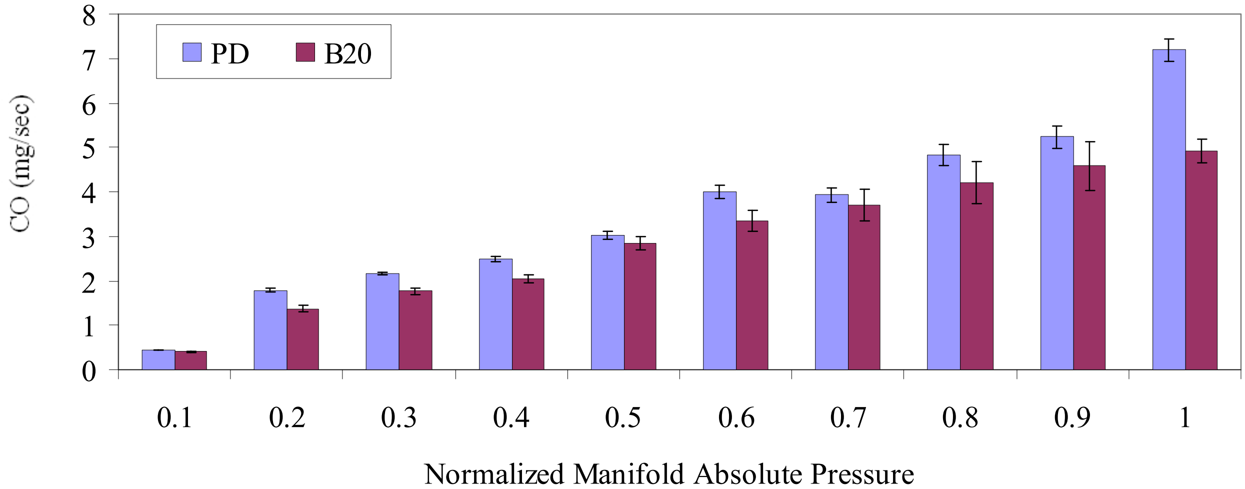


Figure A77. Continued



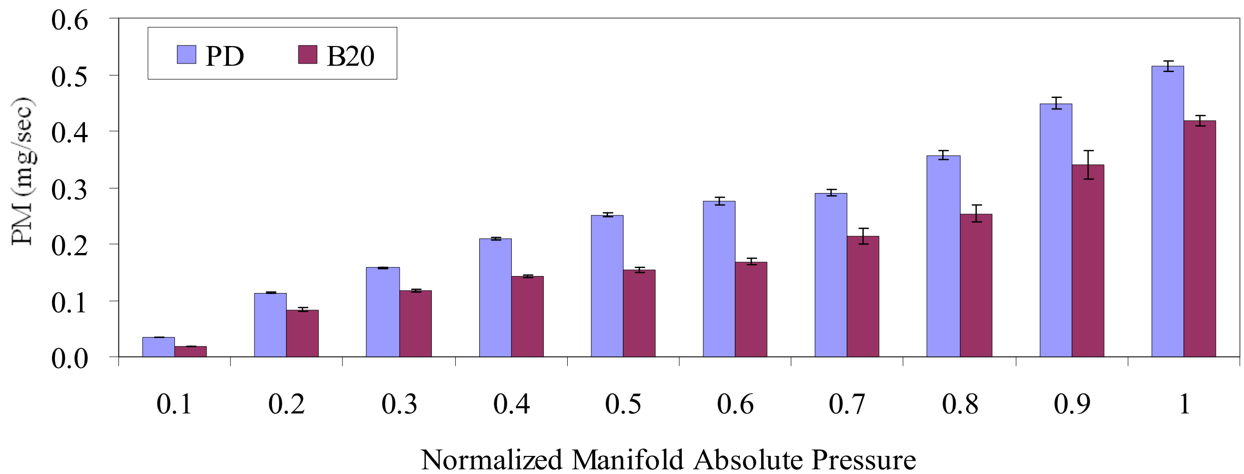
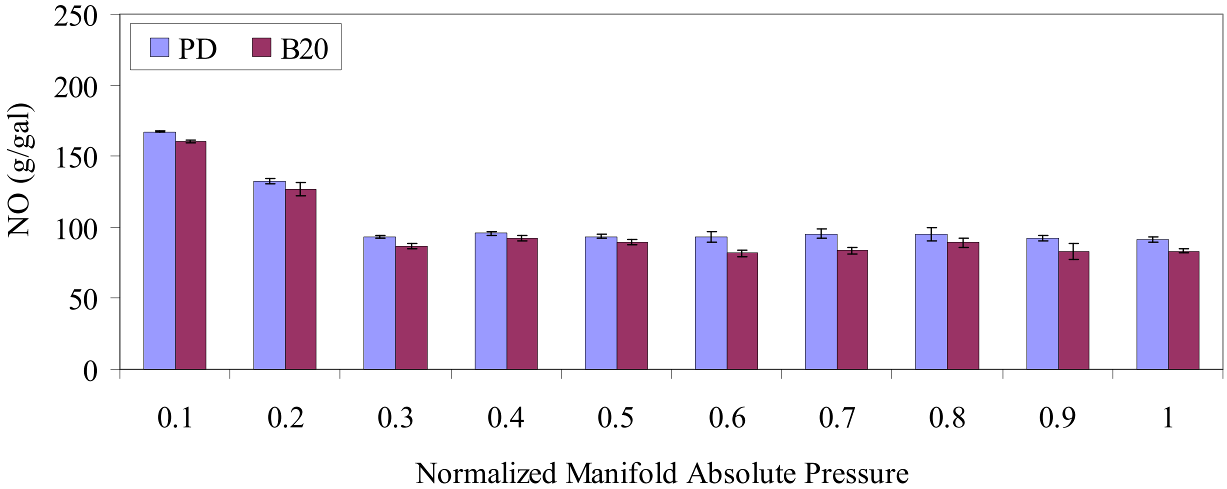
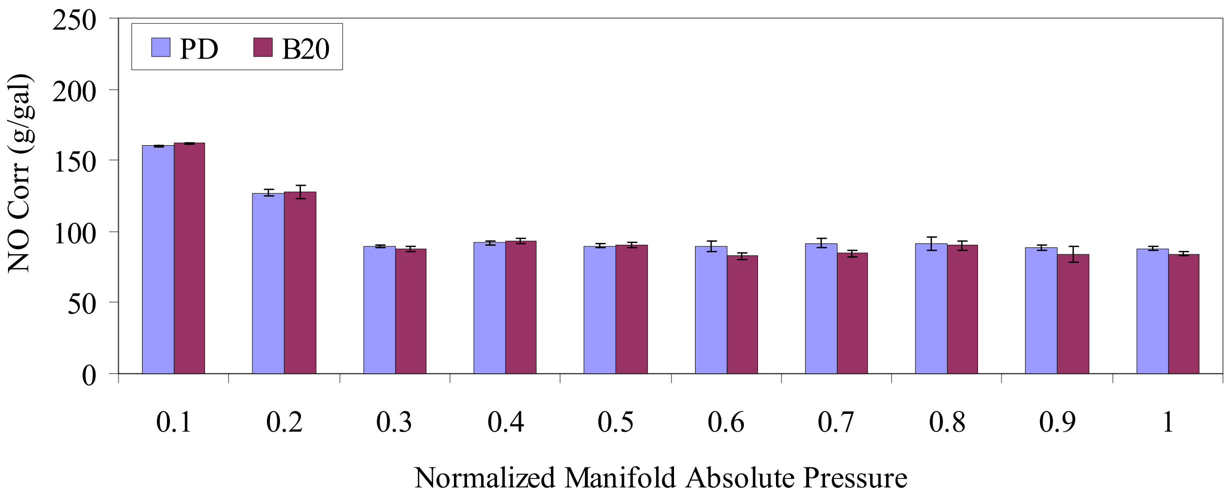


Figure A77. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 79 ^{o}F and the relative humidity was 52 %. For the B20 biodiesel test, the ambient temperature was 77 ^{o}F and the relative humidity was 60 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A78. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Backhoe 4 (continued on next page)

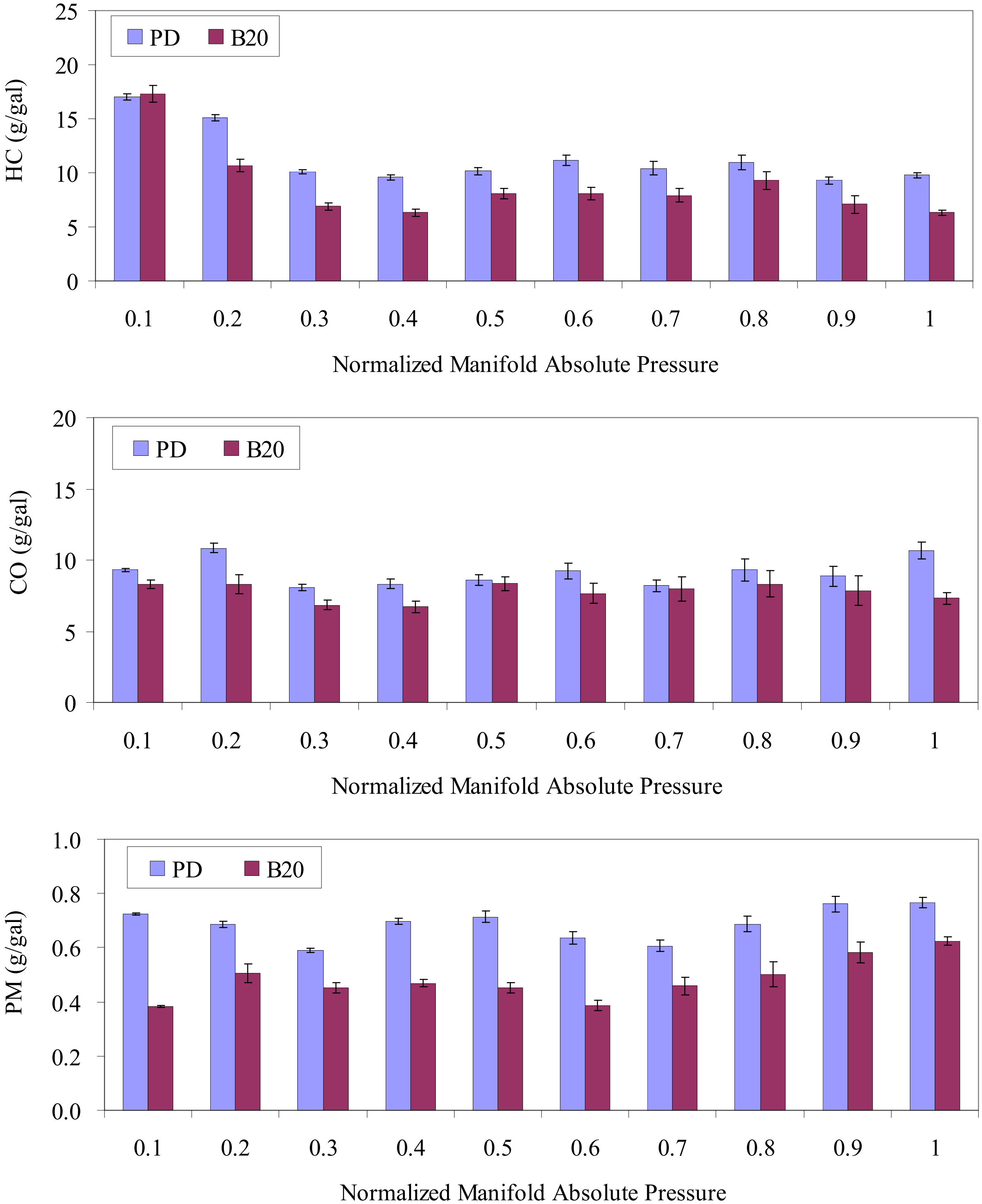
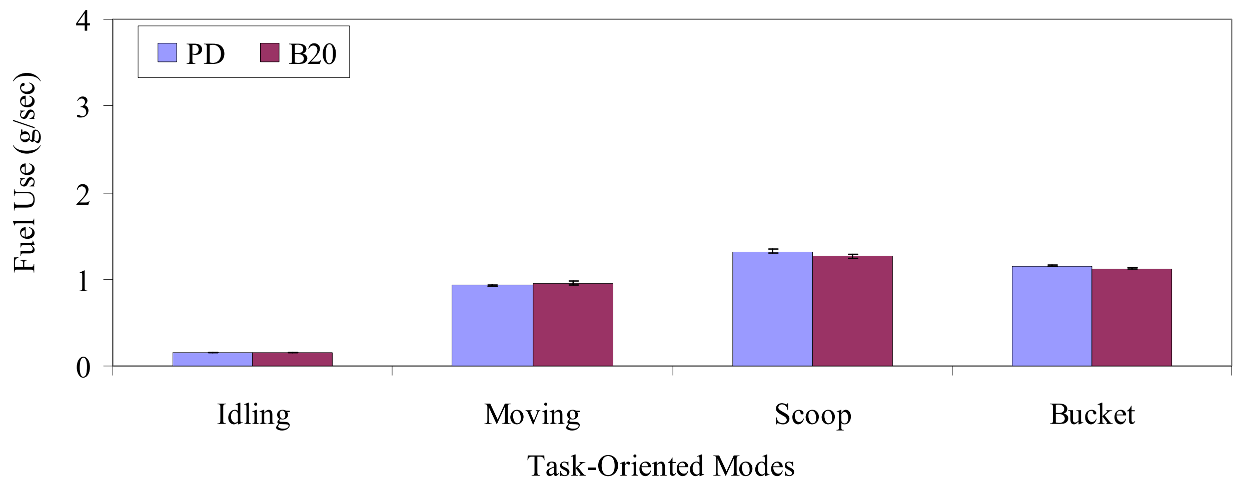
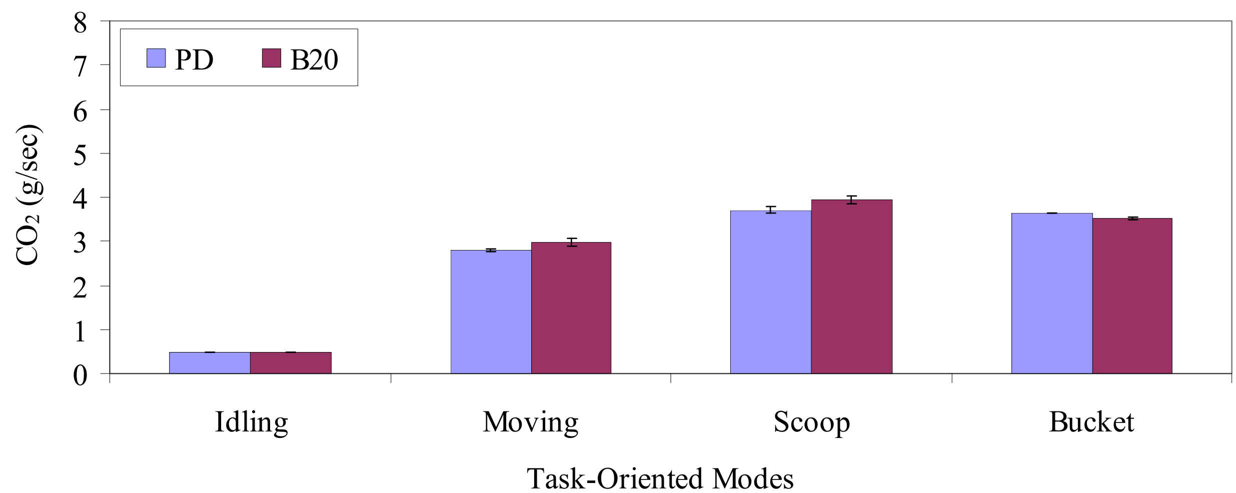


Figure A78. Continued

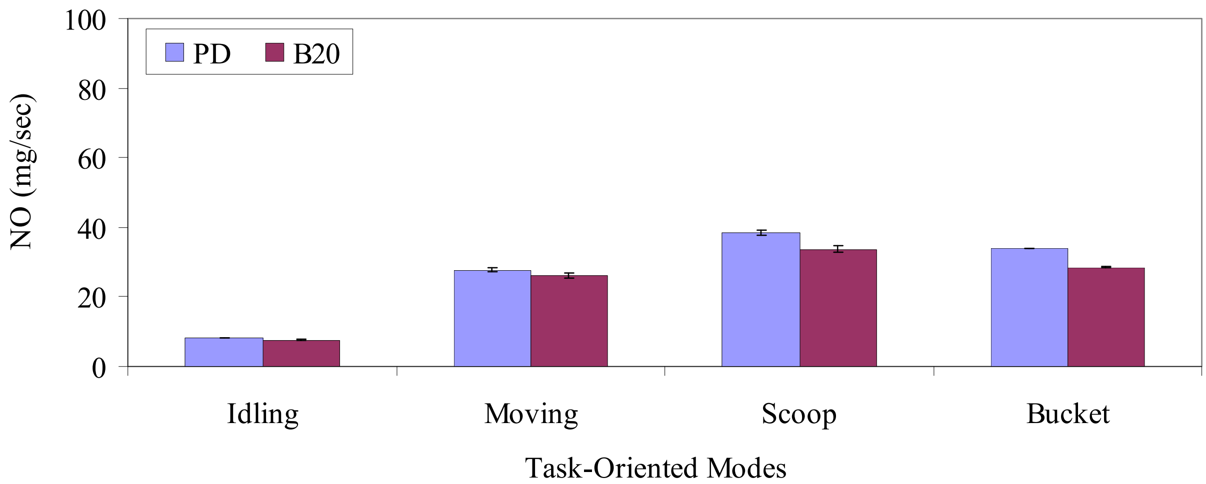


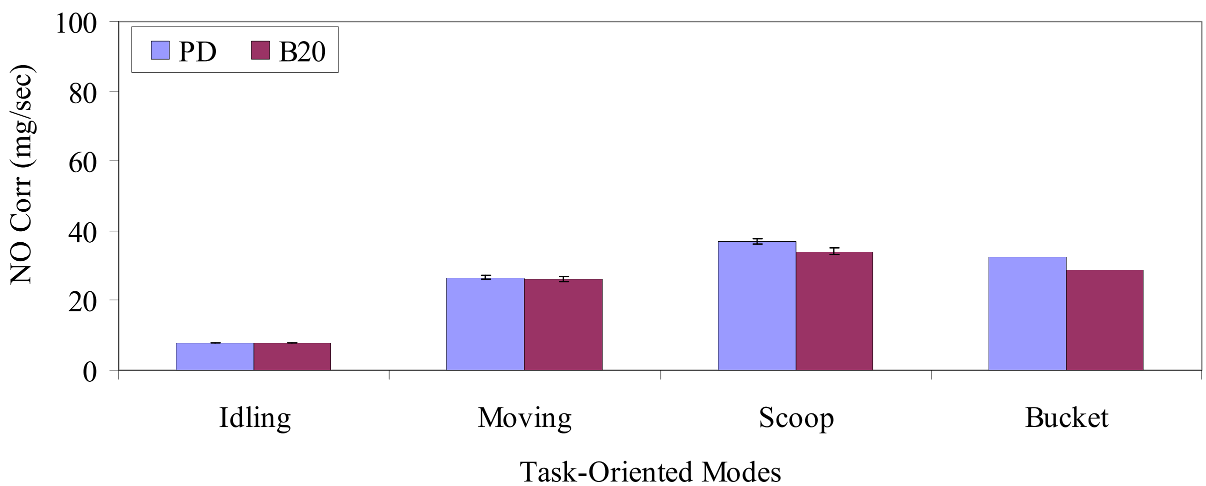


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 79 °F and the relative humidity was 52 %. For the B20 biodiesel test, the ambient temperature was 77 °F and the relative humidity was 60 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A79. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 4 (continued on next page)





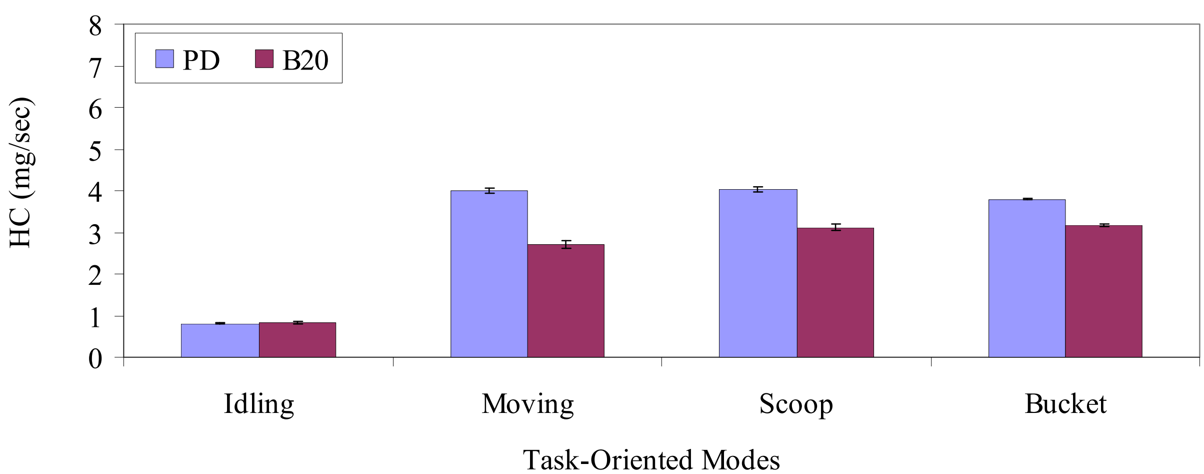
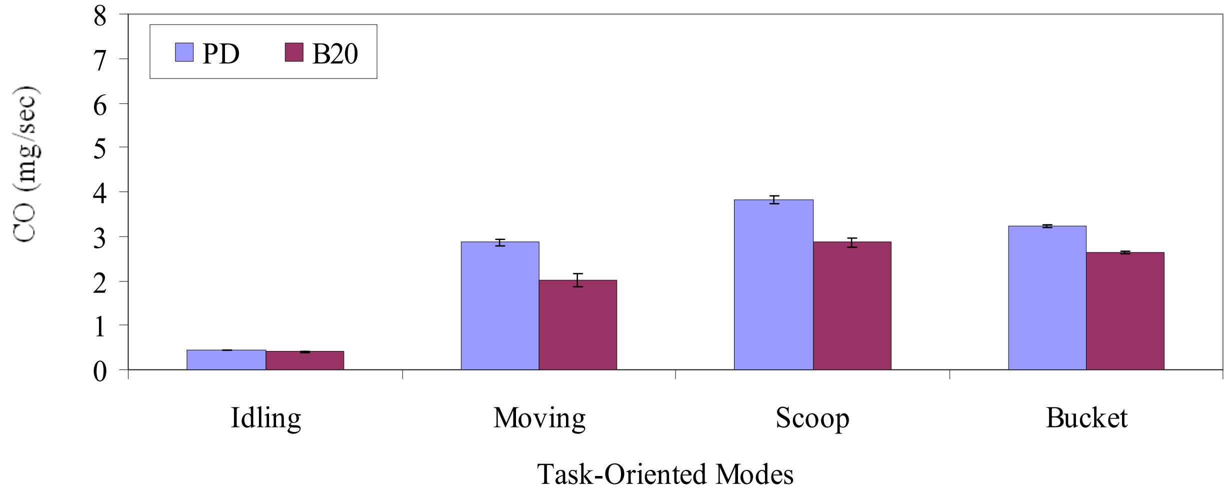


Figure A79. Continued



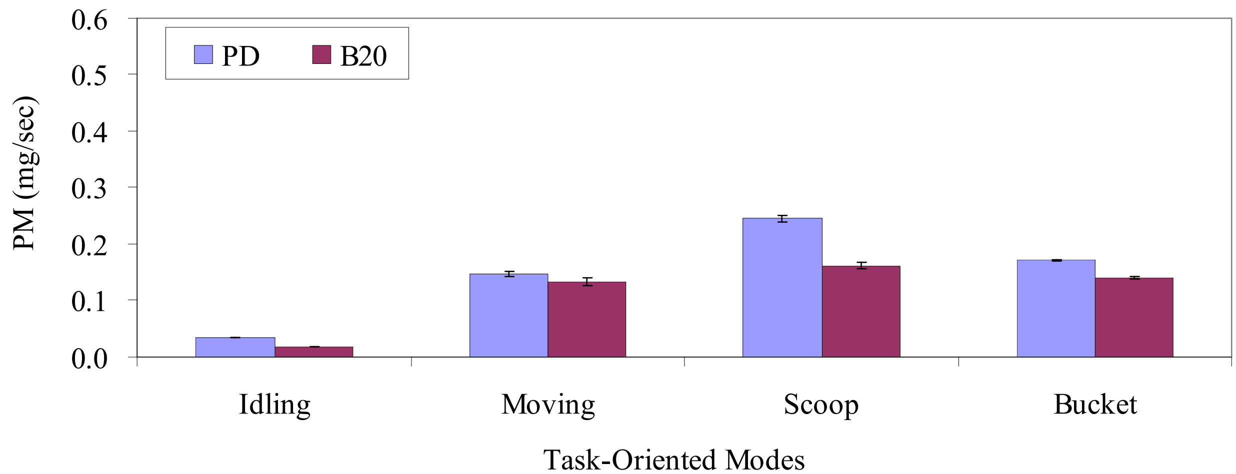
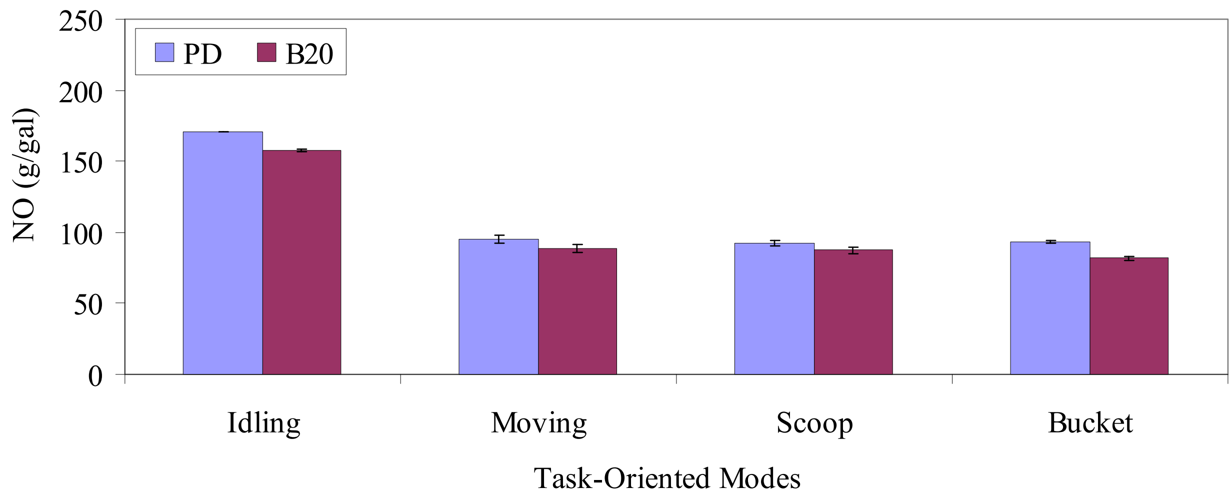
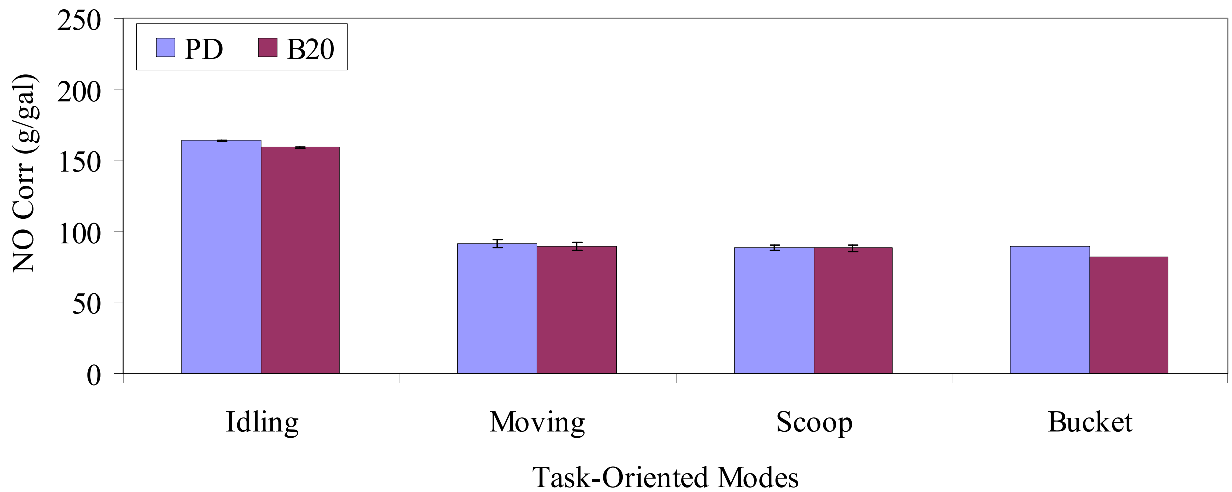


Figure A79. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 79 ^{o}F and the relative humidity was 52 %. For the B20 biodiesel test, the ambient temperature was 77 ^{o}F and the relative humidity was 60 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A80. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 4 (continued on next page)

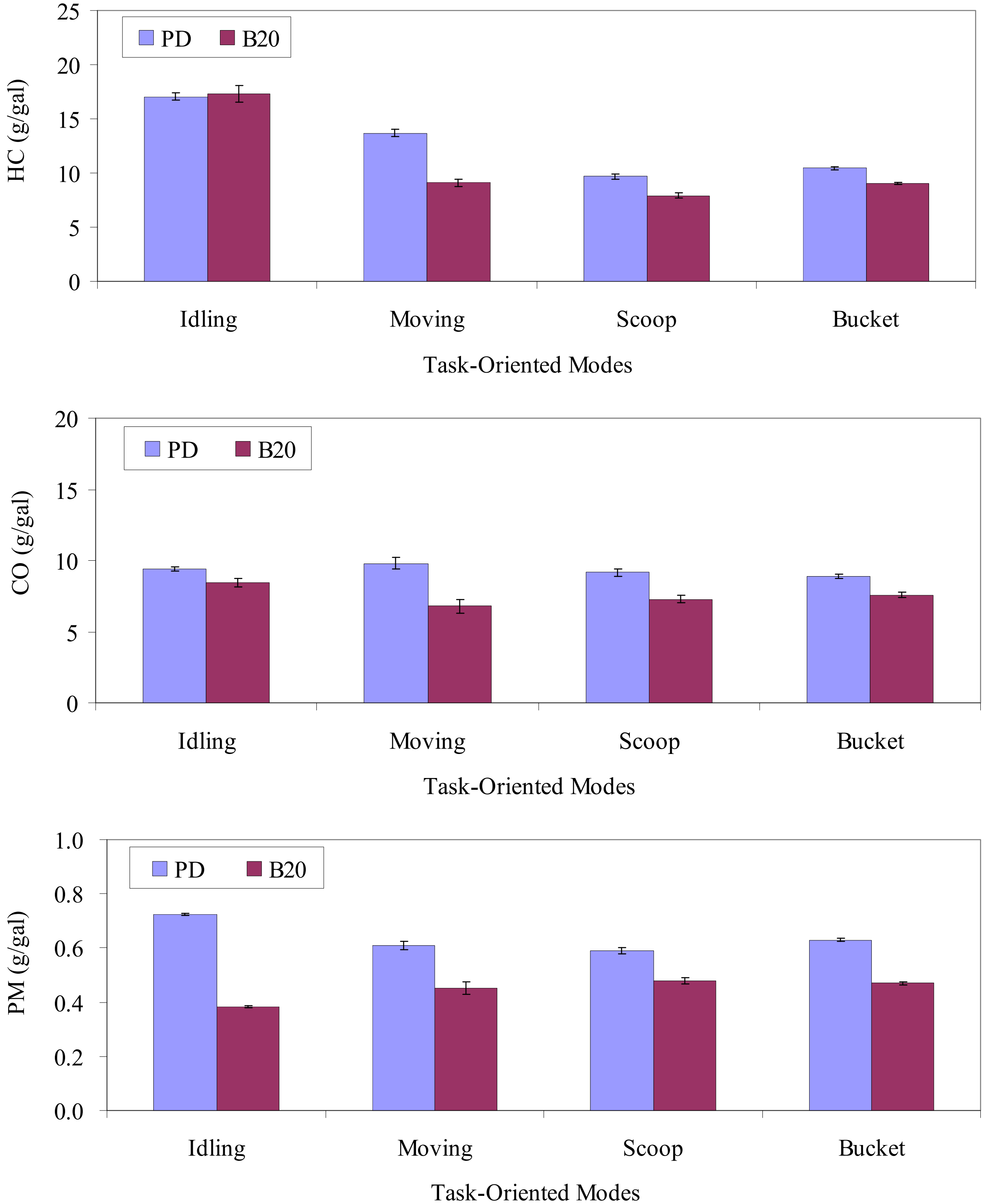
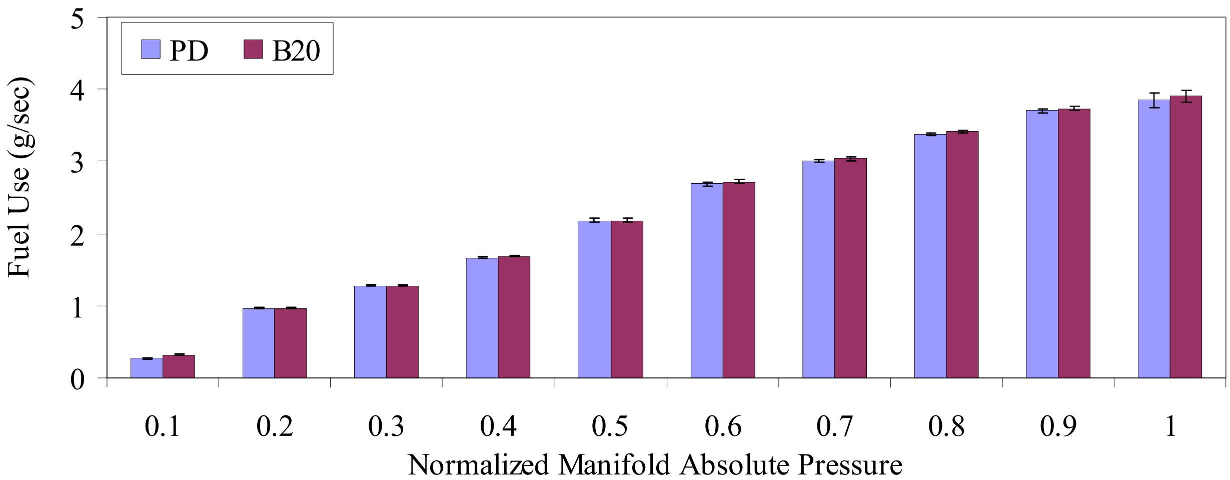
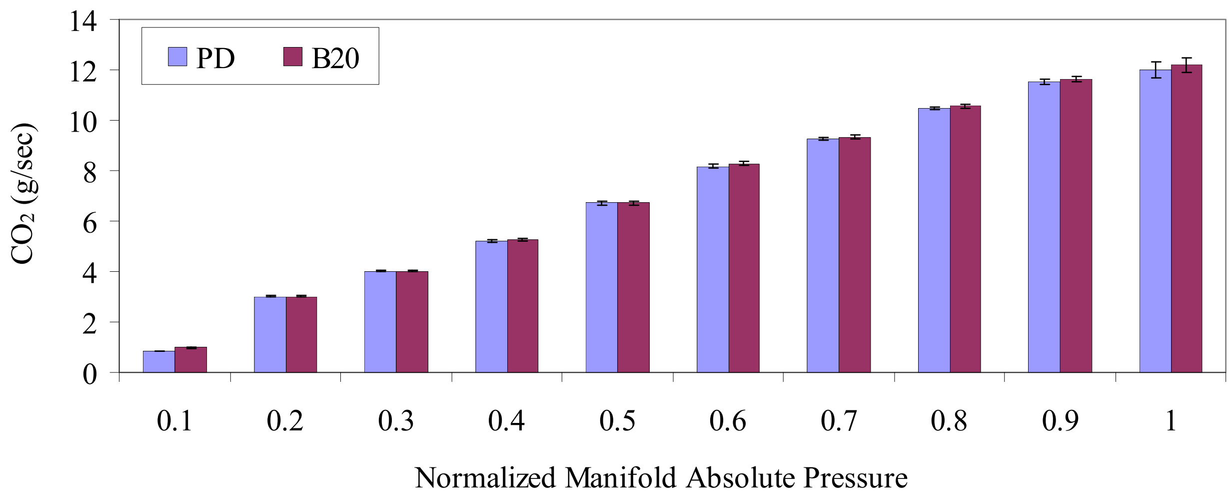


Figure A80. Continued

BACKHOE 5

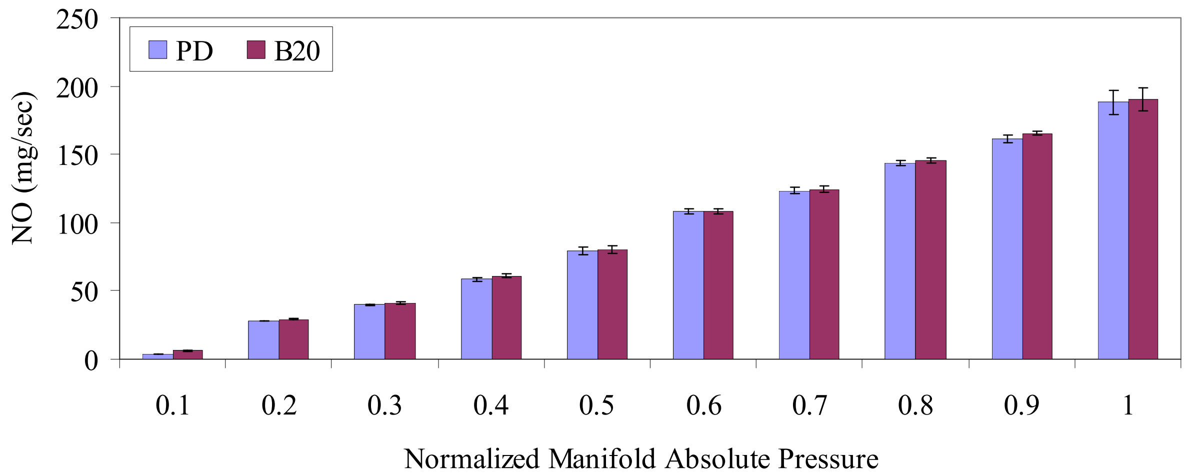


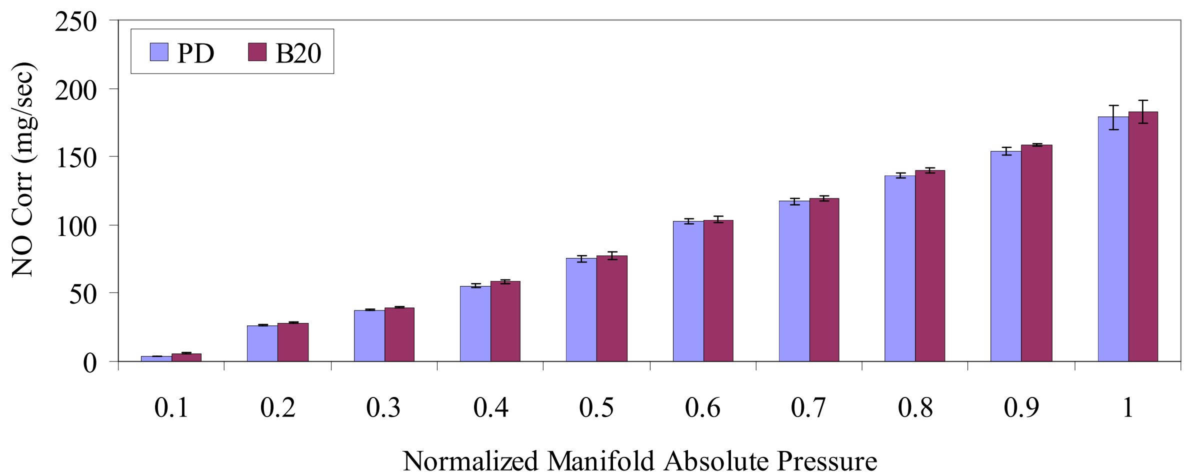


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 60 ^{o}F and the relative humidity was 26 %. For the B20 biodiesel test, the ambient temperature was 58 ^{o}F and the relative humidity was 80 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A81. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Backhoe 5 (continued on next page)





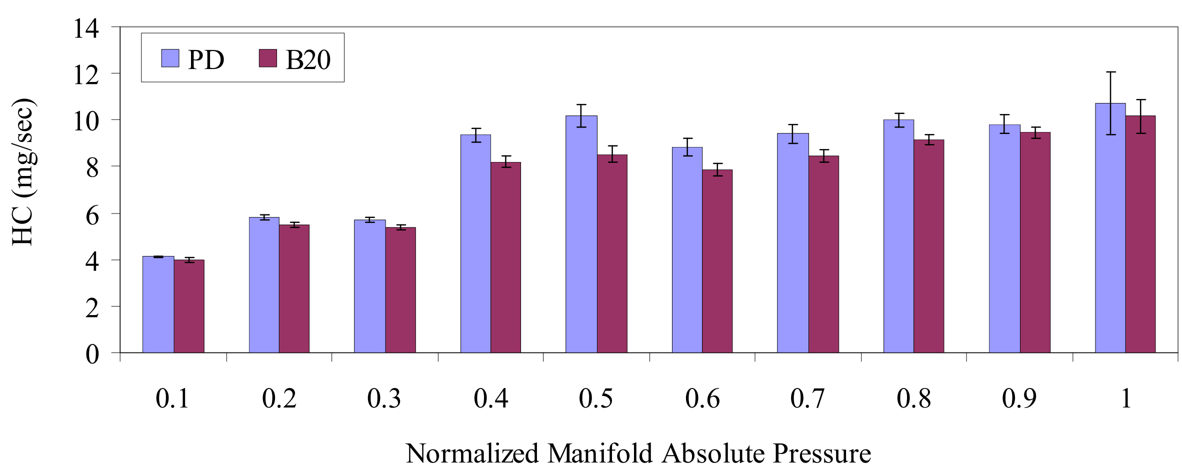
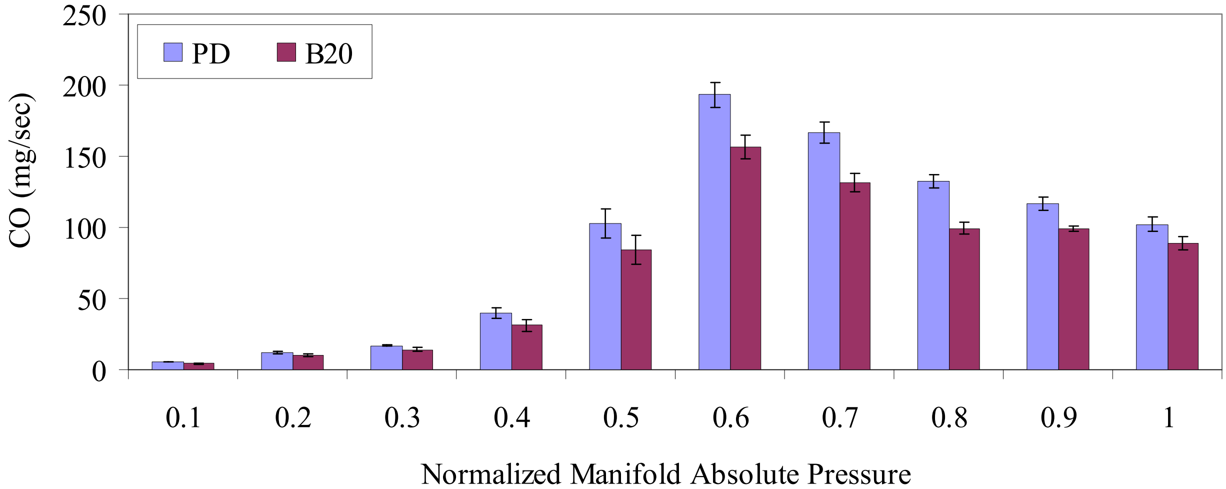


Figure A81. Continued



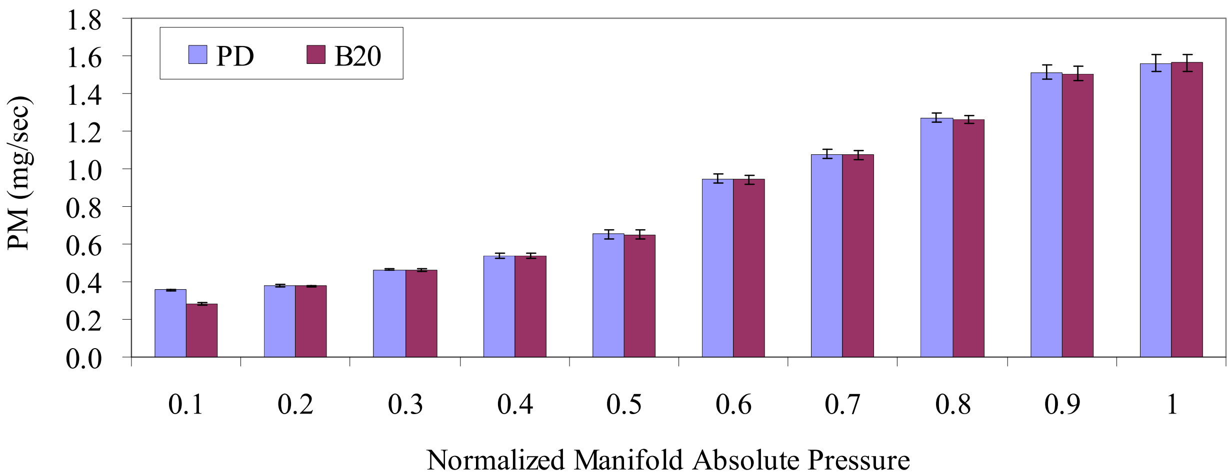
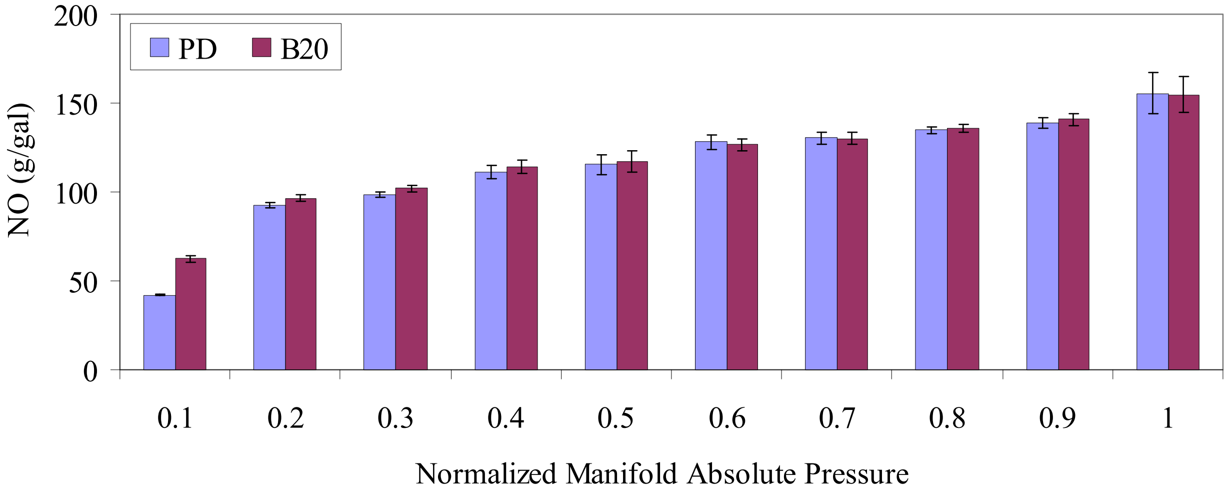
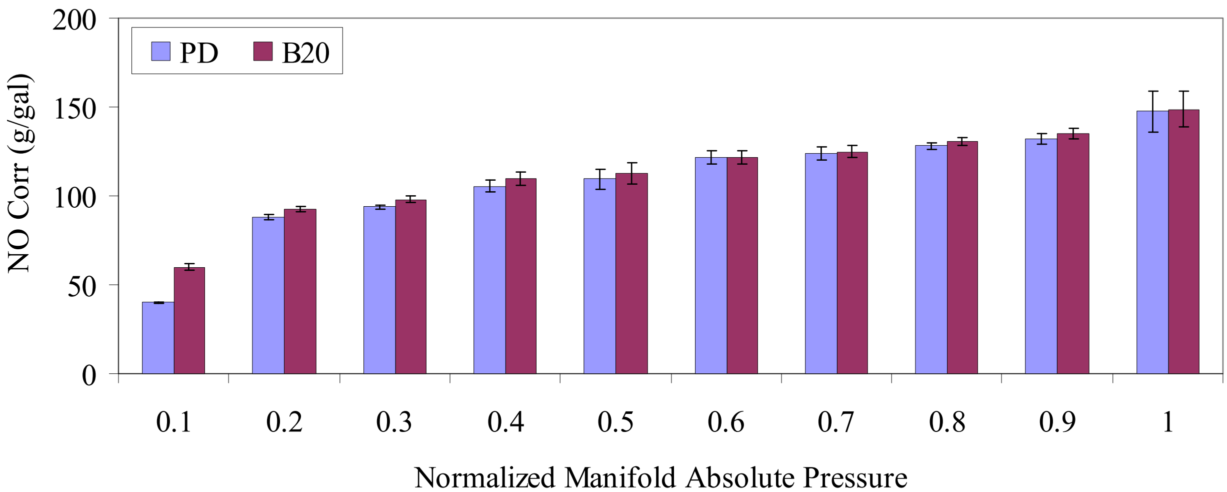


Figure A81. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 60 ^{o}F and the relative humidity was 26 %. For the B20 biodiesel test, the ambient temperature was 58 ^{o}F and the relative humidity was 80 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A82. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Backhoe 5 (continued on next page)

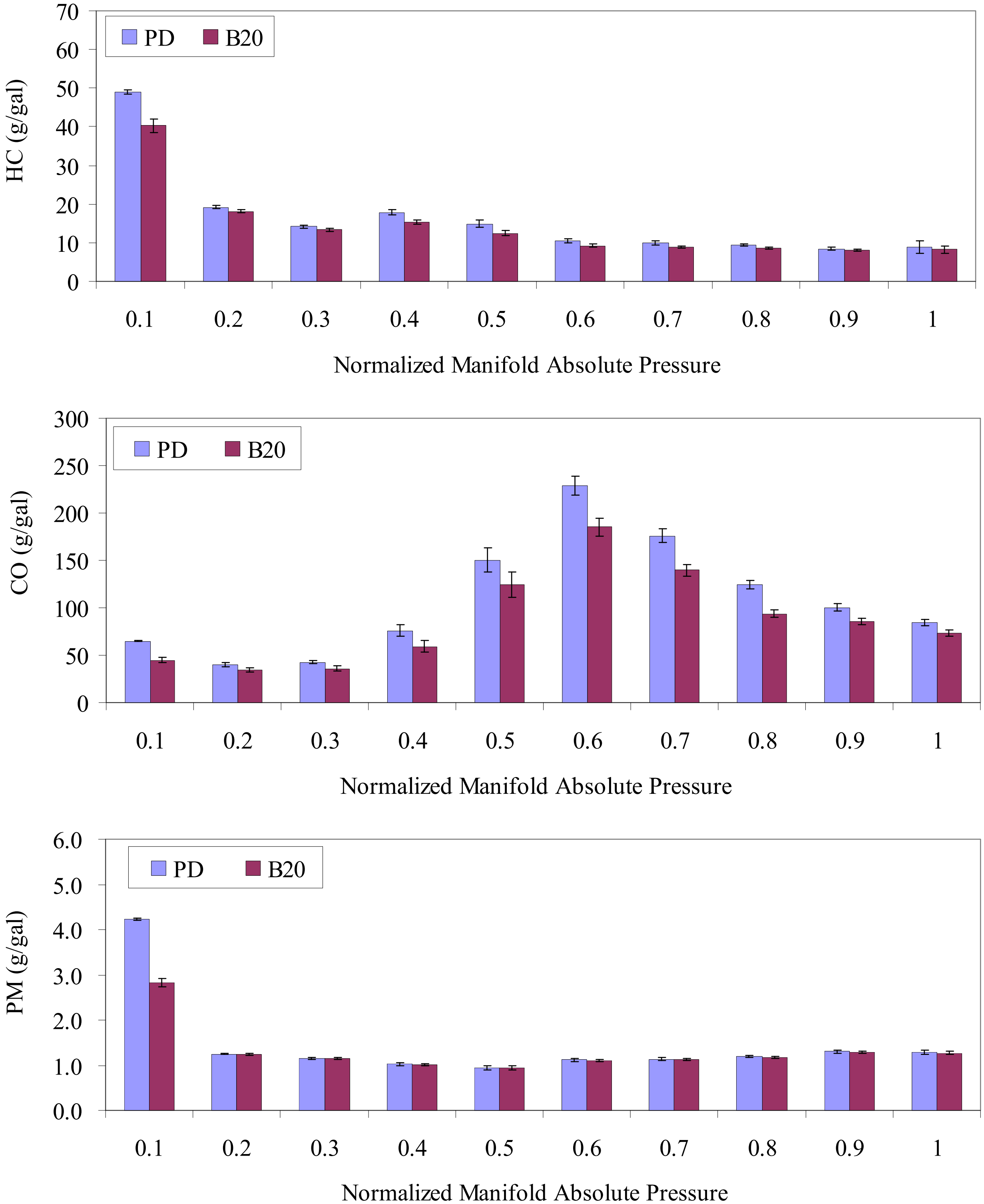
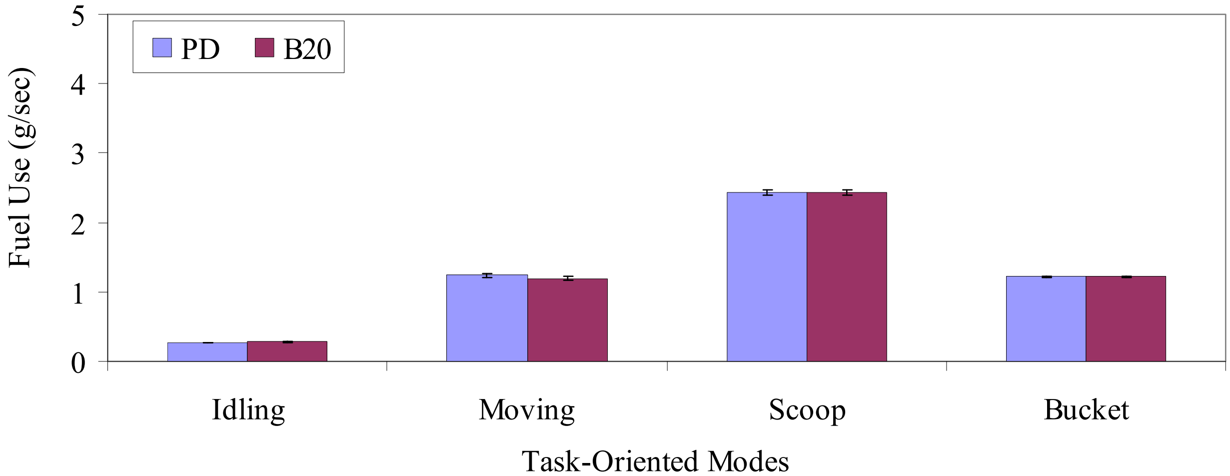
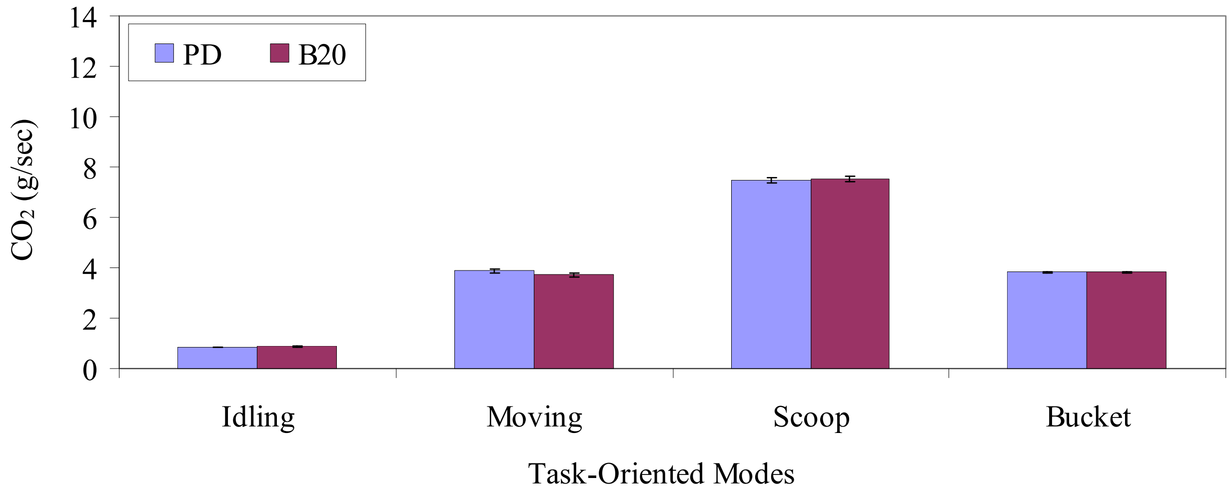


Figure A82. Continued

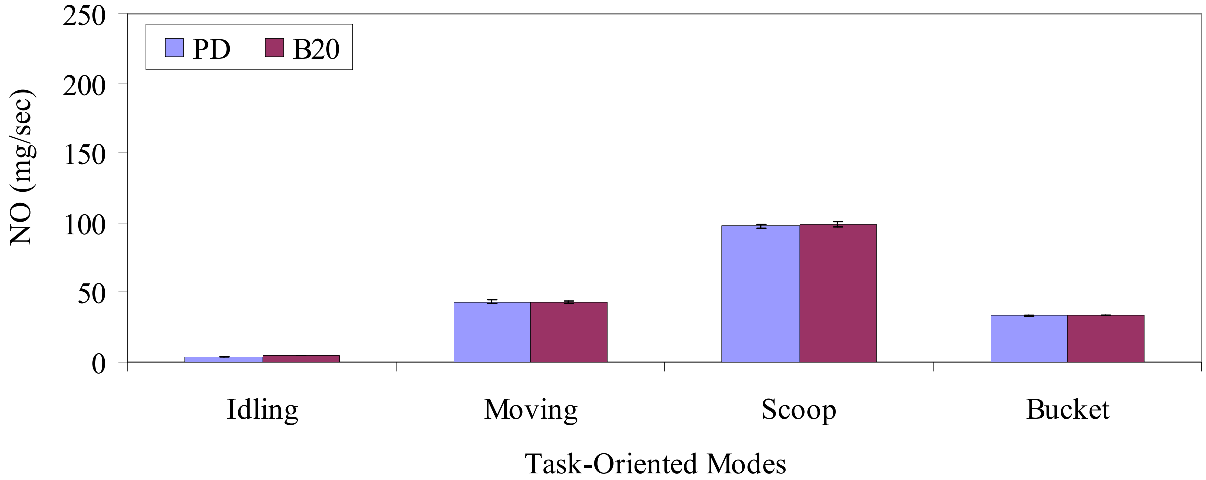


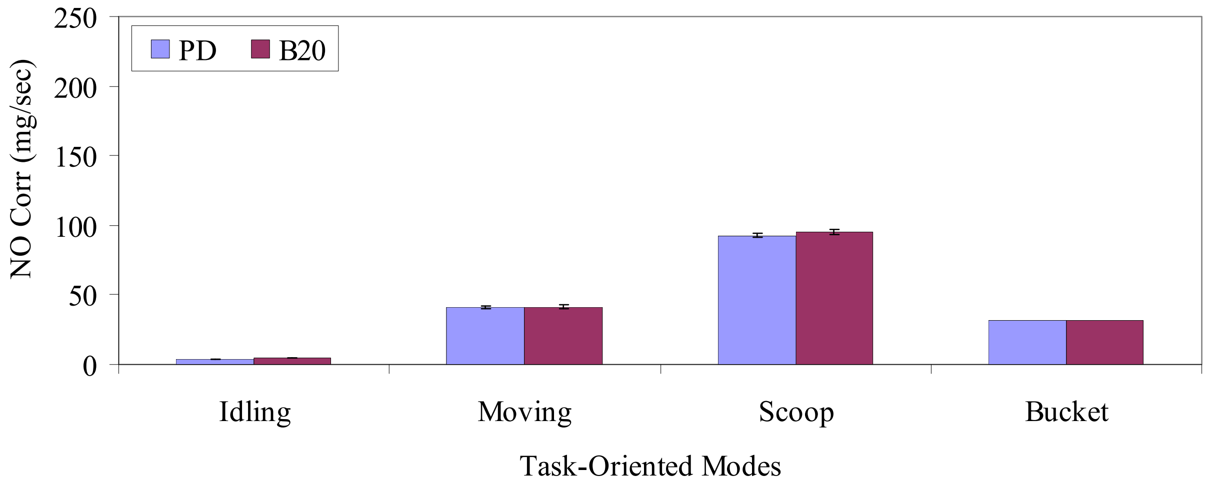


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 60 ^{o}F and the relative humidity was 26 %. For the B20 biodiesel test, the ambient temperature was 58 ^{o}F and the relative humidity was 80 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A83. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 5 (continued on next page)





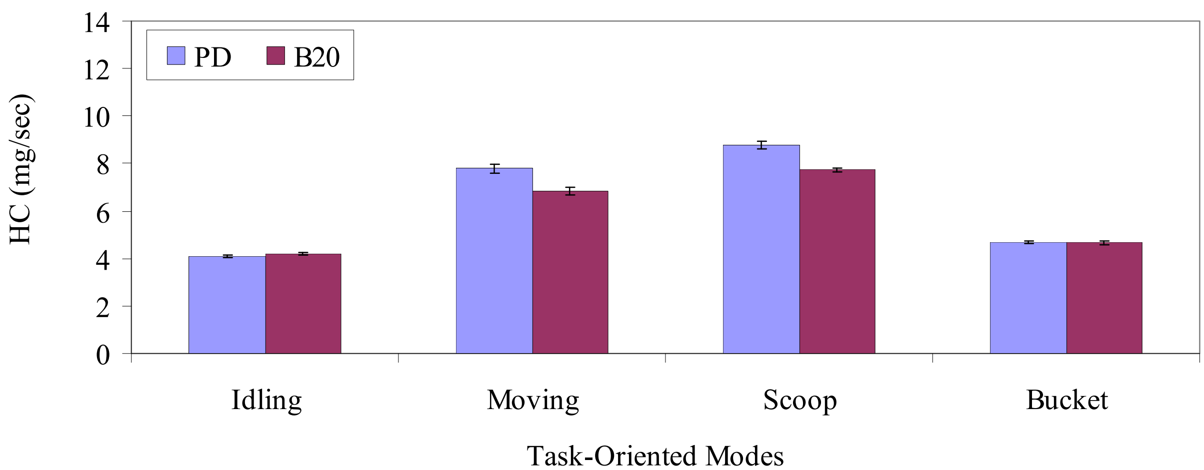


Figure A83. Continued

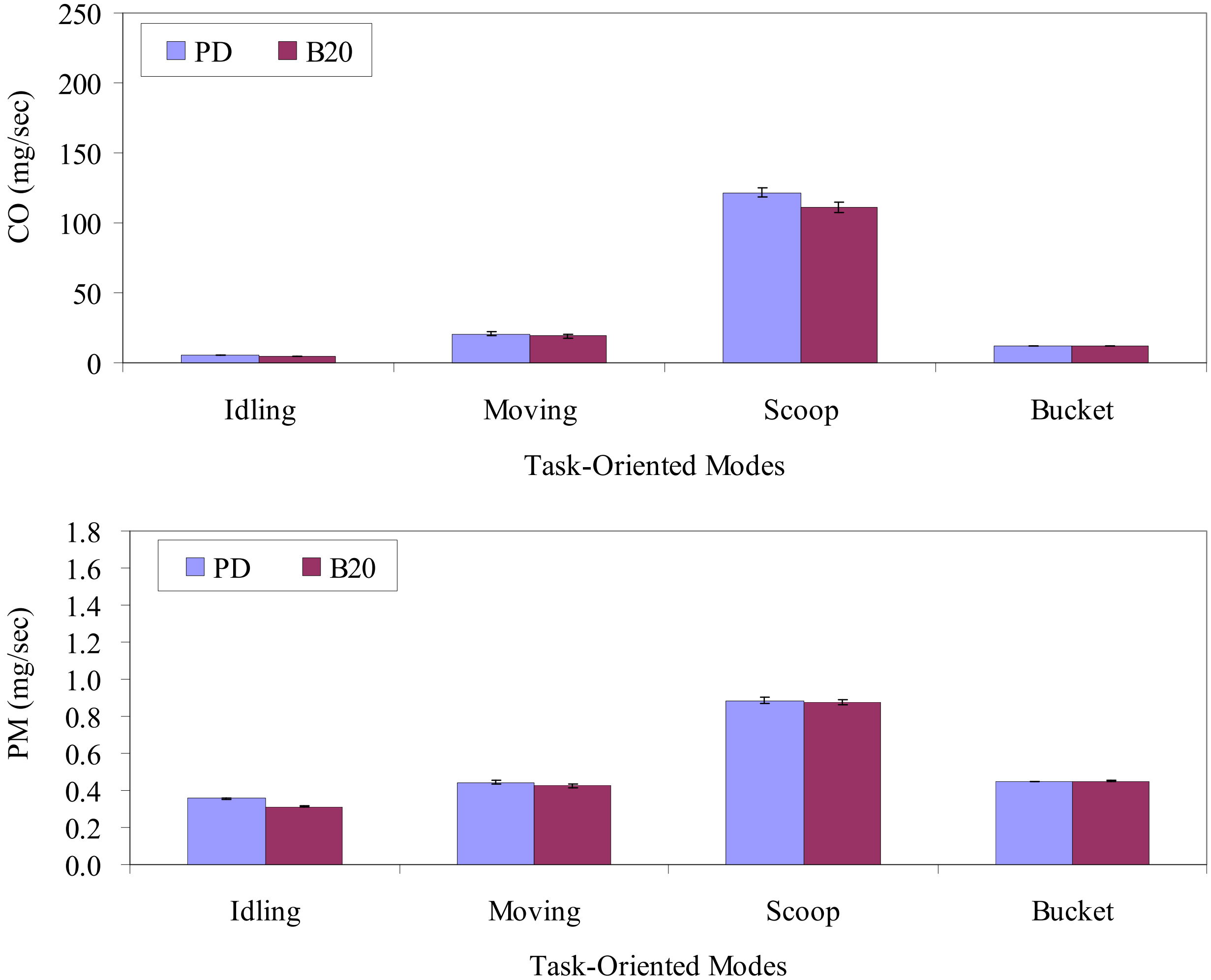
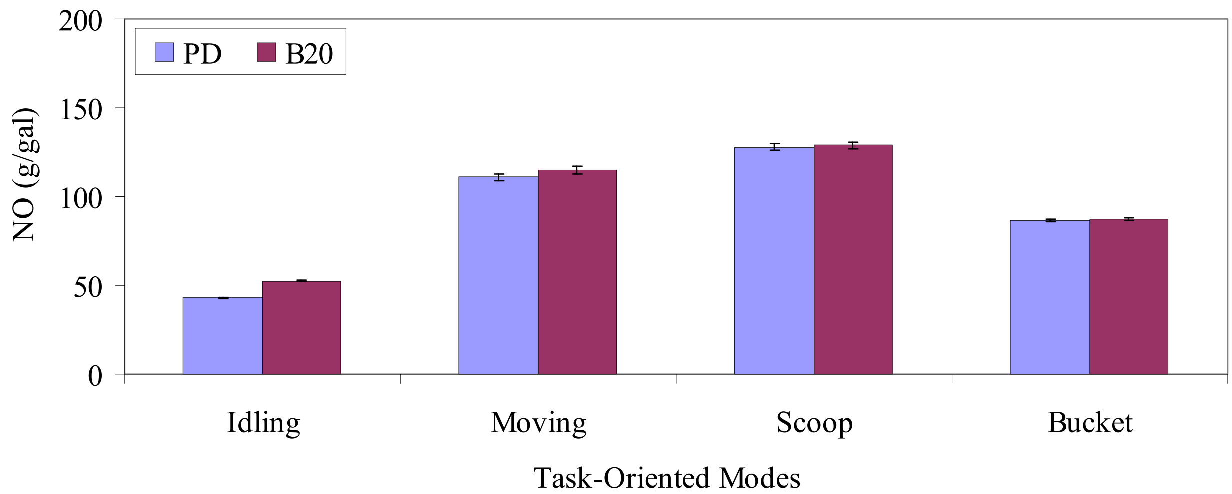
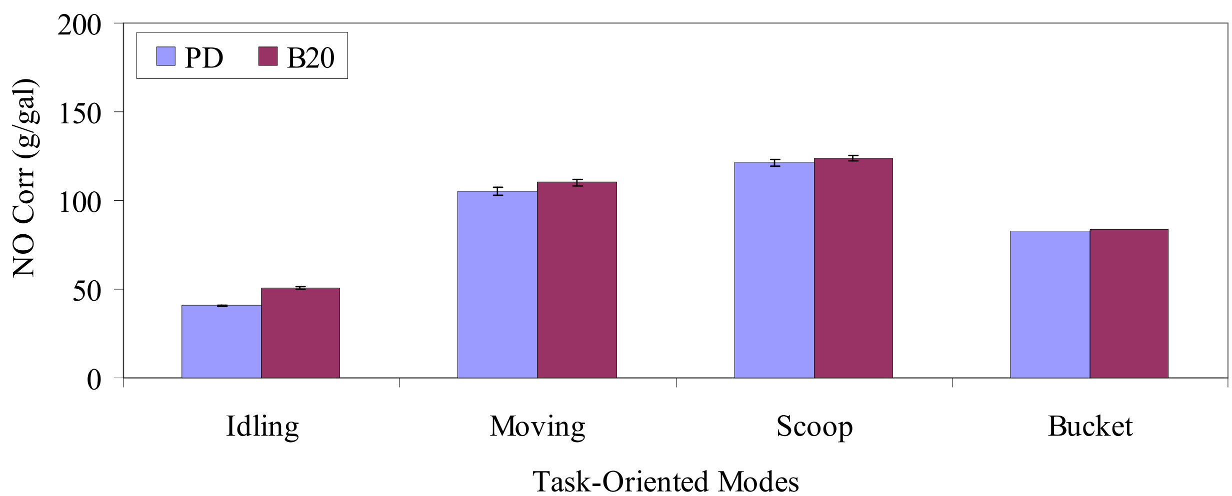


Figure A83. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 60 ^{o}F and the relative humidity was 26 %. For the B20 biodiesel test, the ambient temperature was 58 ^{o}F and the relative humidity was 80 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A84. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 5 (continued on next page)

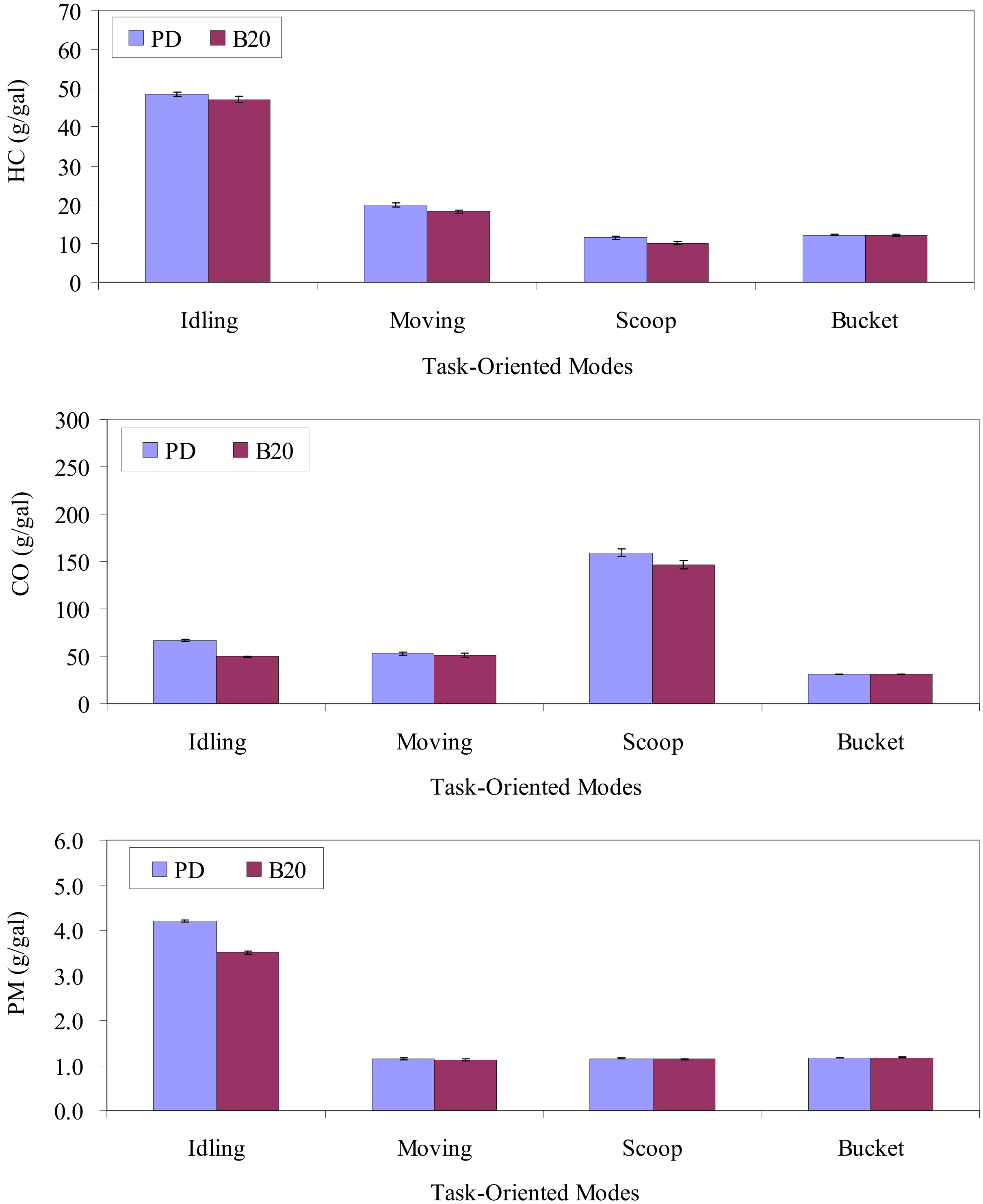
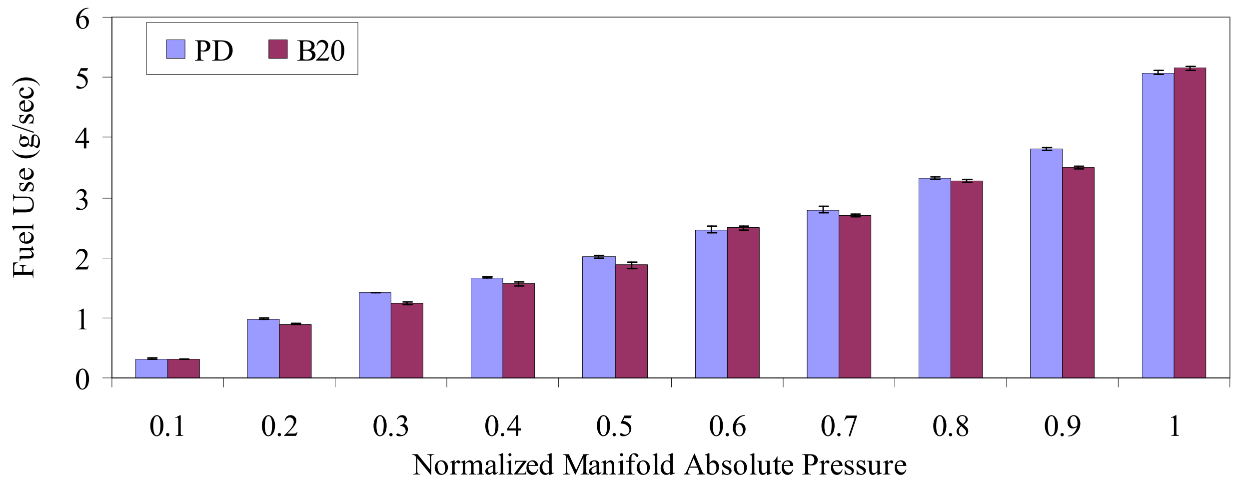
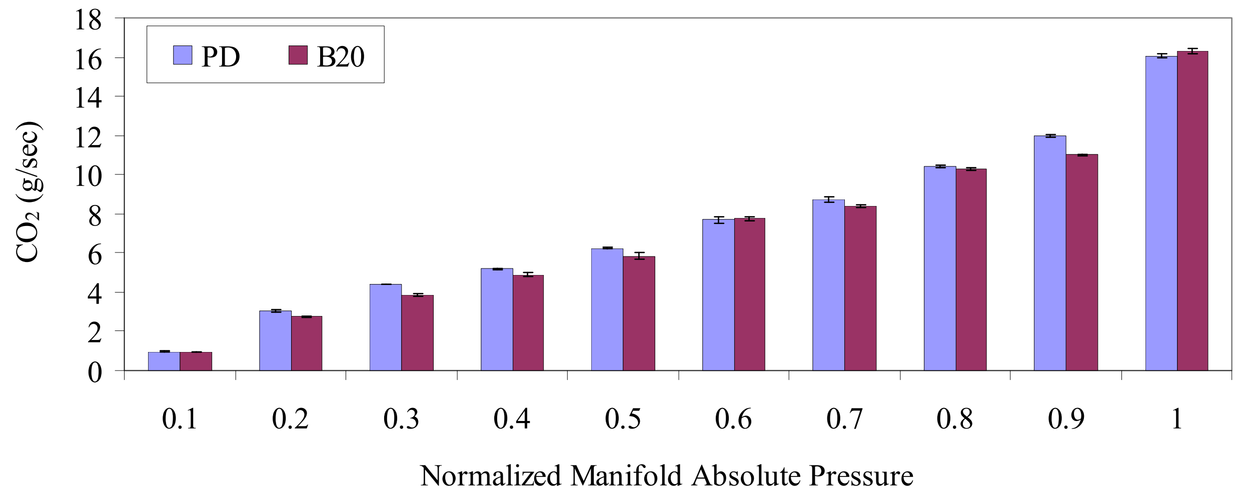


Figure A84. Continued

BACKHOE 6

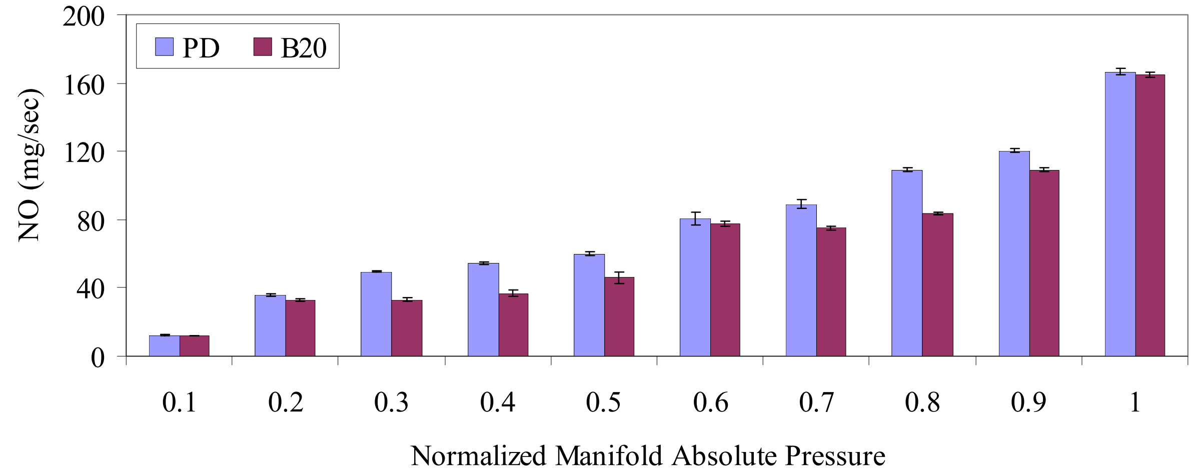


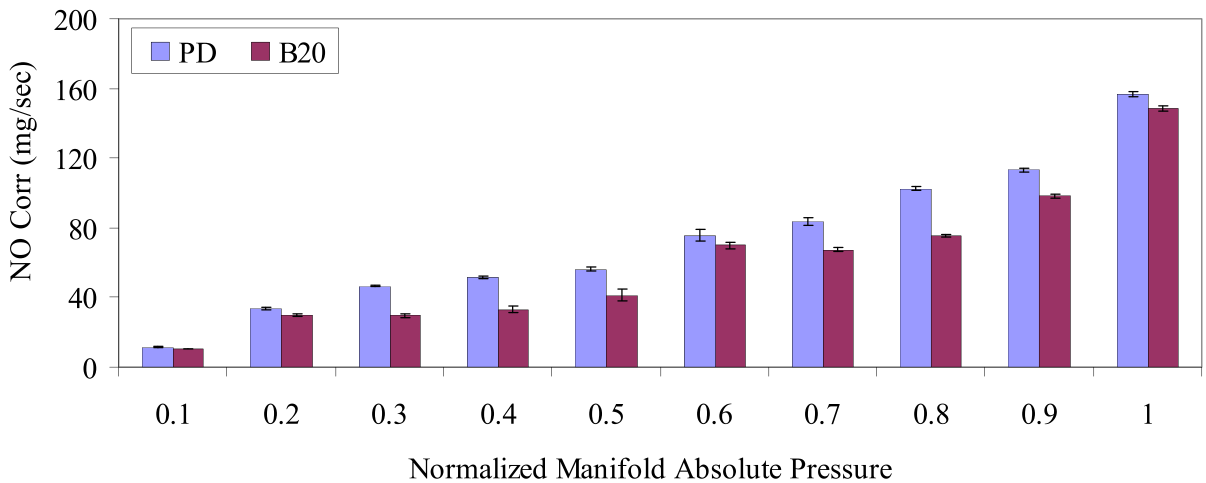


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 67 ^{o}F and the relative humidity was 50 %. For the B20 biodiesel test, the ambient temperature was 63 ^{o}F and the relative humidity was 36 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A85. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Backhoe 6 (continued on next page)





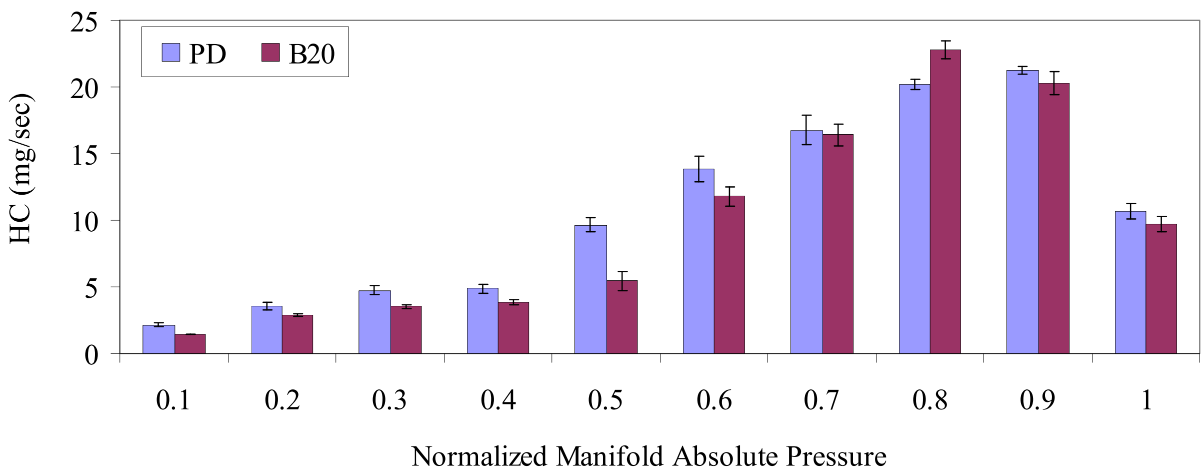
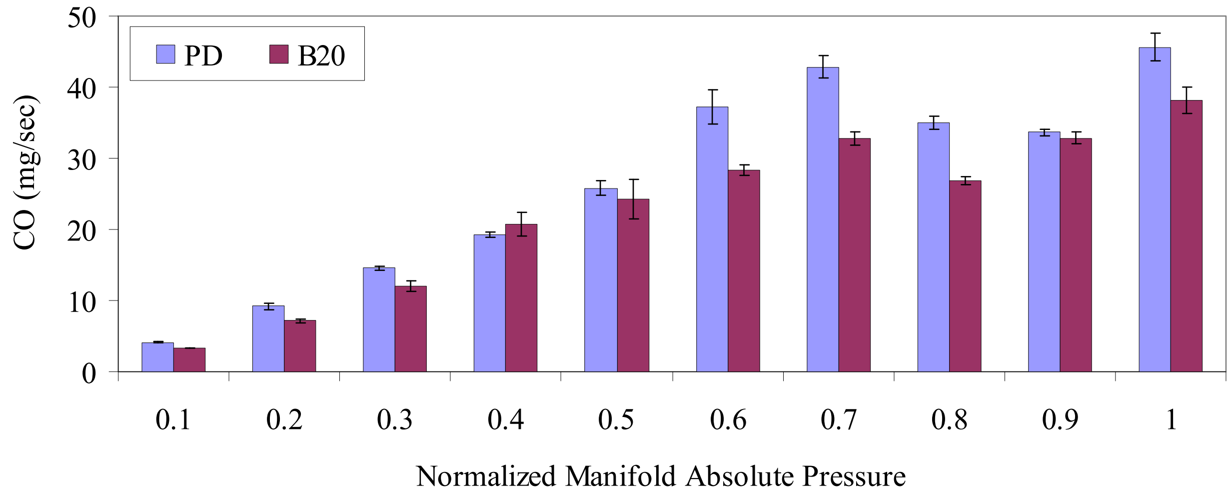


Figure A85. Continued



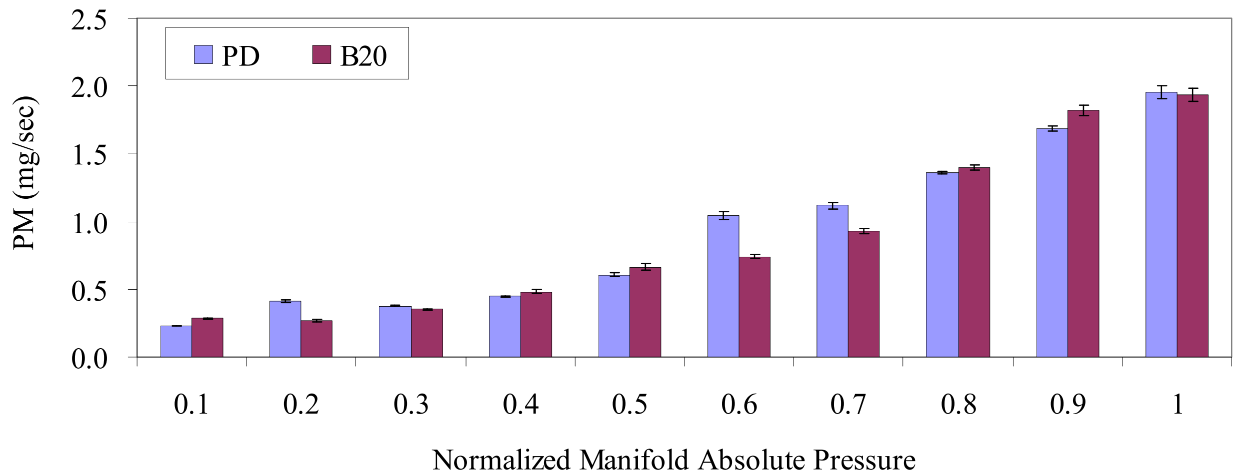
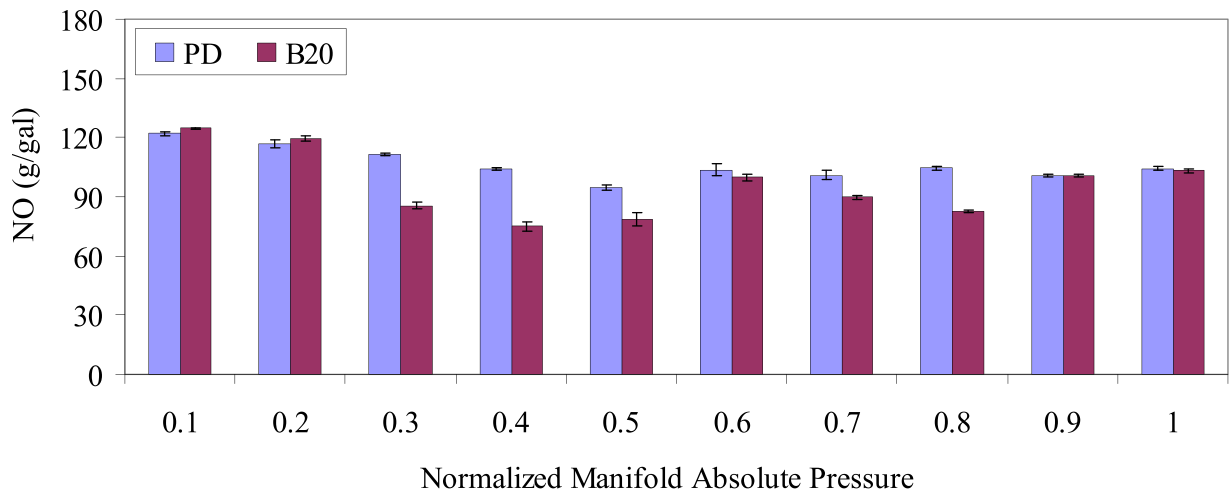
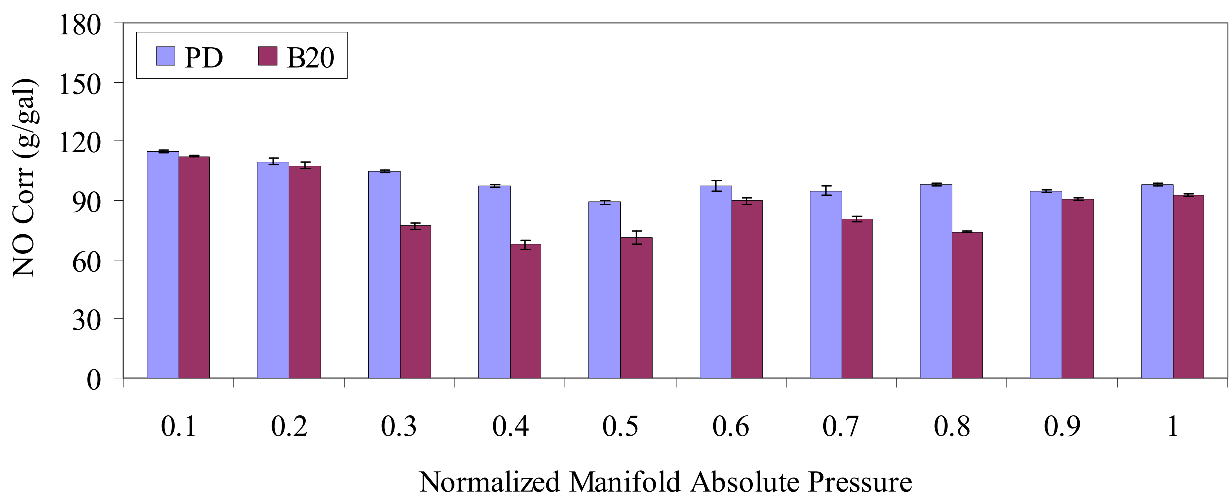


Figure A85. Continued

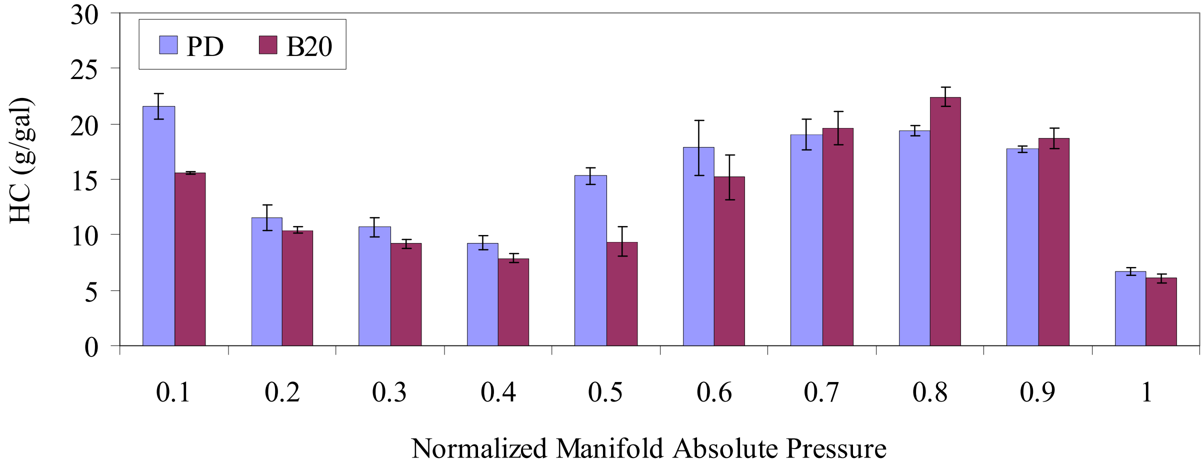


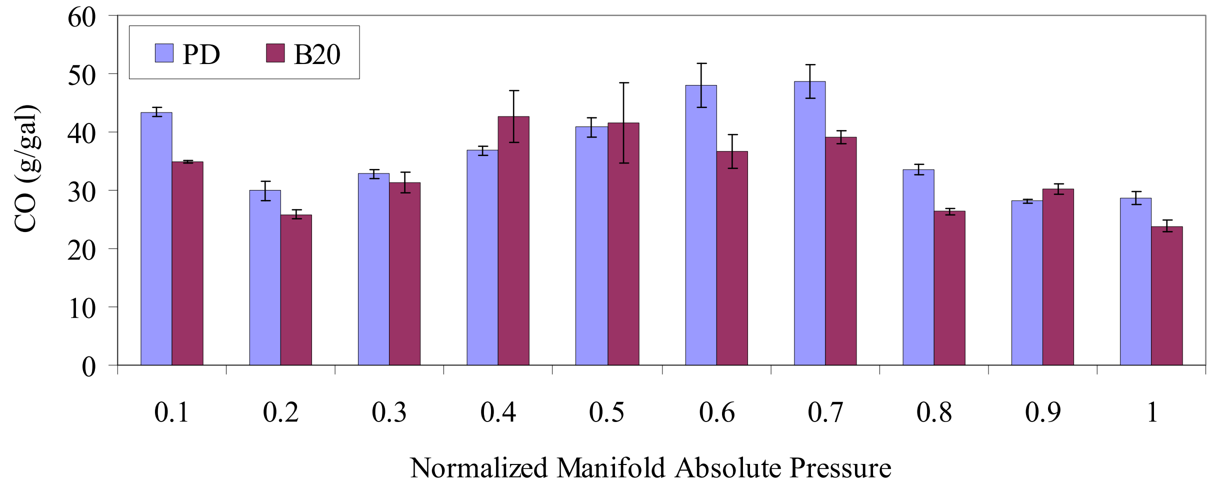


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 67 ^{o}F and the relative humidity was 50 %. For the B20 biodiesel test, the ambient temperature was 63 ^{o}F and the relative humidity was 36 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A86. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Backhoe 6 (continued on next page)





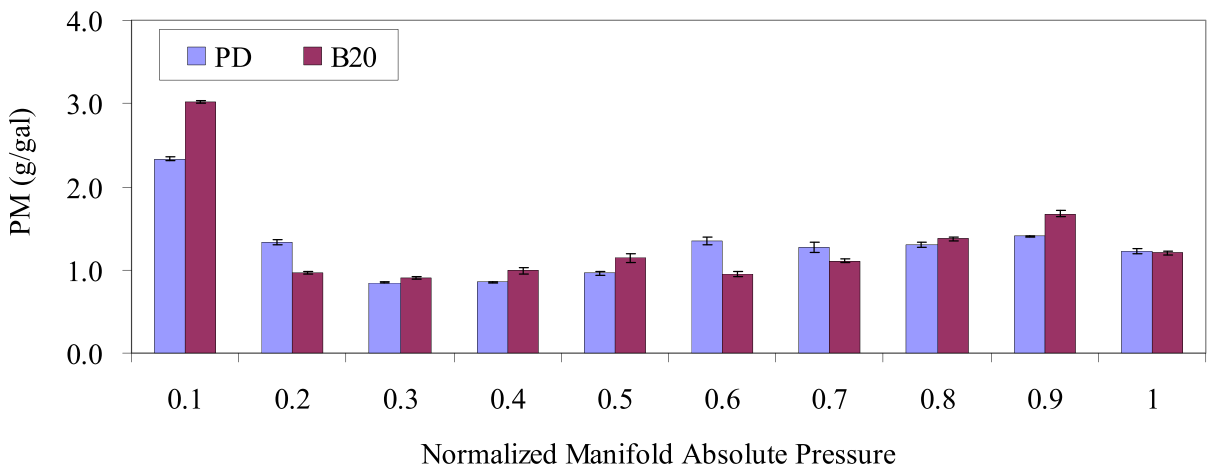
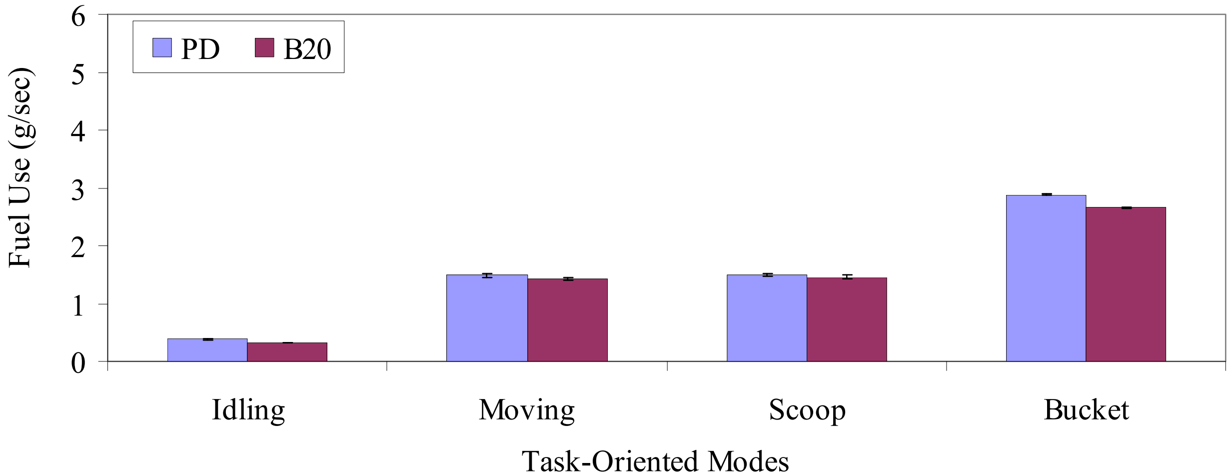
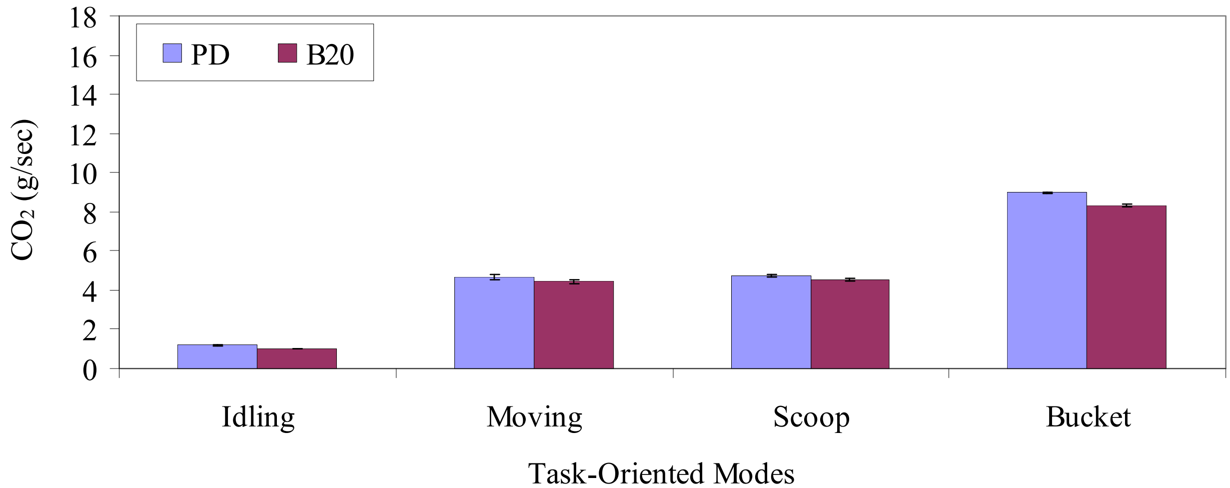


Figure A86. Continued

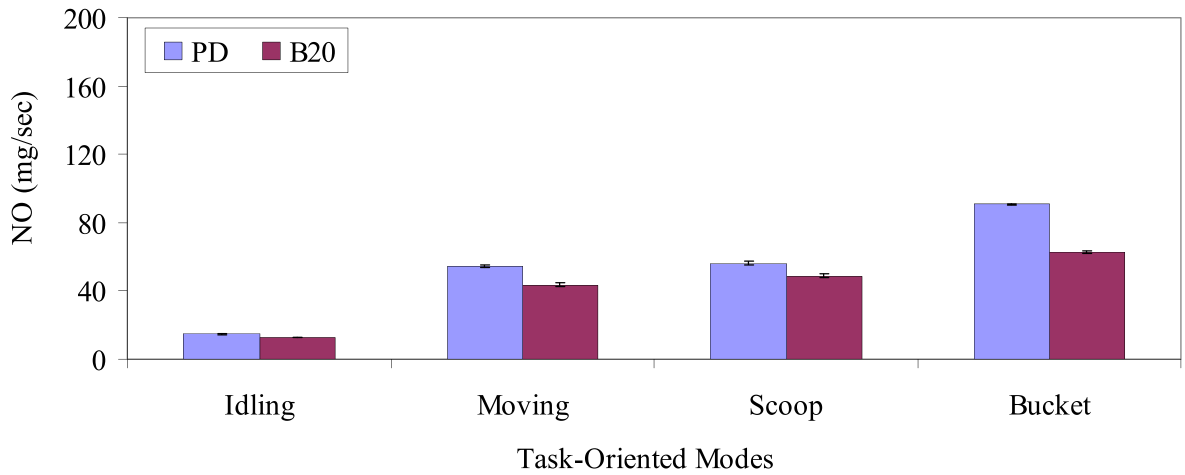


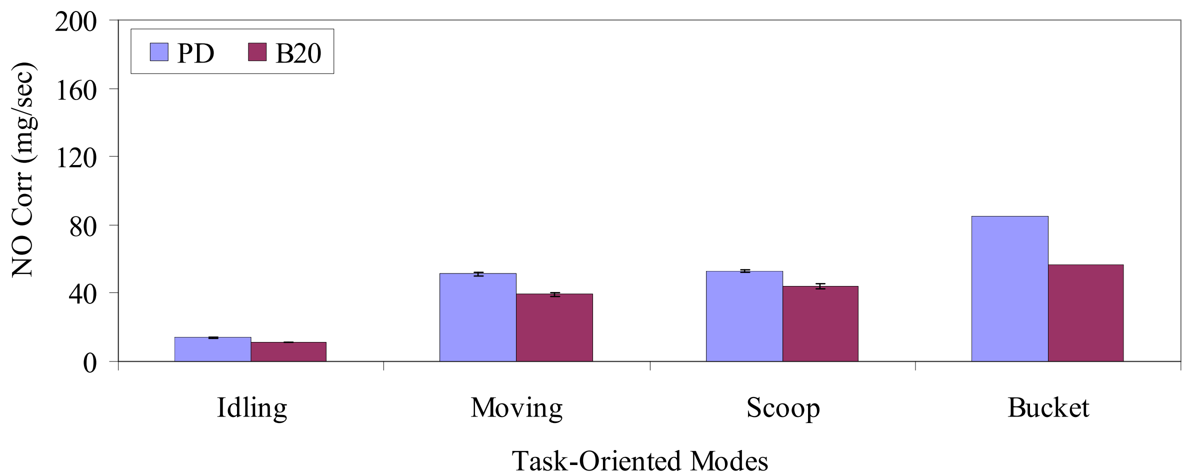


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 67 ^{o}F and the relative humidity was 50 %. For the B20 biodiesel test, the ambient temperature was 63 ^{o}F and the relative humidity was 36 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A87. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 6 (continued on next page)





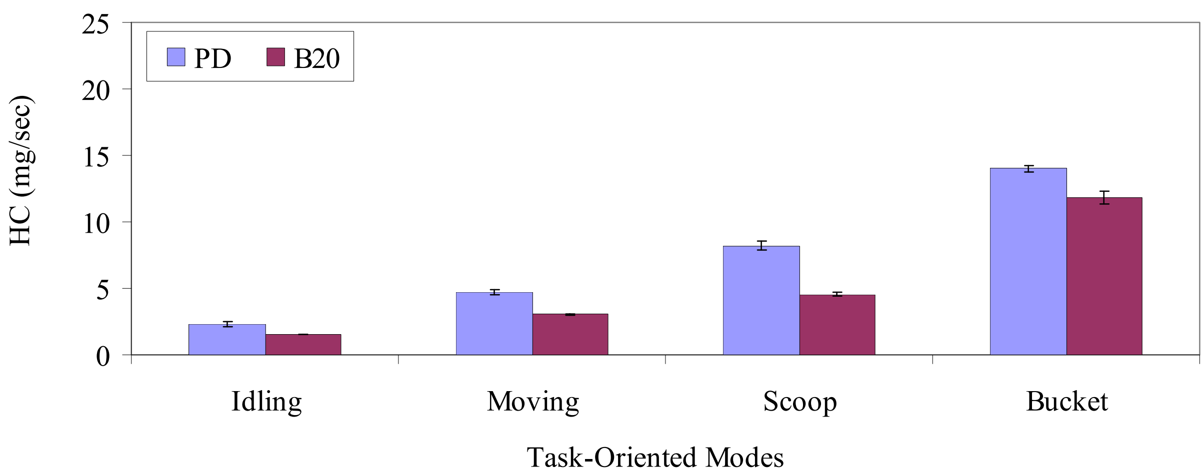


Figure A87. Continued

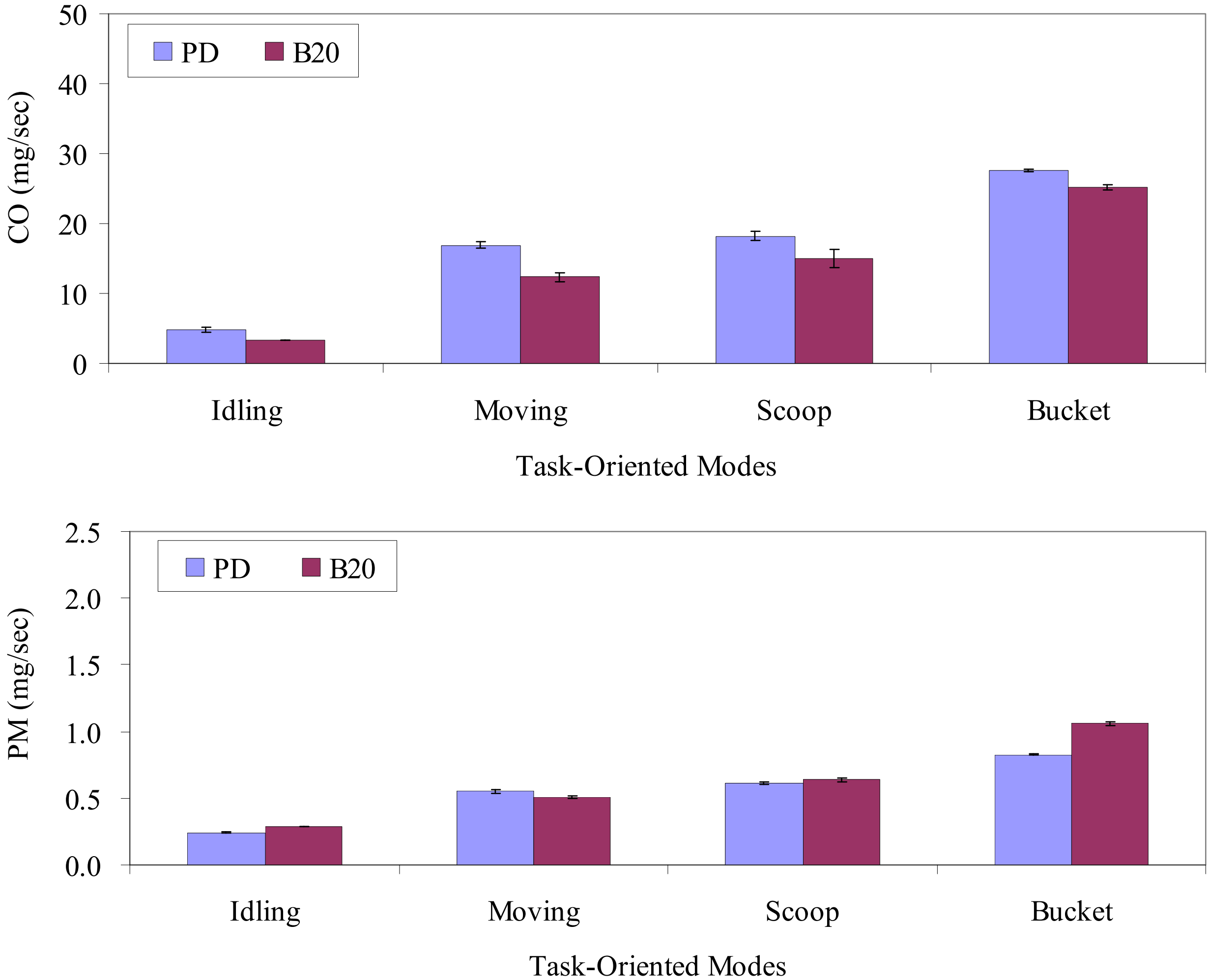
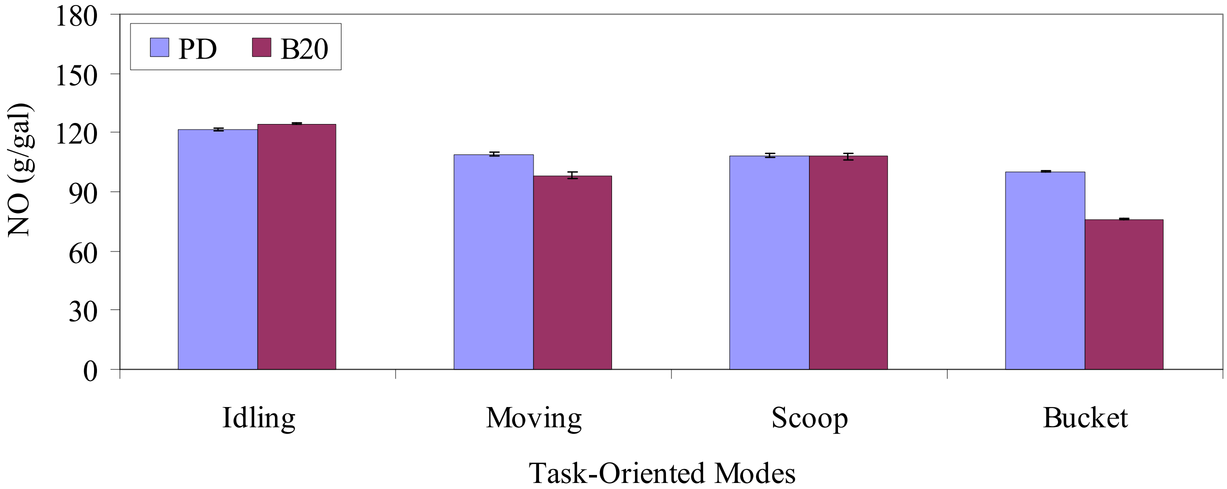
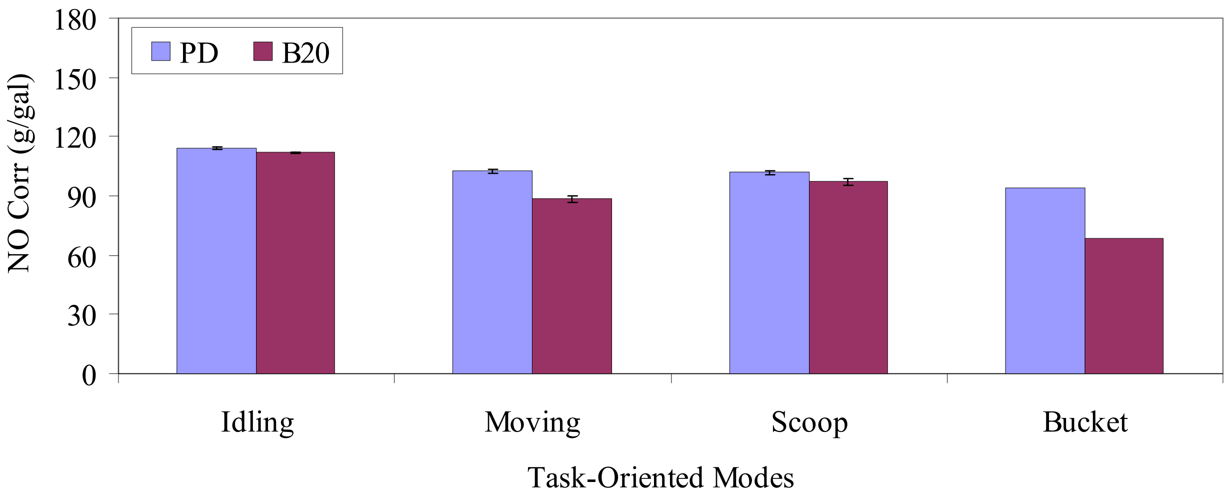


Figure A87. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 67 ^{o}F and the relative humidity was 50 %. For the B20 biodiesel tests, the ambient temperature was 63 ^{o}F and the relative humidity was 36 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A88. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 6 (continued on next page)

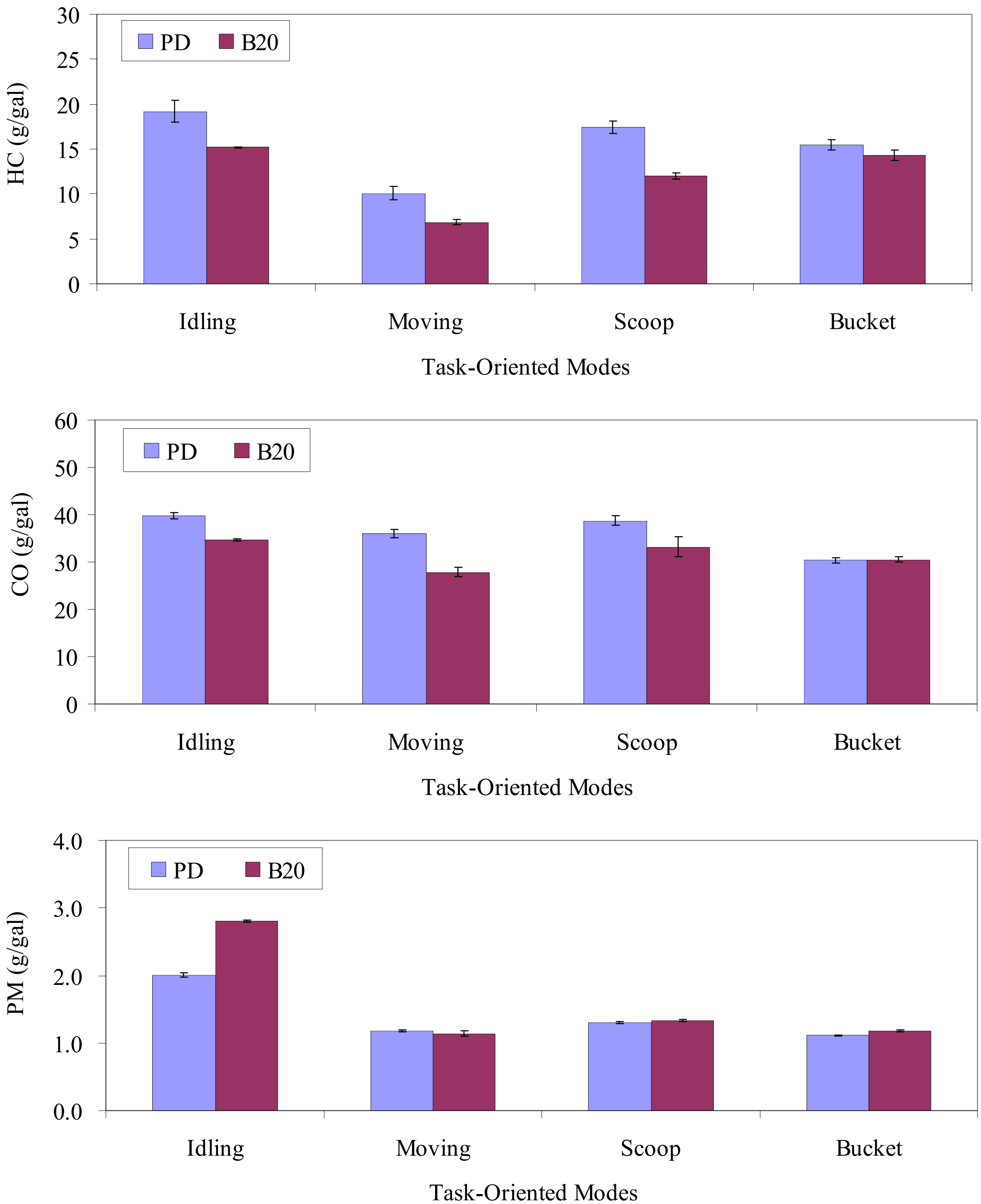
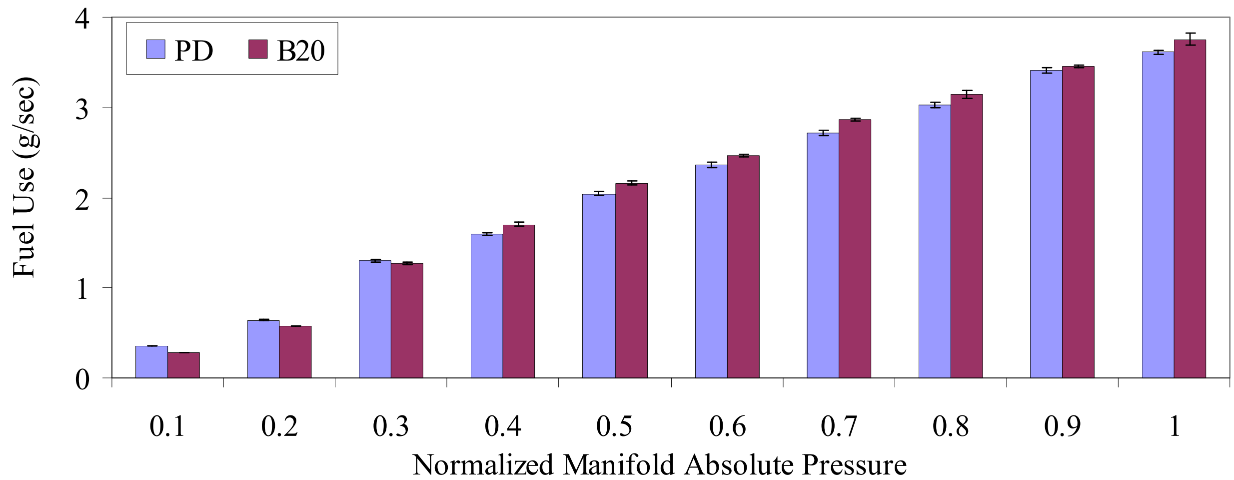
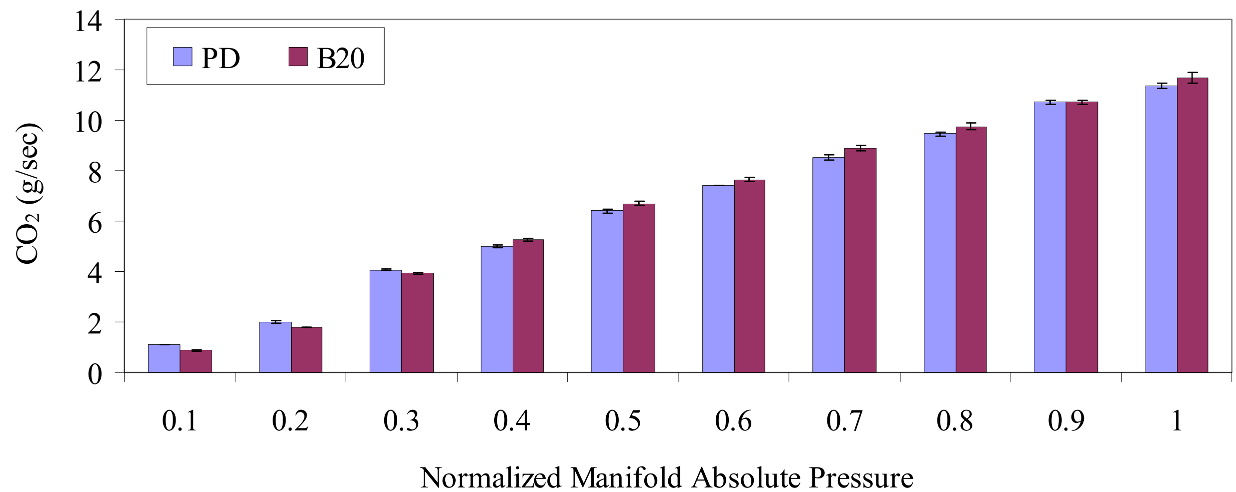


Figure A88. Continued

BACKHOE 7

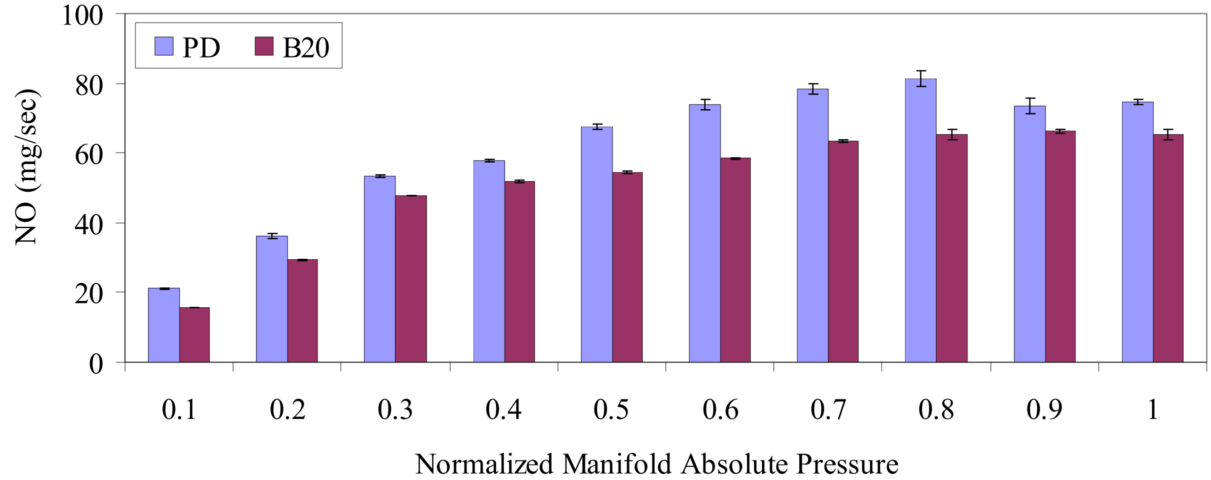


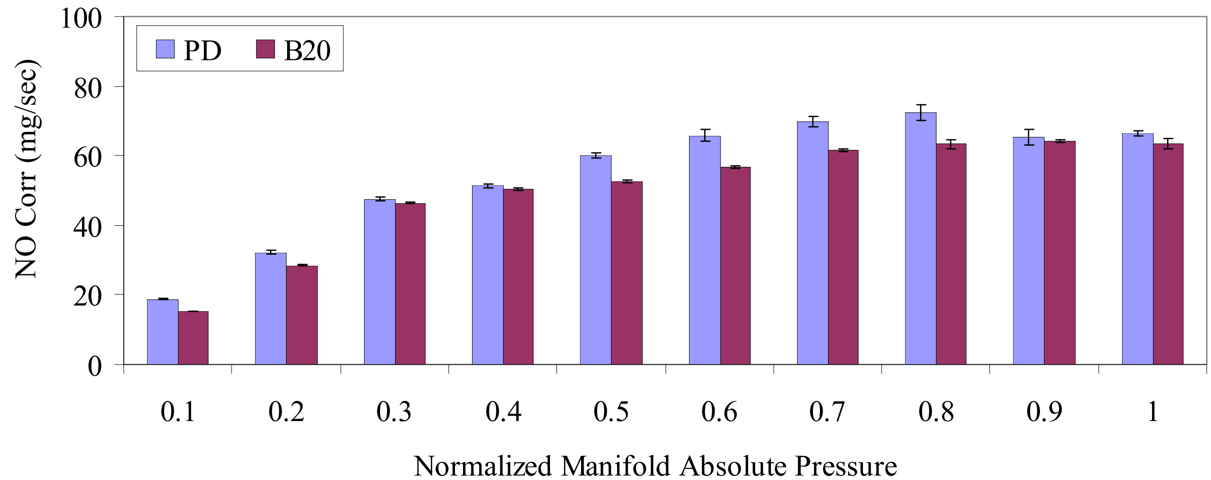


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 54 ^{o}F and the relative humidity was 42 %. For the B20 biodiesel test, the ambient temperature was 83 ^{o}F and the relative humidity was 38 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 $\leq$ Normalized MAP < 0.1; "0.2" = 0.1 $\leq$ Normalized MAP < 0.2, and so on.

Figure A89. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Backhoe 7 (continued on next page)





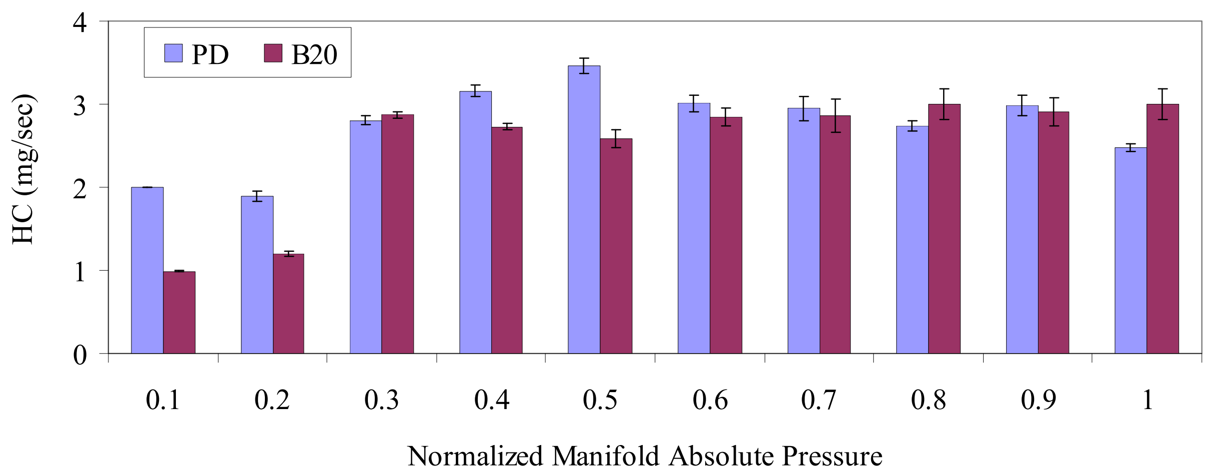
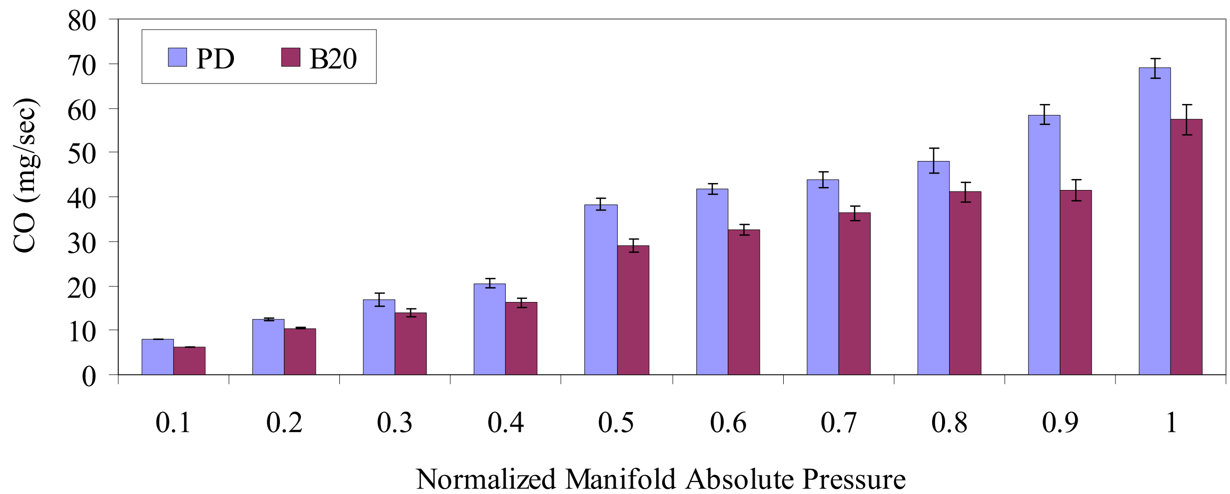


Figure A89. Continued



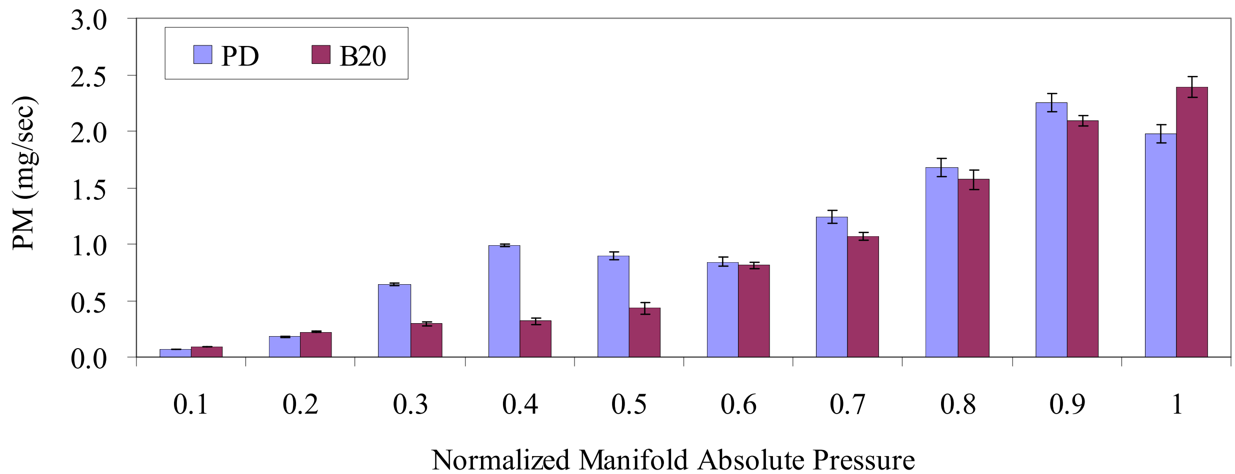
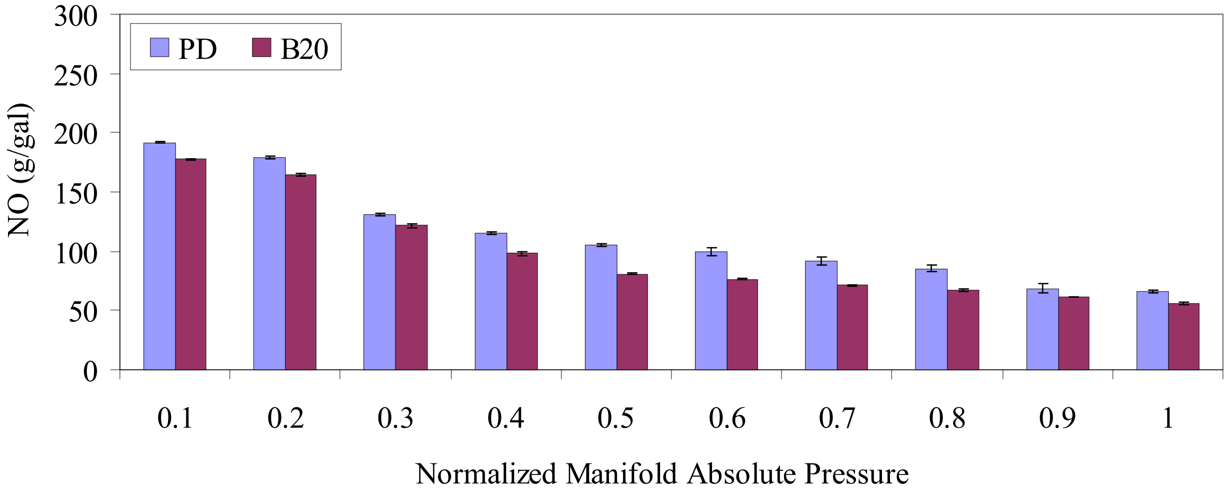
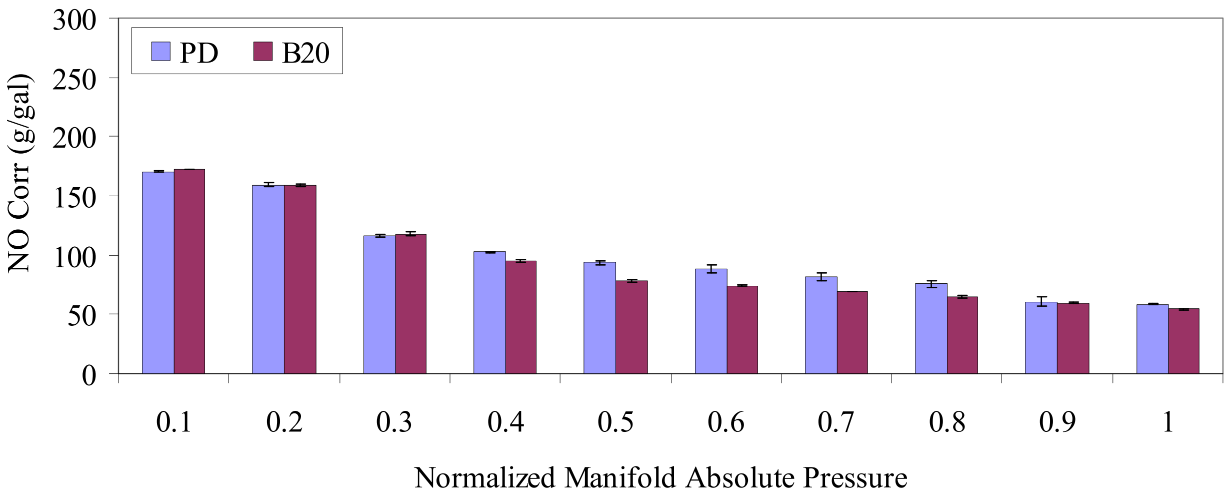


Figure A89. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 54 ^{o}F and the relative humidity was 42 %. For the B20 biodiesel test, the ambient temperature was 83 ^{o}F and the relative humidity was 38 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A90. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Backhoe 7 (continued on next page)

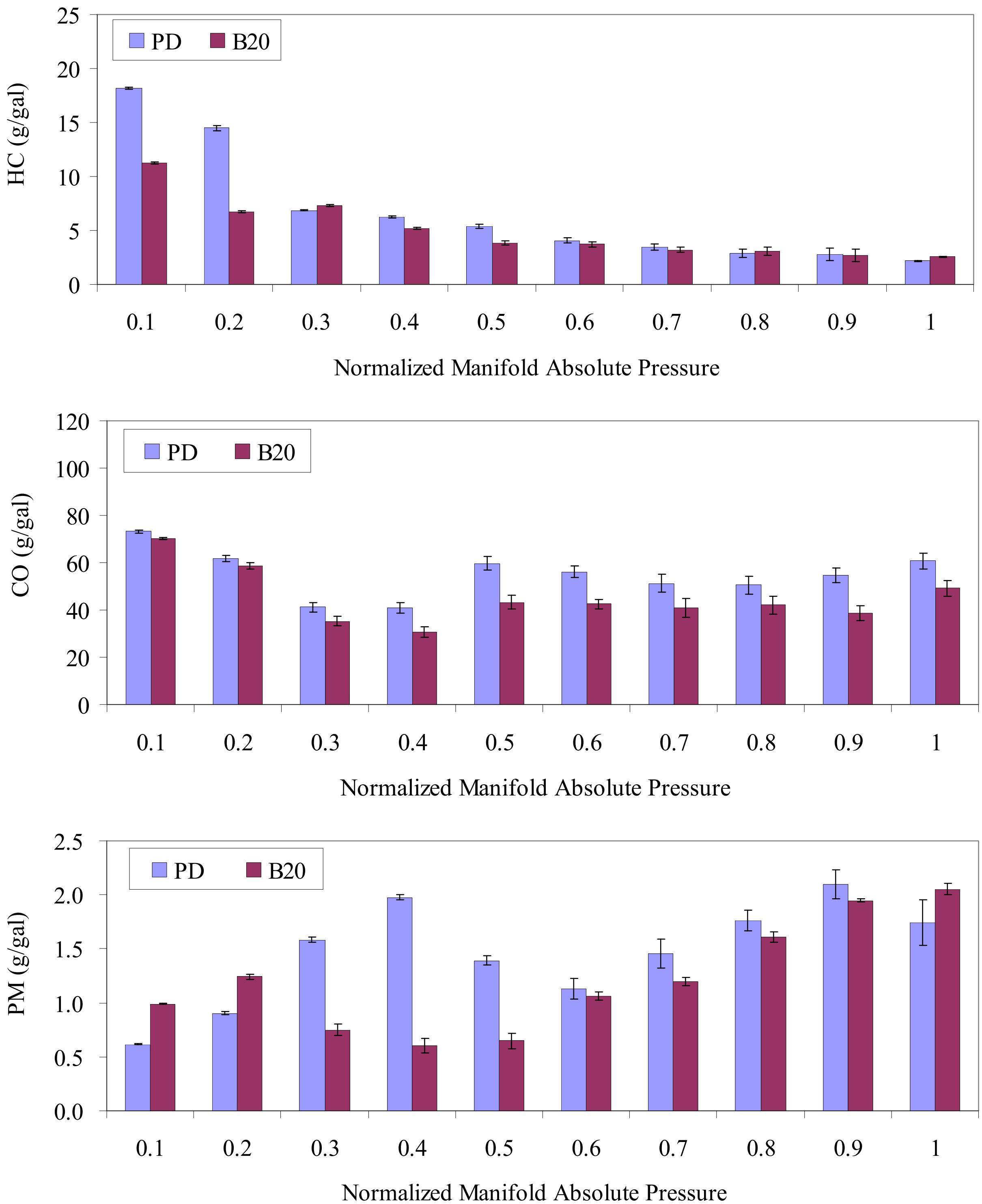
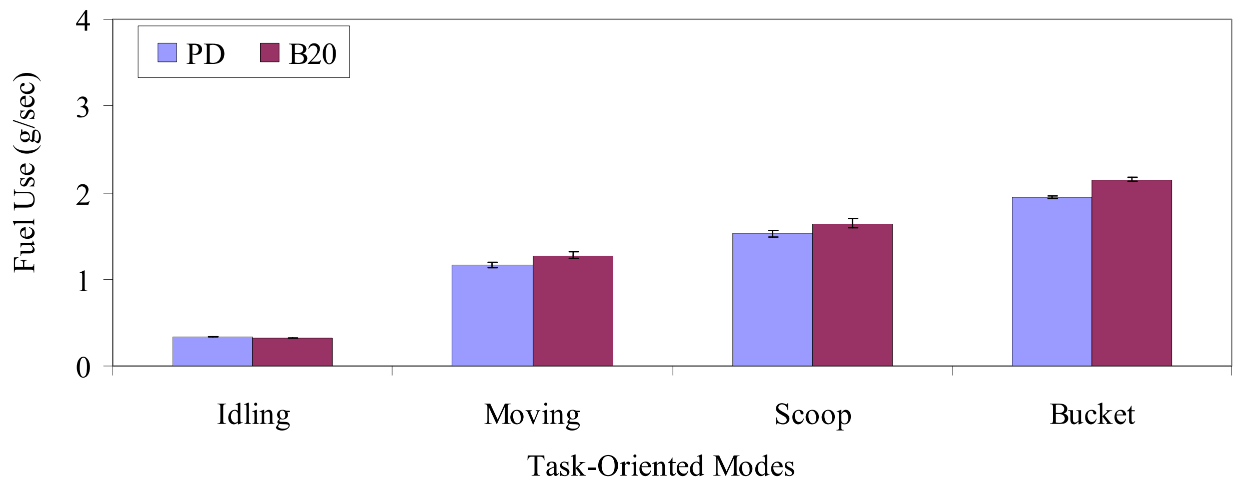
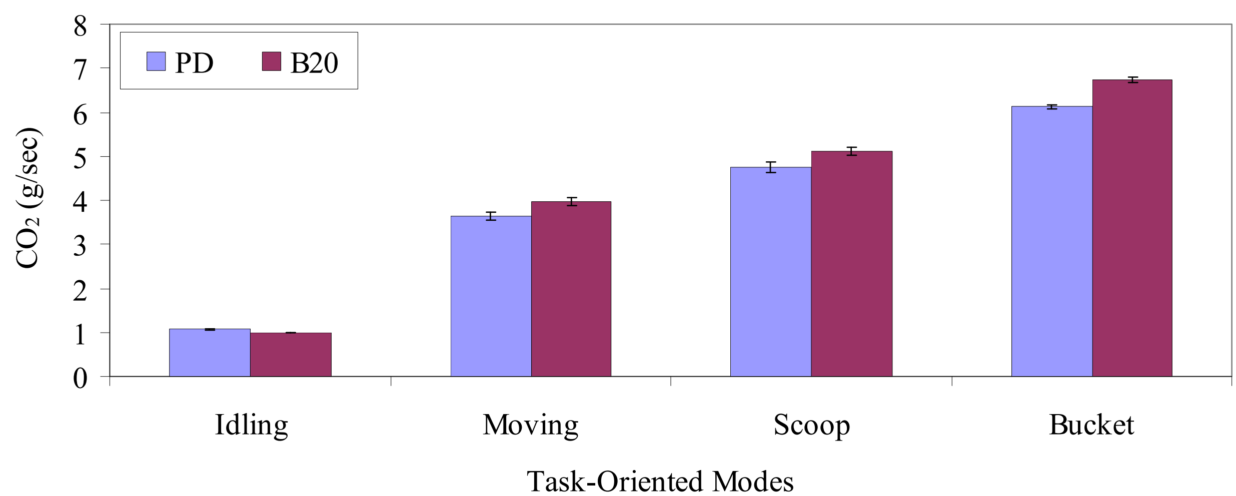


Figure A90. Continued

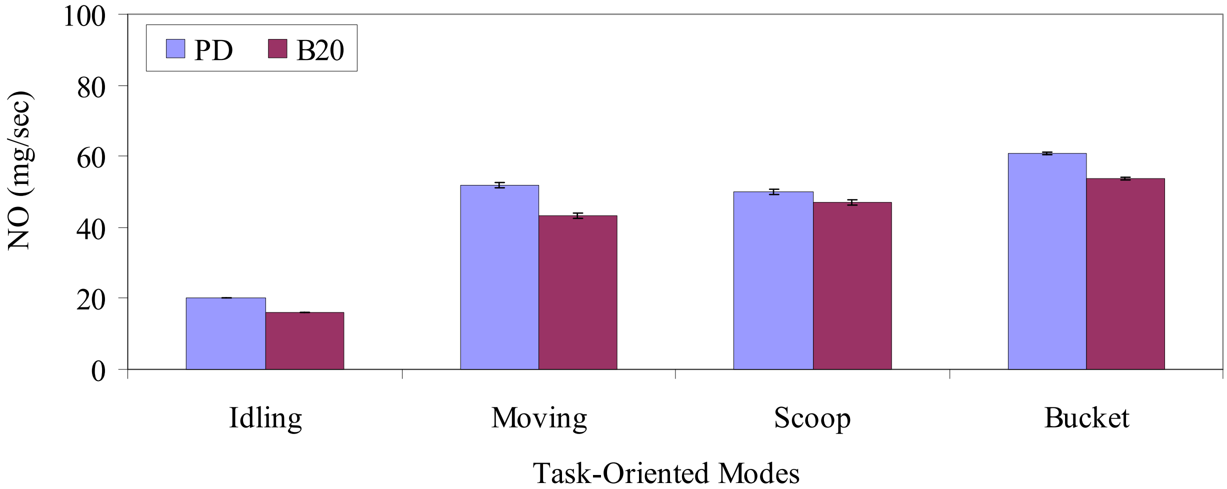


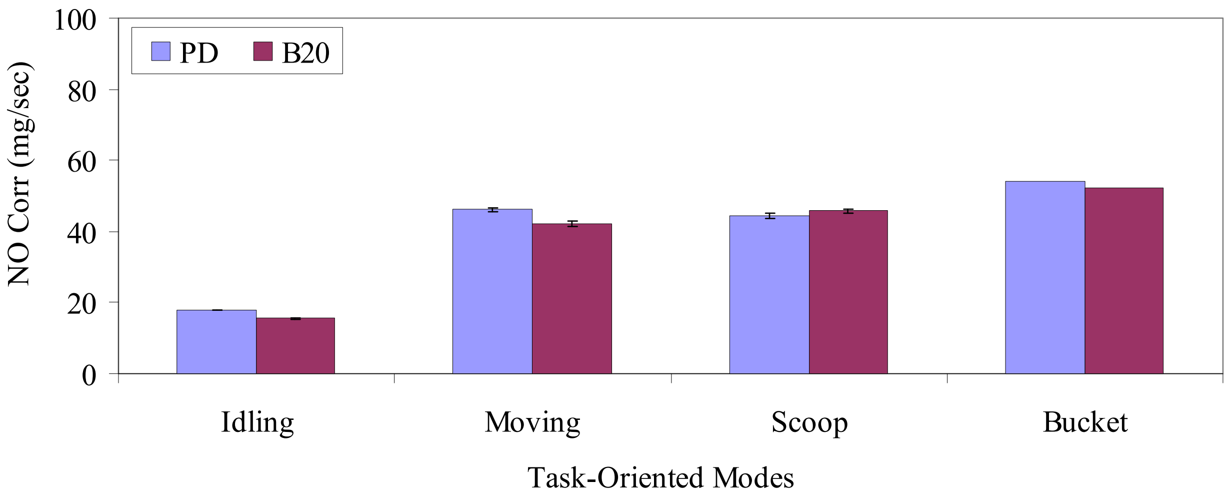


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 54 ^{o}F and the relative humidity was 42 %. For the B20 biodiesel test, the ambient temperature was 83 ^{o}F and the relative humidity was 38 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A91. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 7 (continued on next page)





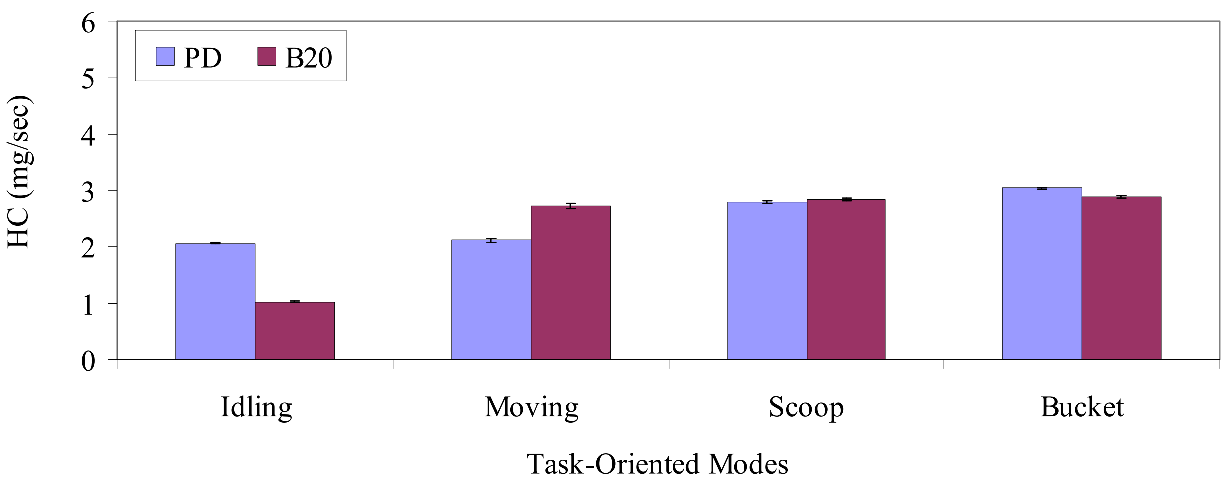
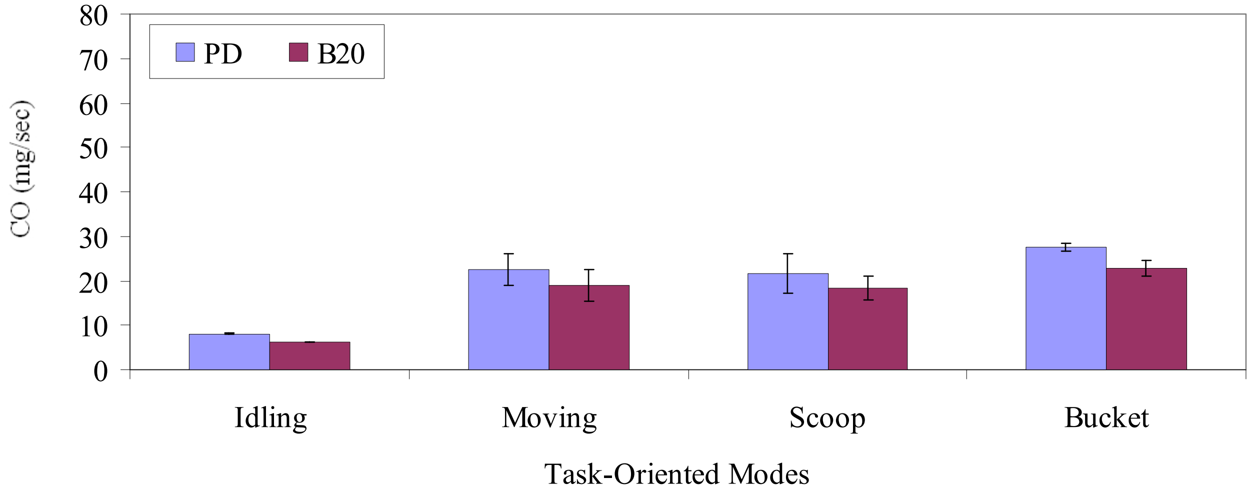


Figure A91. Continued



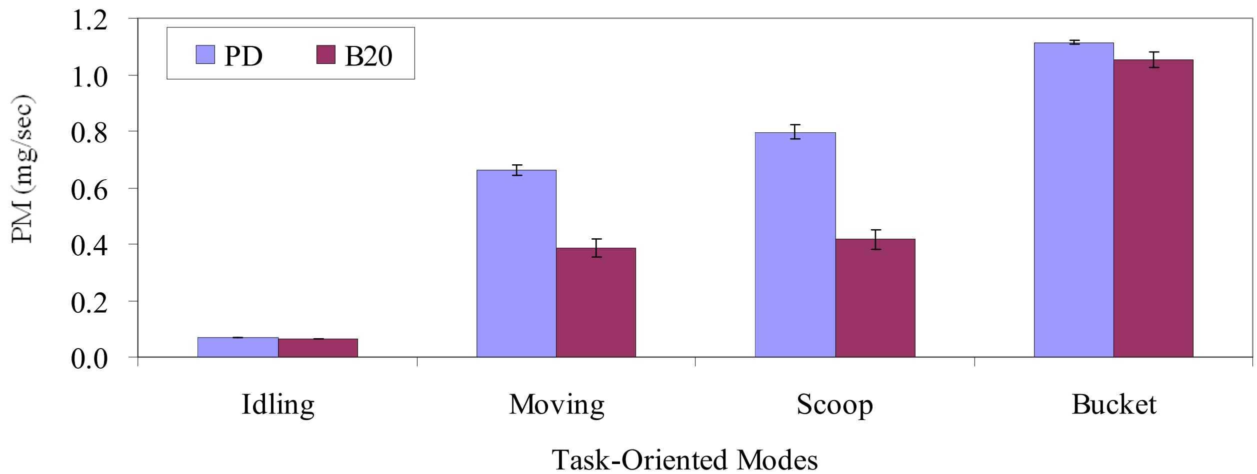
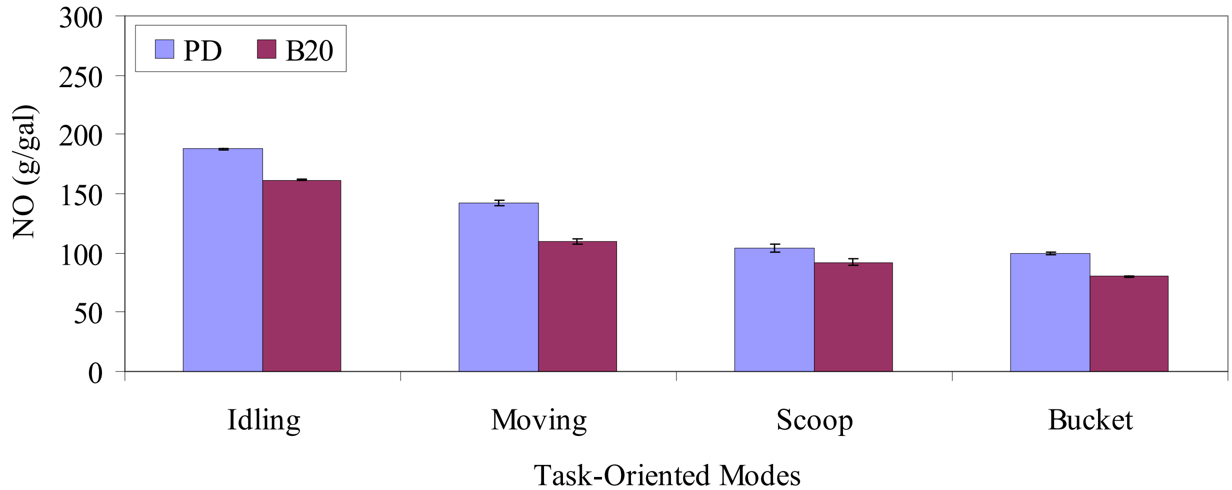
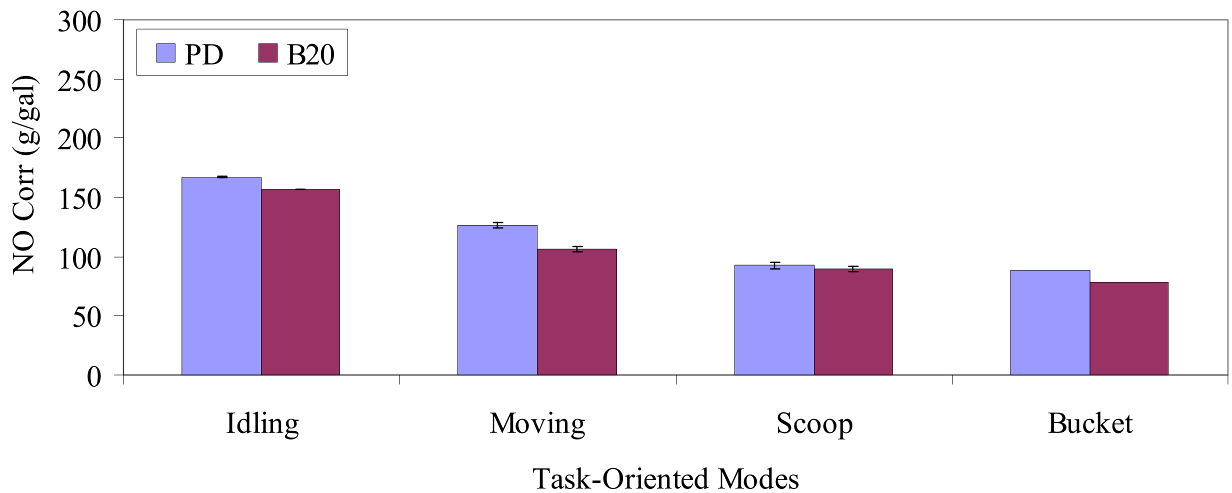


Figure A91. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 54 ^{o}F and the relative humidity was 42 %. For the B20 biodiesel test, the ambient temperature was 83 ^{o}F and the relative humidity was 38 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A92. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 7 (continued on next page)

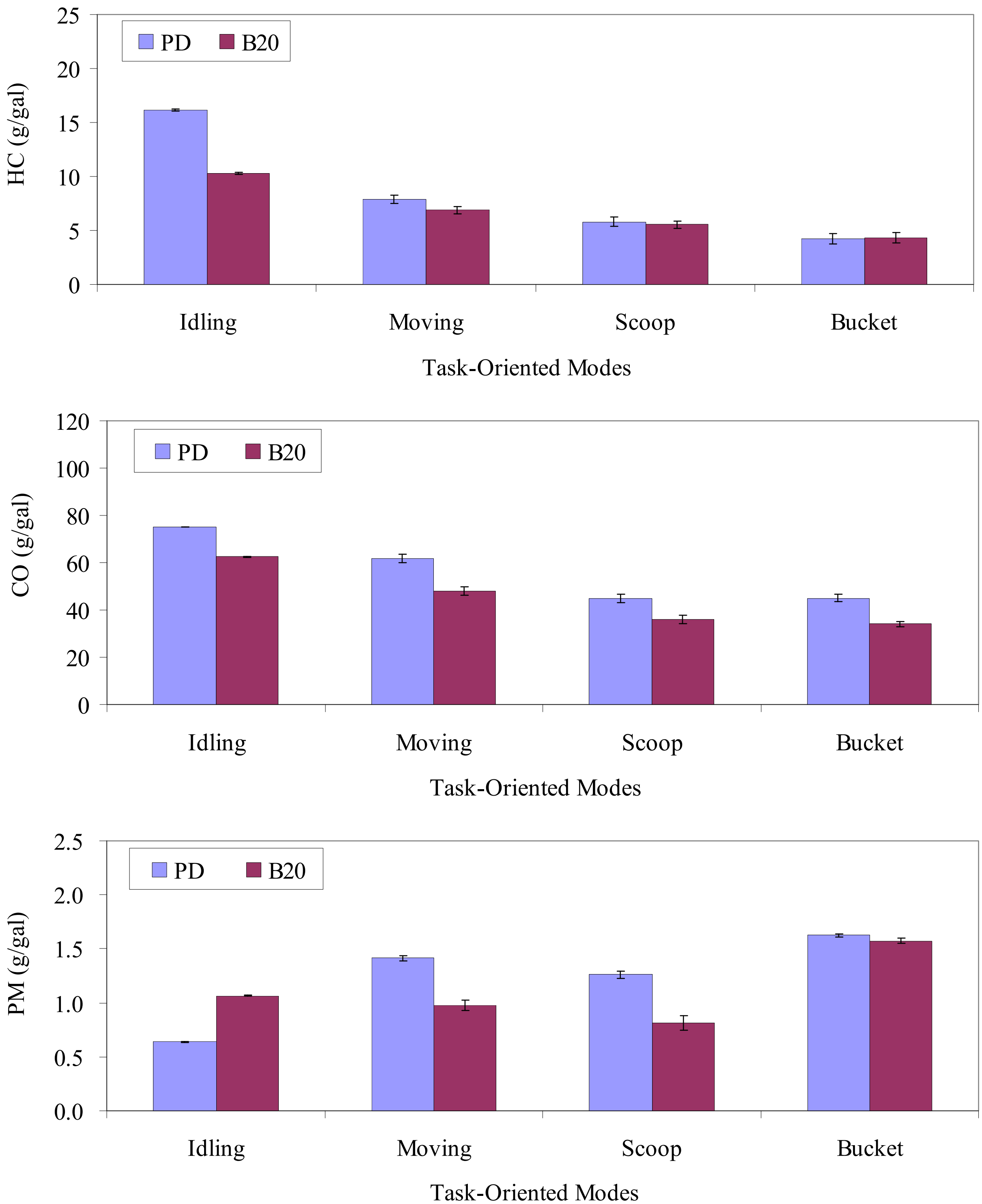
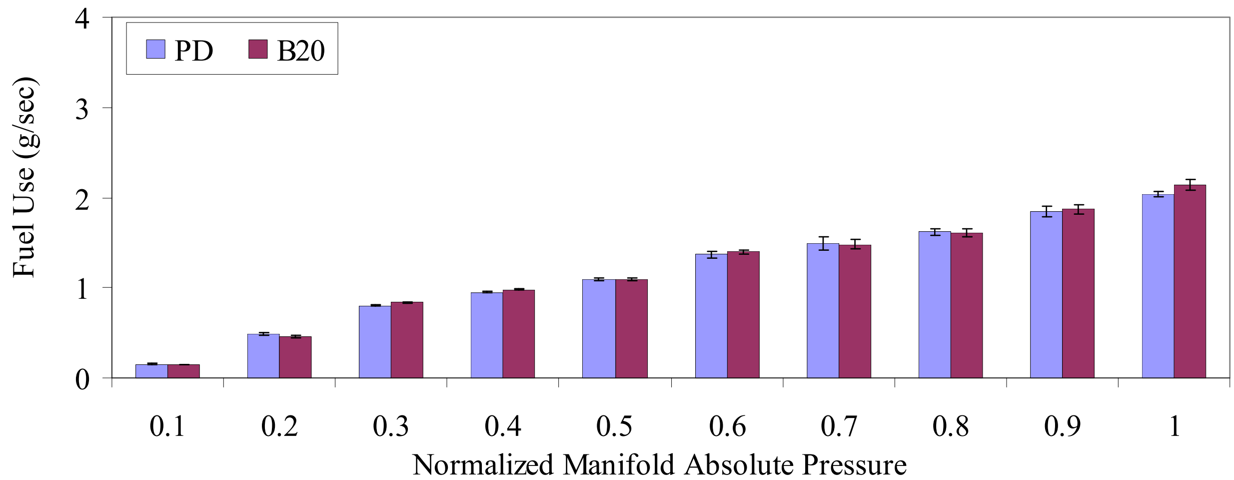
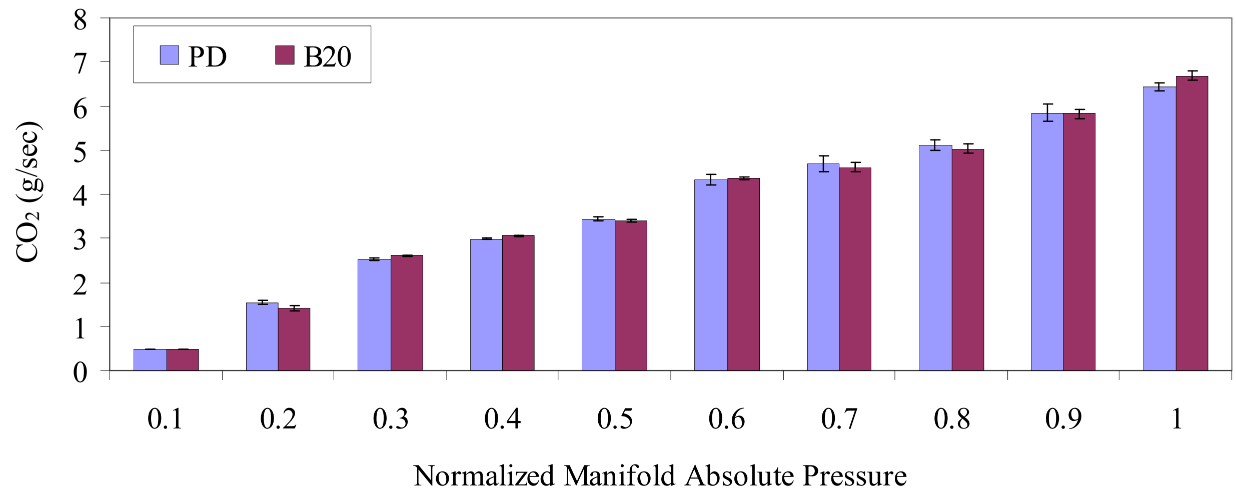


Figure A92. Continued

BACKHOE 8

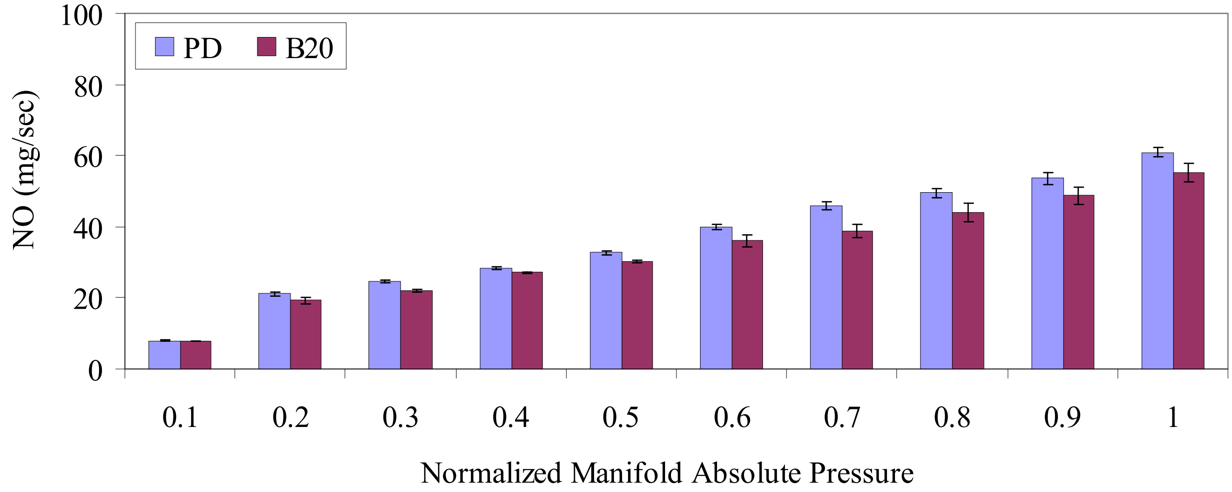


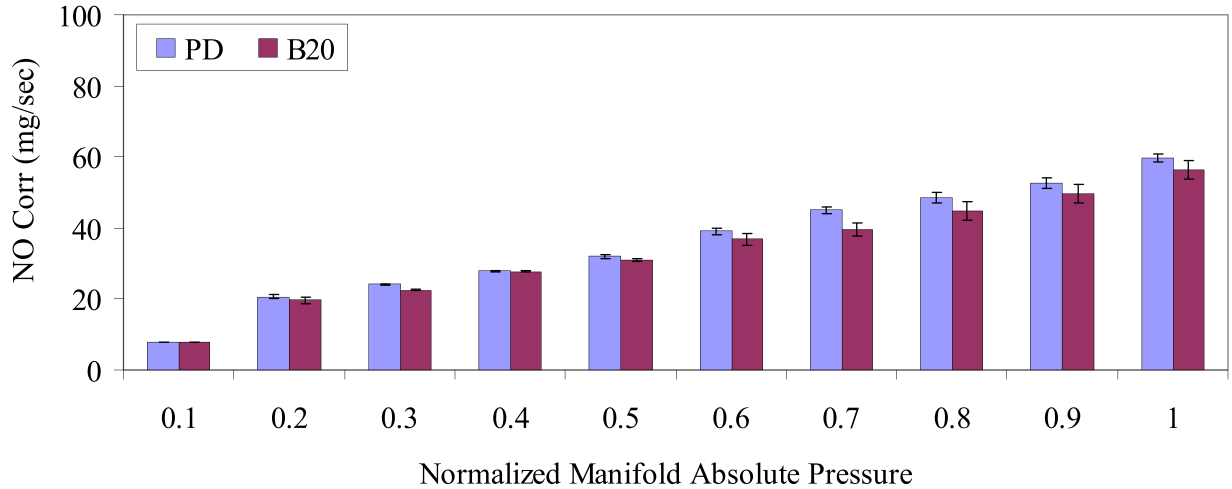


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 70 ^{o}F and the relative humidity was 56 %. For the B20 biodiesel tests the ambient temperature was 76 ^{o}F and the relative humidity was 61 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A93. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Backhoe 8 (continued on next page)





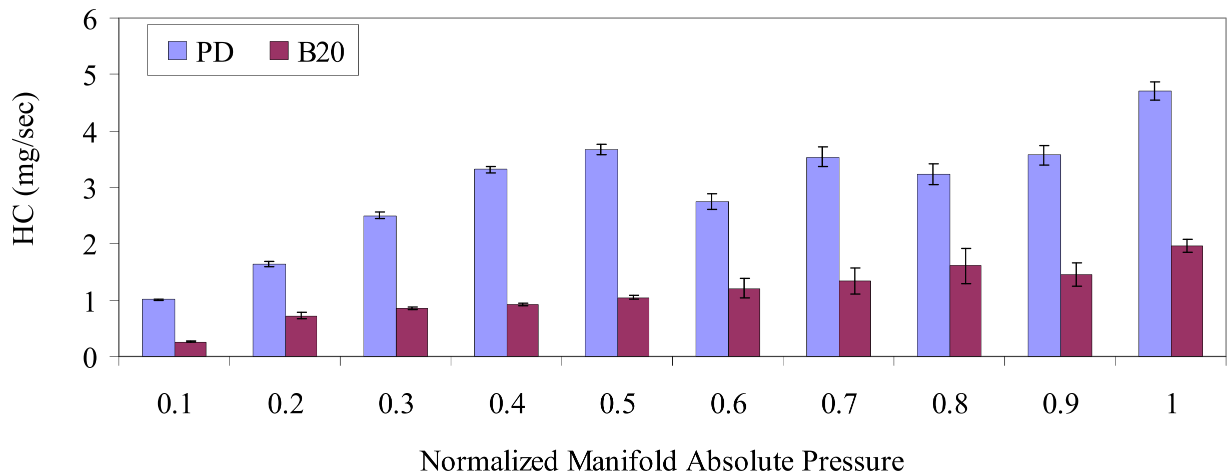


Figure A93. Continued

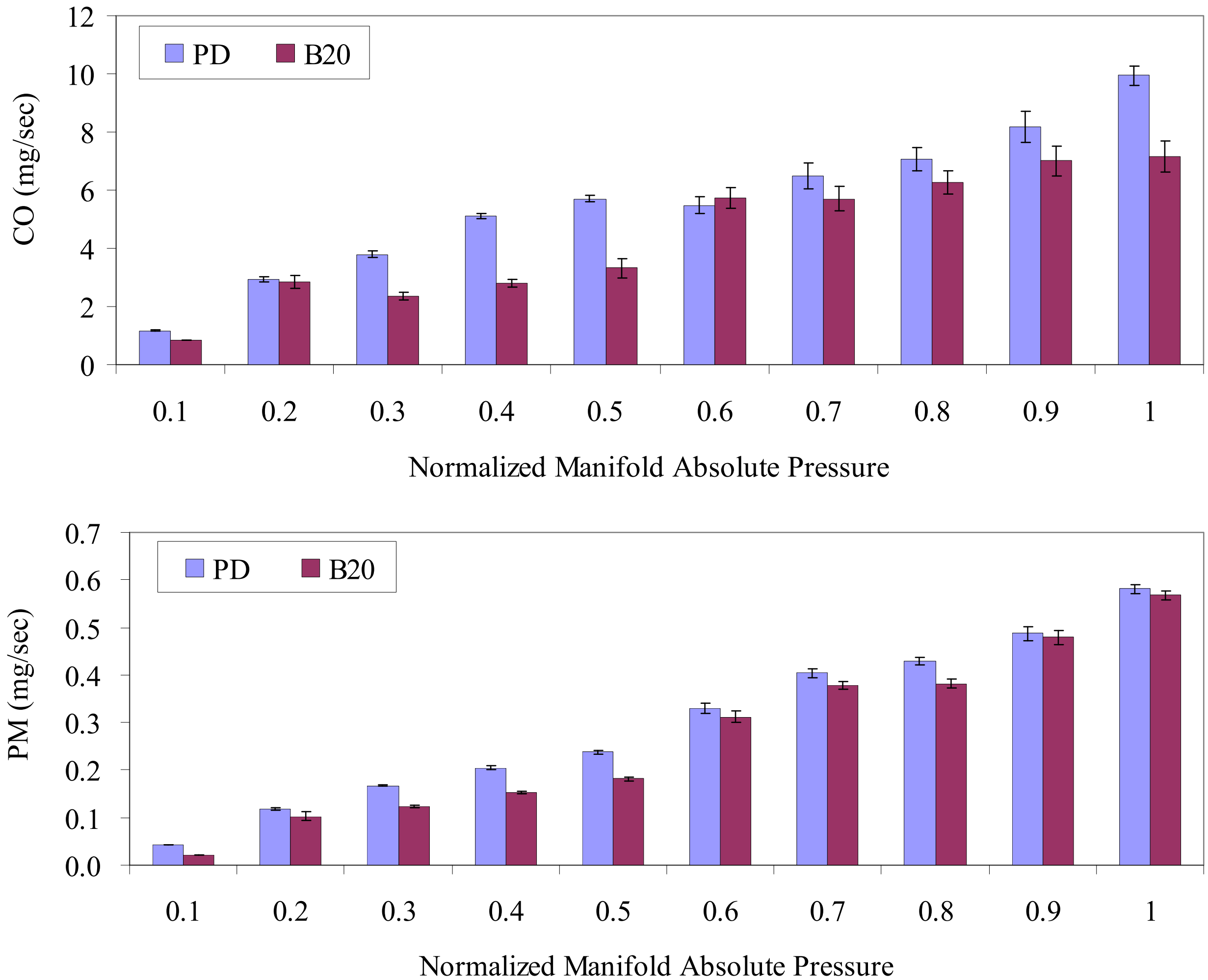
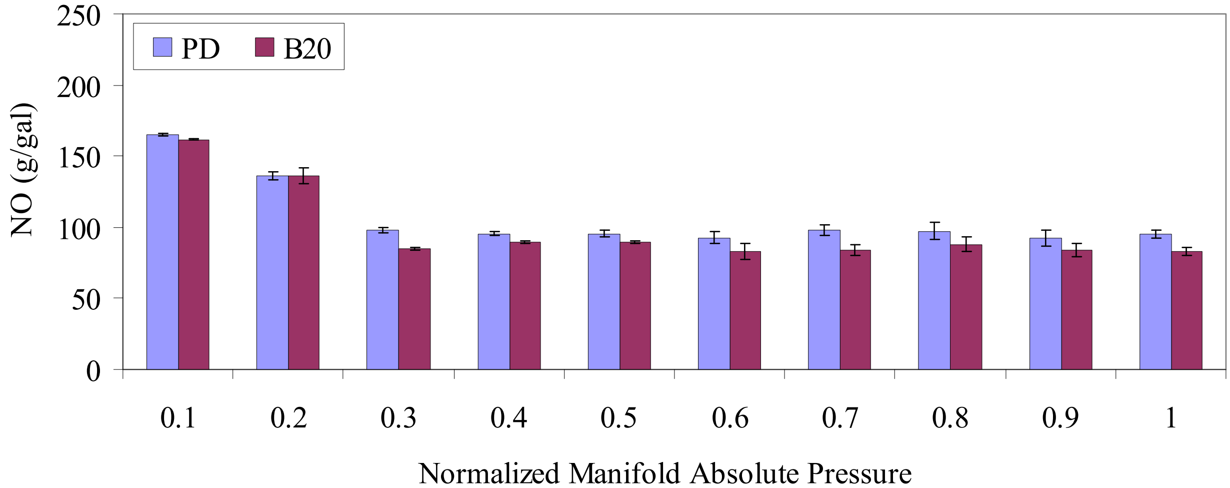
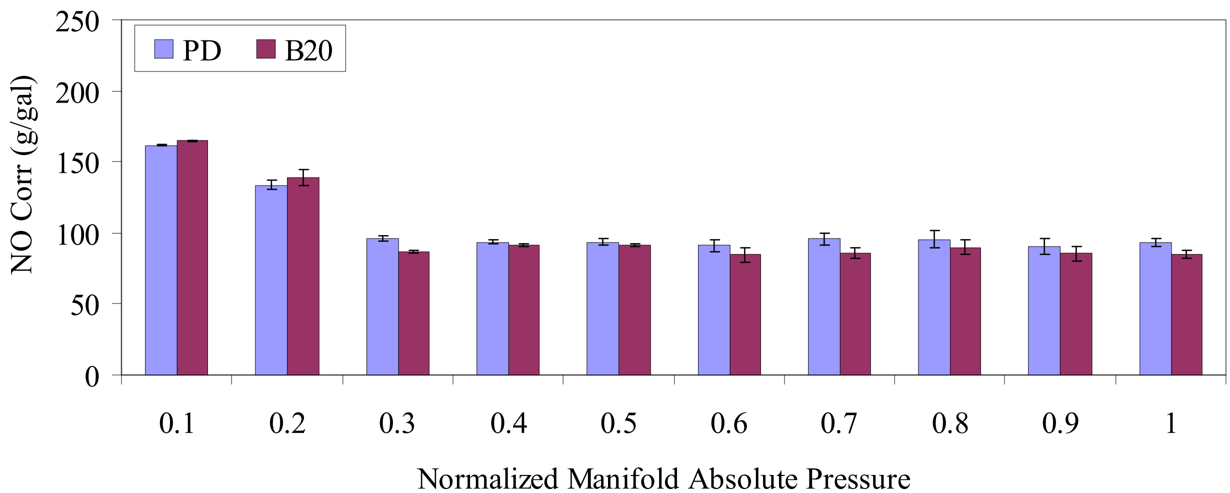


Figure A93. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 70 ^oF and the relative humidity was 56 %. For the B20 biodiesel test, the ambient temperature was 76 ^oF and the relative humidity was 61 %.

Values shown in the figure are the upper end of the range: "0.1" = $0 \le$ Normalized MAP < 0.1; "0.2" = $0.1 \le$ Normalized MAP < 0.2, and so on.

Figure A94. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Backhoe 8 (continued on next page)

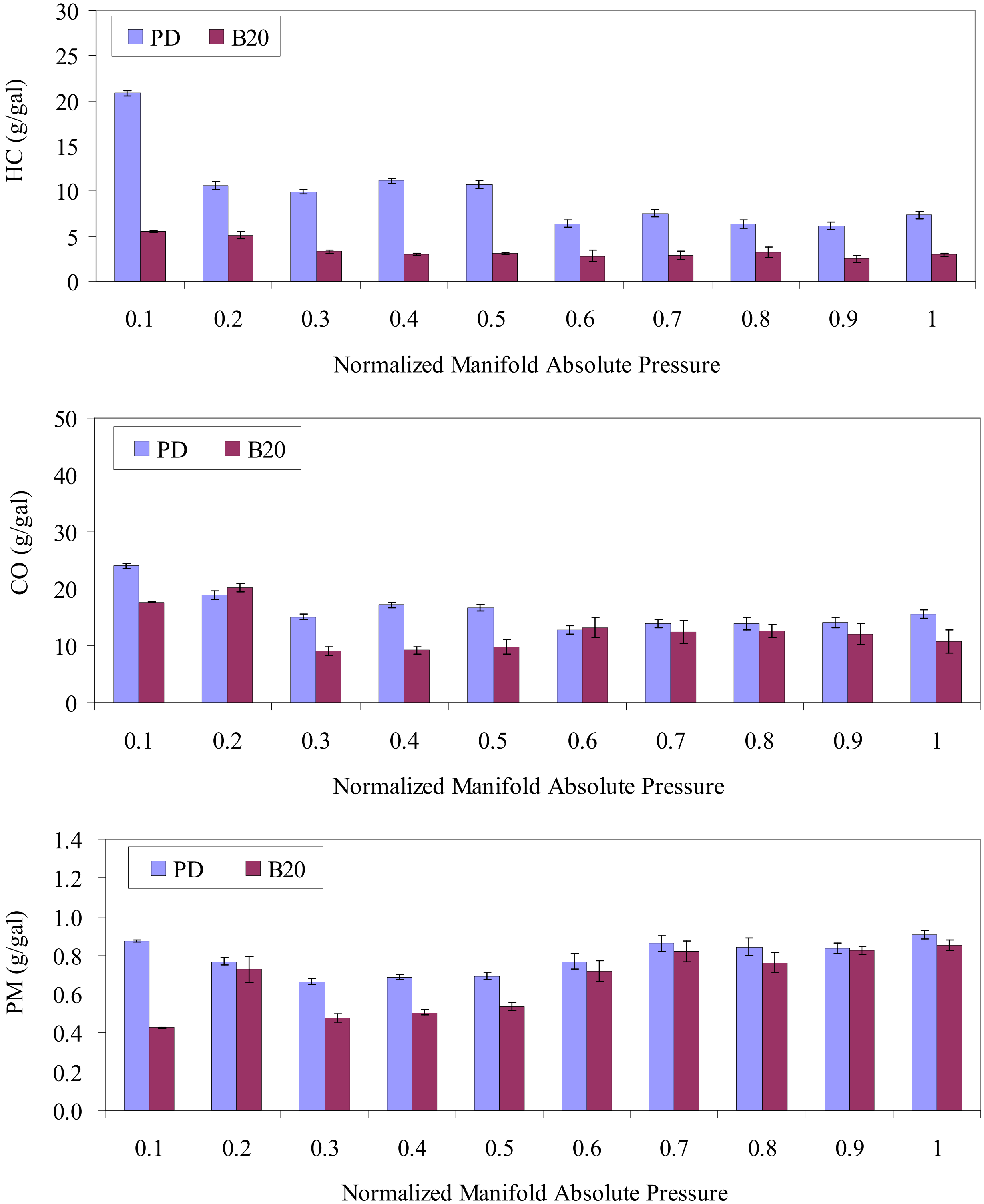
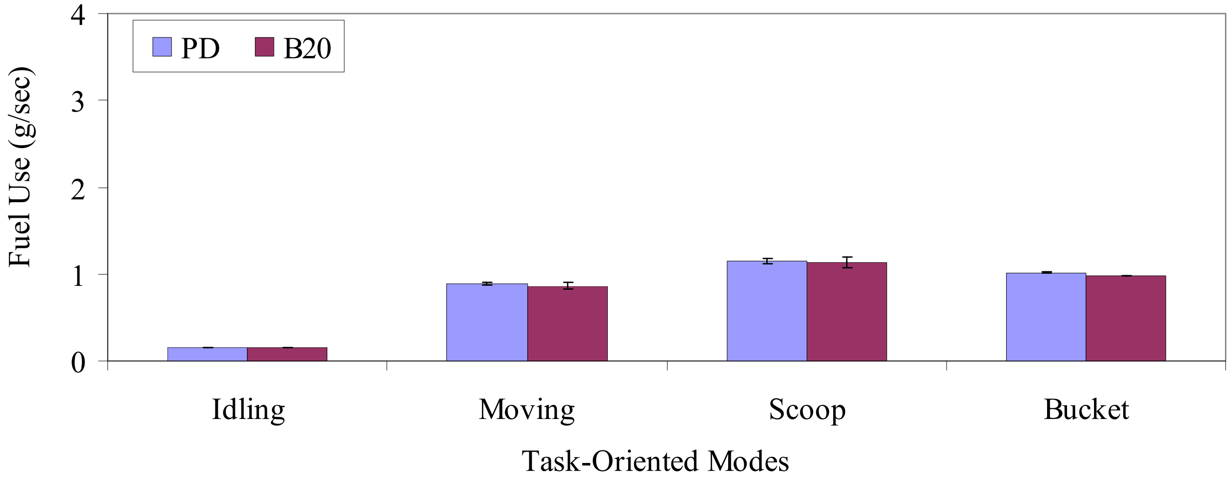
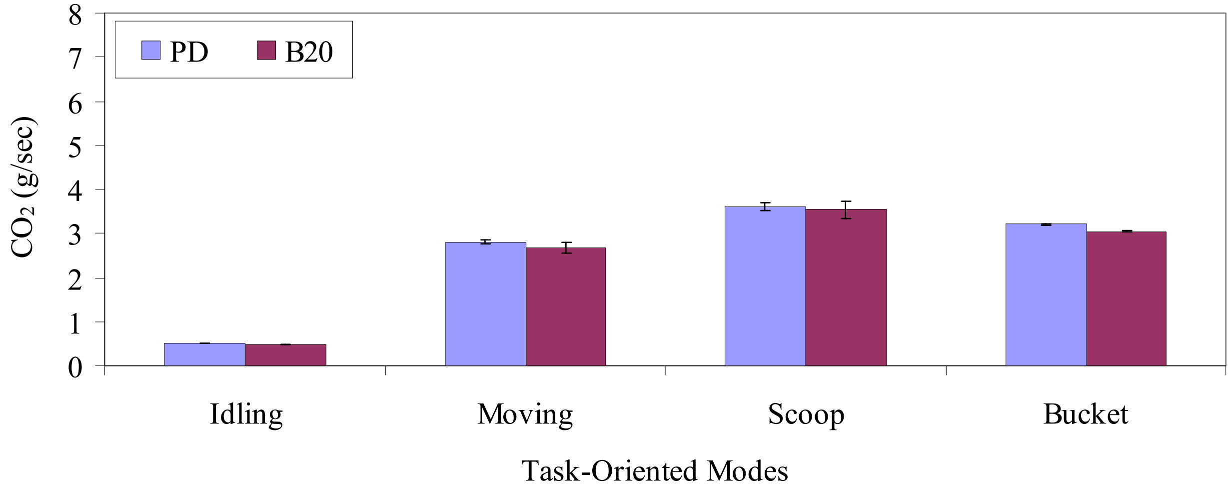


Figure A94. Continued

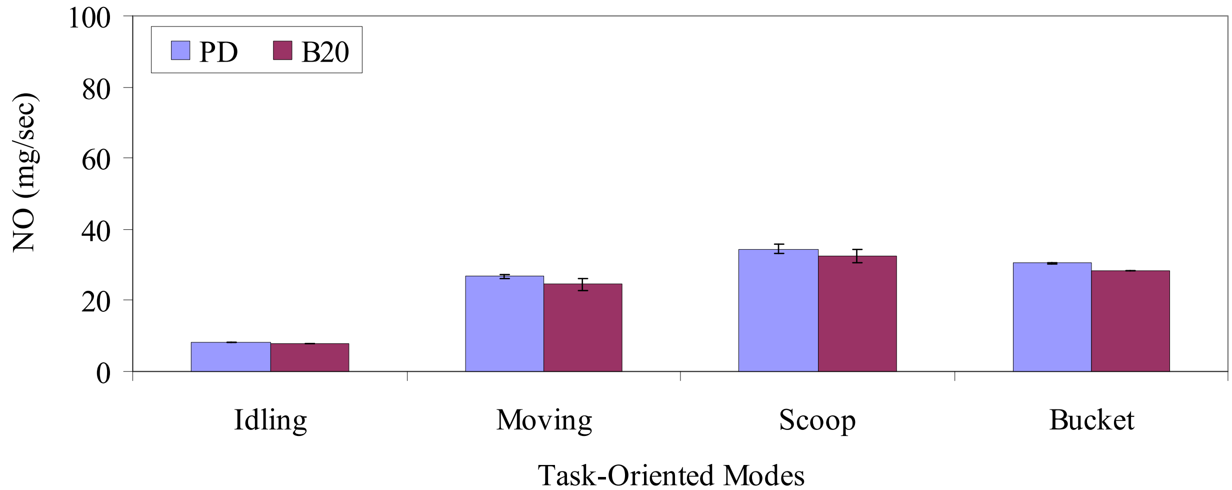


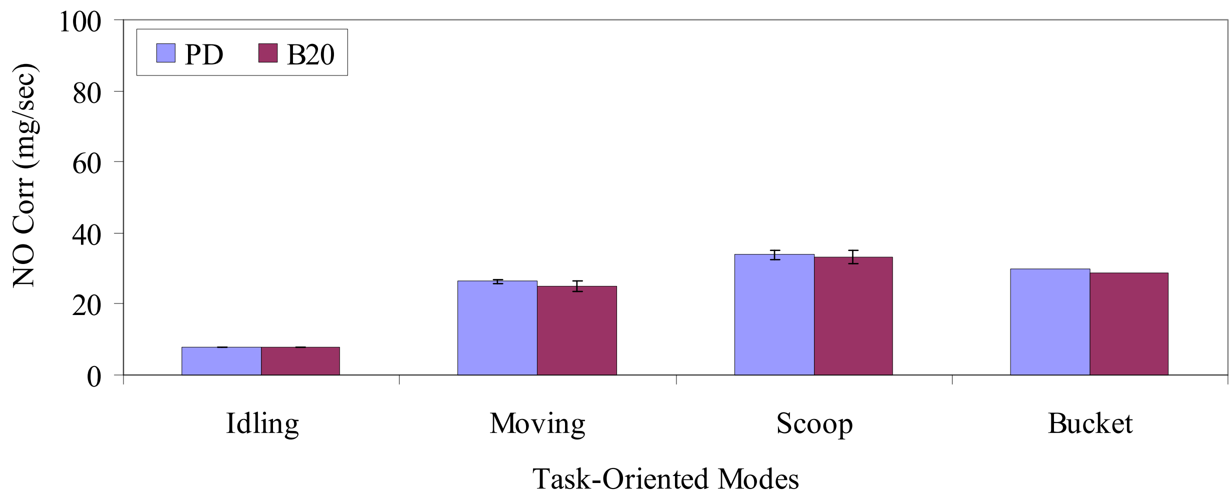


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 70 ^{o}F and the relative humidity was 56 %. For the B20 biodiesel test, the ambient temperature was 76 ^{o}F and the relative humidity was 61 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A95. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 8 (continued on next page)





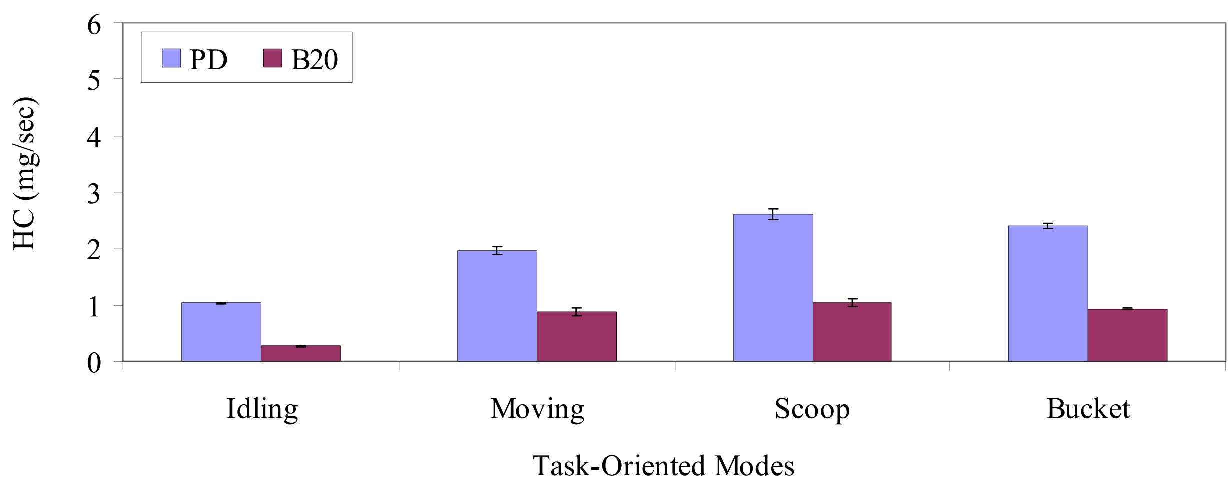


Figure A95. Continued

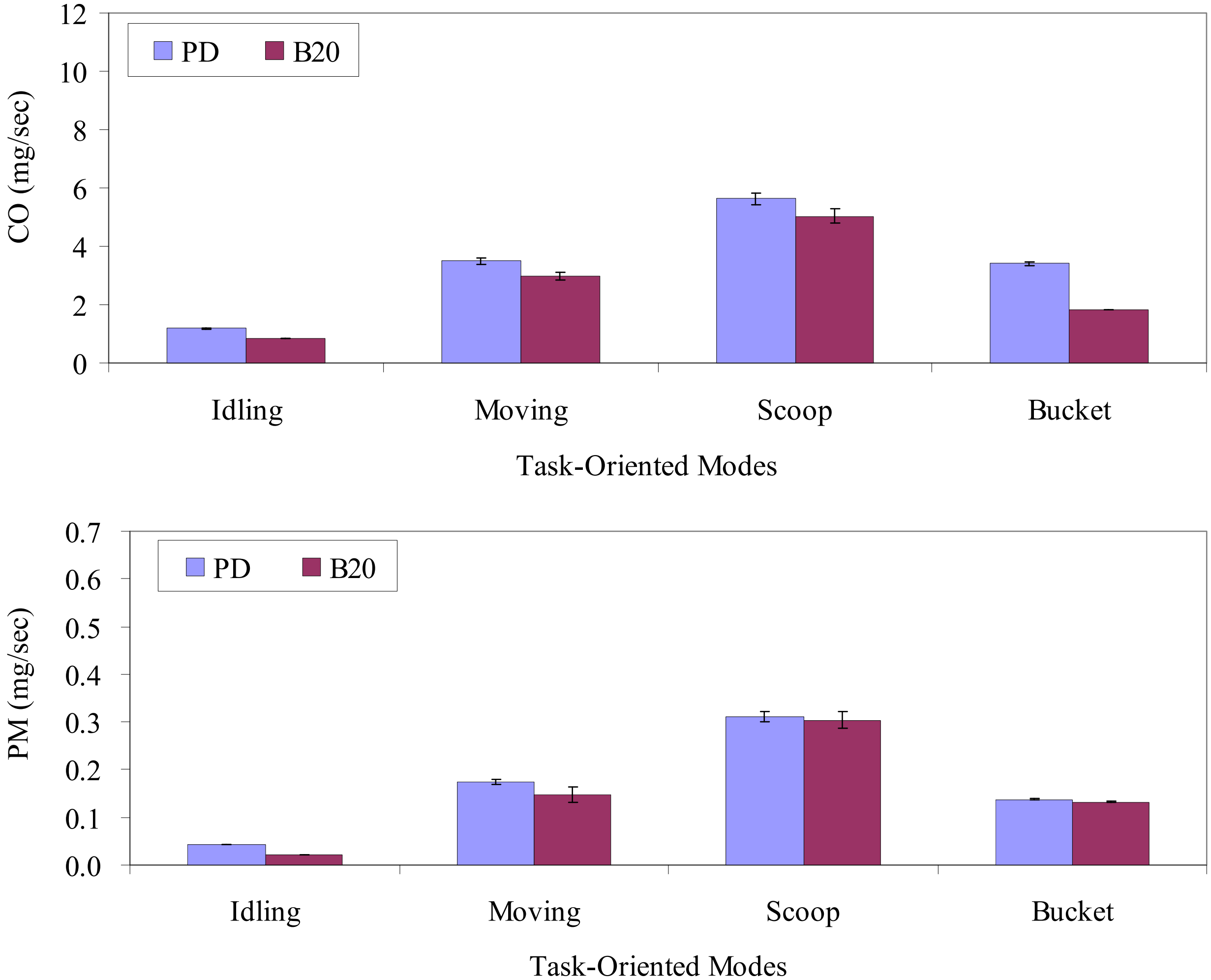
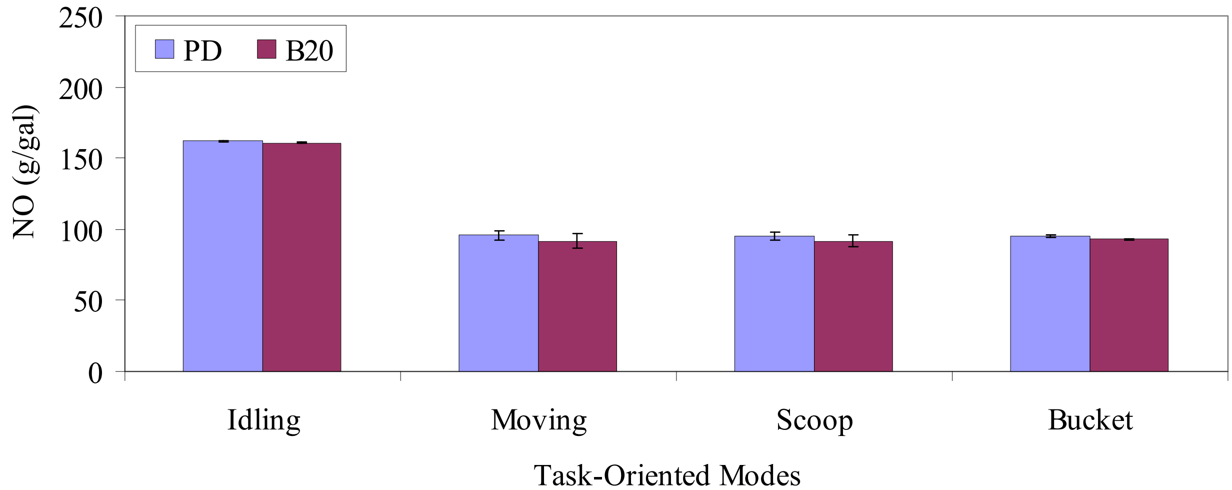
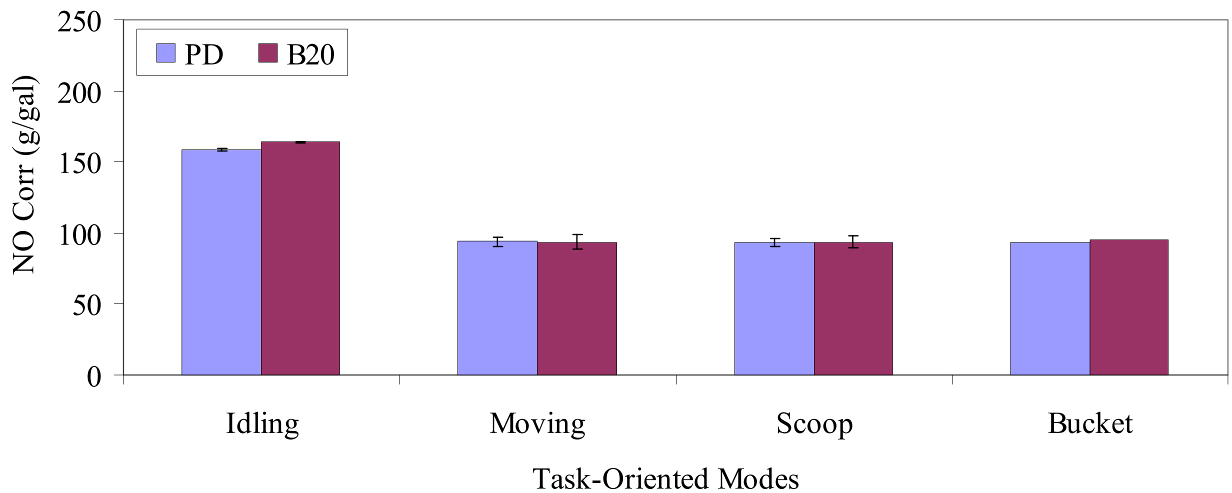


Figure A95. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 70 ^{o}F and the relative humidity was 56 %. For the B20 biodiesel test, the ambient temperature was 76 ^{o}F and the relative humidity was 61 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A96. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 8 (continued on next page)

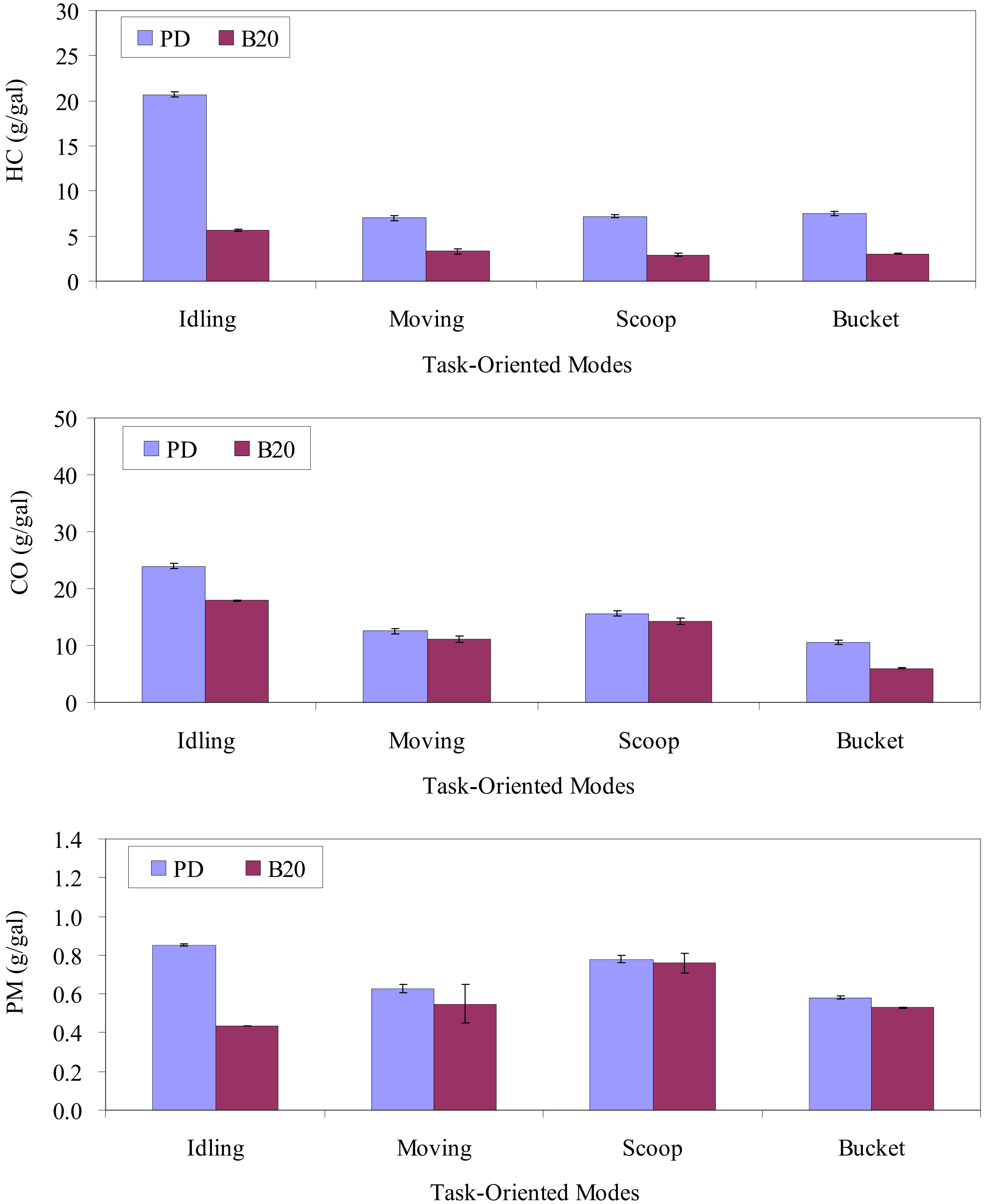
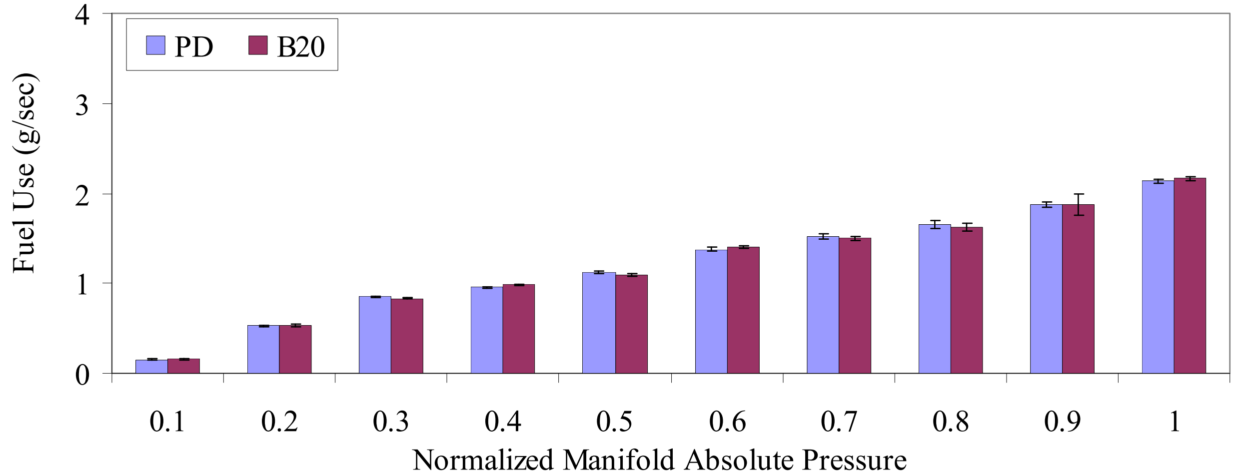
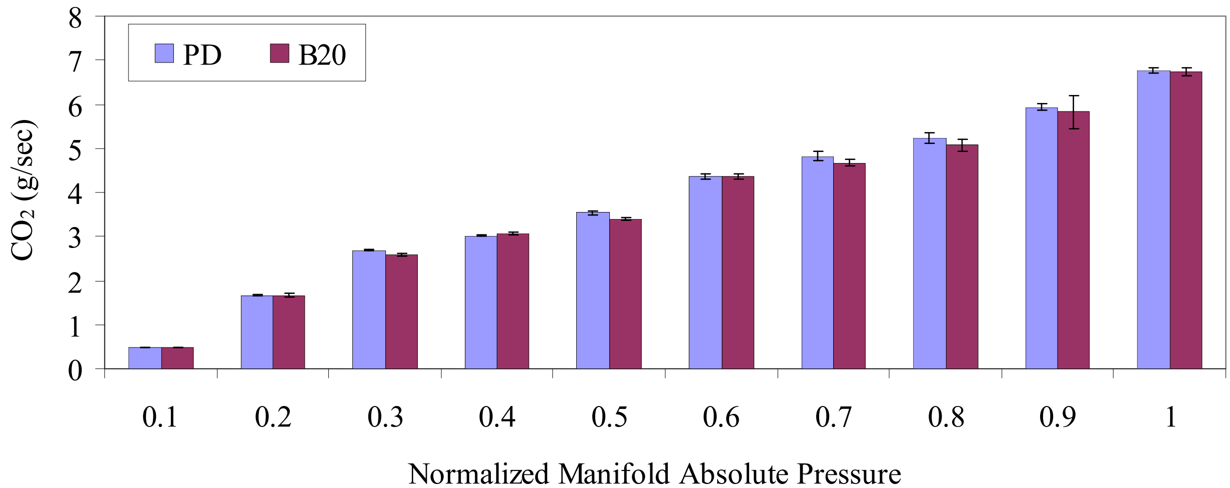


Figure A96. Continued

SKID STEER LOADER

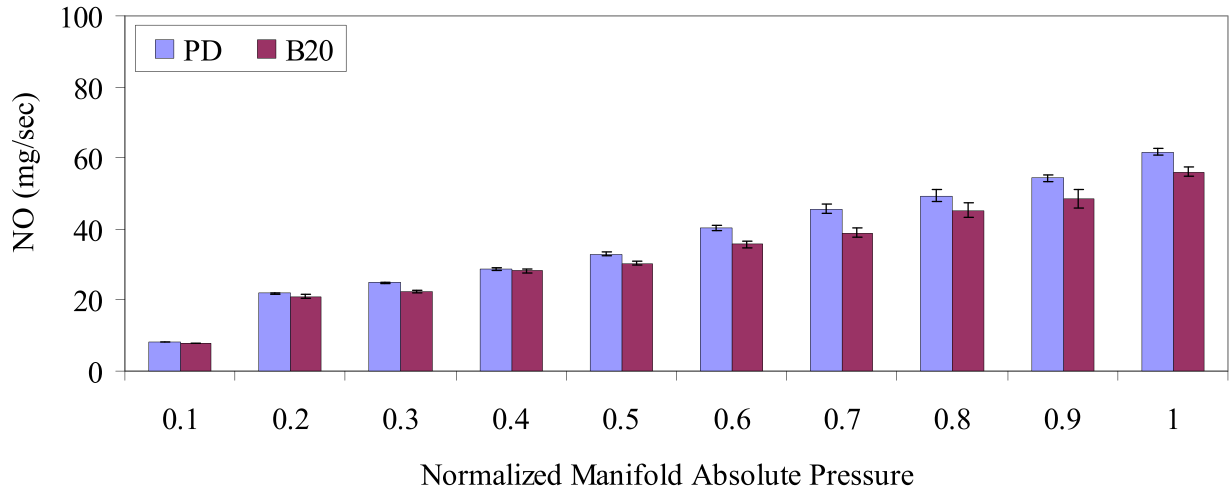


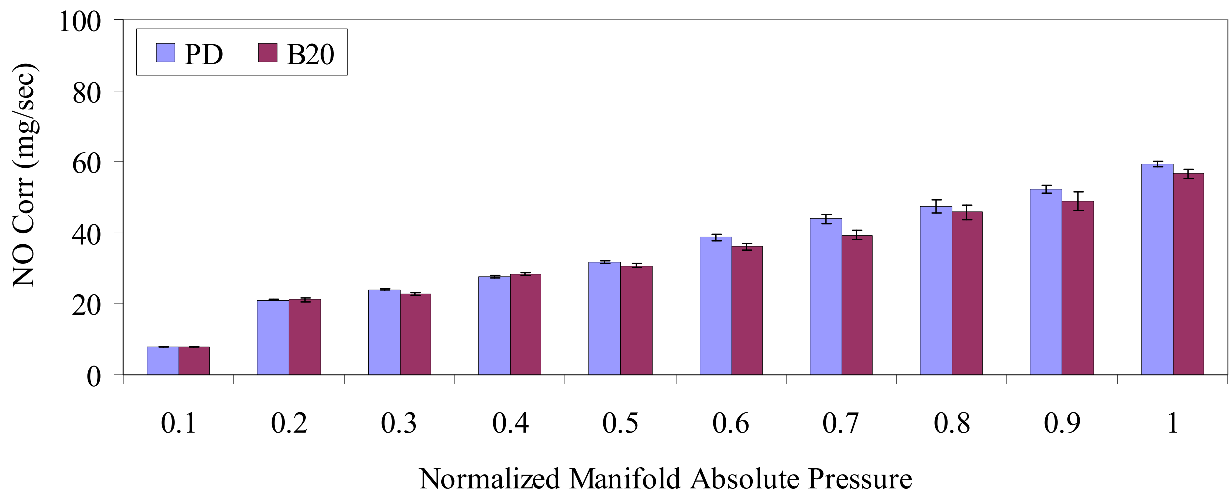


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 79 ^{o}F and the relative humidity was 52 %. For the B20 biodiesel test, the ambient temperature was 77 ^{o}F and the relative humidity was 60 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 $\leq$ Normalized MAP < 0.1; "0.2" = 0.1 $\leq$ Normalized MAP < 0.2, and so on.

Figure A97. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Skid Steer Loader (continued on next page)





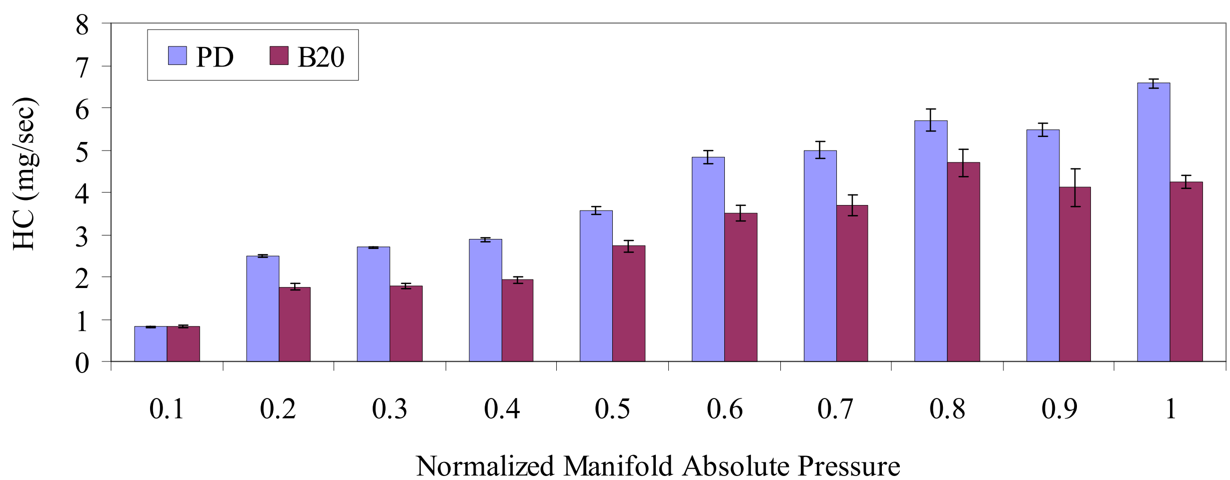


Figure A97. Continued

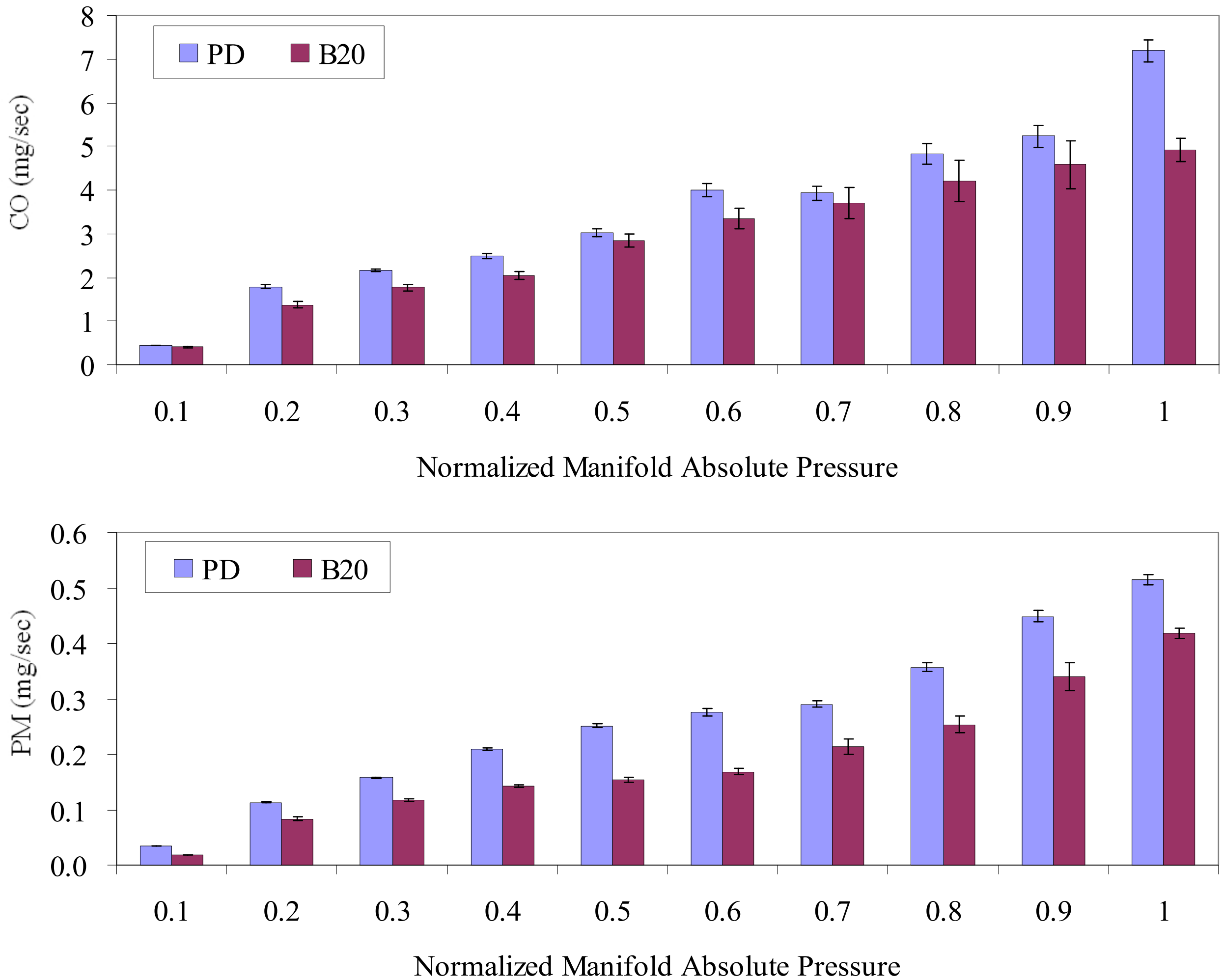
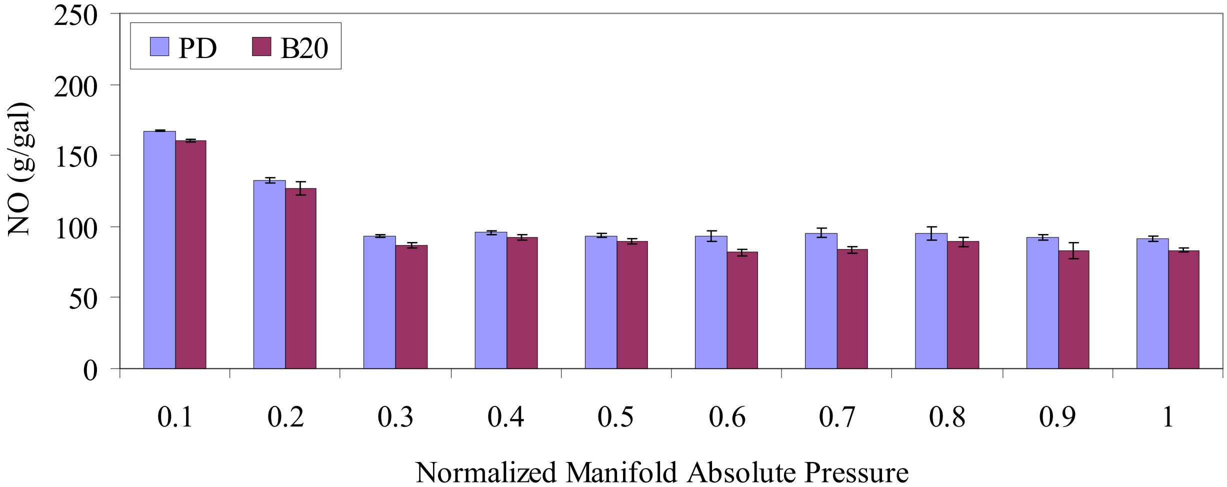
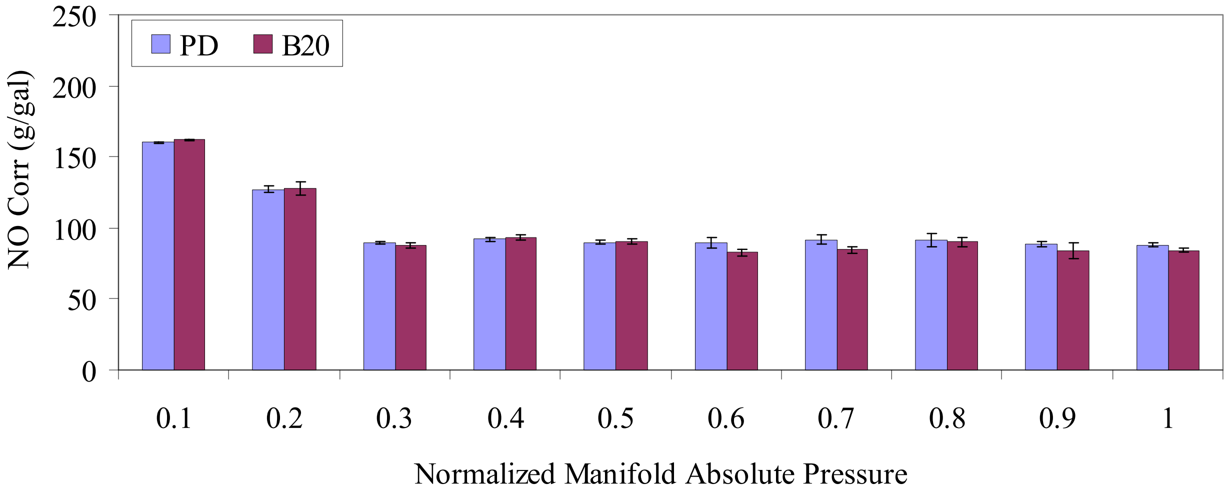


Figure A97. Continued

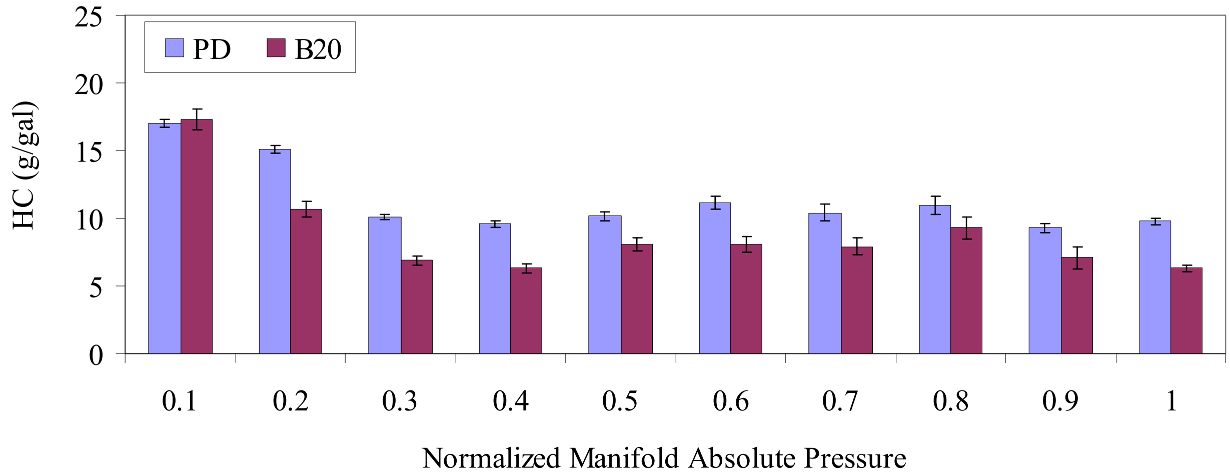


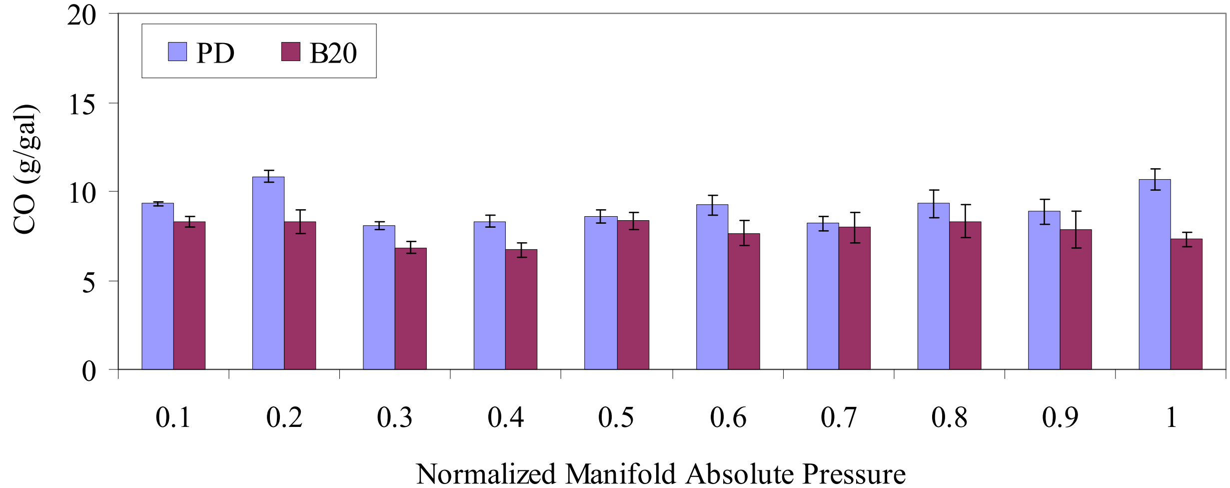


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 79 ^{o}F and the relative humidity was 52 %. For the B20 biodiesel test, the ambient temperature was 77 ^{o}F and the relative humidity was 60 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A98. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Skid Steer Loader (continued on next page)





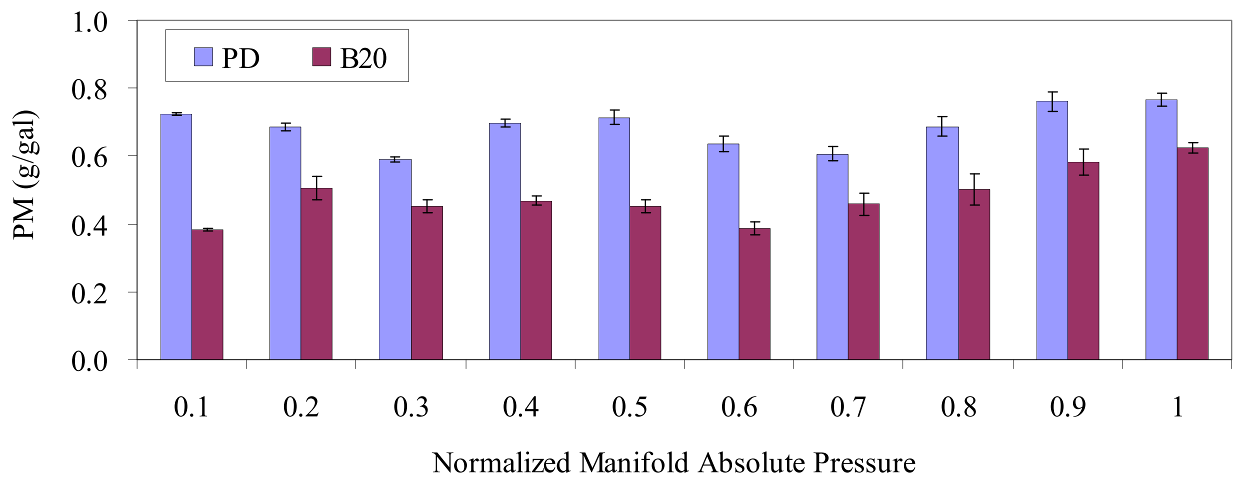
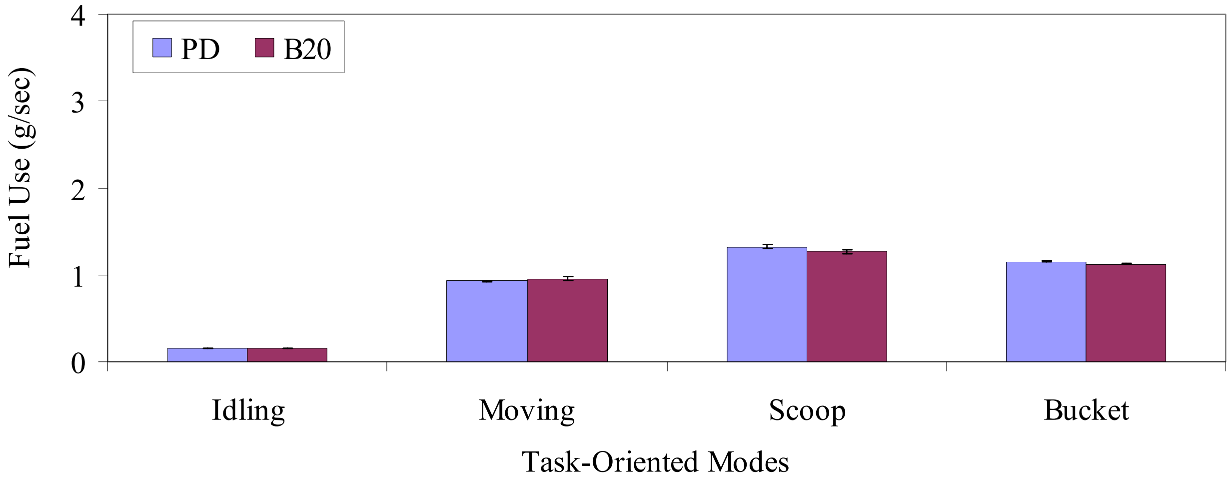
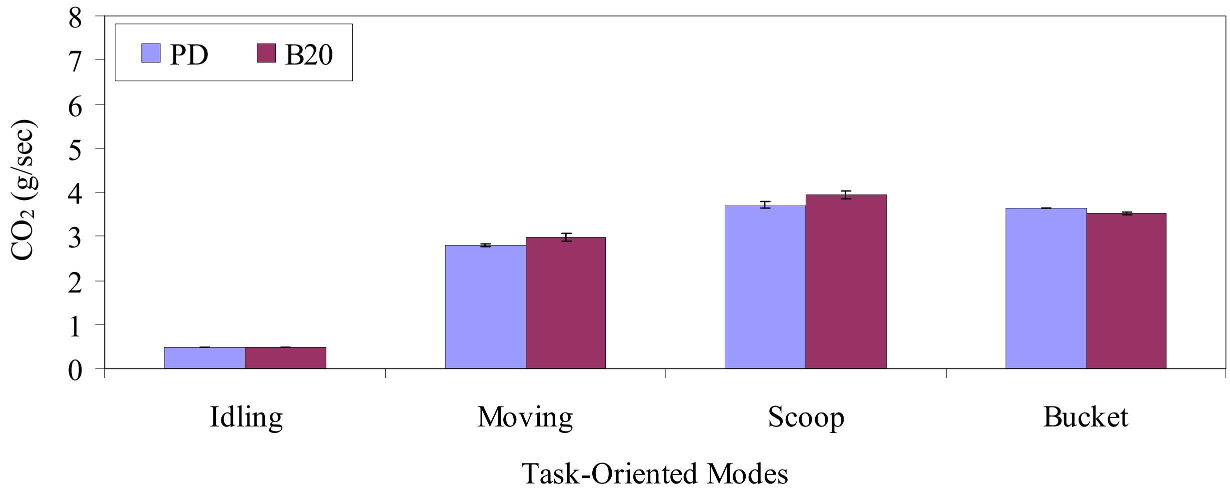


Figure A98. Continued

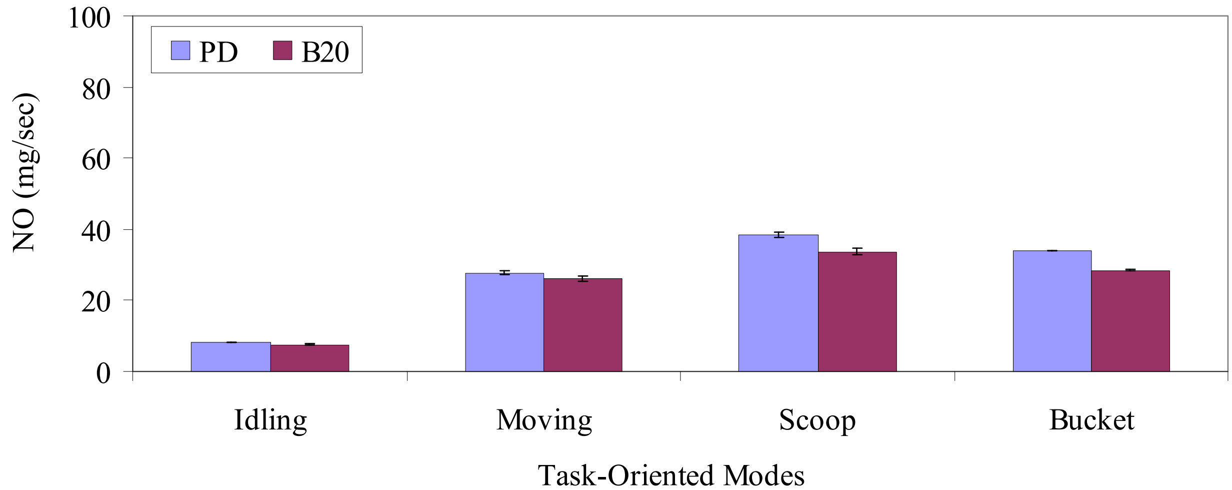


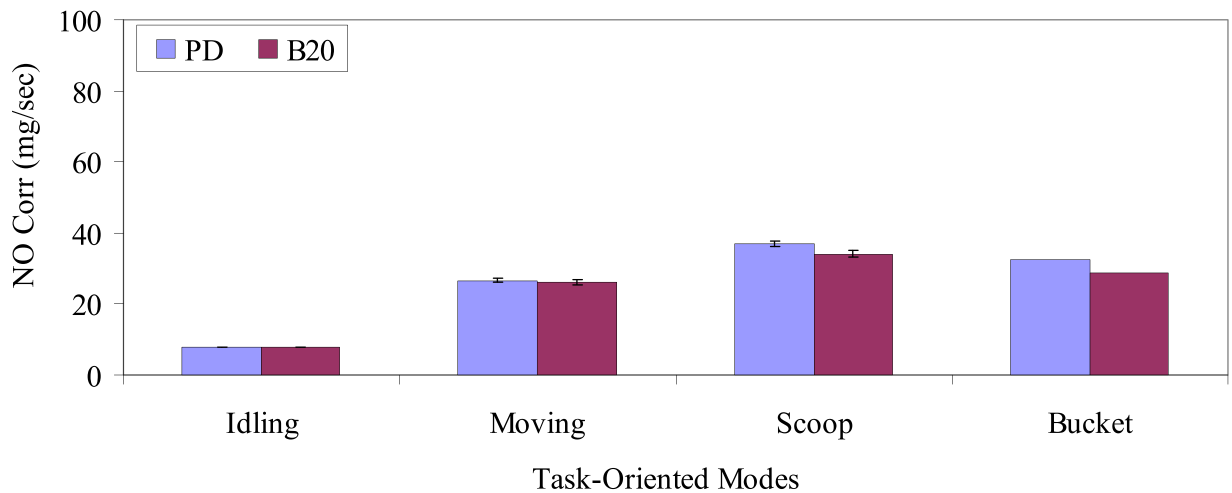


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 79 ^{o}F and the relative humidity was 52 %. For the B20 biodiesel test, the ambient temperature was 77 ^{o}F and the relative humidity was 60 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A99. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Skid Steer Loader (continued on next page)





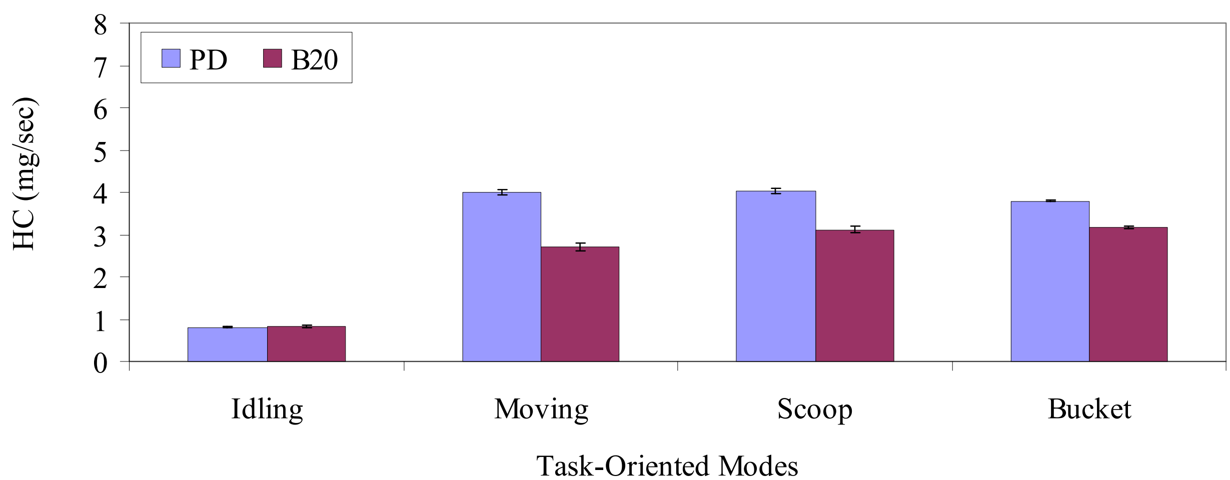
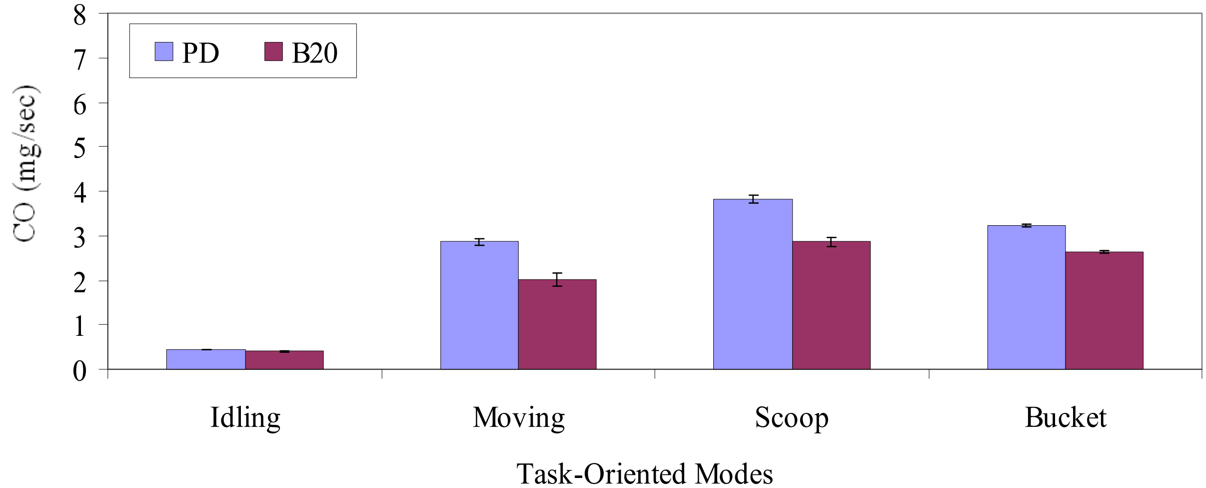


Figure A99. Continued



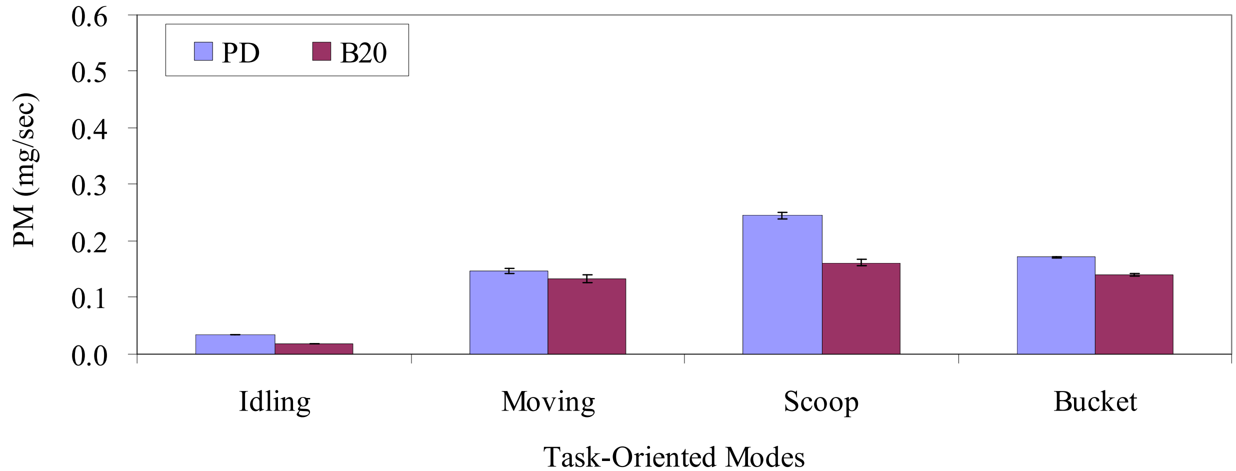
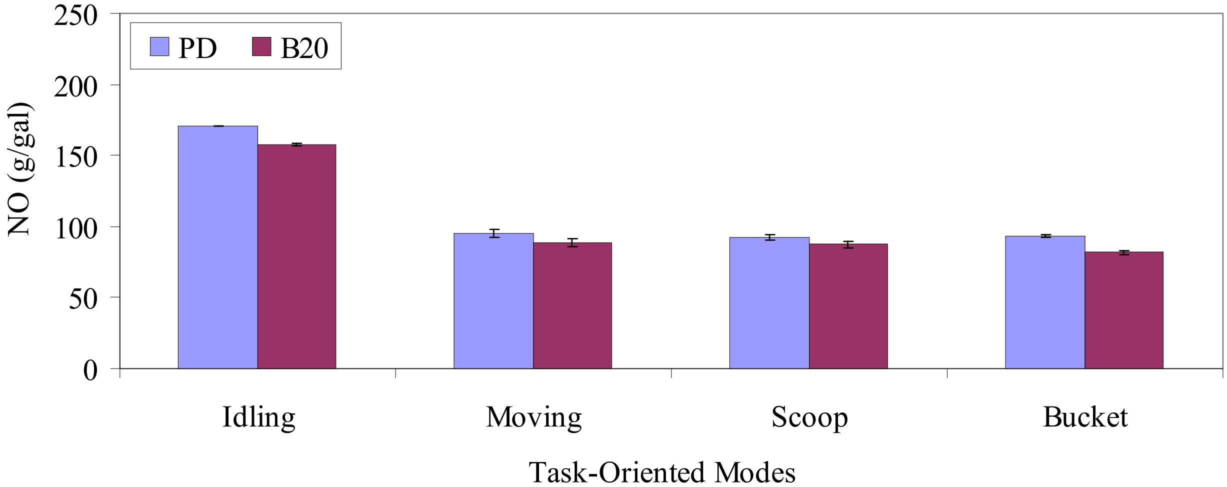
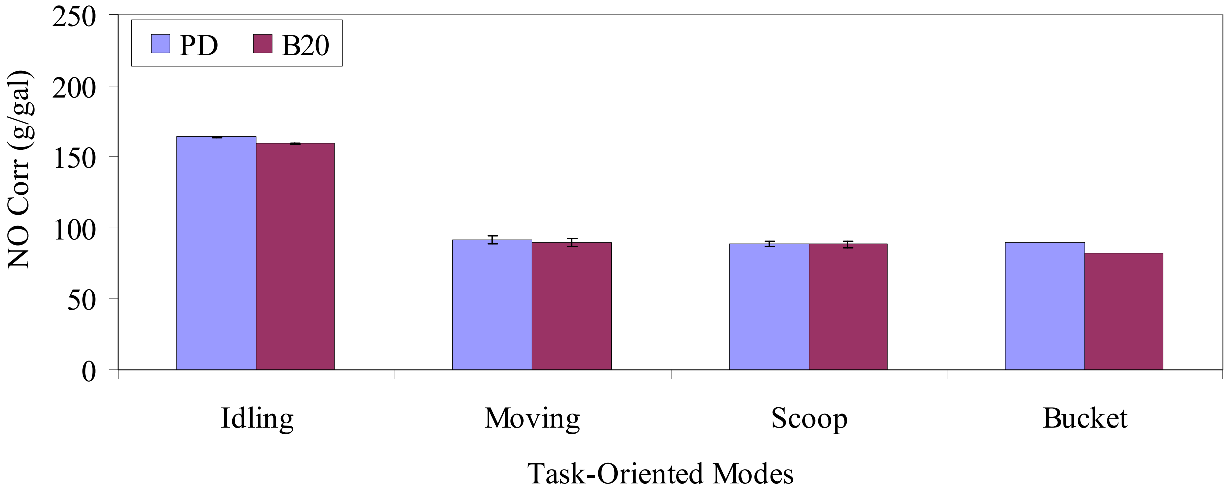


Figure A99. Continued

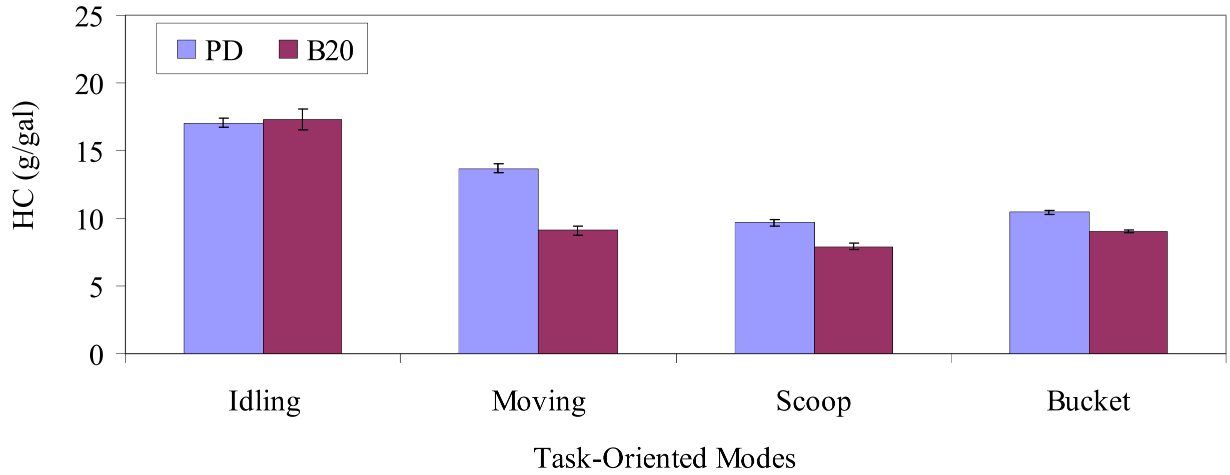


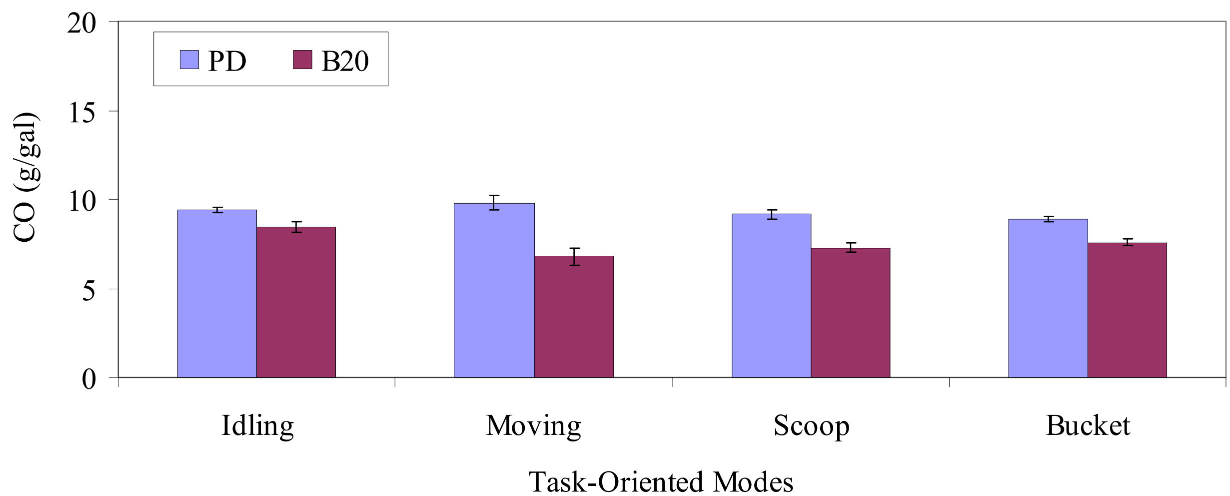


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 79 ^{o}F and the relative humidity was 52 %. For the B20 biodiesel test, the ambient temperature was 77 ^{o}F and the relative humidity was 60 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the backhoe when the loader bucket is not in contact with the ground (forward or backward); *scoop*: movement of the backhoe when the loader bucket is in contact with the ground; *bucket*: digging, swing, and dumping with excavator bucket.

Figure A100. Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Skid Steer Loader (continued on next page)





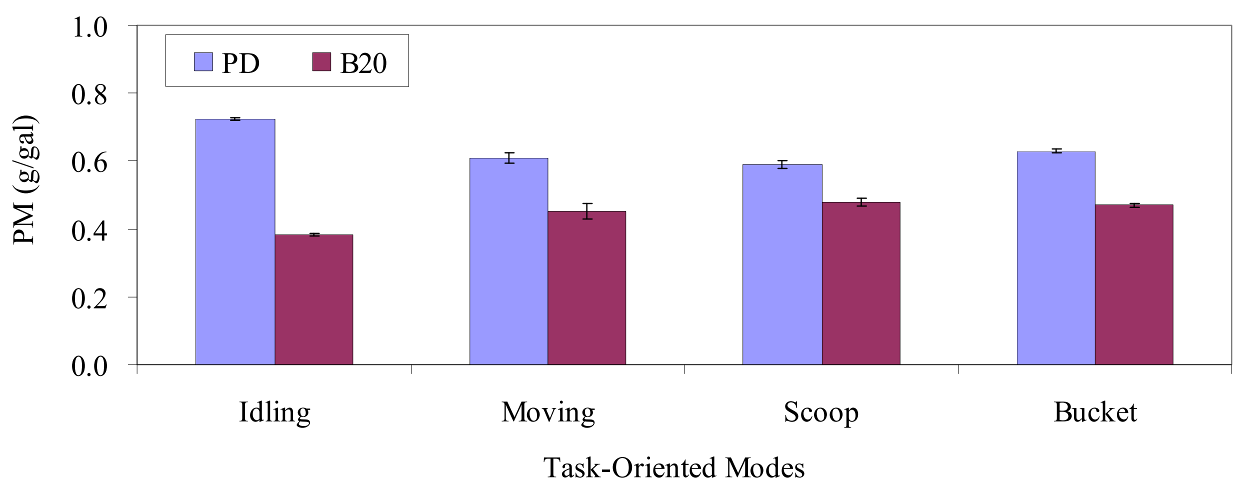
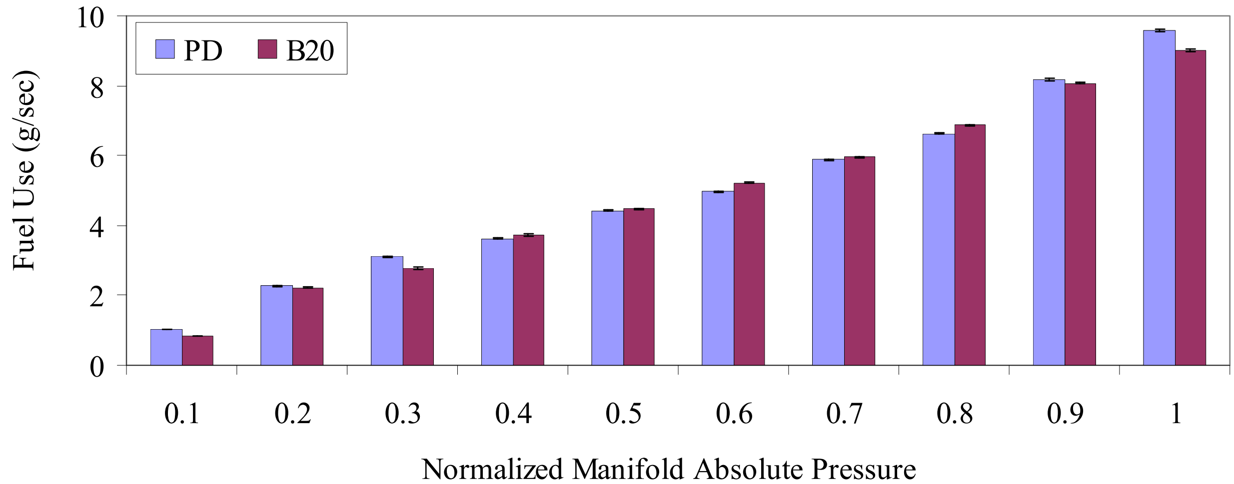
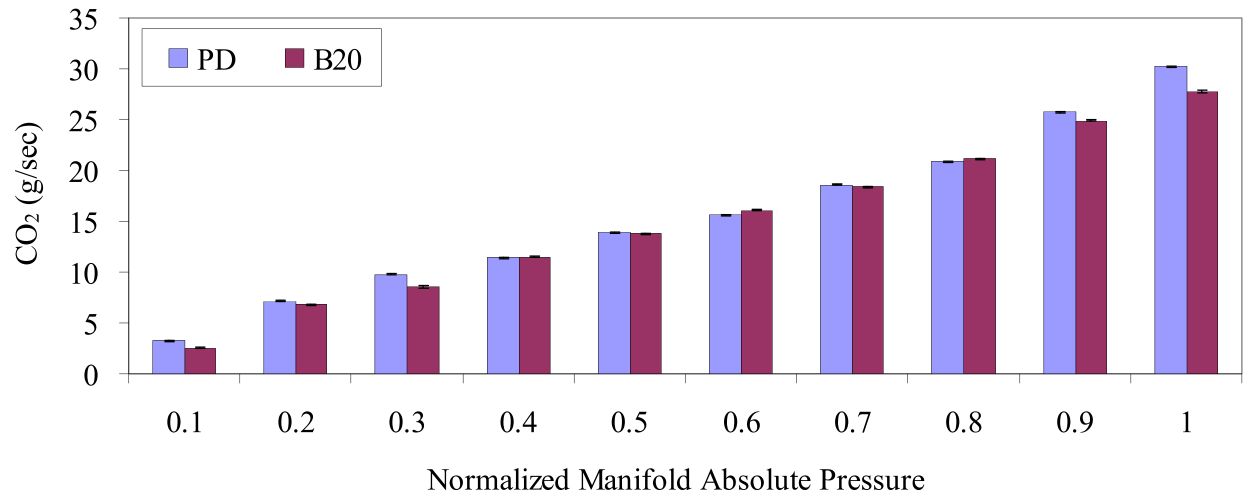


Figure A100. Continued

MOTOR GRADER 1





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 48 ^{o}F and the relative humidity was 43 %. For the B20 biodiesel test, the ambient temperature was 48 ^{o}F and the relative humidity was 38 %.

Values shown in the figure are the upper end of the range: "0.1" = $0 \leq$ Normalized MAP < 0.1; "0.2" = $0.1 \leq$ Normalized MAP < 0.2, and so on.

Figure A101. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Motor Grader 1 (continued on next page)

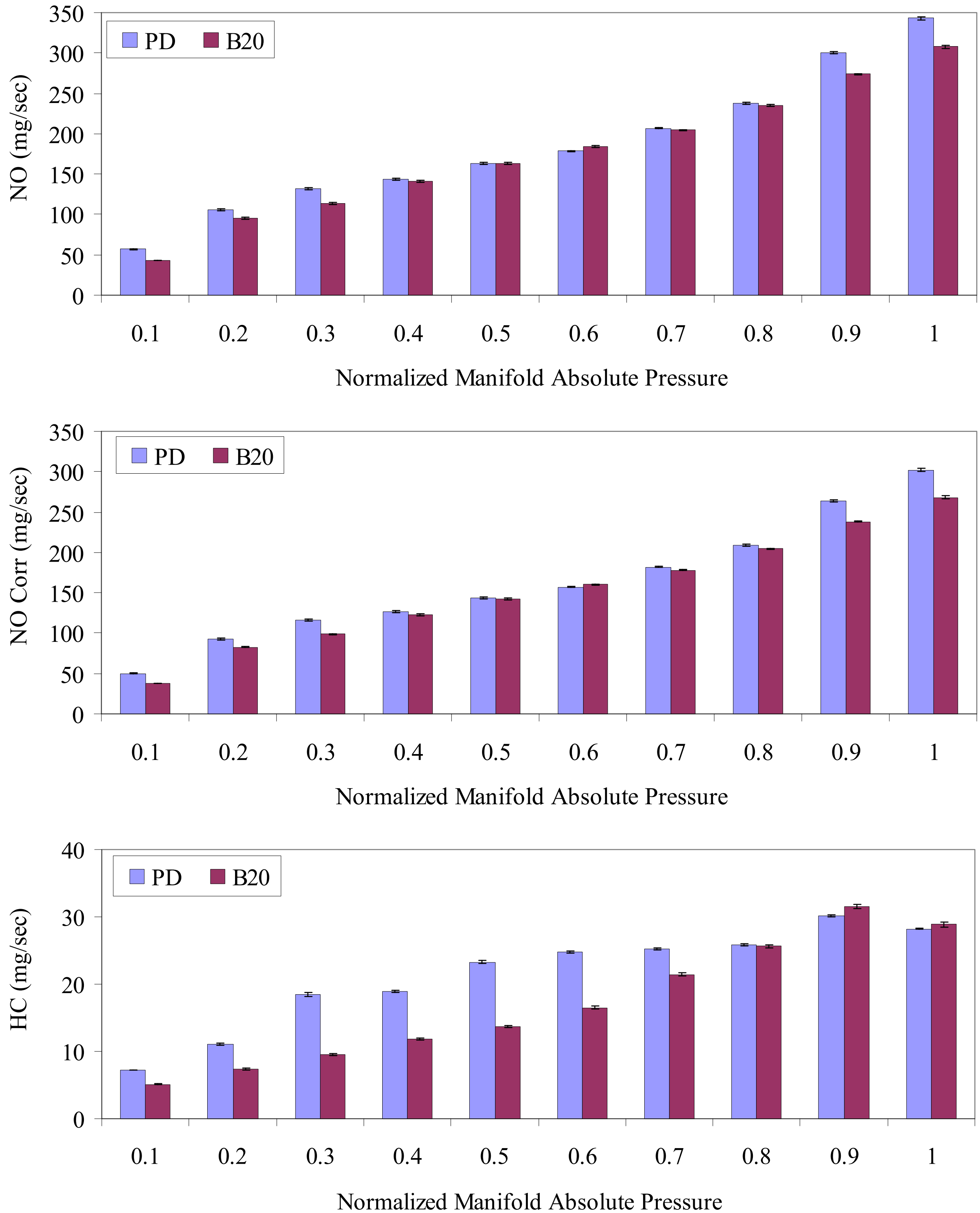
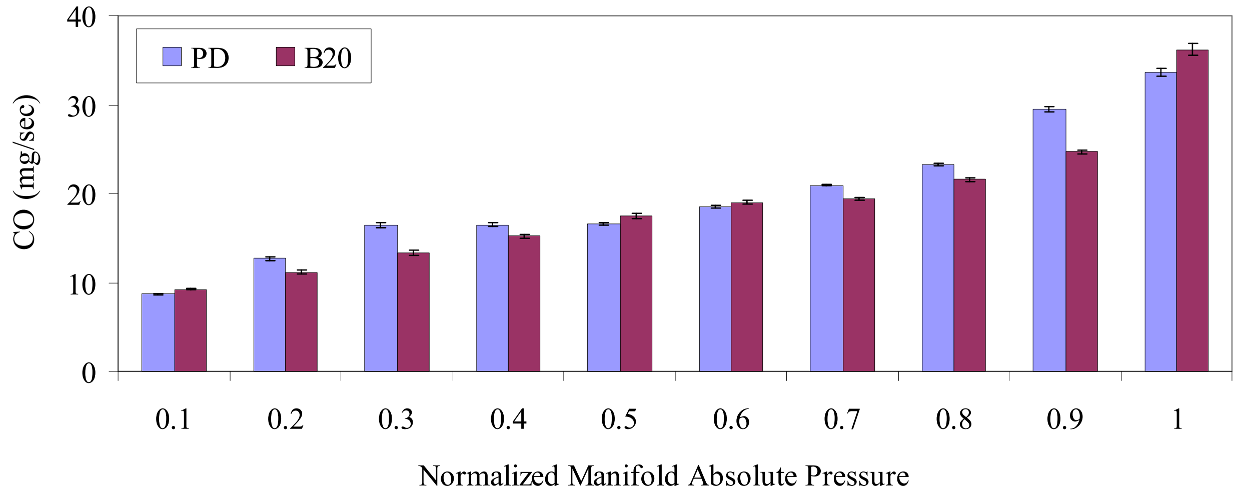


Figure A101. Continued



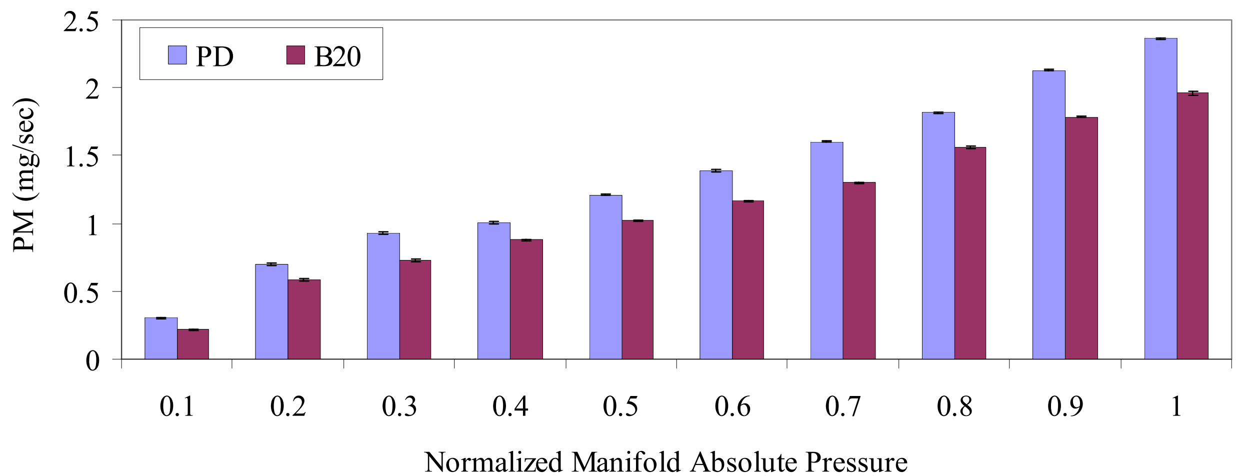
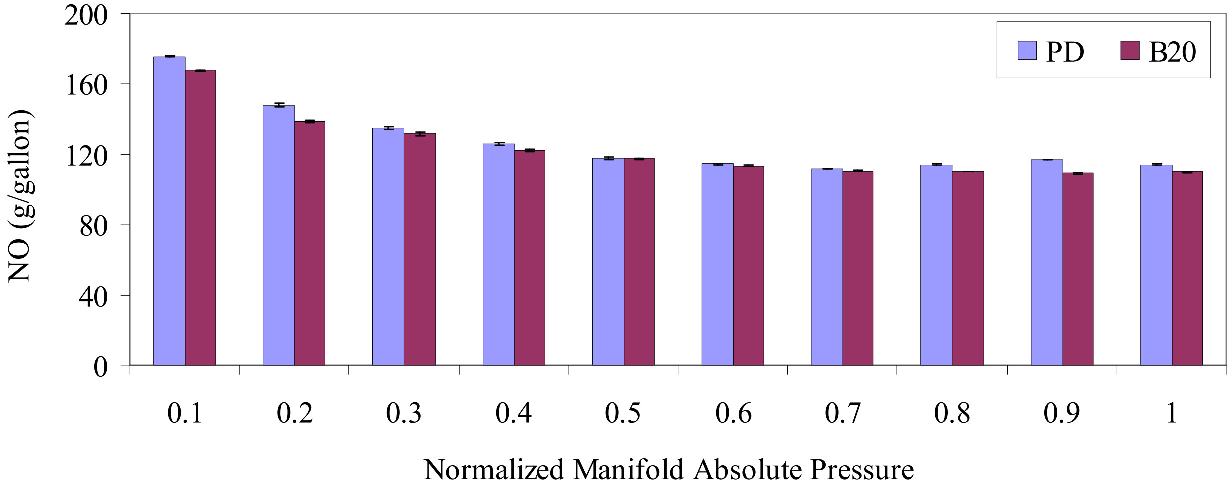
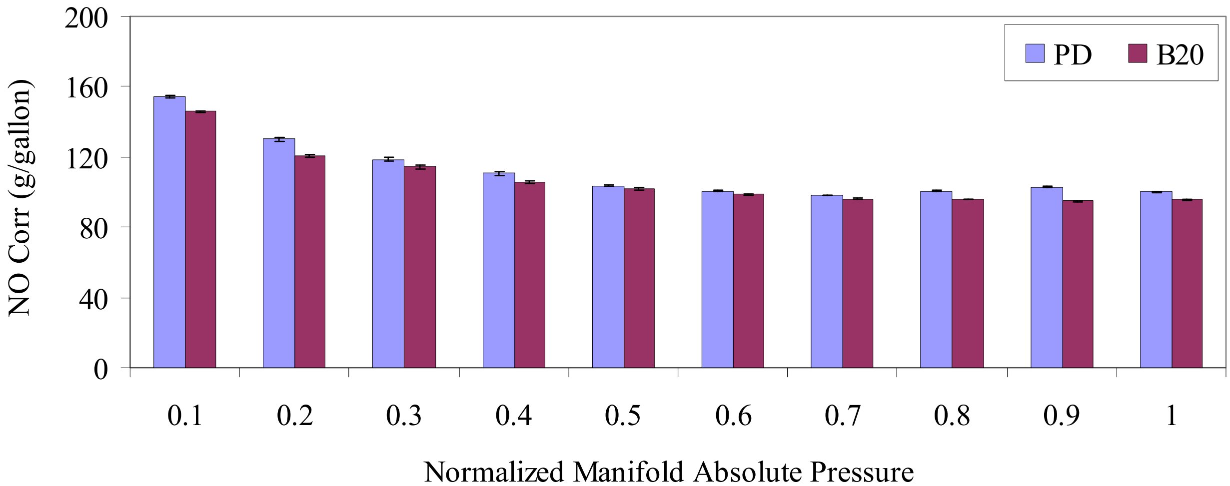


Figure A101. Continued

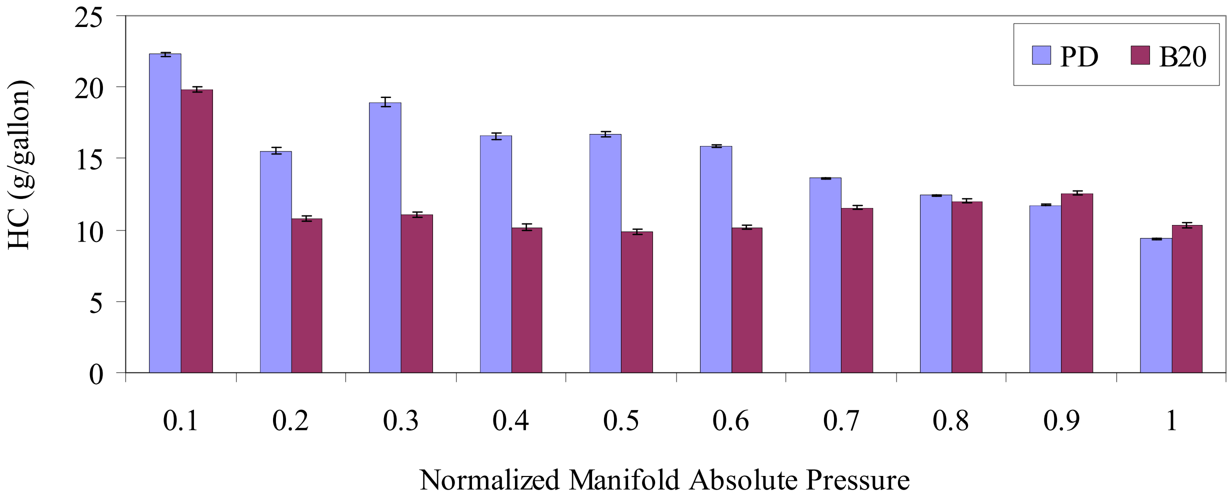


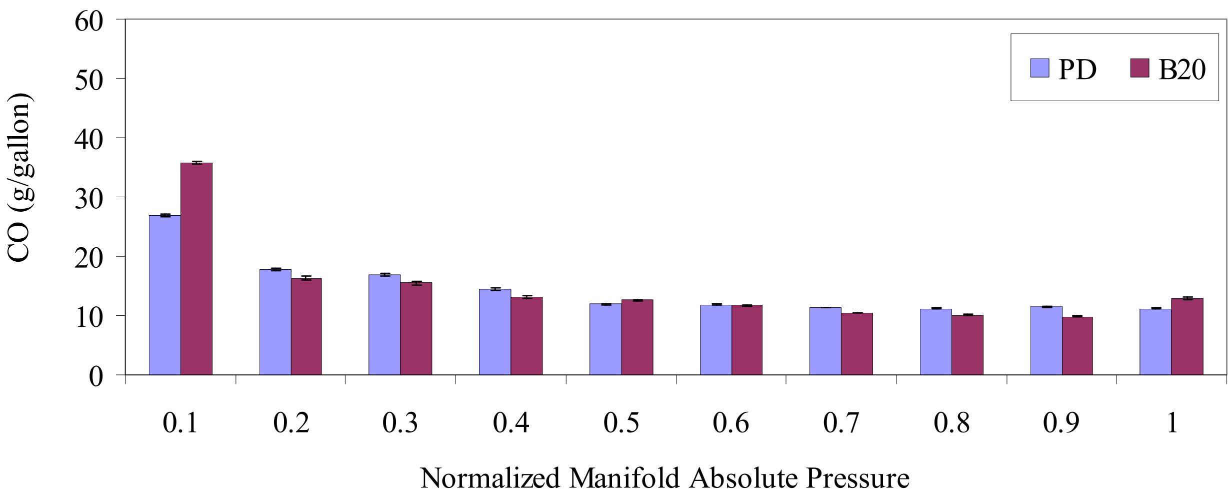


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 48 ^{o}F and the relative humidity was 43 %. For the B20 biodiesel test, the ambient temperature was 48 ^{o}F and the relative humidity was 38 %.

Values shown in the figure are the upper end of the range: "0.1" = $0 \leq$ Normalized MAP < 0.1; "0.2" = $0.1 \leq$ Normalized MAP < 0.2, and so on.

Figure A102. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Motor Grader 1 (continued on next page)





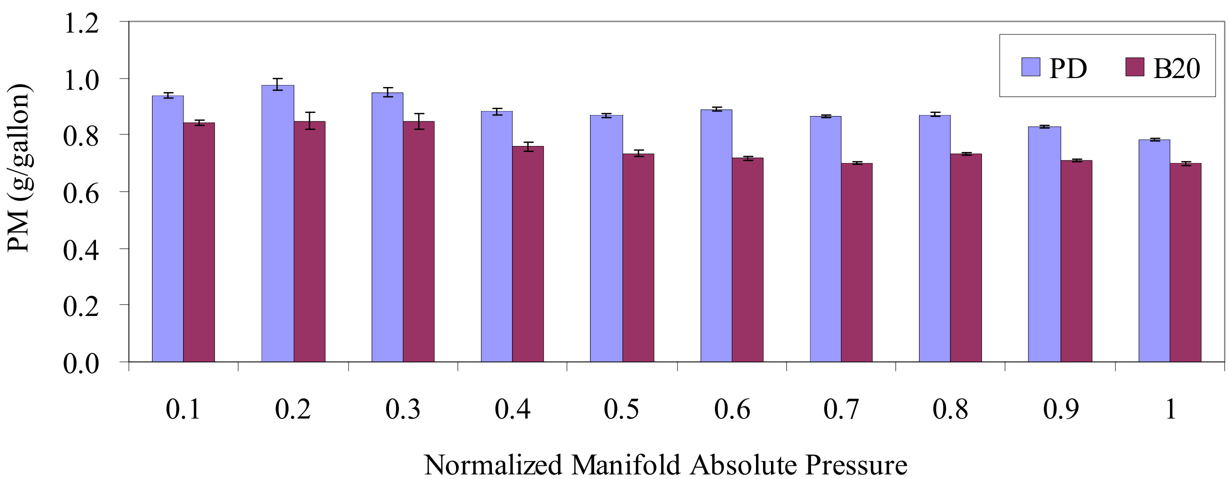
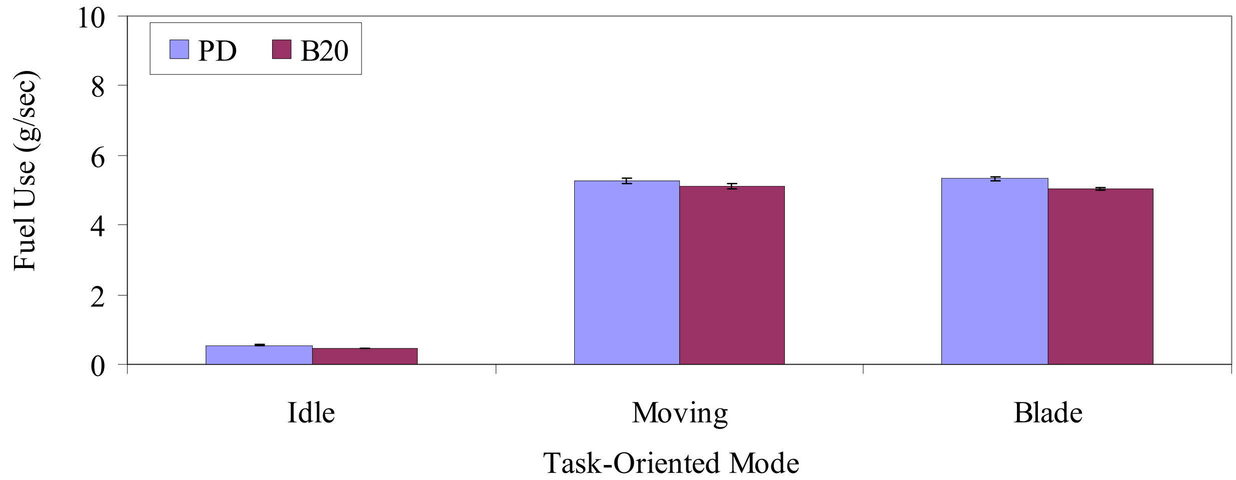
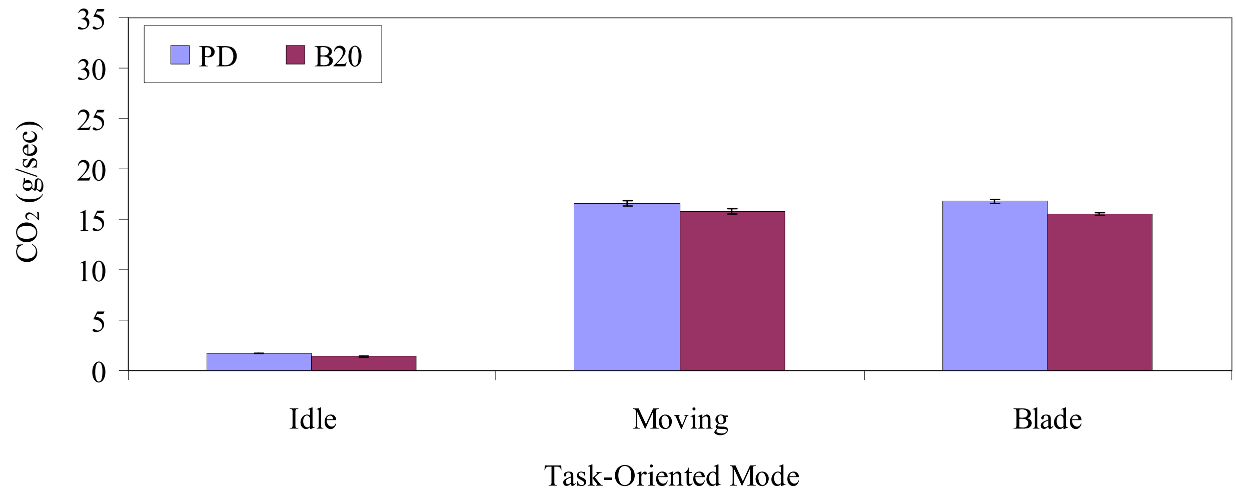


Figure A102. Continued

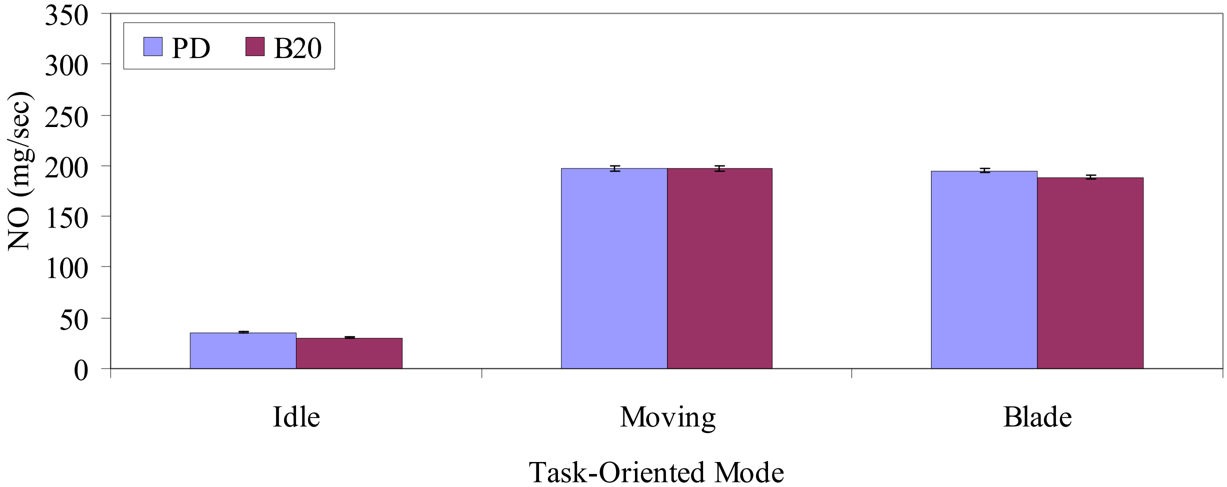


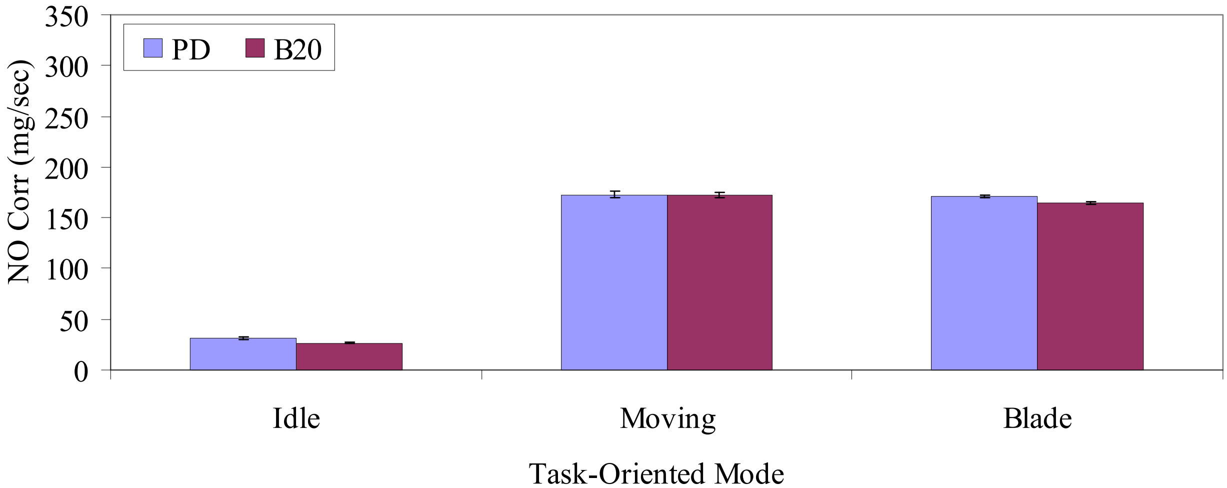


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 48 ^{o}F and the relative humidity was 43 %. For the B20 biodiesel test, the ambient temperature was 48 ^{o}F and the relative humidity was 38 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A103. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Motor Grader 1 (continued on next page)





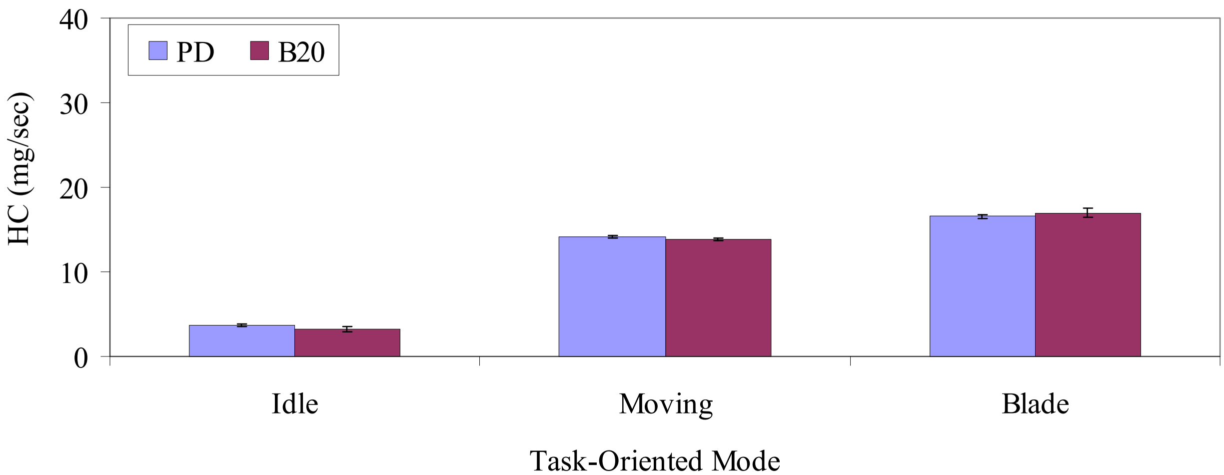
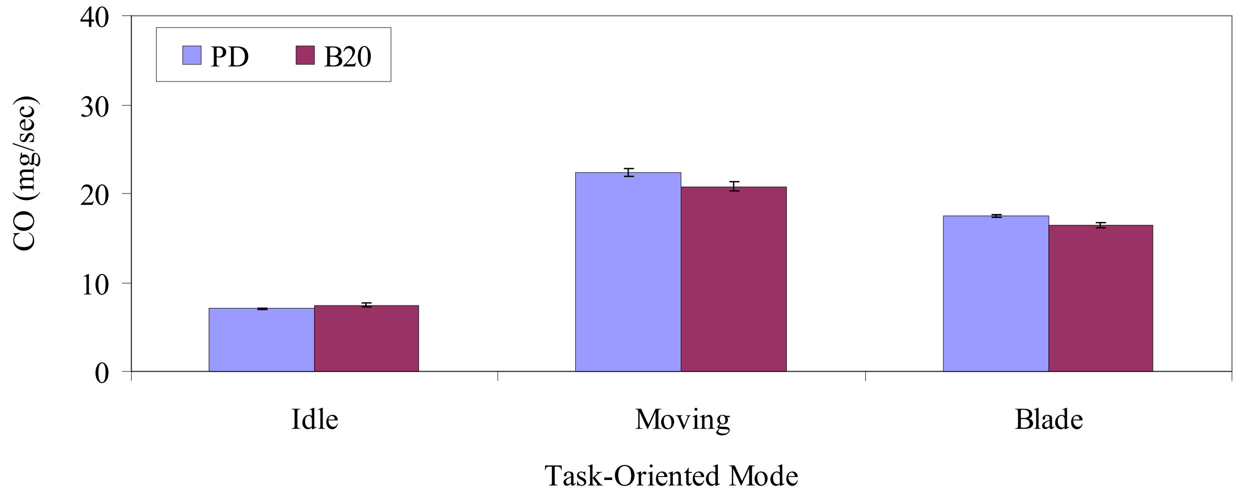


Figure A103. Continued



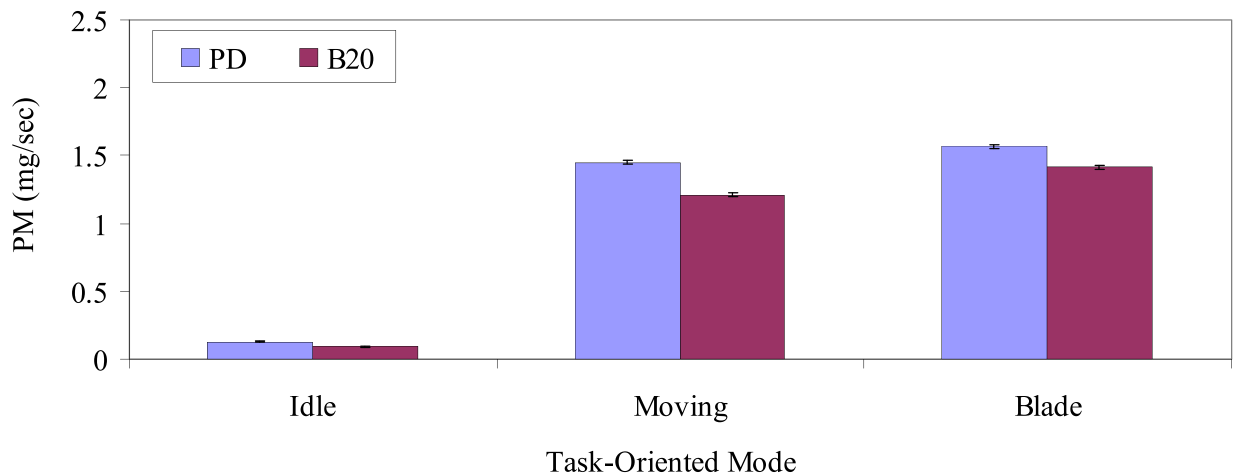
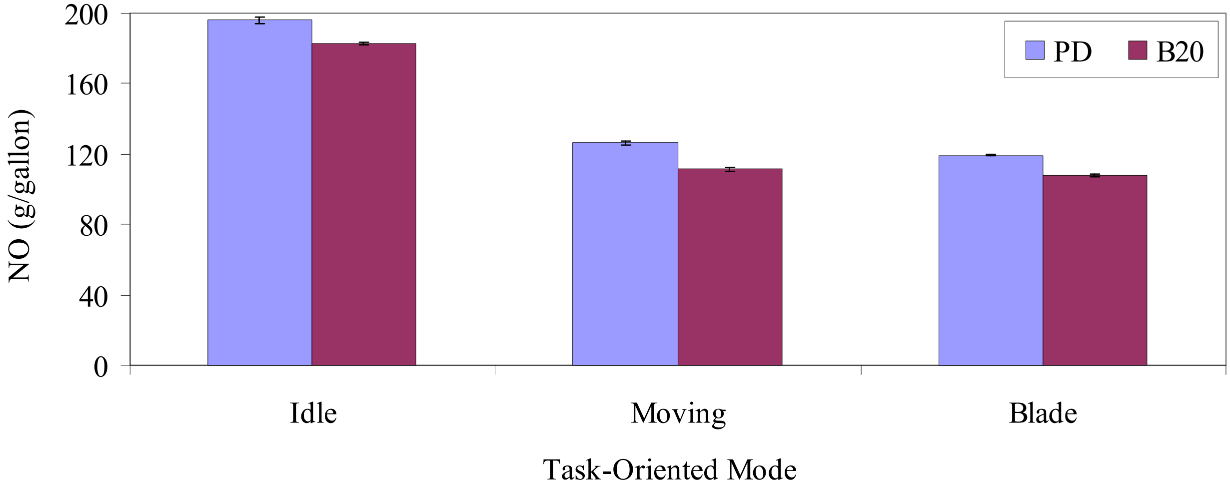
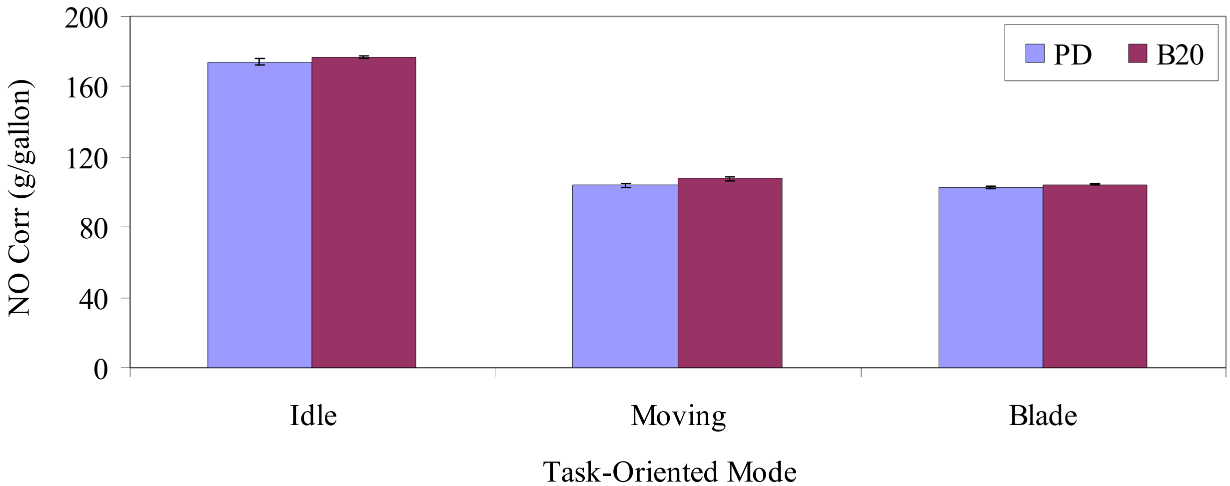


Figure A103. Continued

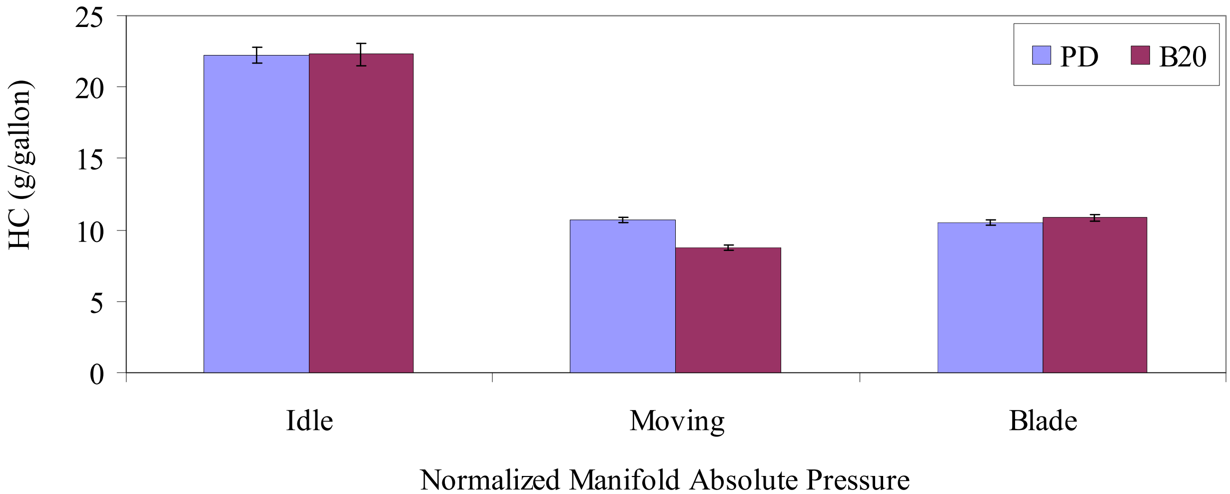


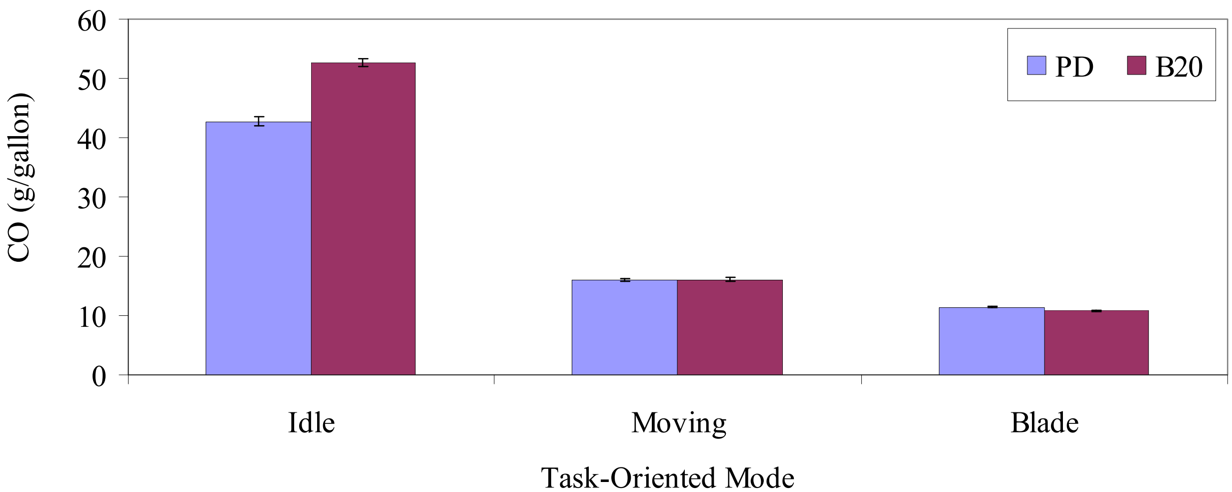


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 48 ^{o}F and the relative humidity was 43 %. For the B20 biodiesel test, the ambient temperature was 48 ^{o}F and the relative humidity was 38 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A104. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Motor Grader 1 (continued on next page)





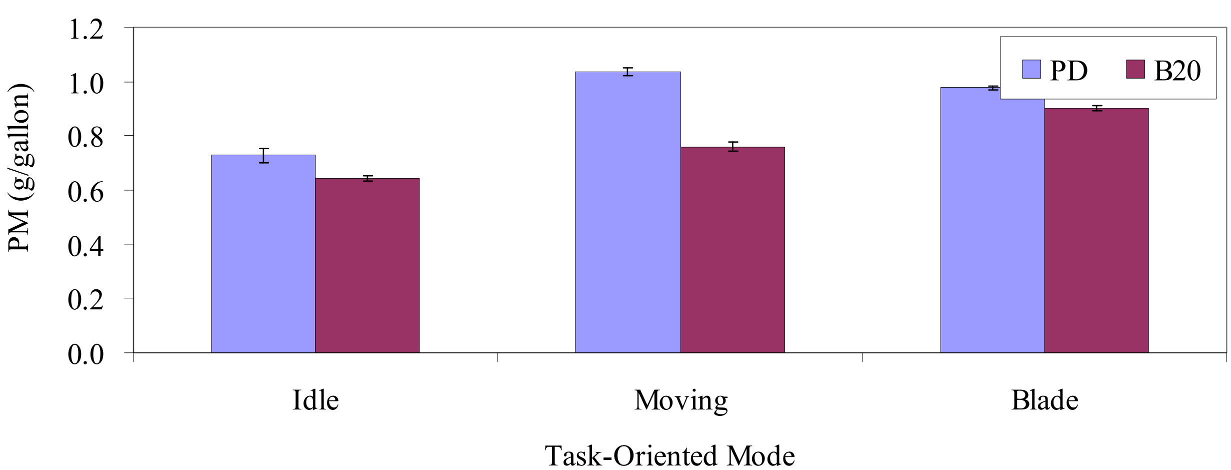
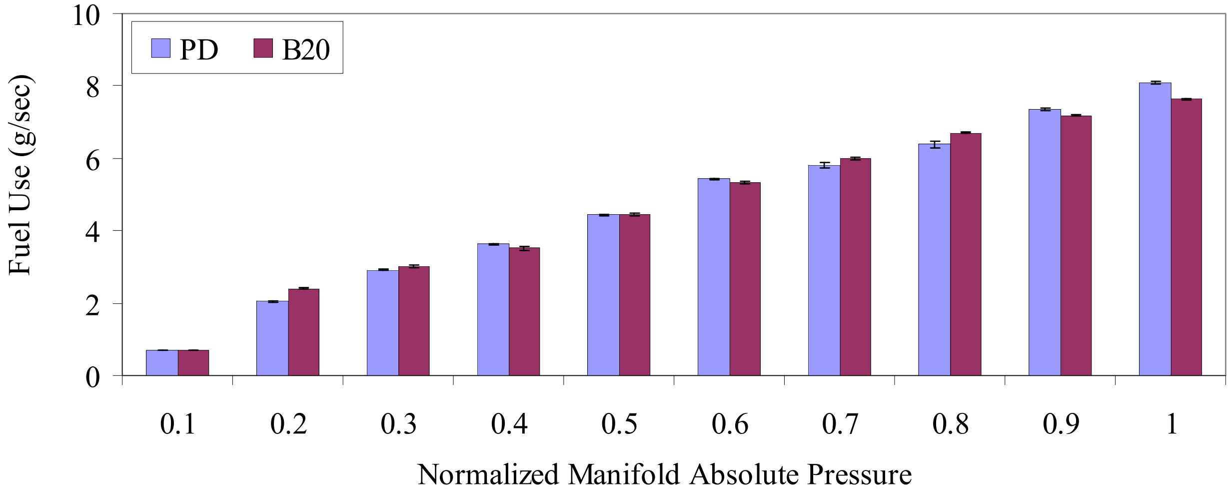
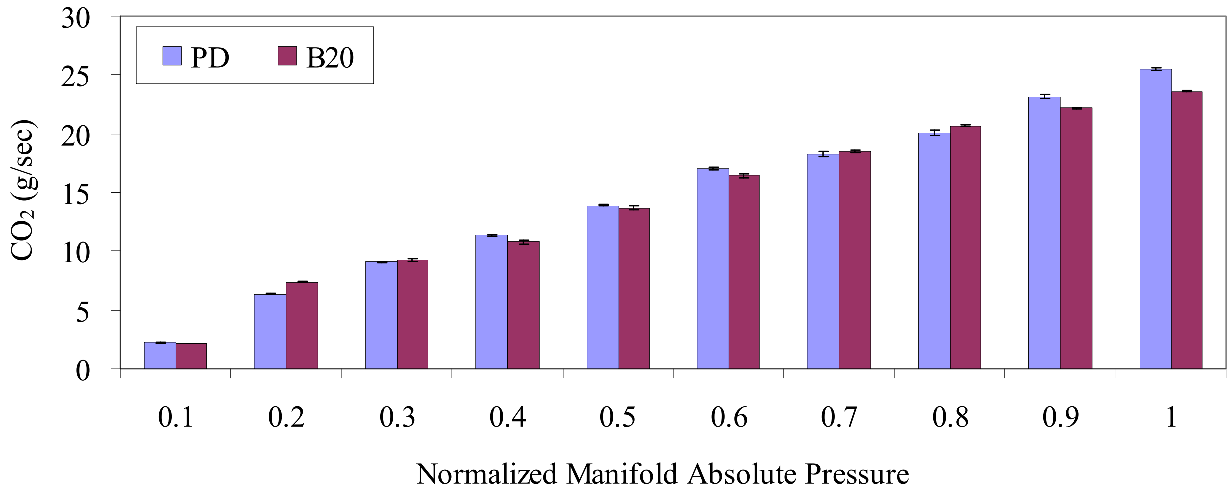


Figure A104. Continued

MOTOR GRADER 2

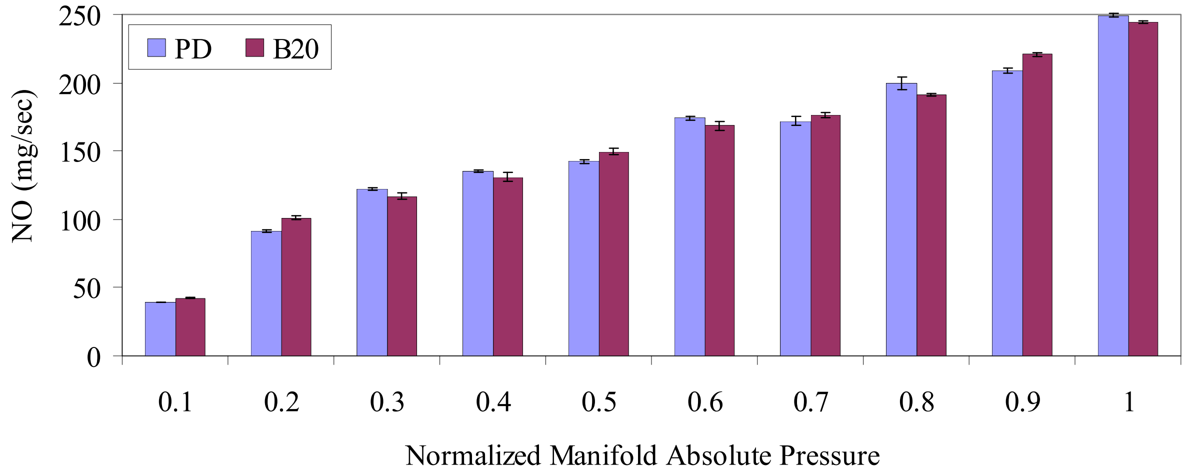


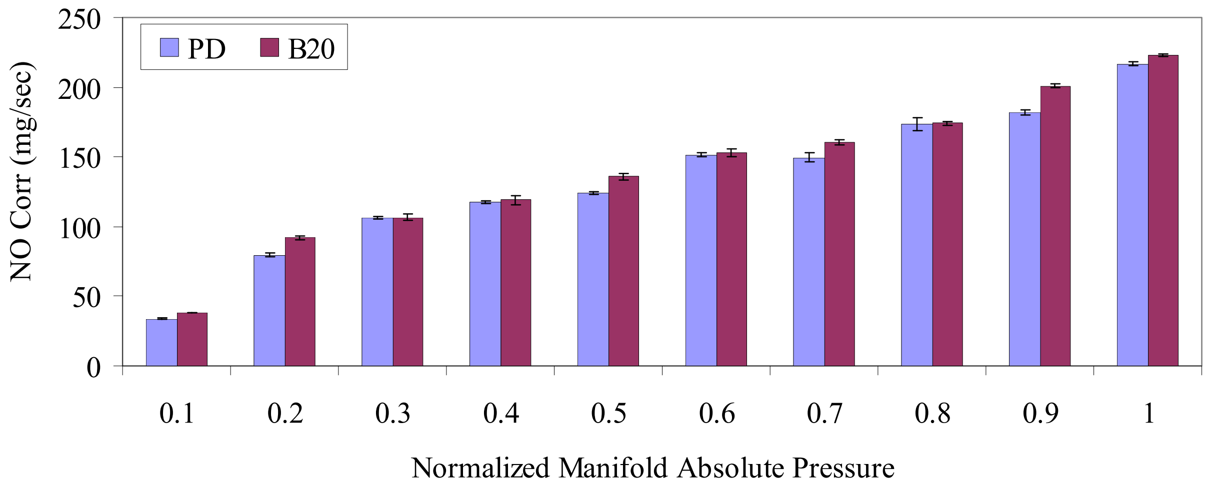


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 47 ^{o}F and the relative humidity was 42 %. For the B20 biodiesel test, the ambient temperature was 64 ^{o}F and the relative humidity was 44 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A105. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Motor Grader 2 (continued on next page)





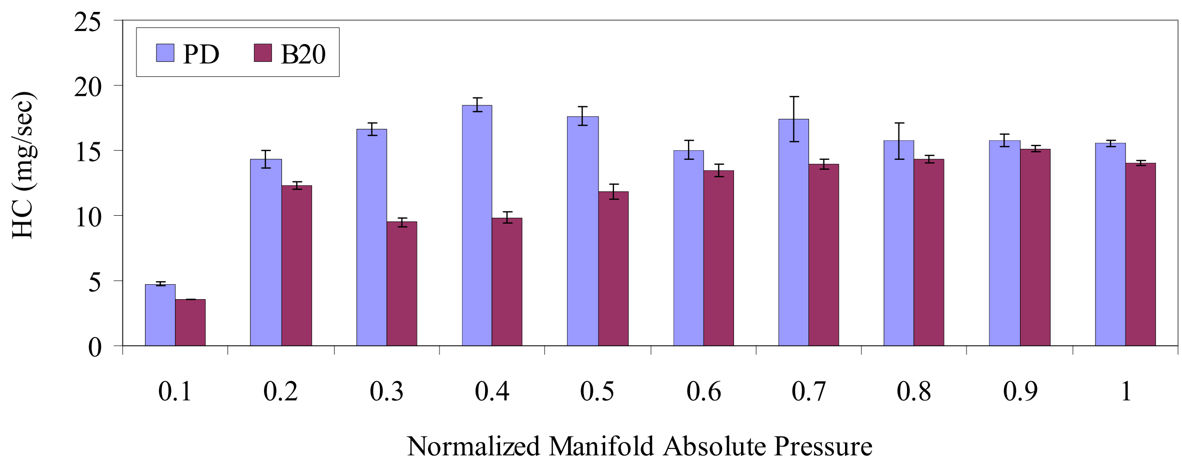
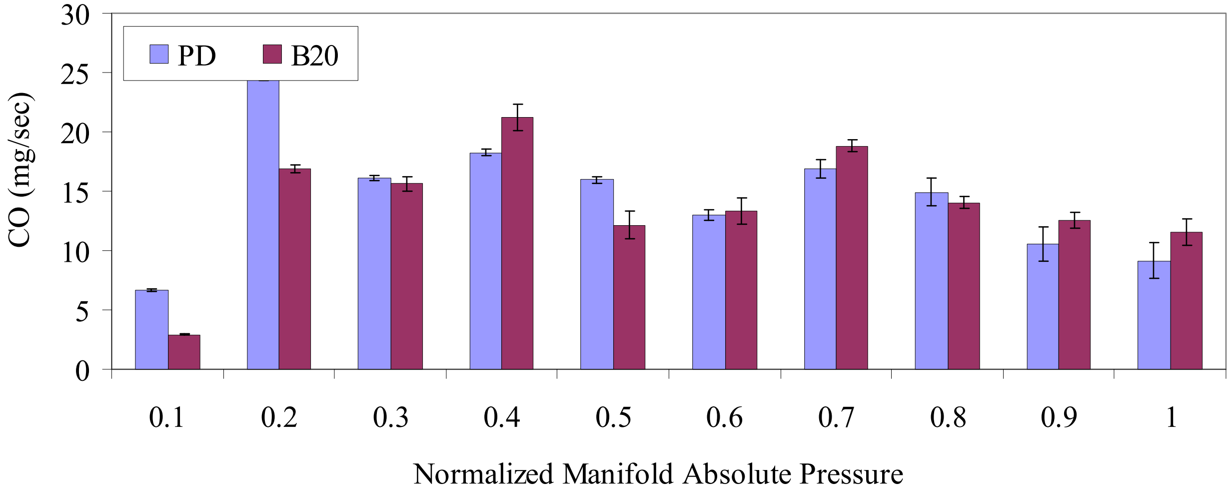


Figure A105. Continued



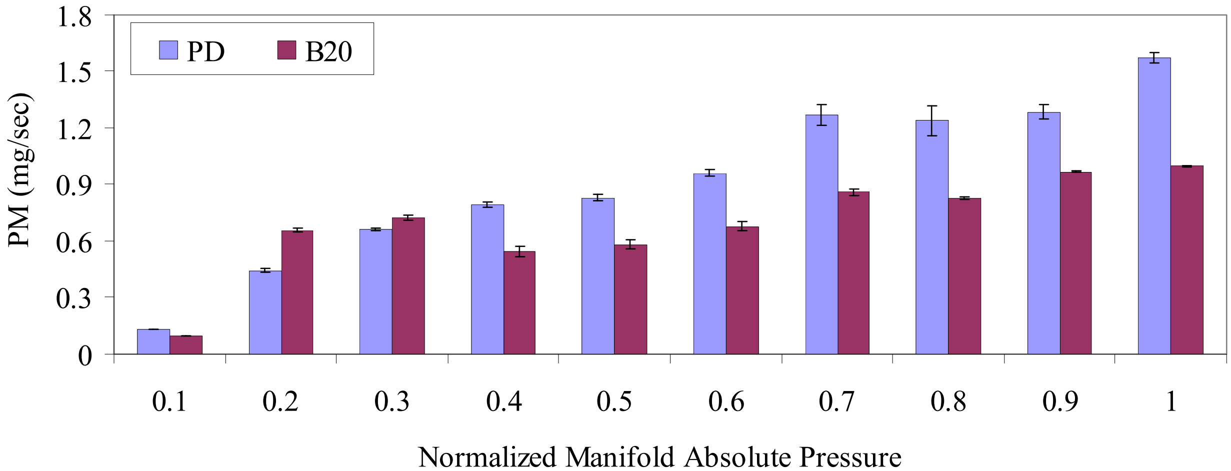
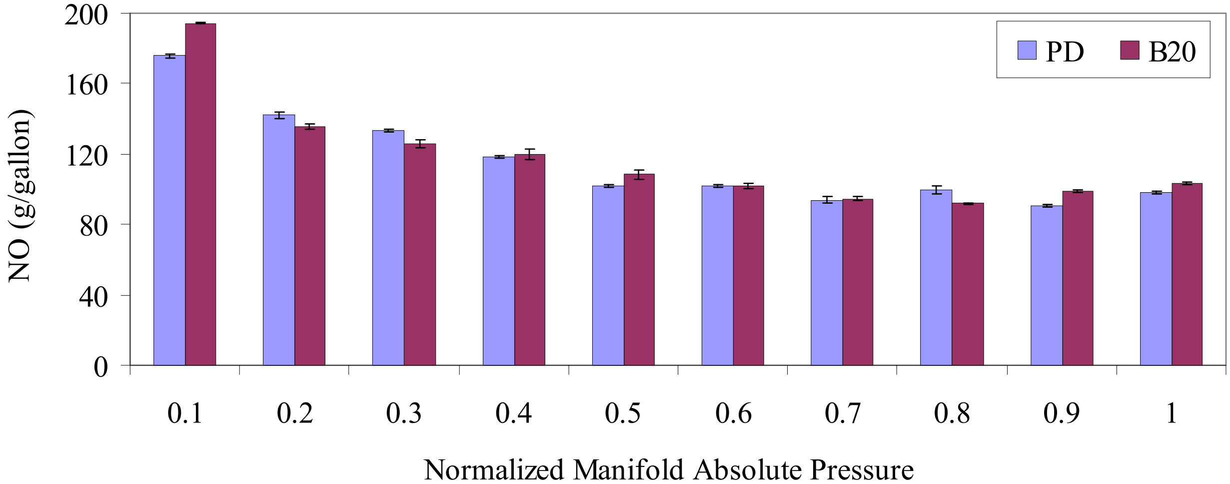
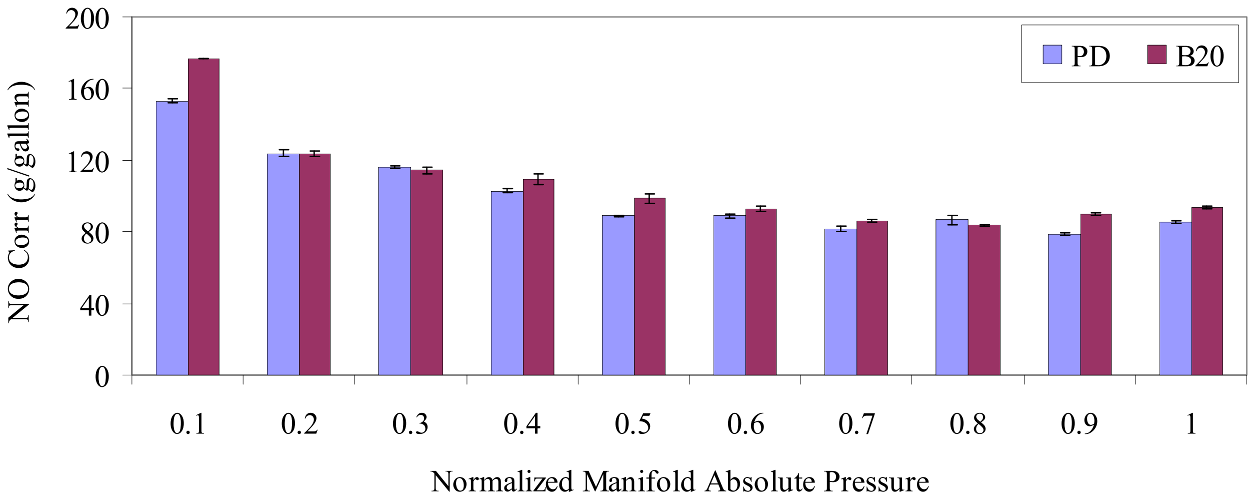


Figure A105. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 47 ^{o}F and the relative humidity was 42 %. For the B20 biodiesel test, the ambient temperature was 64 ^{o}F and the relative humidity was 44 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A106. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Motor Grader 2 (continued on next page)

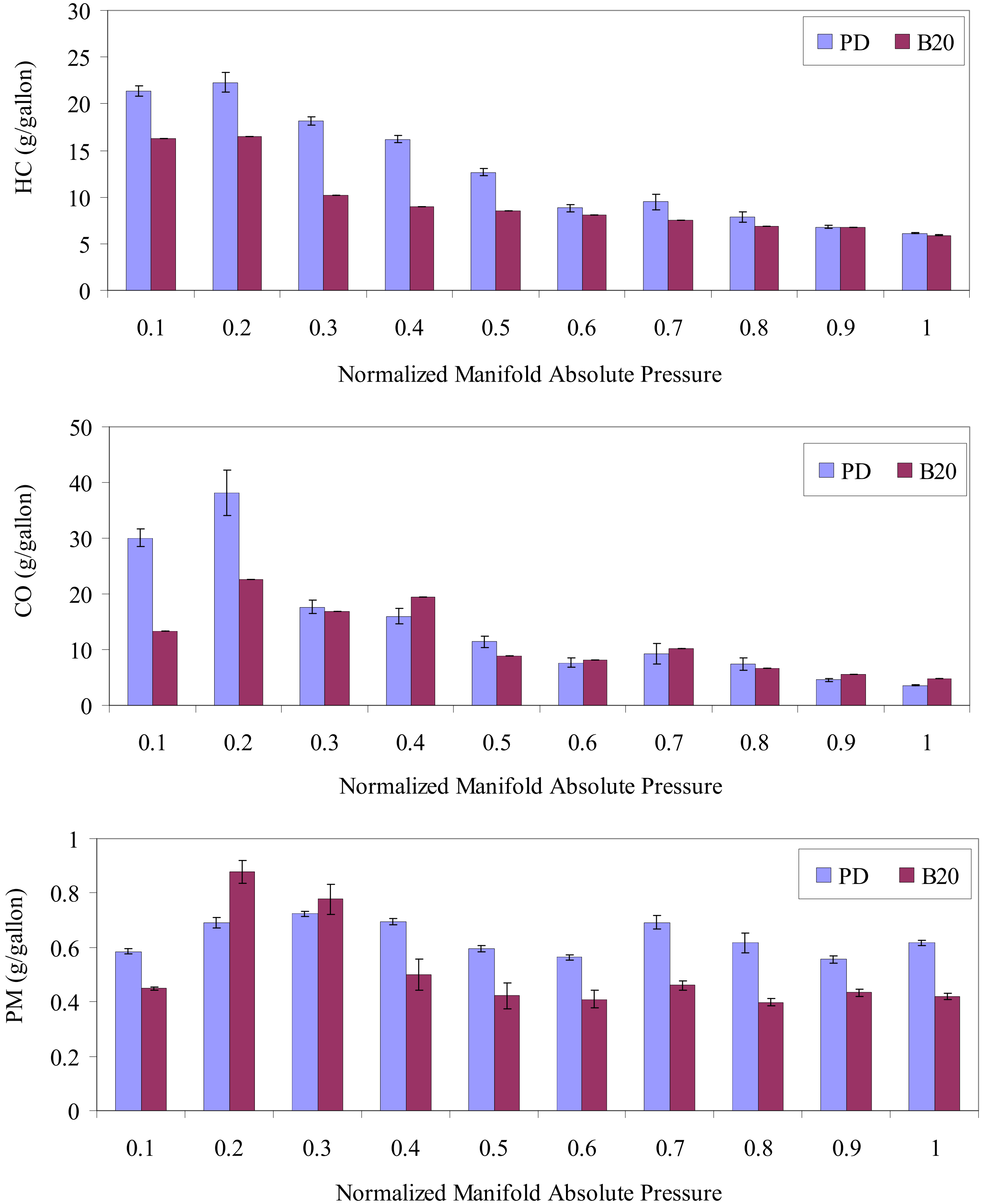
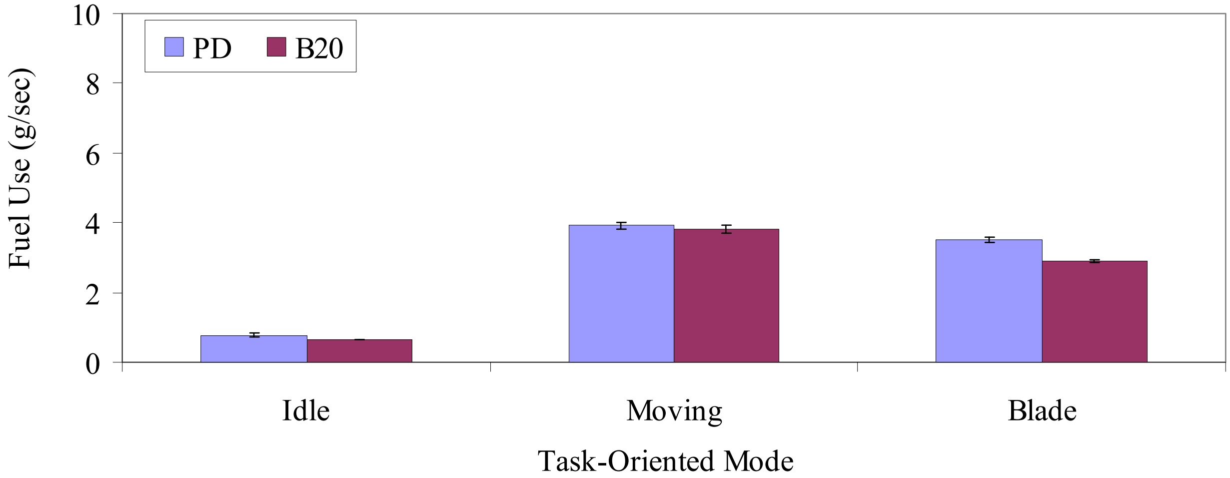
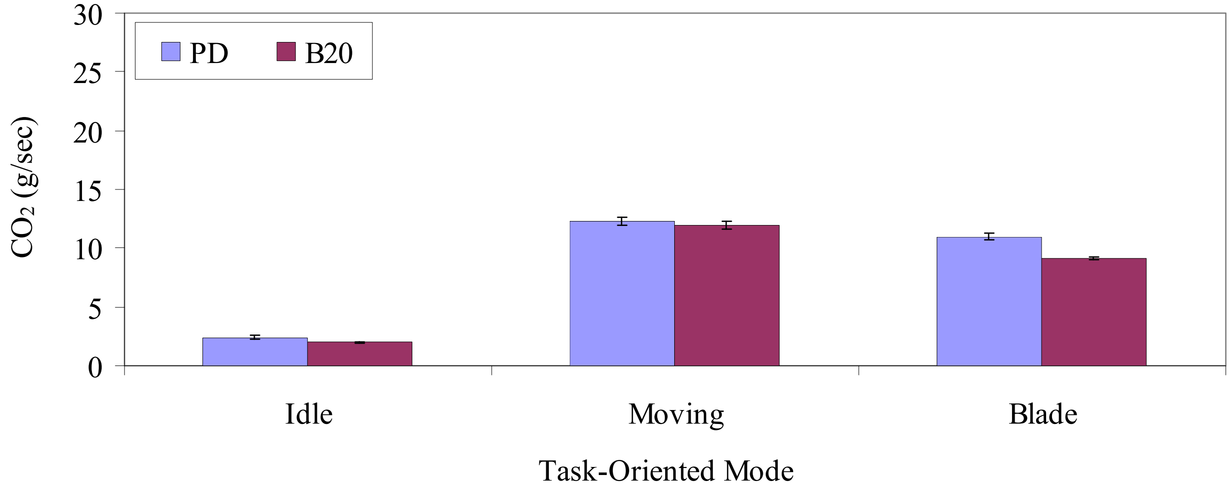


Figure A106. Continued

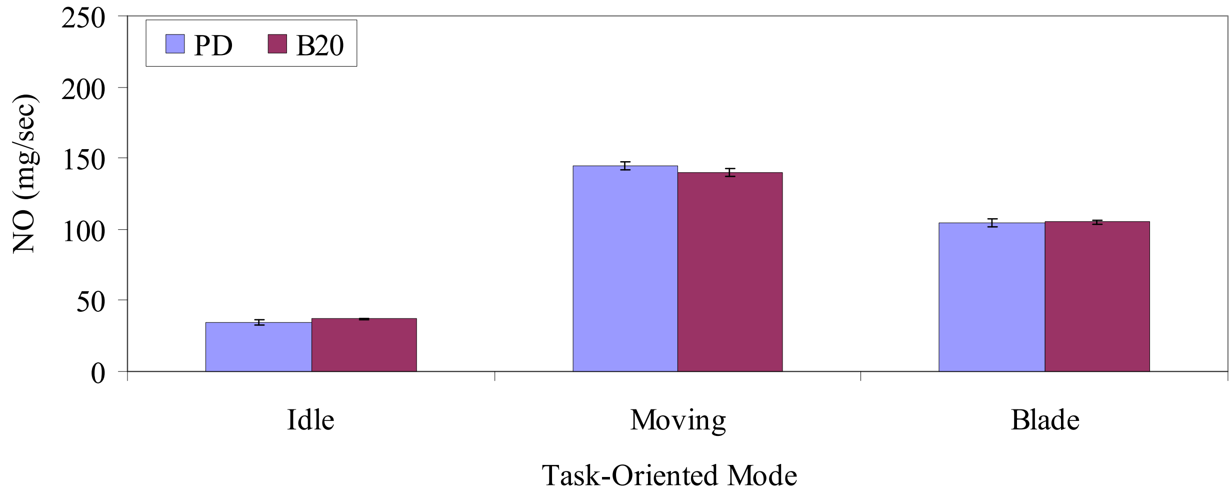


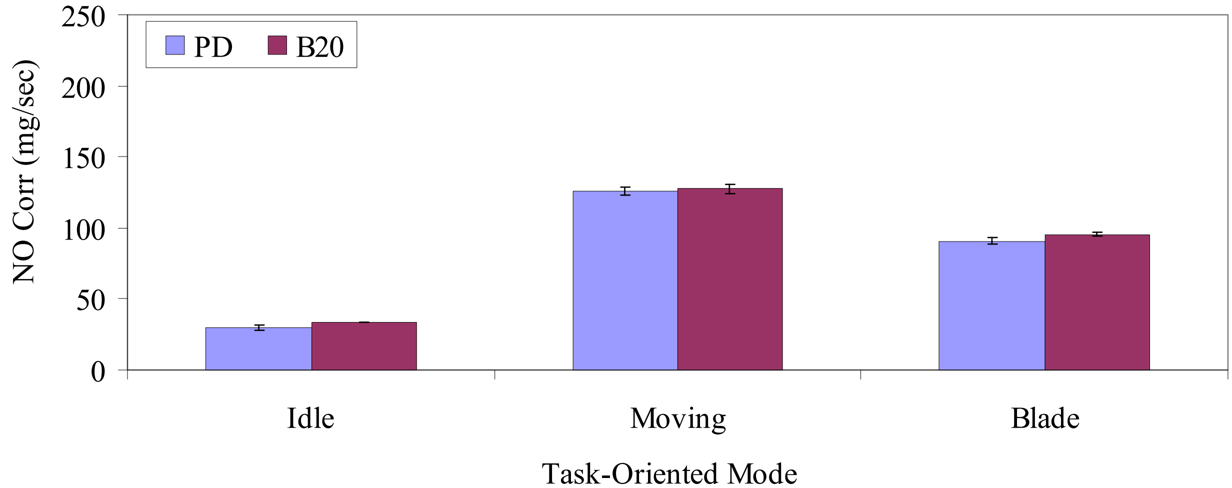


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 47 ^{o}F and the relative humidity was 42 %. For the B20 biodiesel test, the ambient temperature was 64 ^{o}F and the relative humidity was 44 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A107. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Motor Grader 2 (continued on next page)





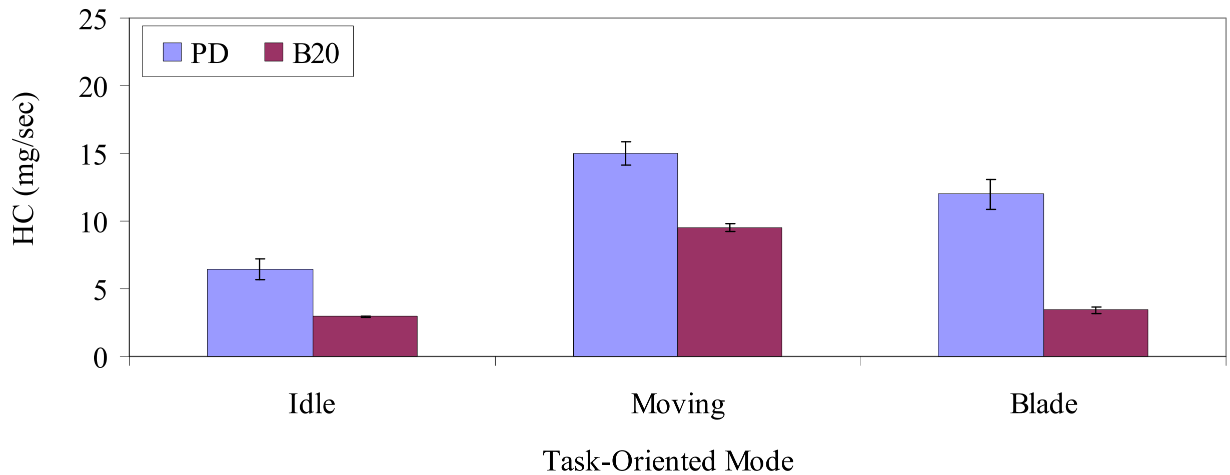


Figure A107. Continued

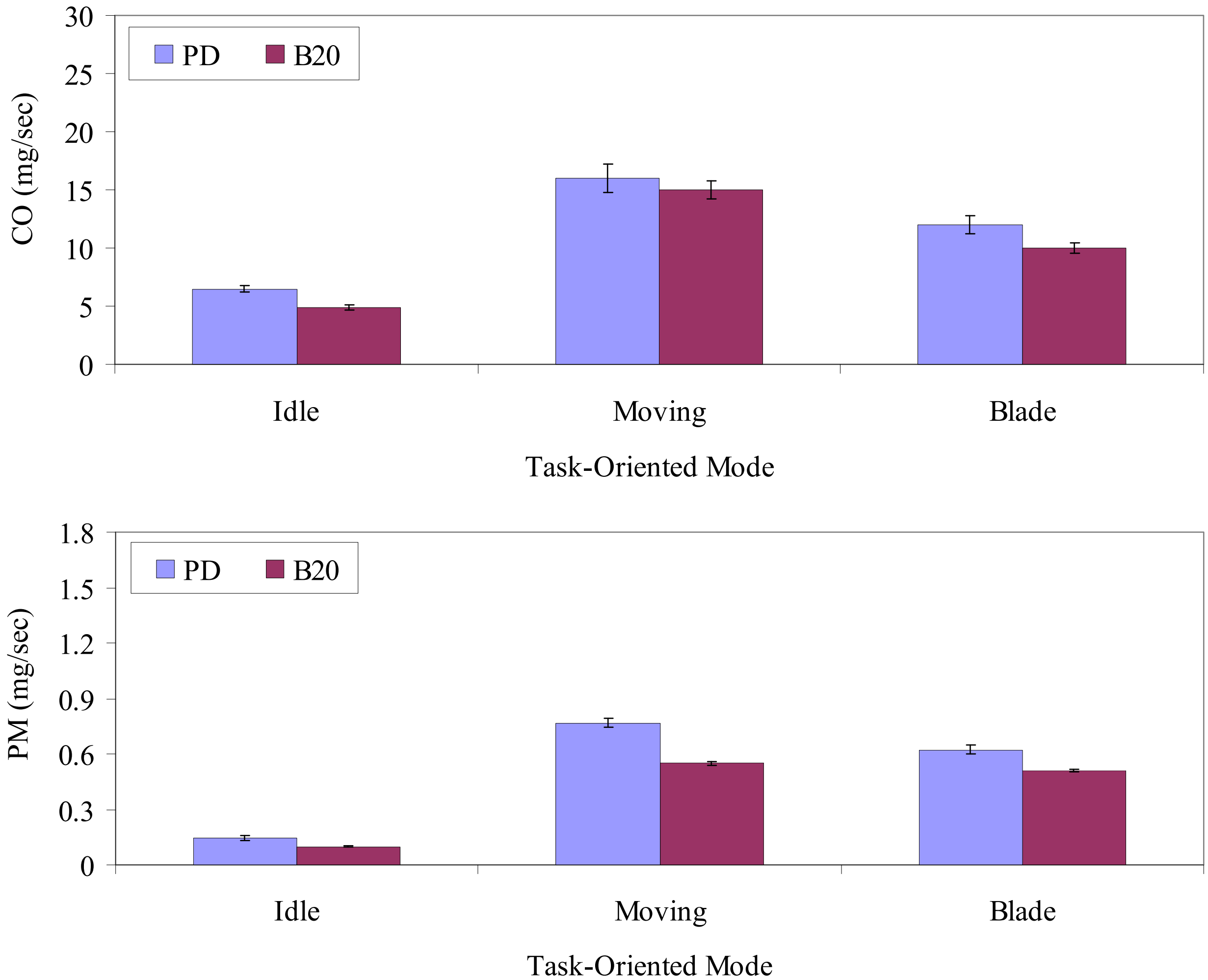
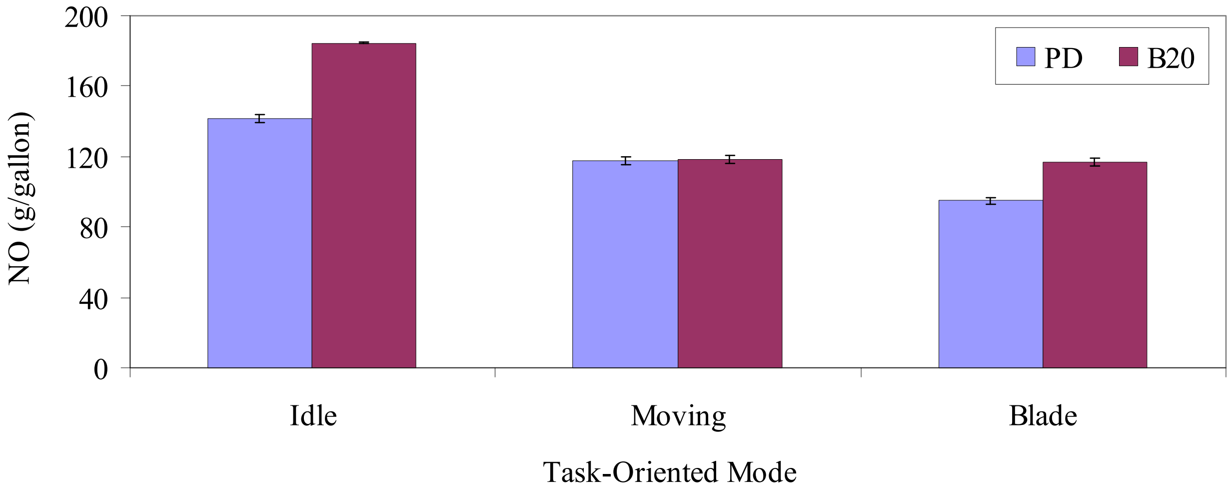
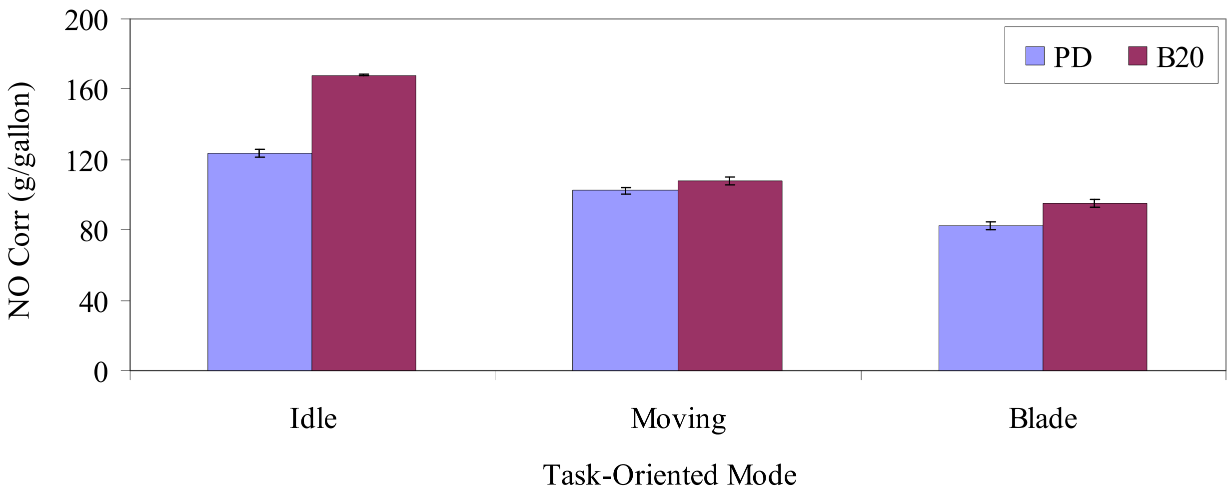


Figure A107. Continued

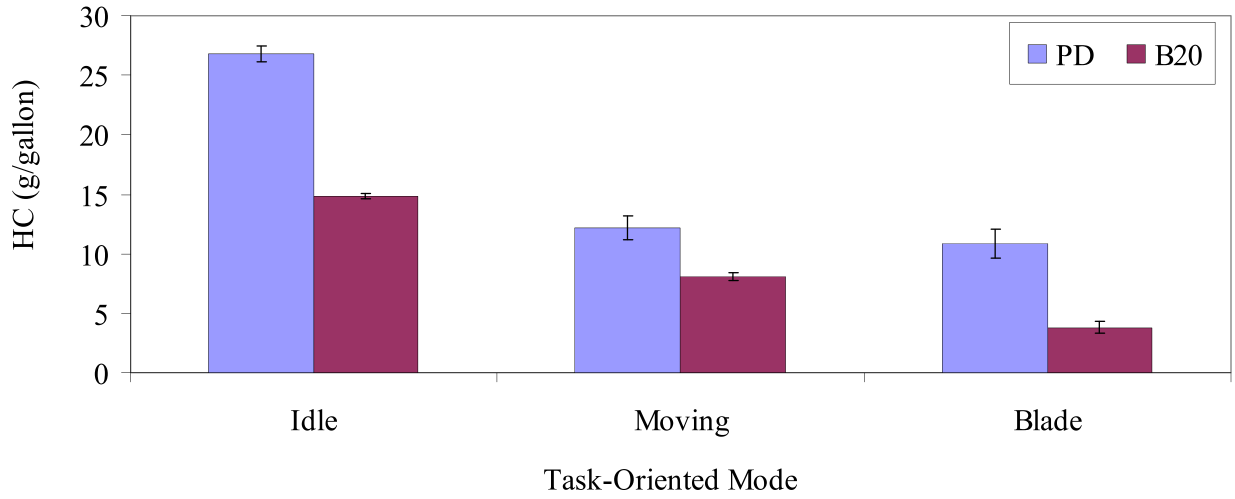


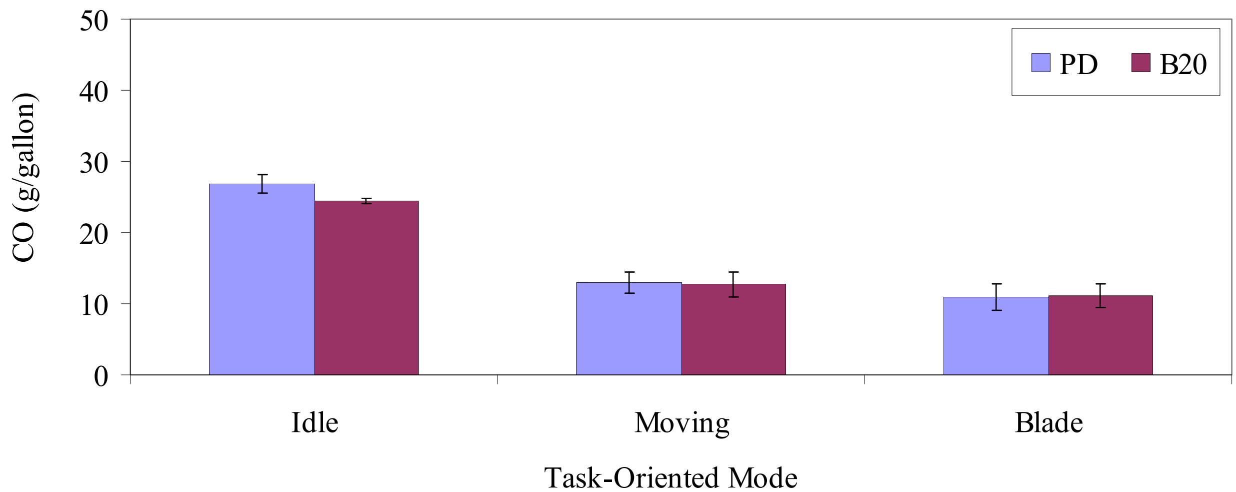


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 47 ^{o}F and the relative humidity was 42 %. For the B20 biodiesel test, the ambient temperature was 64 ^{o}F and the relative humidity was 44 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A108. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Motor Grader 2 (continued on next page)





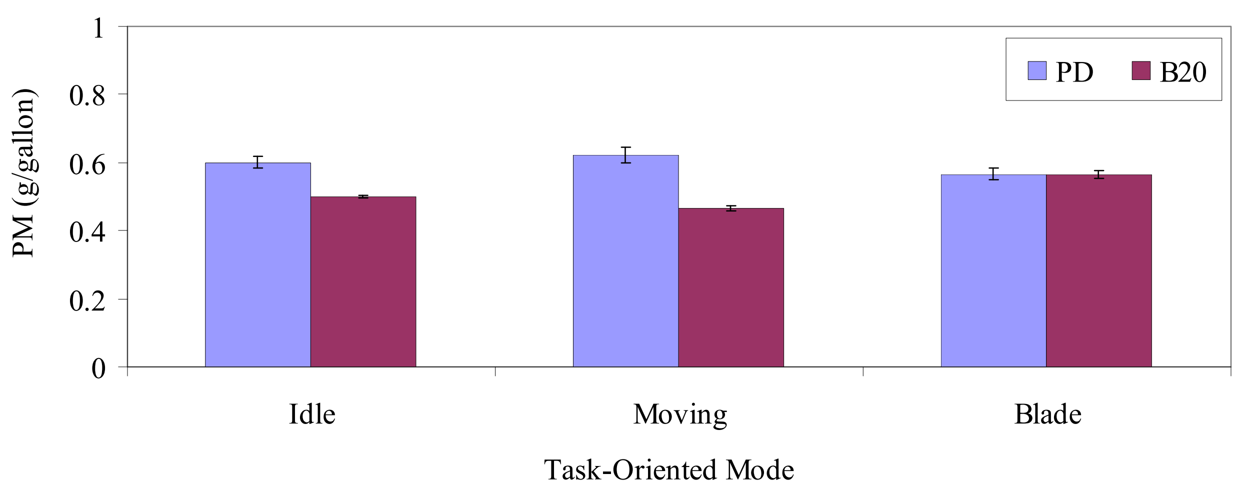
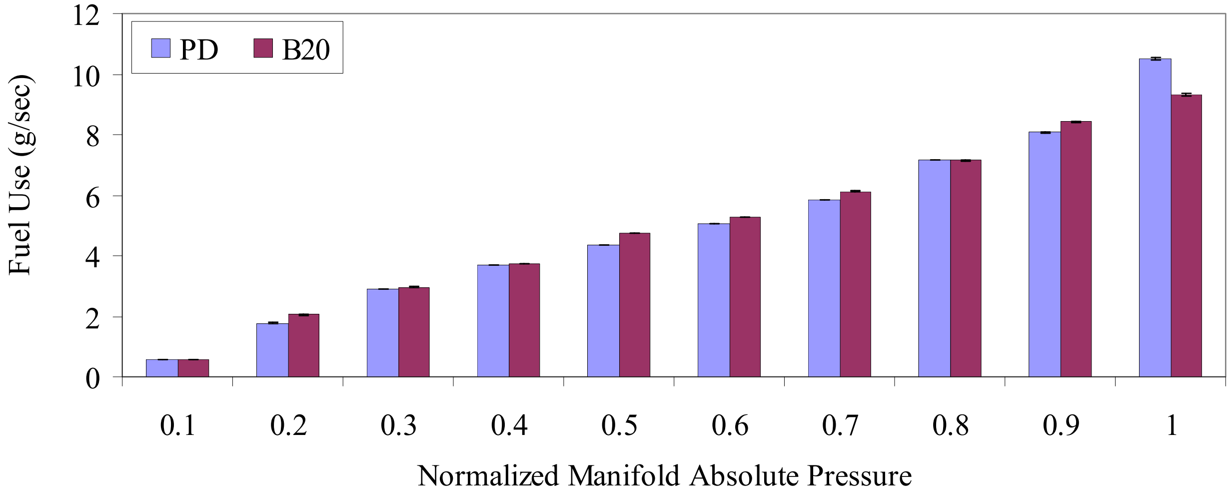
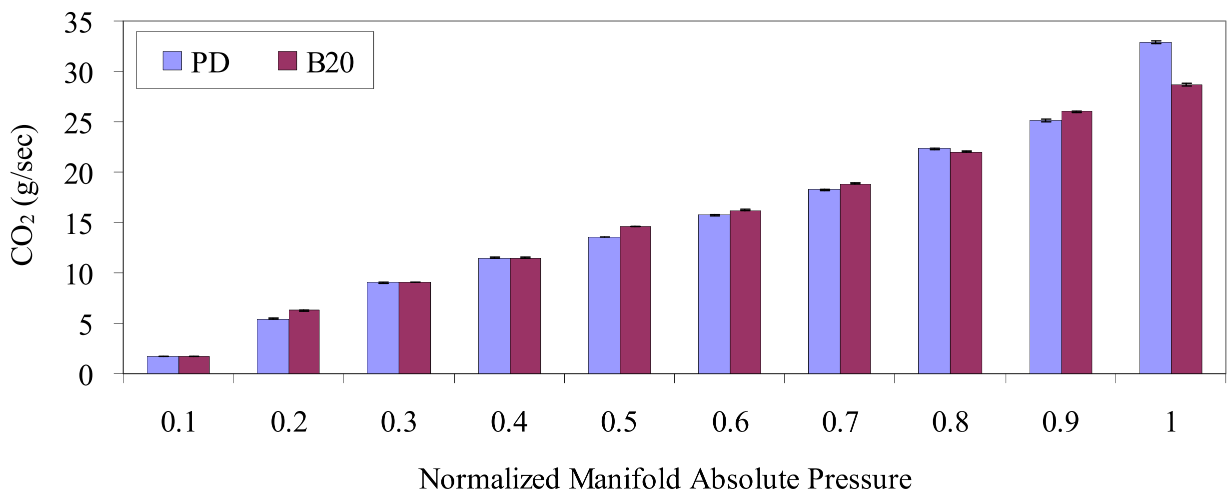


Figure A108. Continued

MOTOR GRADER 3





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 74 ^{o}F and the relative humidity was 54 %. For the B20 biodiesel test, the ambient temperature was 87 ^{o}F and the relative humidity was 63 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A109. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Motor Grader 3 (continued on next page)

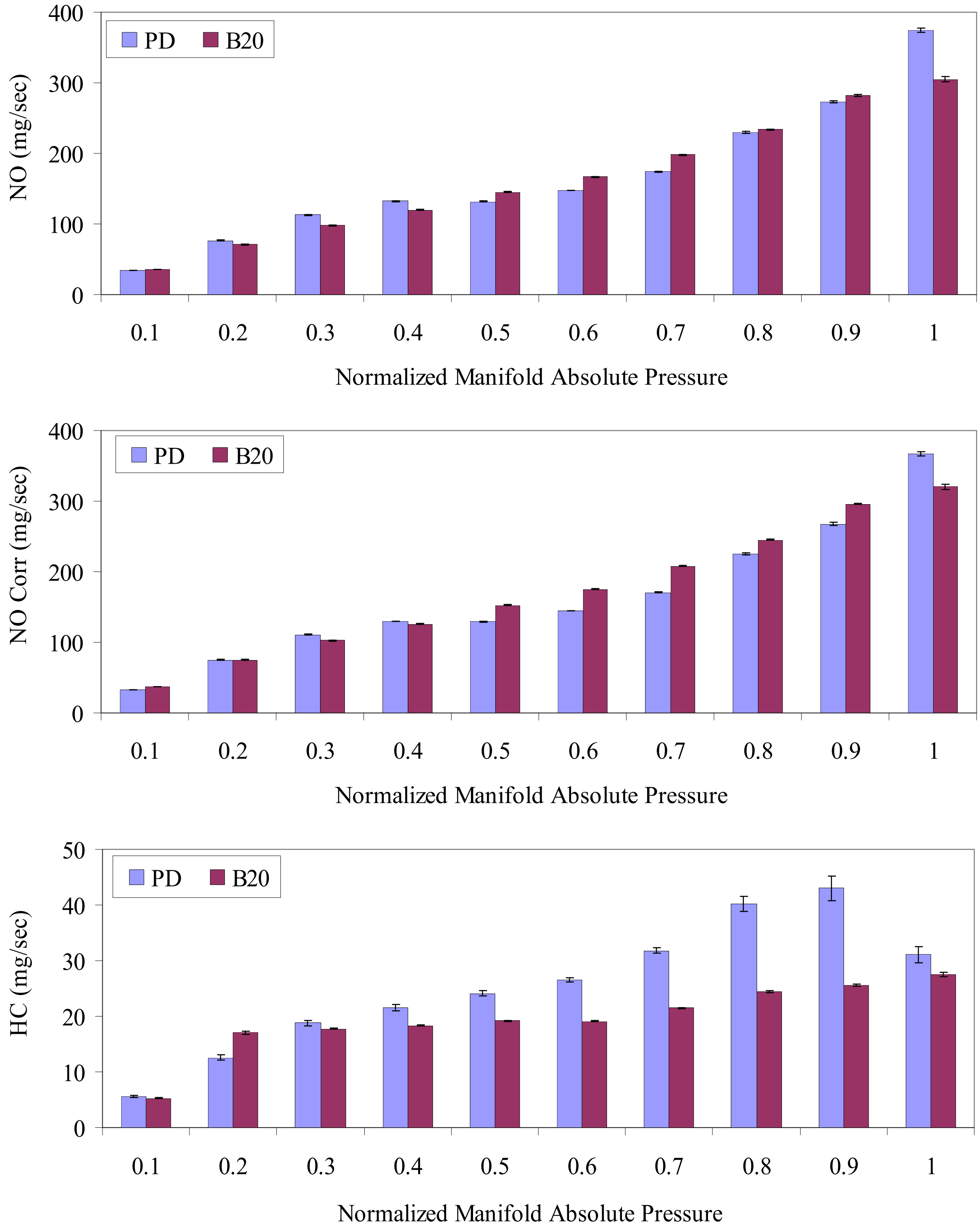
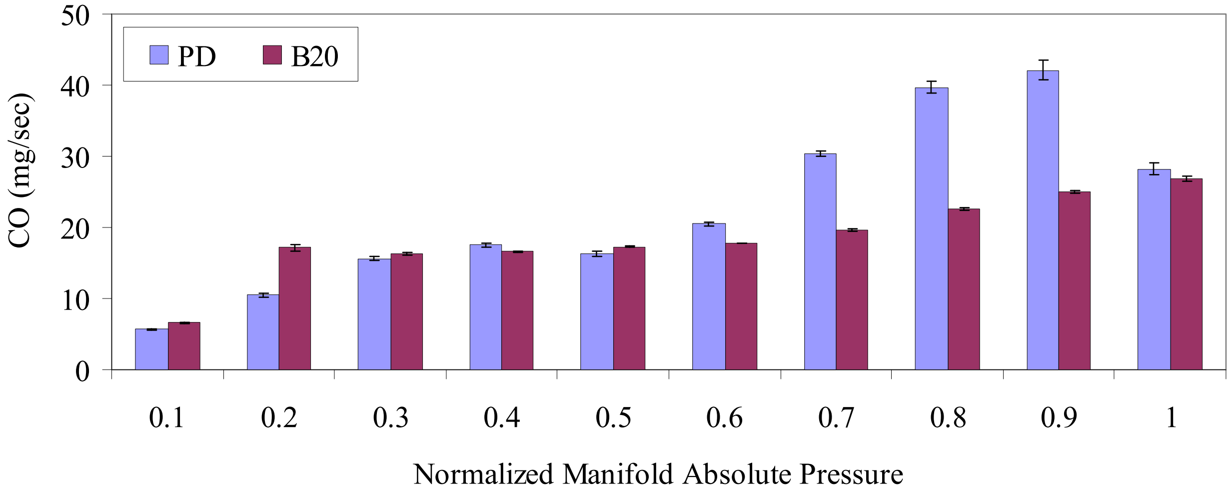


Figure A109. Continued



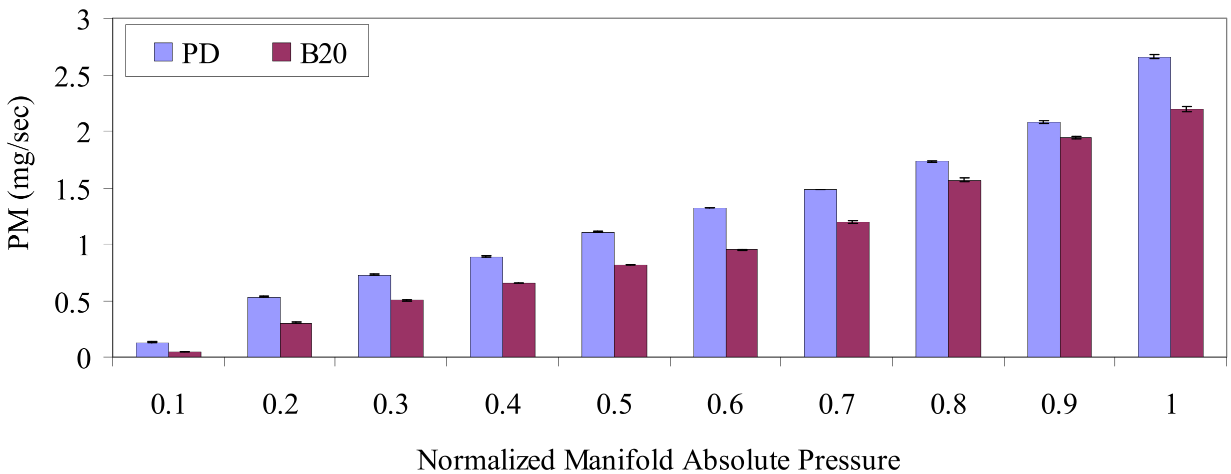
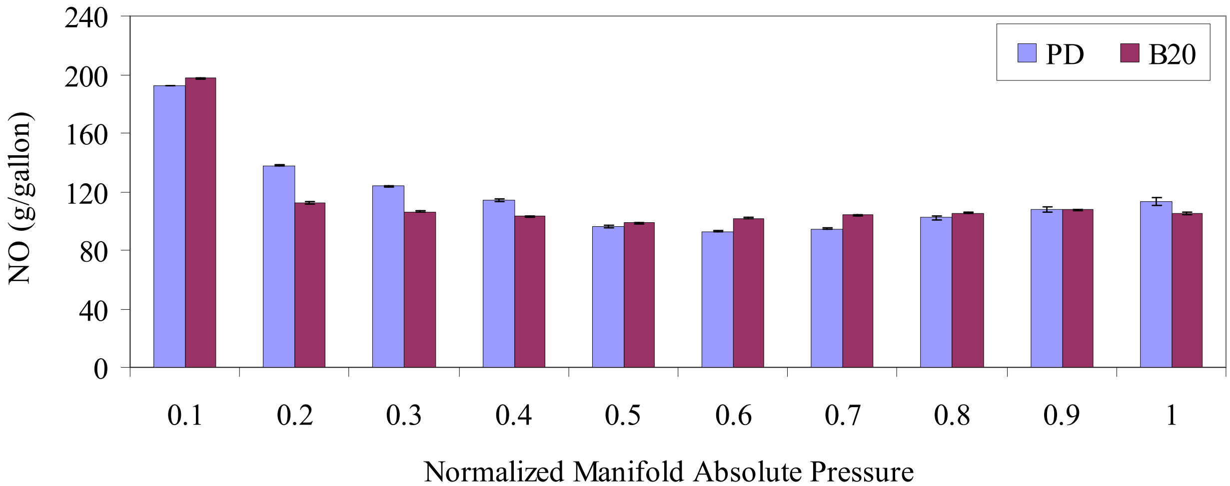
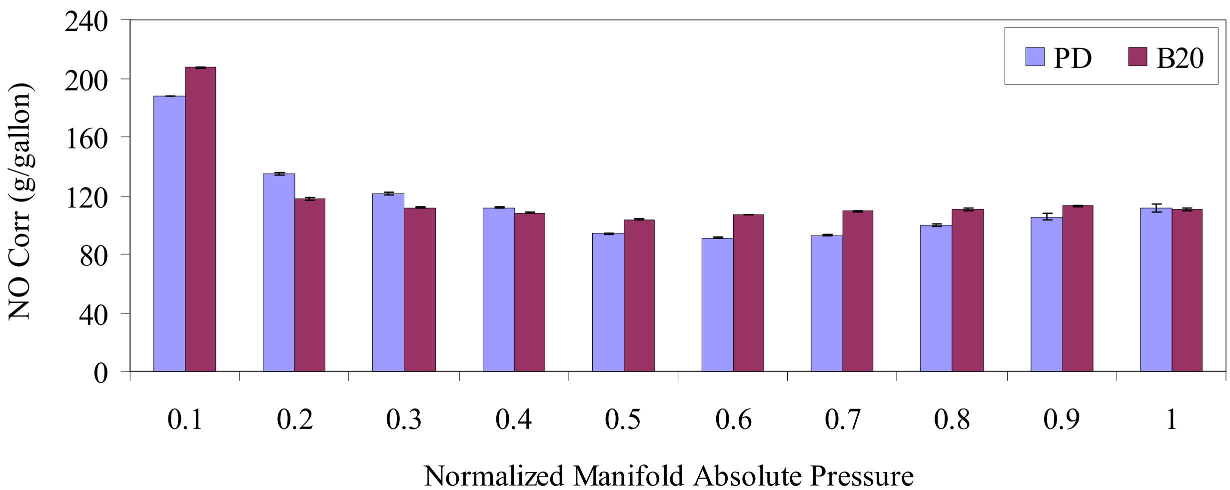


Figure A109. Continued

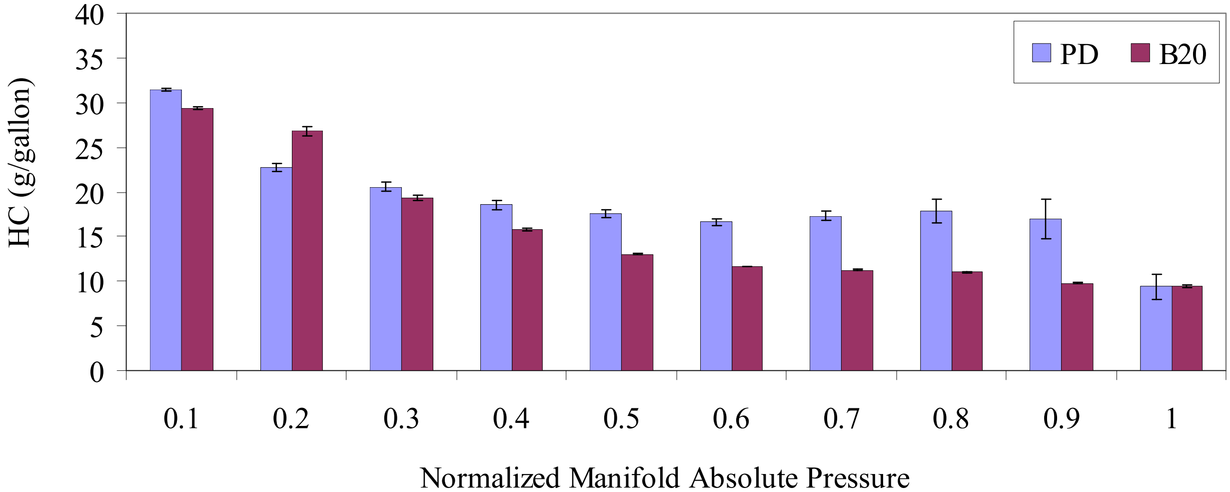


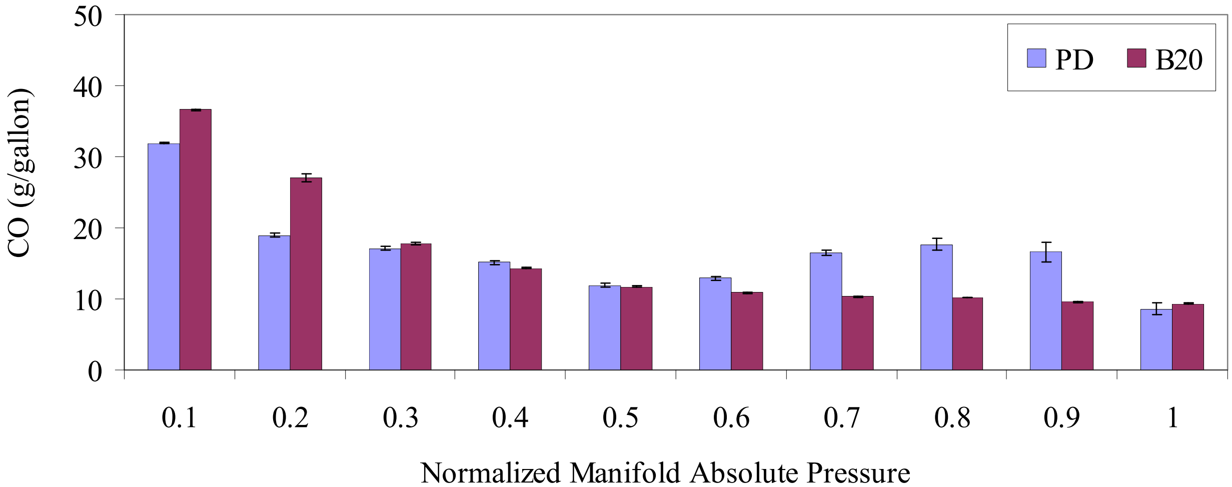


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 74 ^{o}F and the relative humidity was 54 %. For the B20 biodiesel test, the ambient temperature was 87 ^{o}F and the relative humidity was 63 %.

Values shown in the figure are the upper end of range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A110. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Motor Grader 3 (continued on next page)





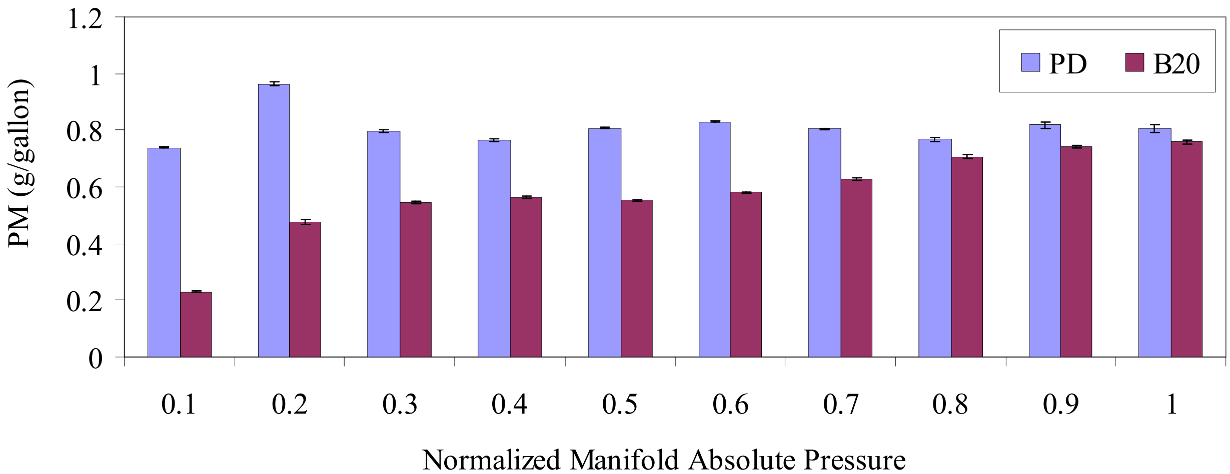
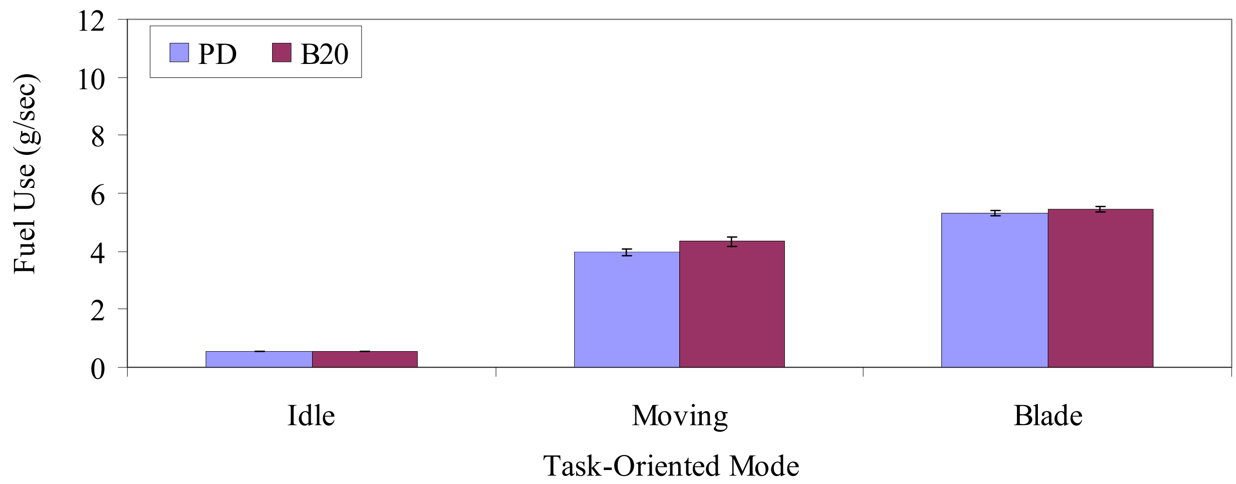
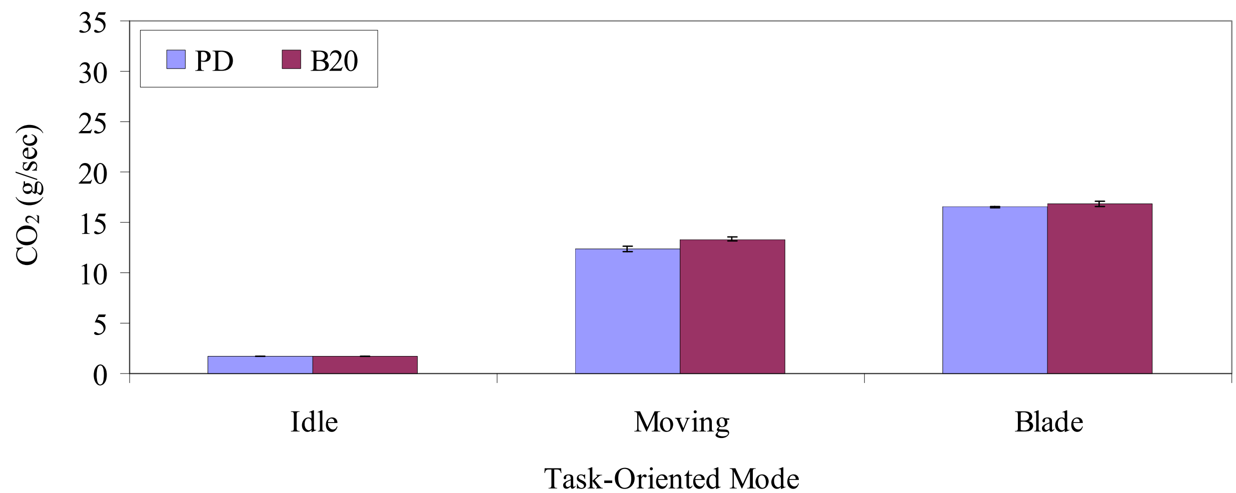


Figure A110. Continued

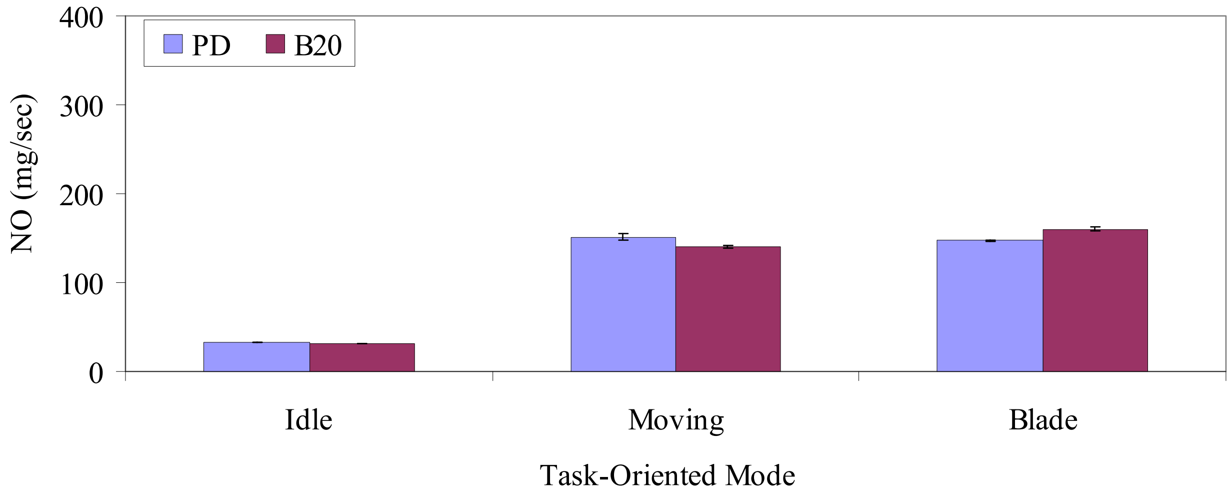


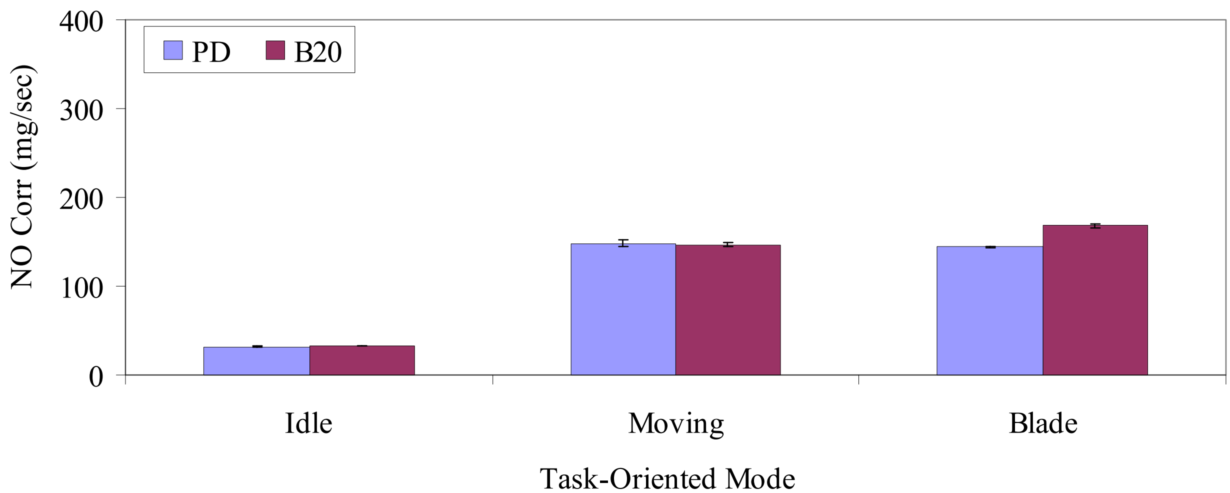


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 74 ^{o}F and the relative humidity was 54 %. For the B20 biodiesel test, the ambient temperature was 87 ^{o}F and the relative humidity was 63 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A111. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Motor Grader 3 (continued on next page)





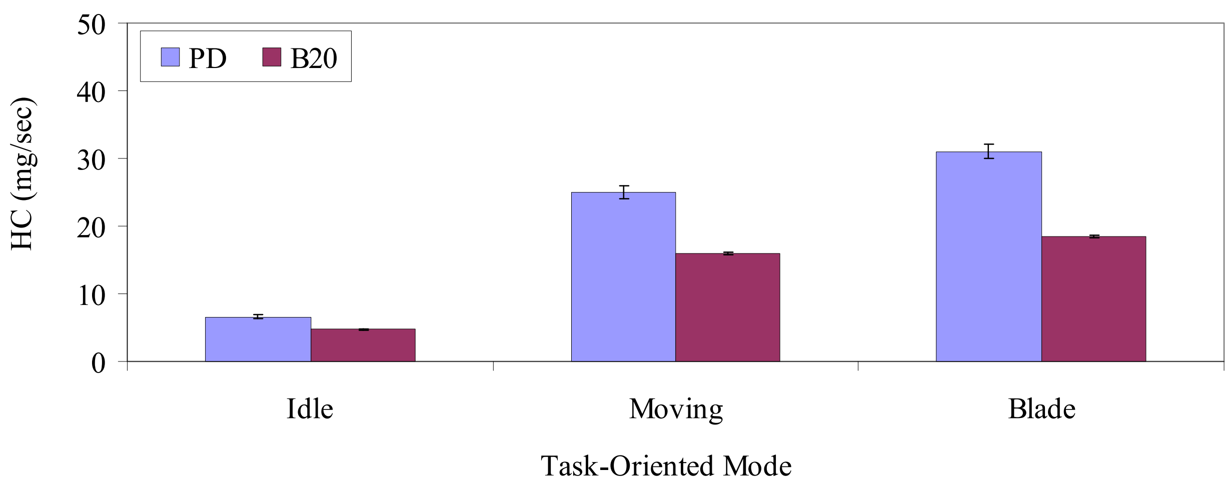
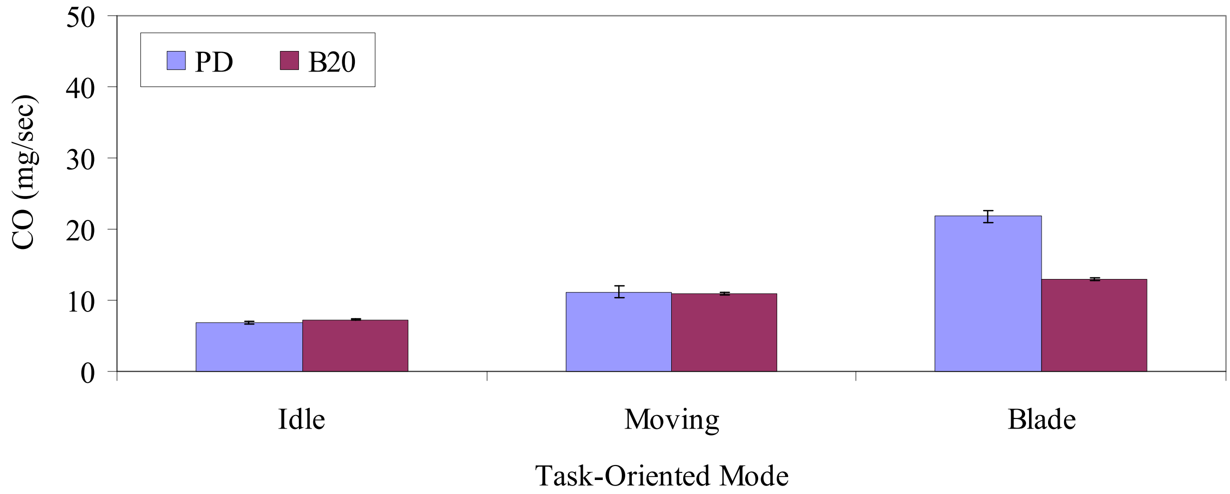


Figure A111. Continued



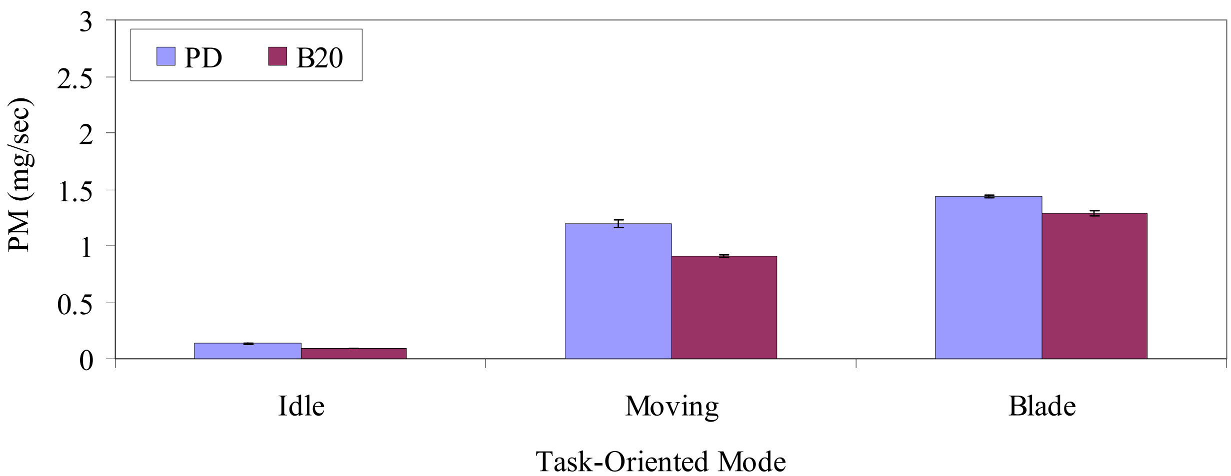
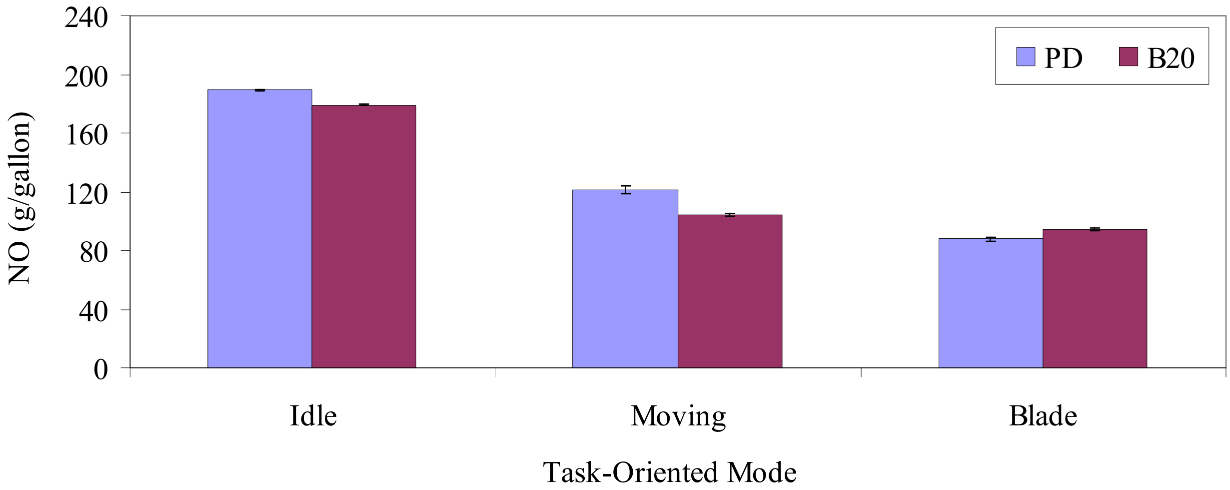
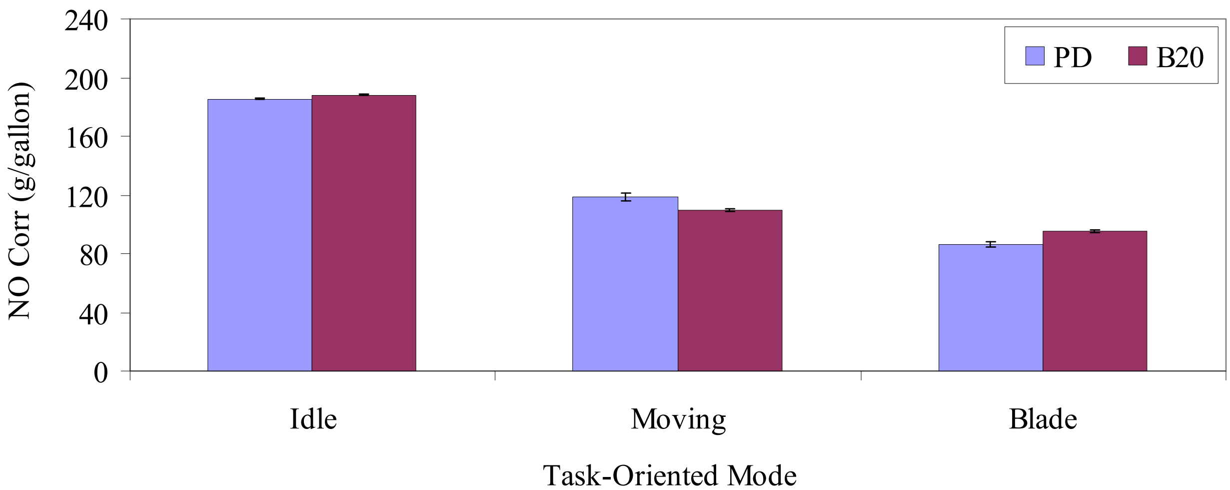


Figure A111. Continued

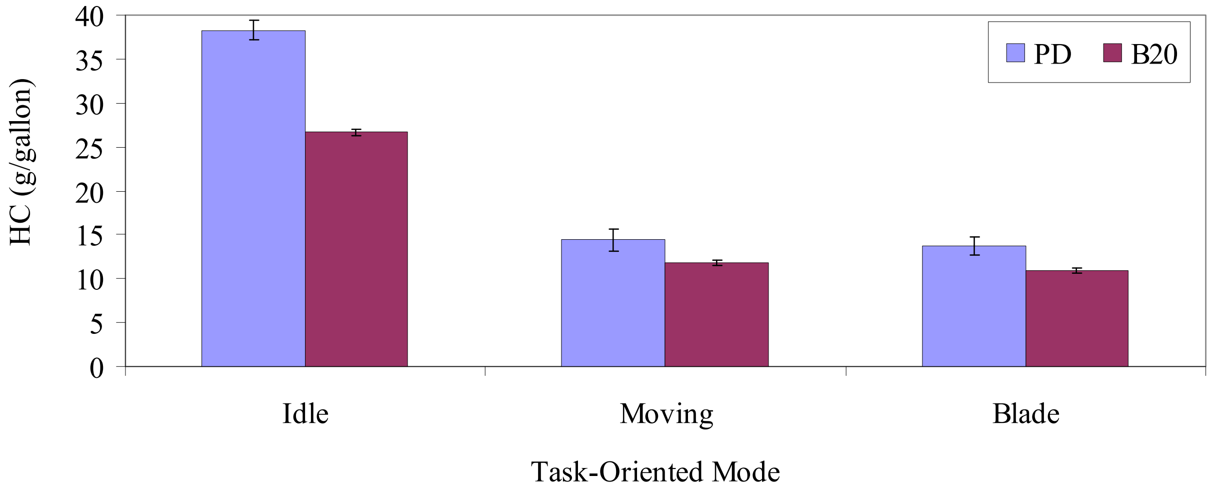


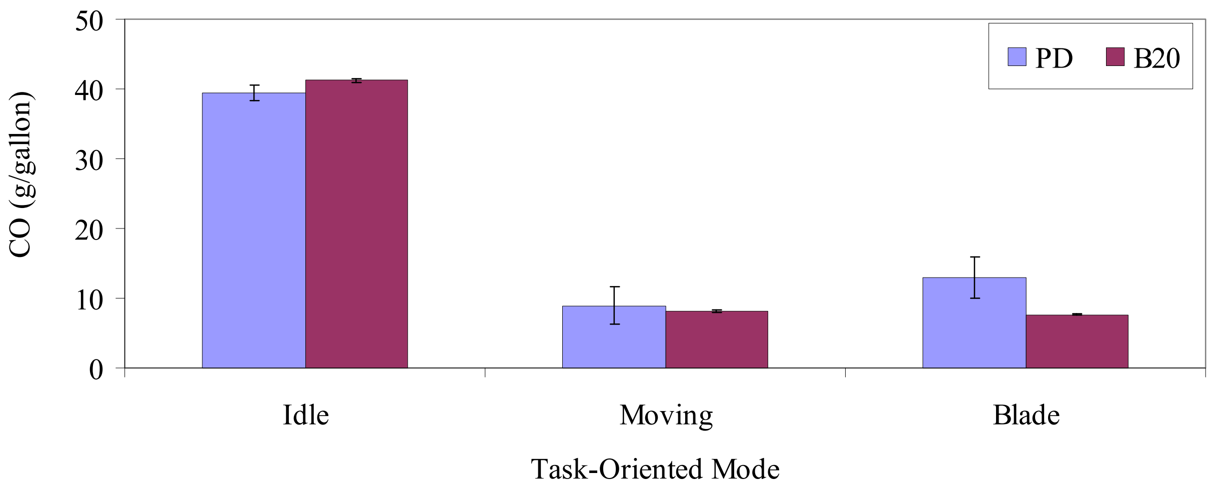


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 74 ^{o}F and the relative humidity was 54 %. For the B20 biodiesel test, the ambient temperature was 87 ^{o}F and the relative humidity was 63 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A112. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Motor Grader 3 (continued on next page)





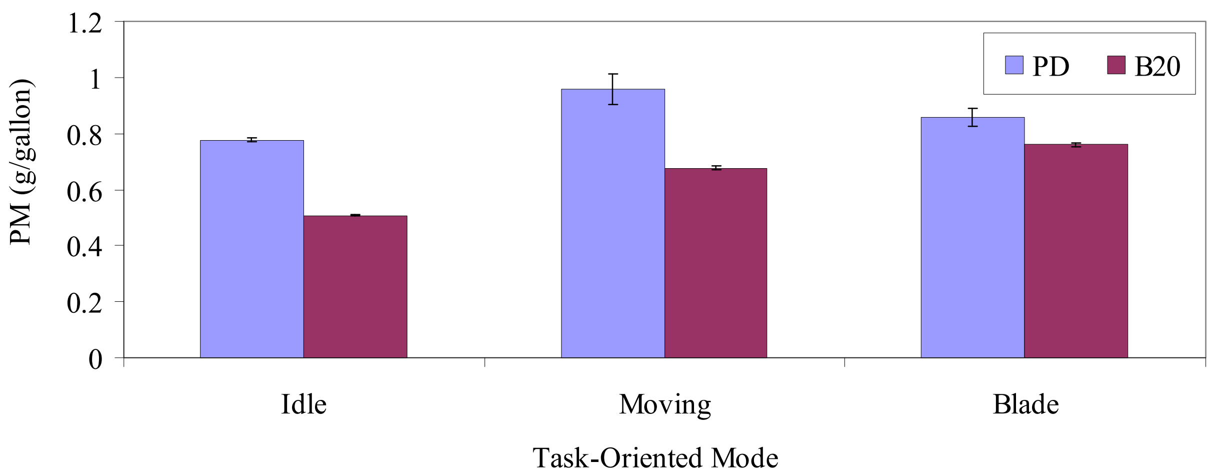
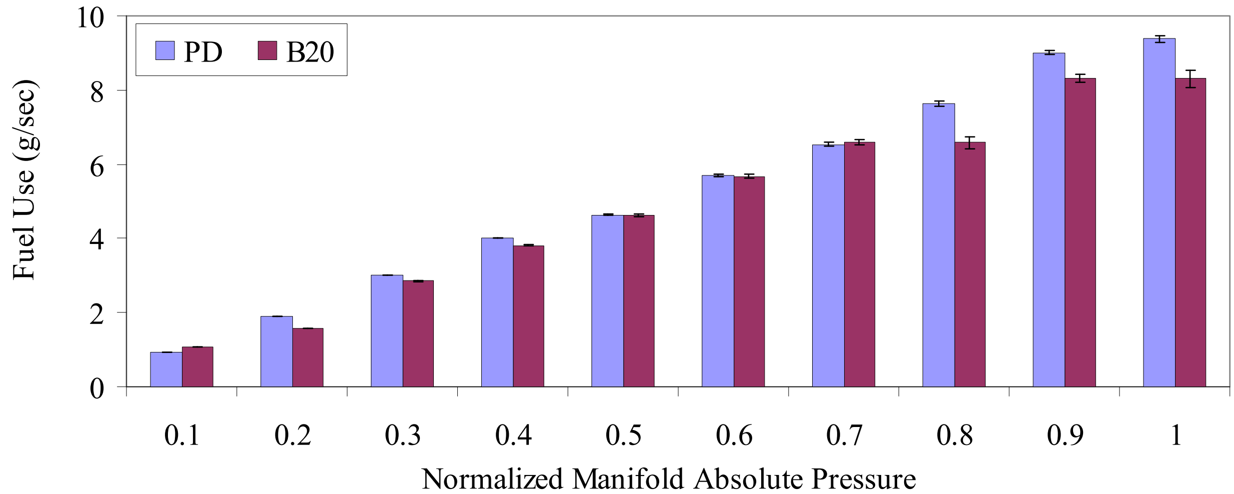
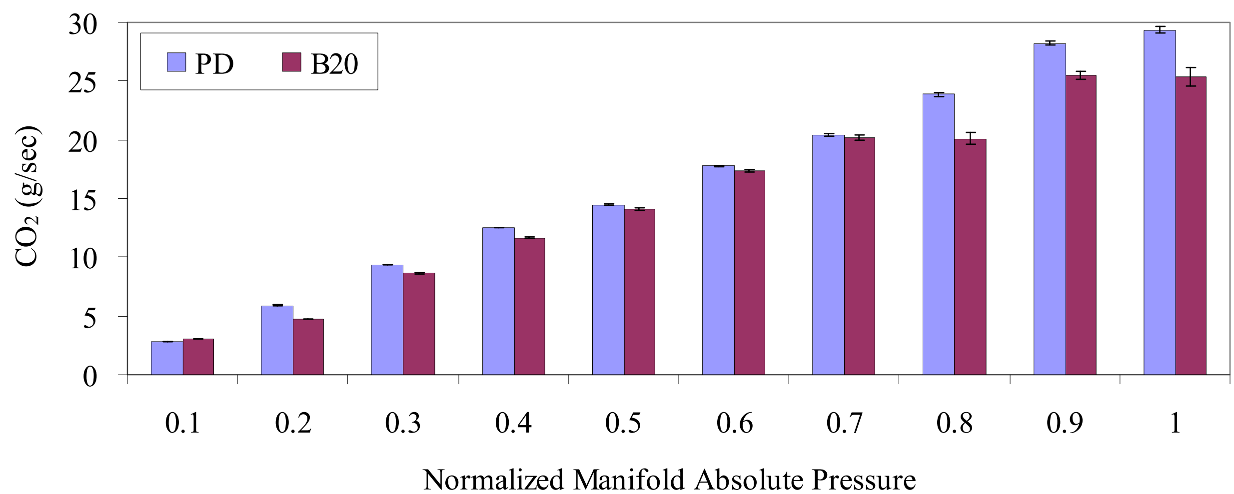


Figure A112. Continued

MOTOR GRADER 4

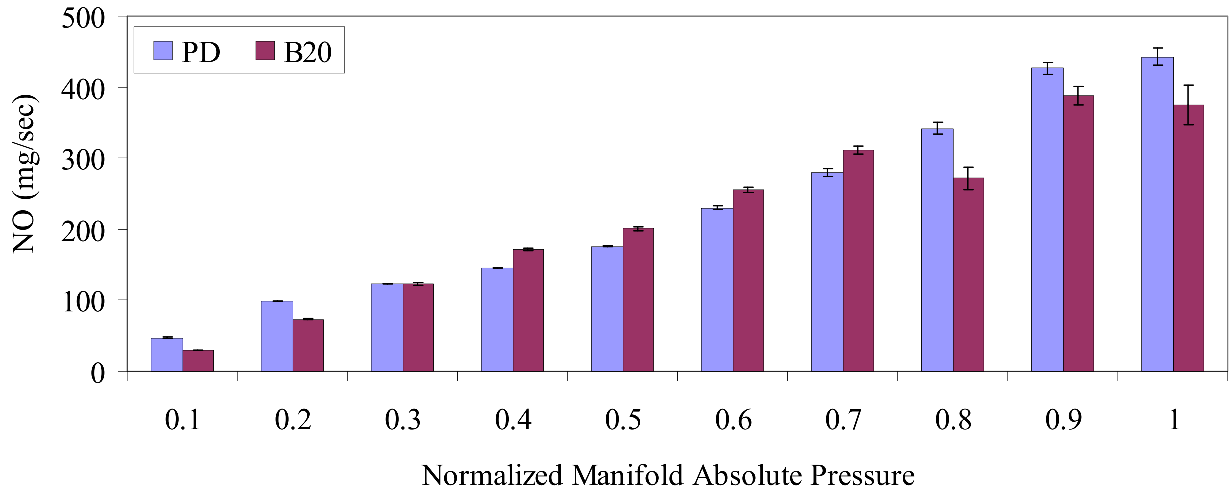


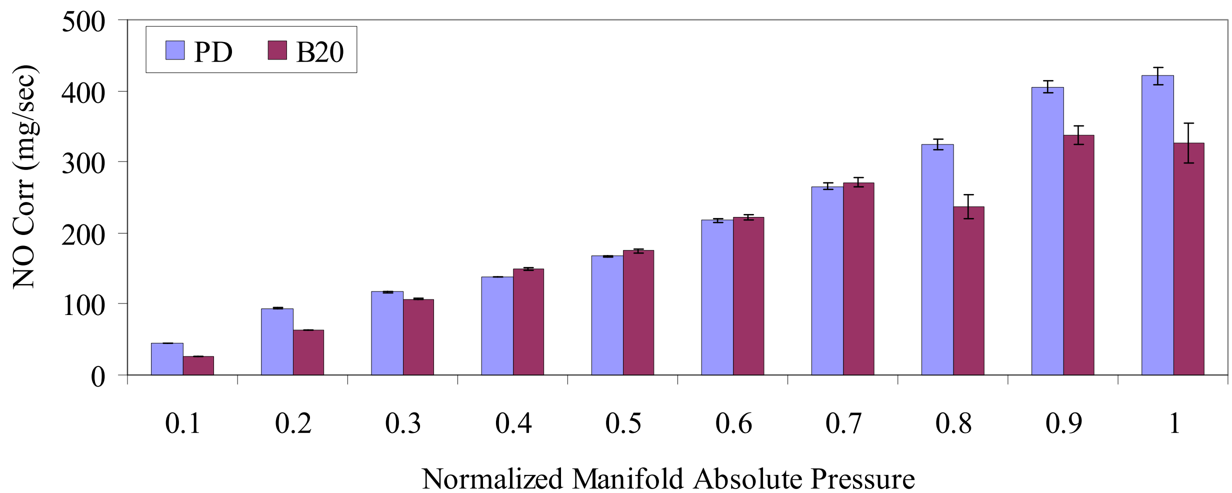


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 73 ^{o}F and the relative humidity was 44 %. For the B20 biodiesel test, the ambient temperature was 45 ^{o}F and the relative humidity was 37 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A113. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Motor Grader 4 (continued on next page)





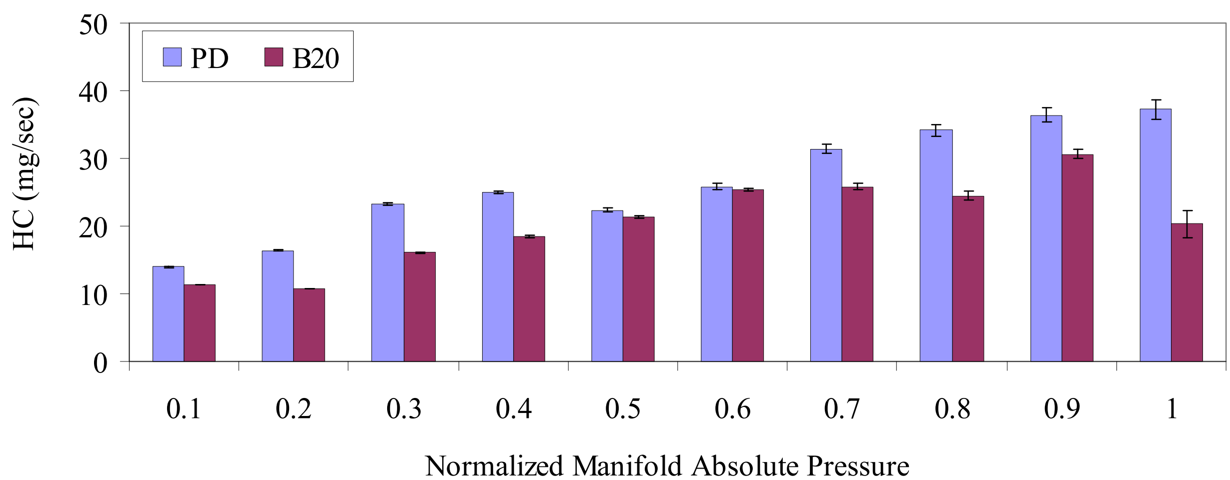
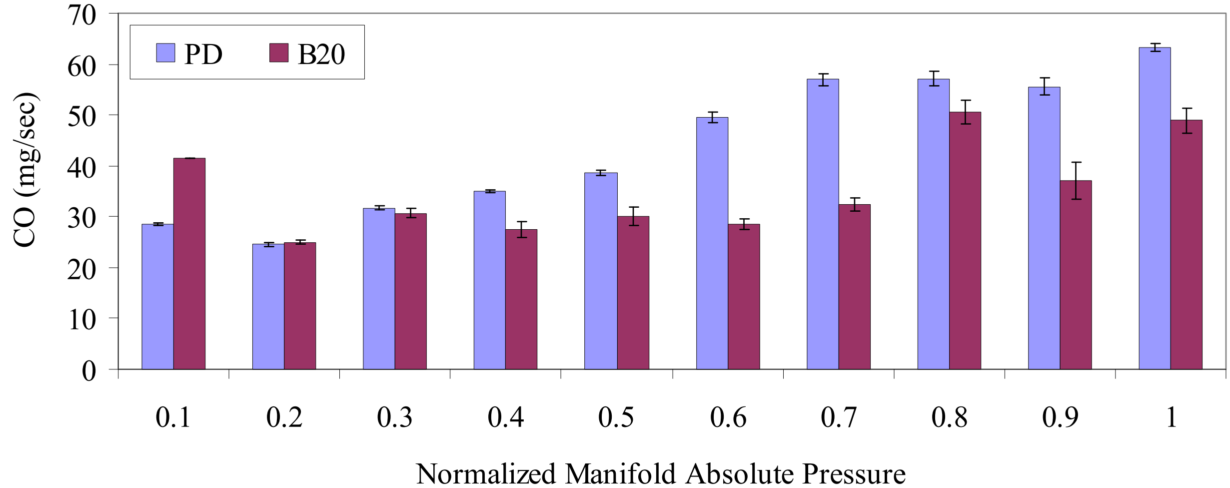


Figure A113. Continued



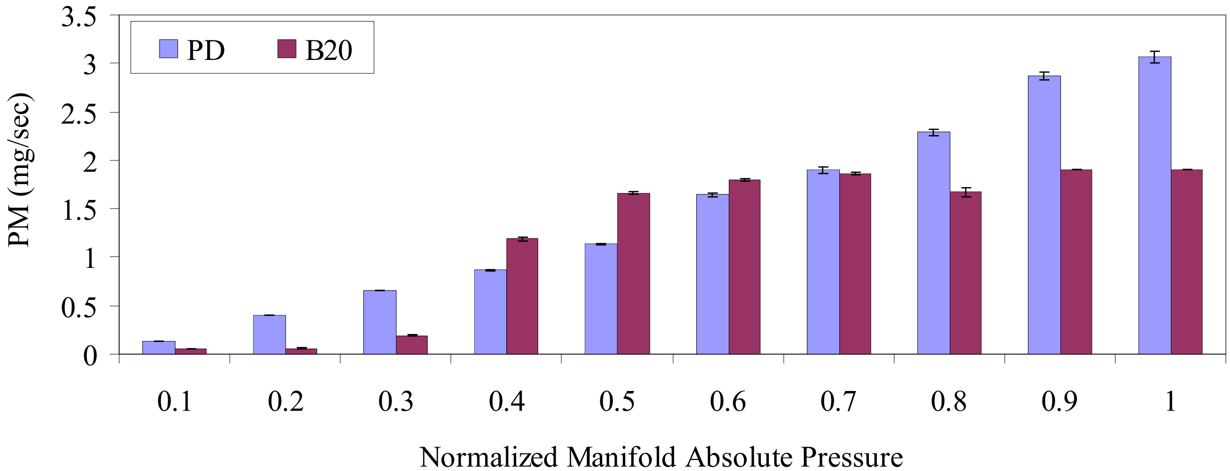
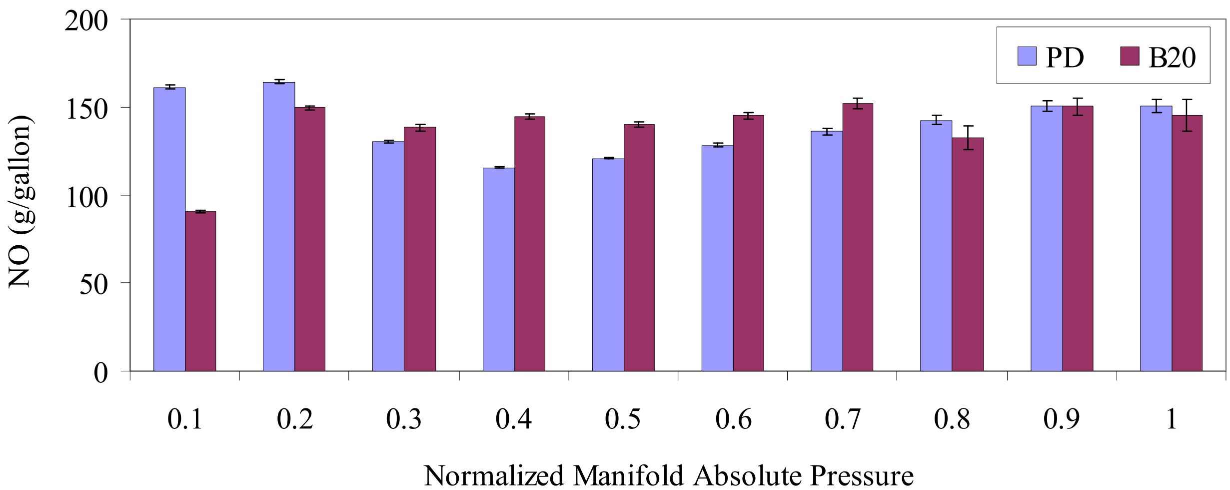
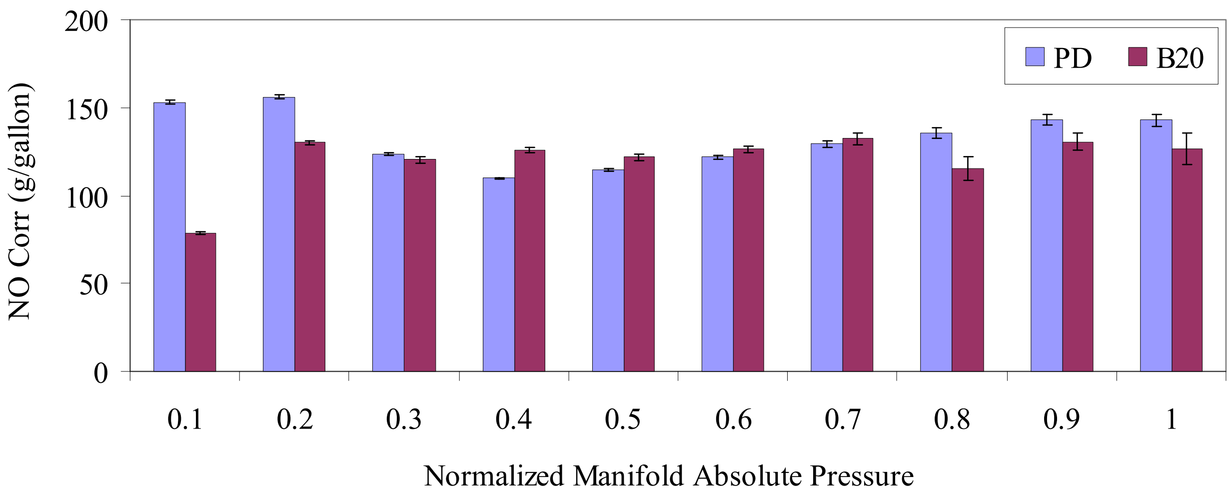


Figure A113. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 73 ^{o}F and the relative humidity was 44 %. For the B20 biodiesel test, the ambient temperature was 45 ^{o}F and the relative humidity was 37 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A114. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Motor Grader 4 (continued on next page)

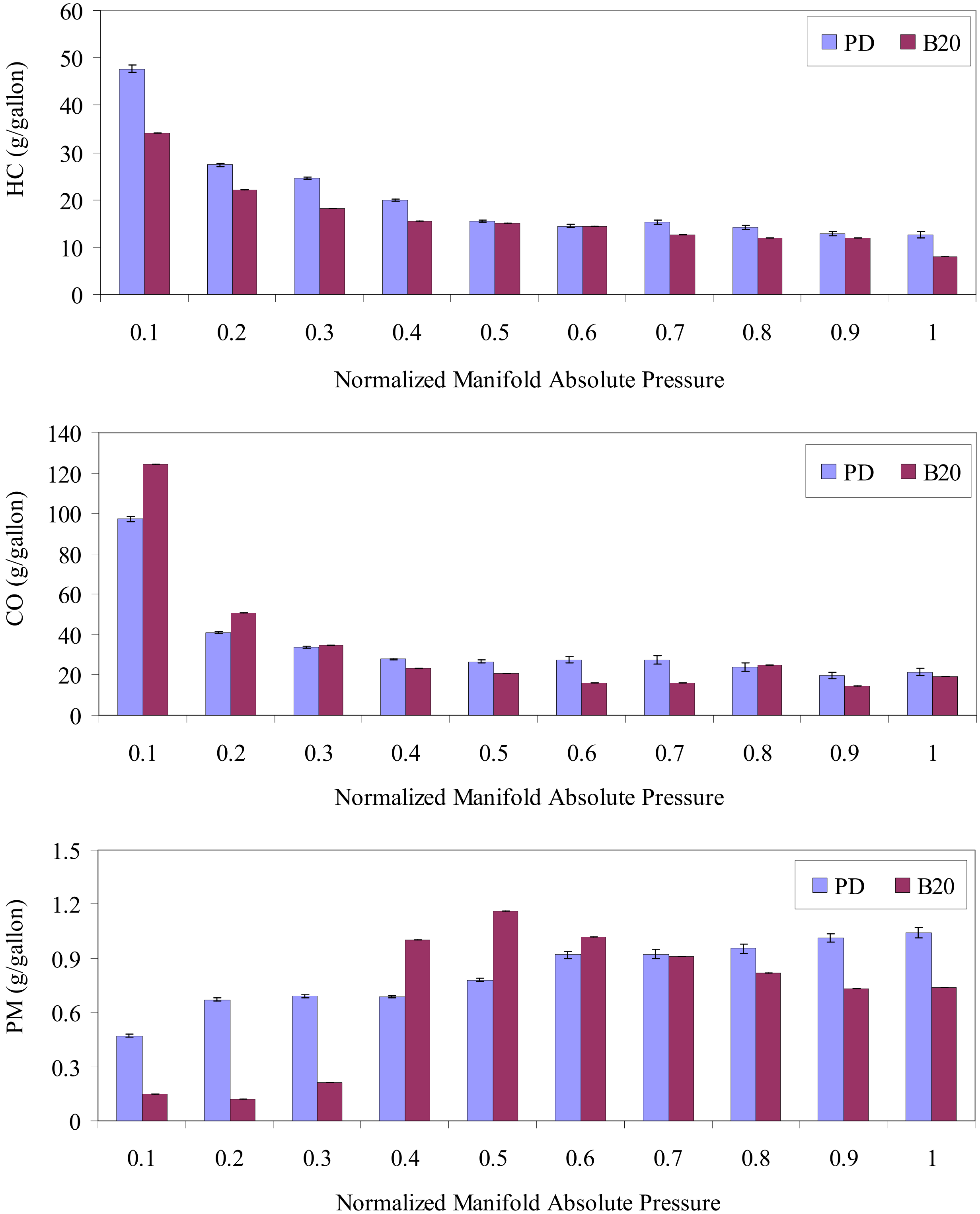
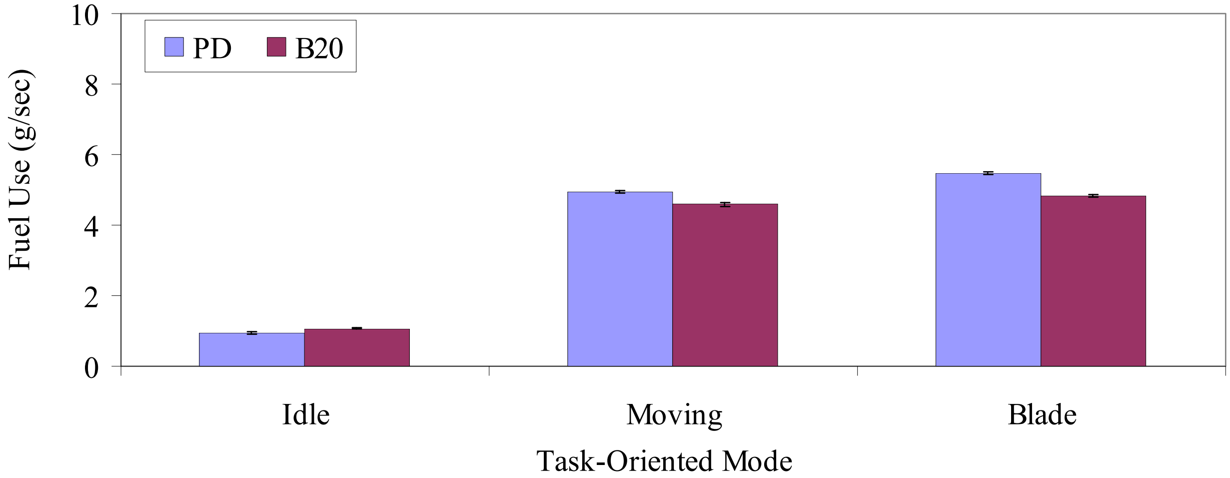
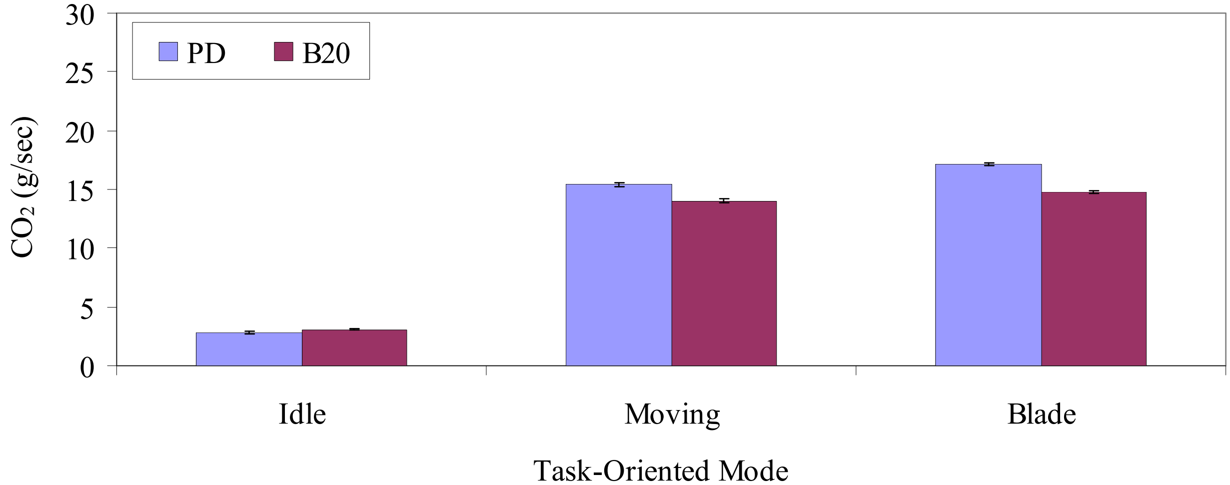


Figure A114. Continued

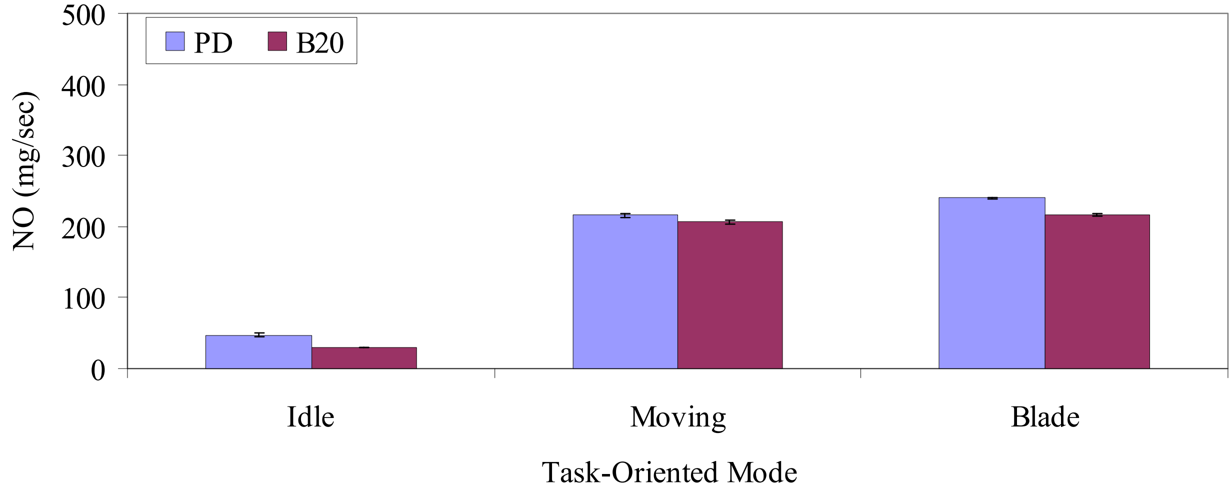


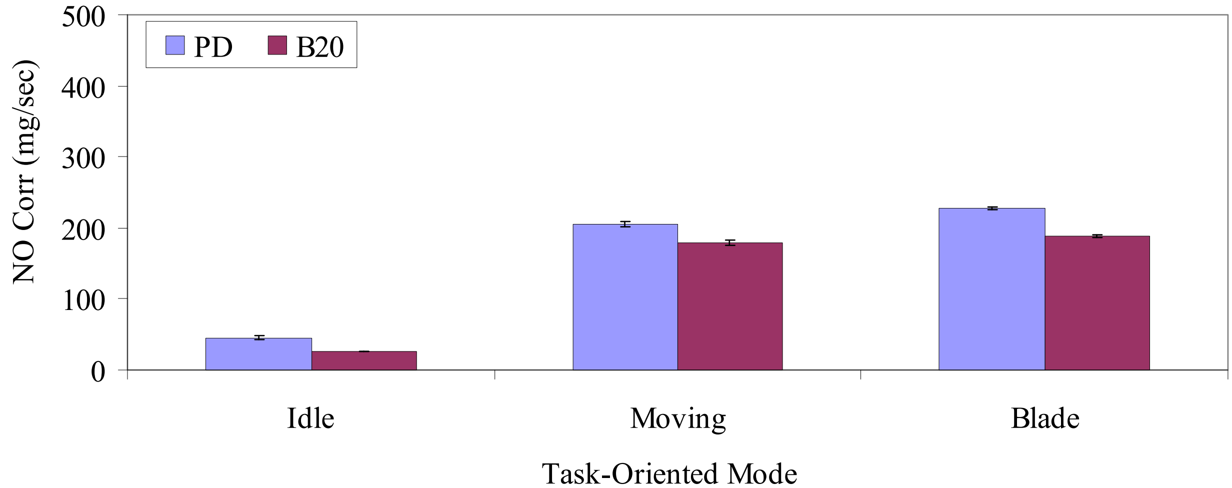


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 73 ^oF and the relative humidity was 44 %. For the B20 biodiesel test, the ambient temperature was 45 ^oF and the relative humidity was 37 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A115. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Motor Grader 4 (continued on next page)





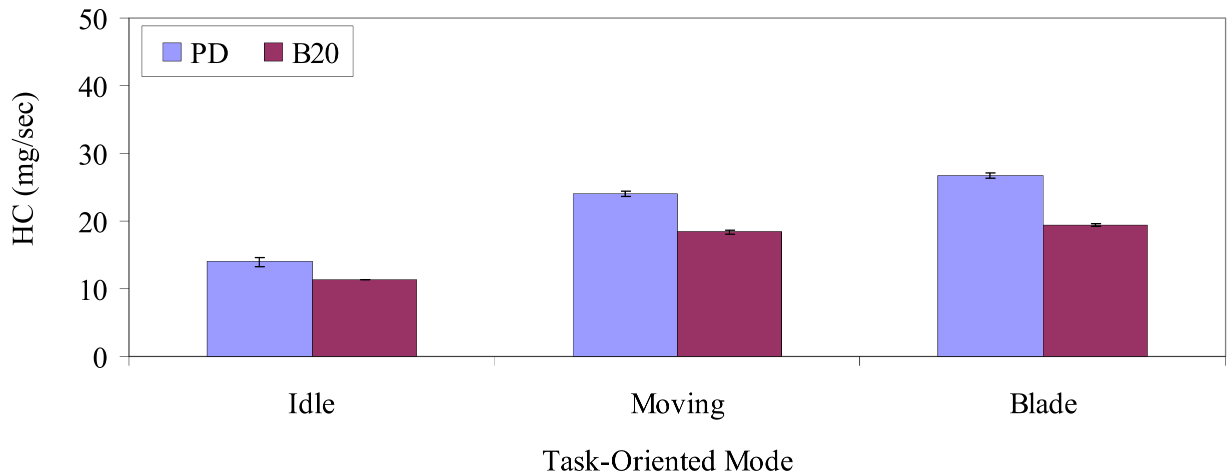


Figure A115. Continued

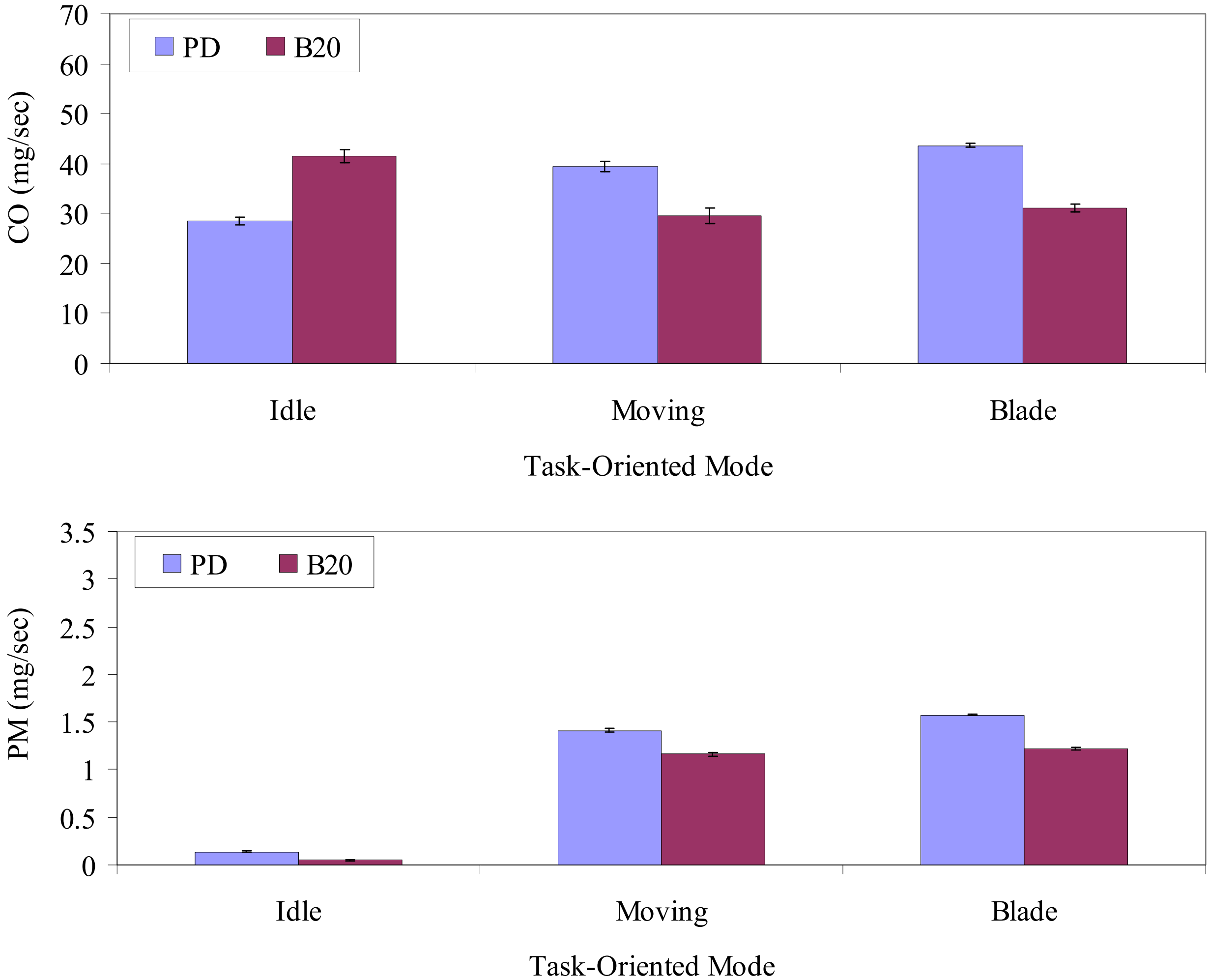
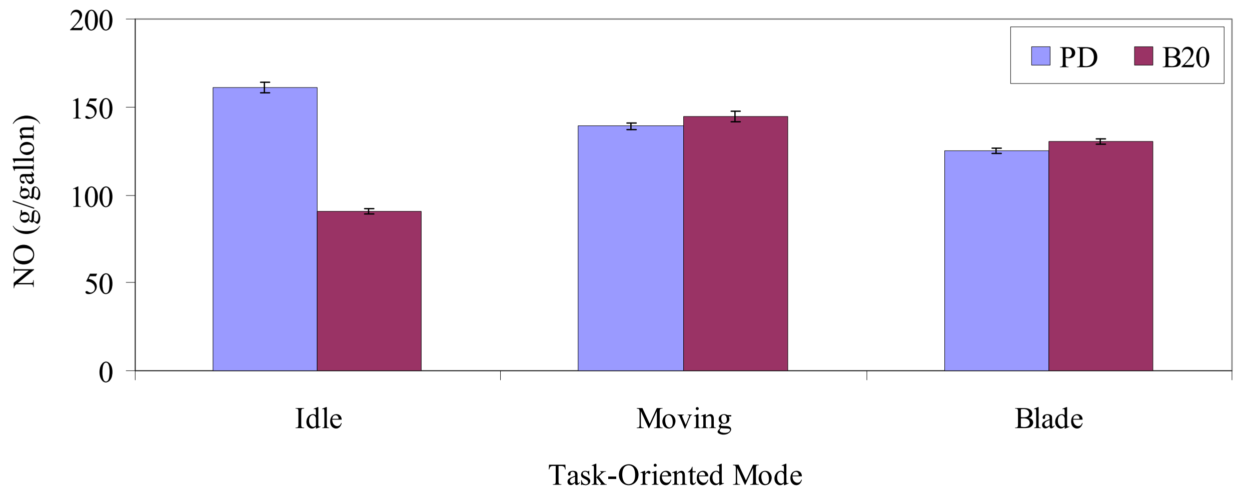
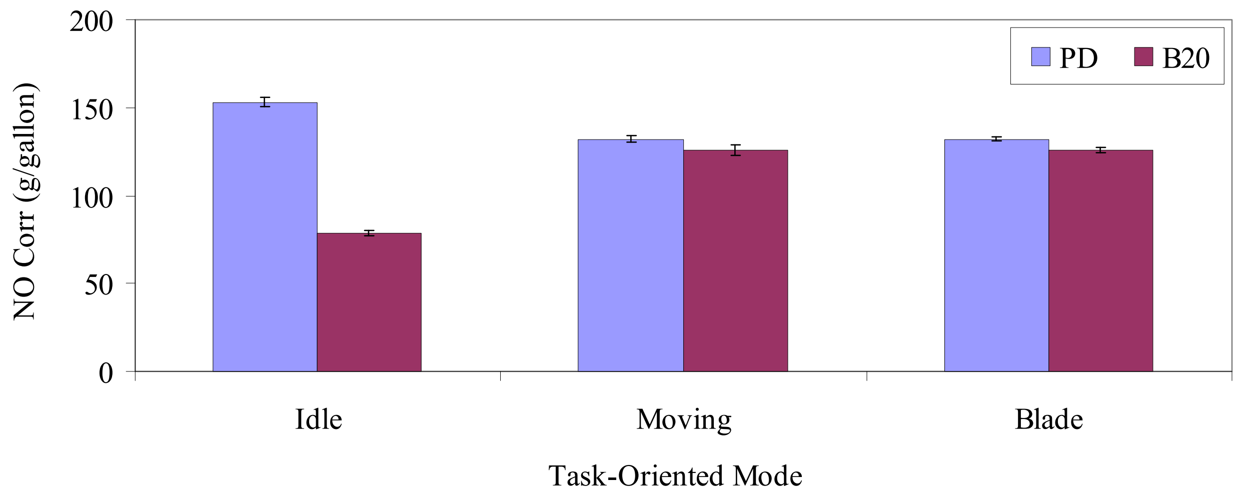


Figure A115. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 73 ^{o}F and the relative humidity was 44 %. For the B20 biodiesel test, the ambient temperature was 45 ^{o}F and the relative humidity was 37 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A116. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Motor Grader 4 (continued on next page)

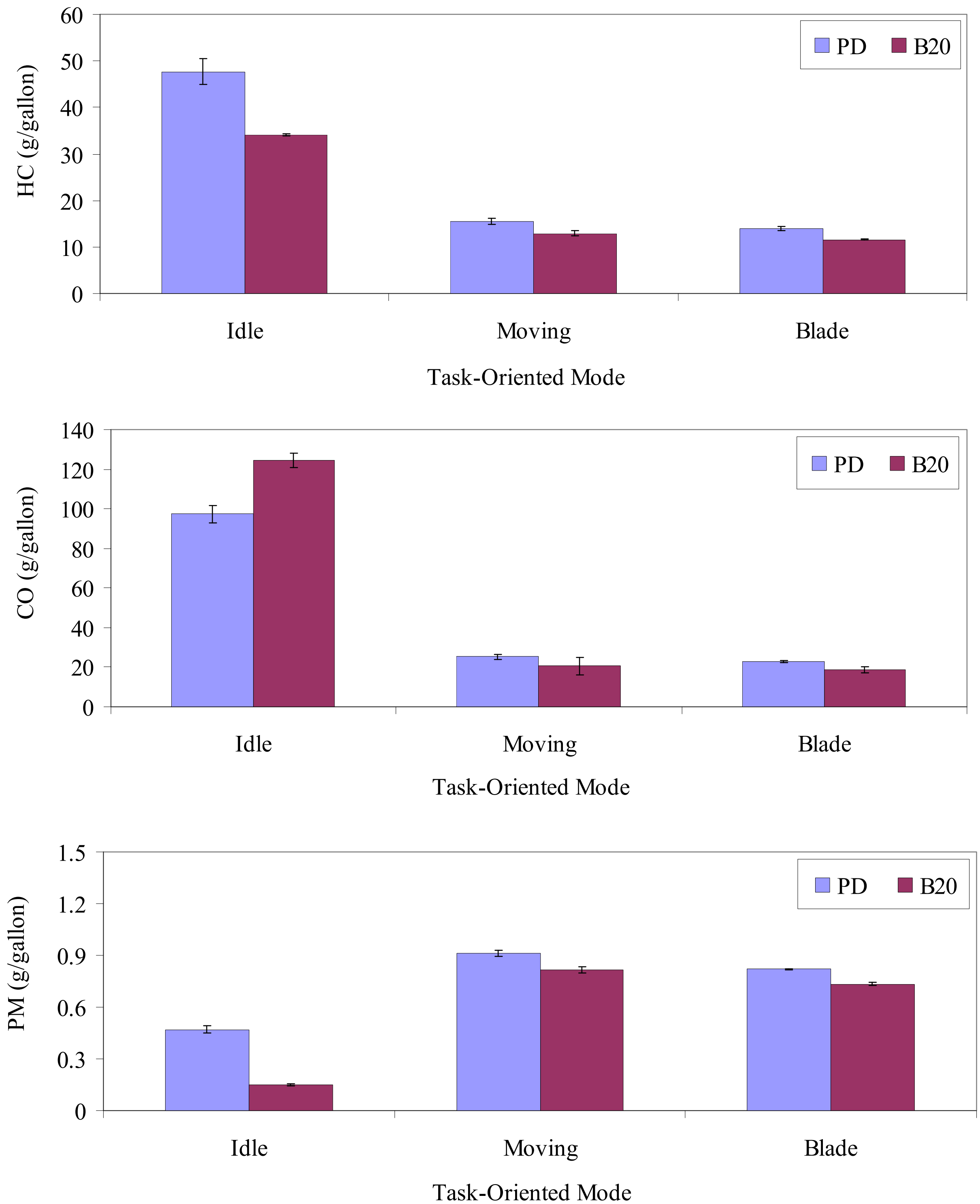
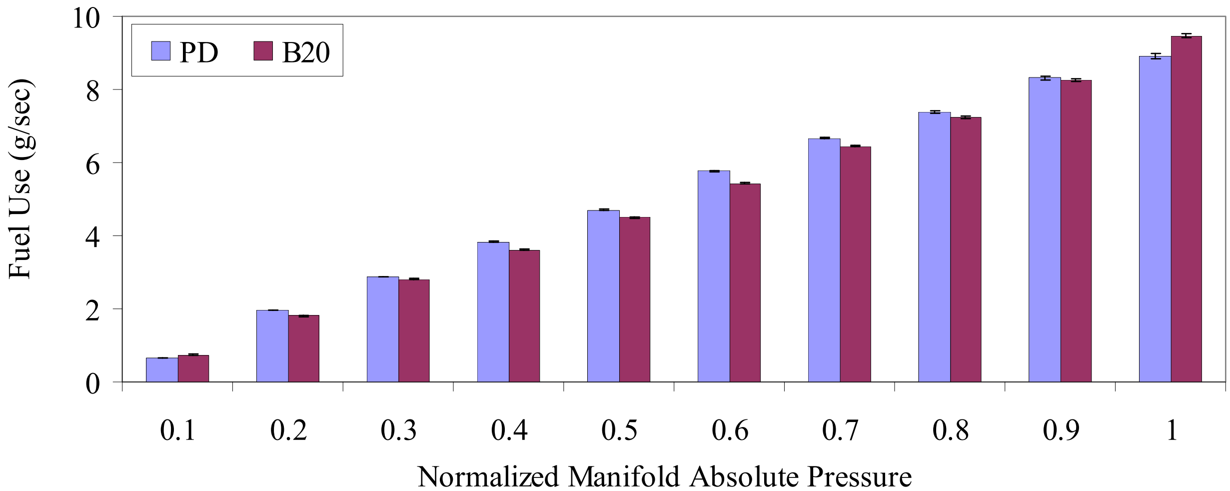
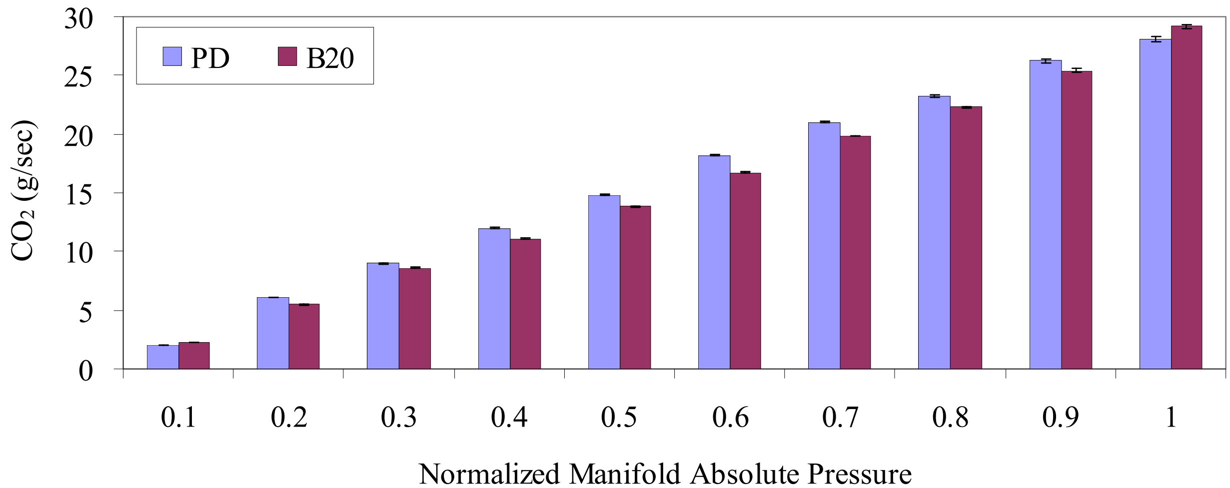


Figure A116. Continued

MOTOR GRADER 5

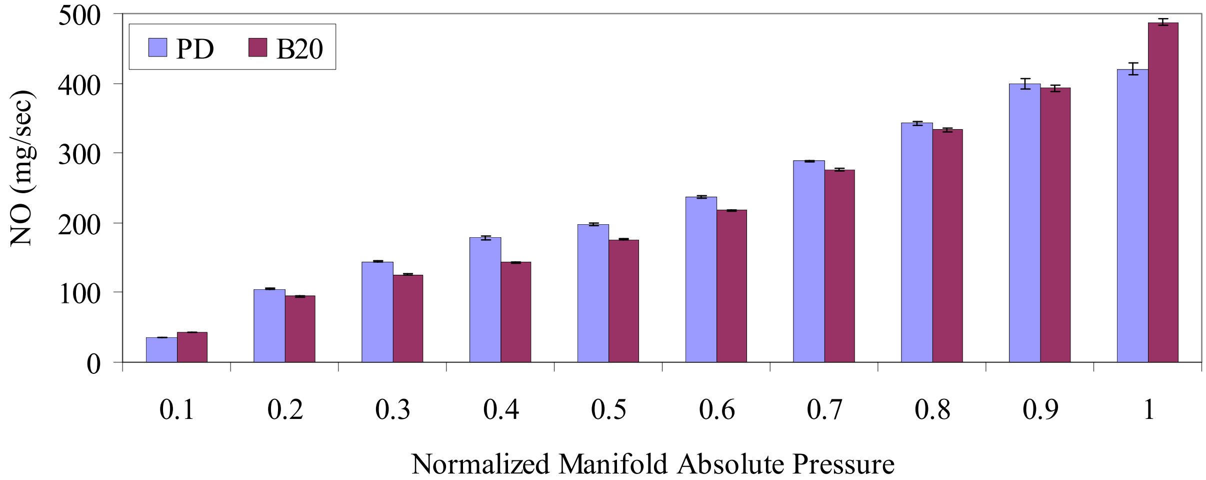


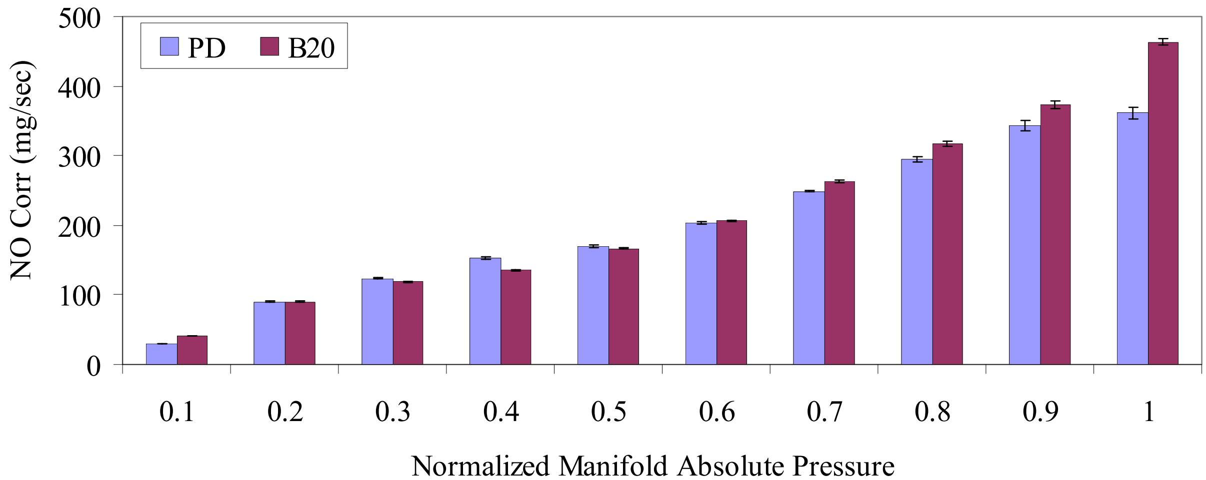


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 35 ^{o}F and the relative humidity was 39 %. For the B20 biodiesel test, the ambient temperature was 60 ^{o}F and the relative humidity was 72 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A117. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Motor Grader 5 (continued on next page)





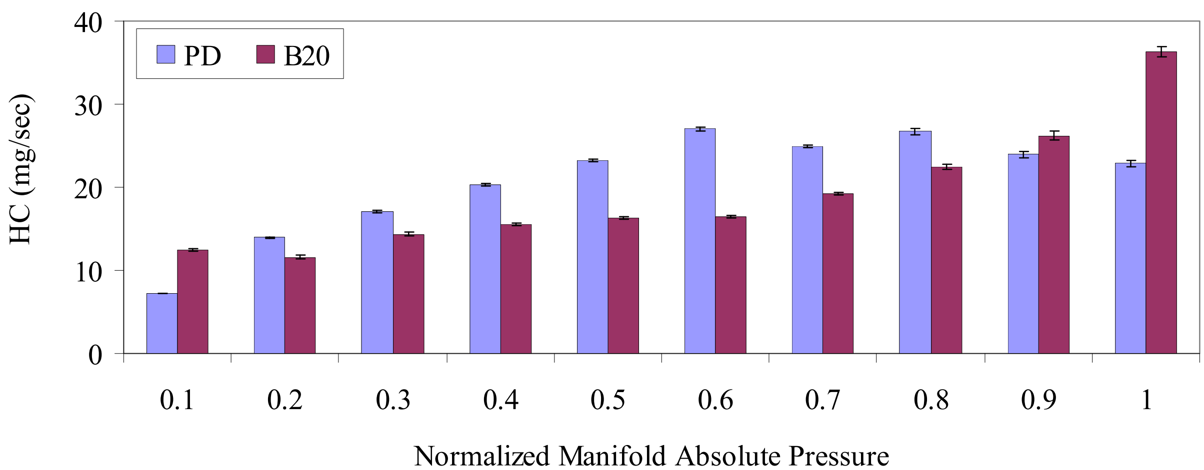
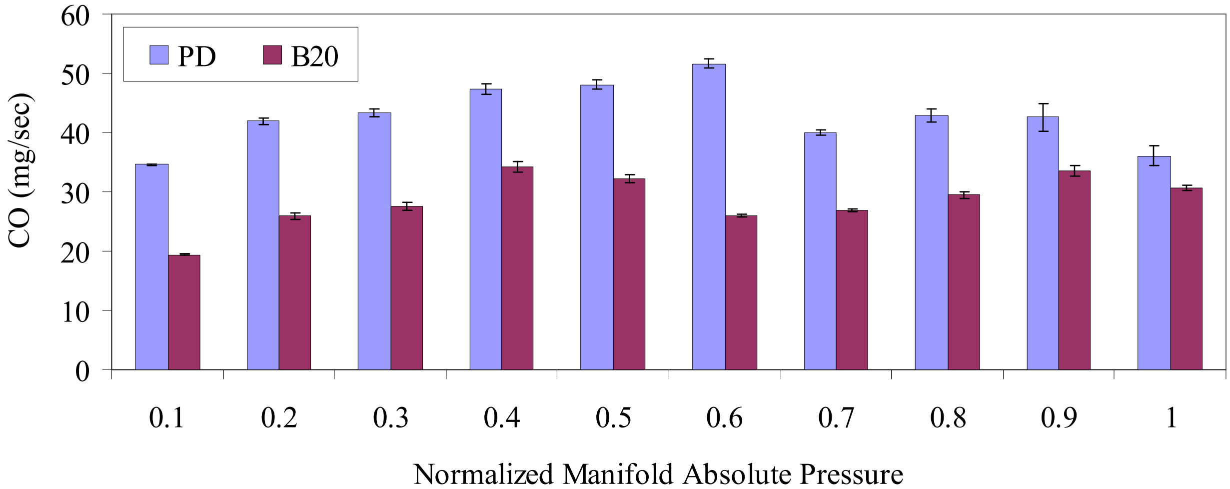


Figure A117. Continued



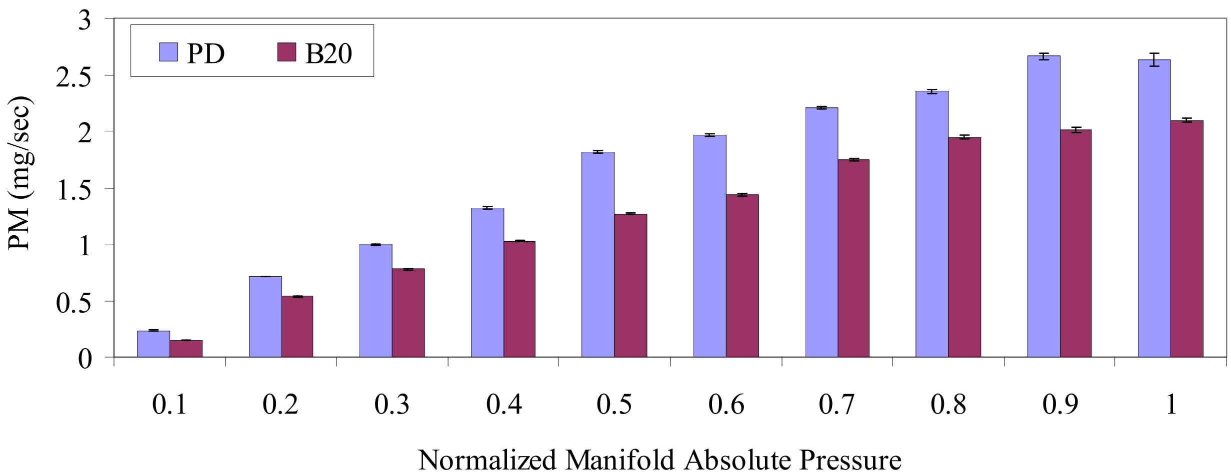
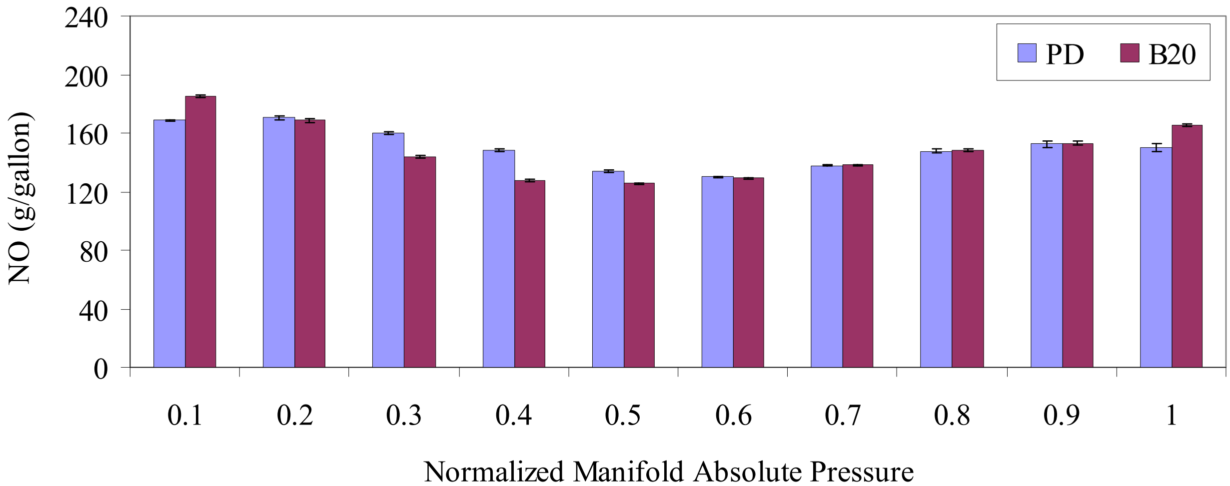
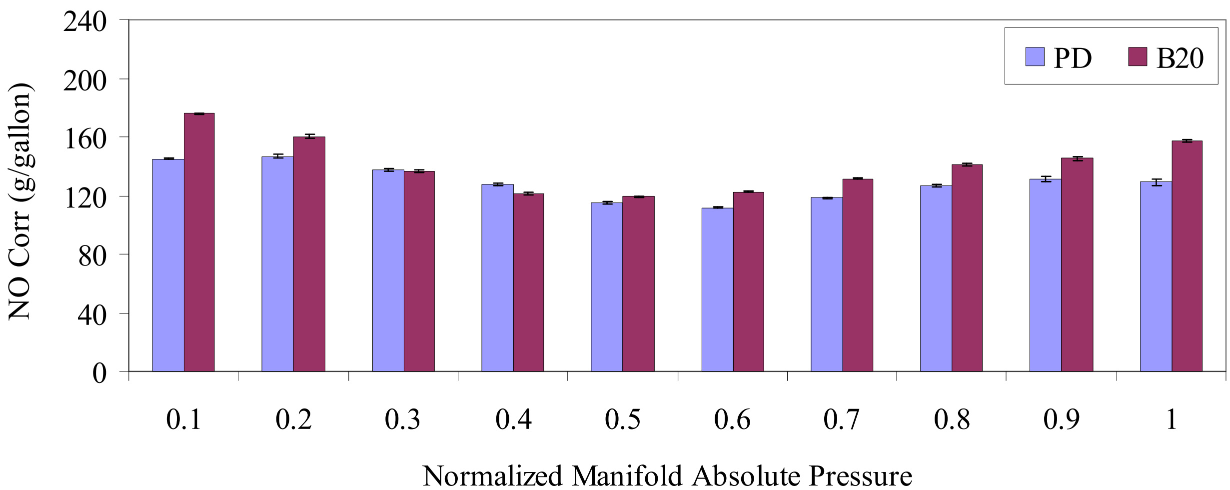


Figure A117. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 35 ^{o}F and the relative humidity was 39 %. For the B20 biodiesel test, the ambient temperature was 60 ^{o}F and the relative humidity was 72 %.

Values shown in the figure are the upper end of the range: “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A118. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Motor Grader 5 (continued on next page)

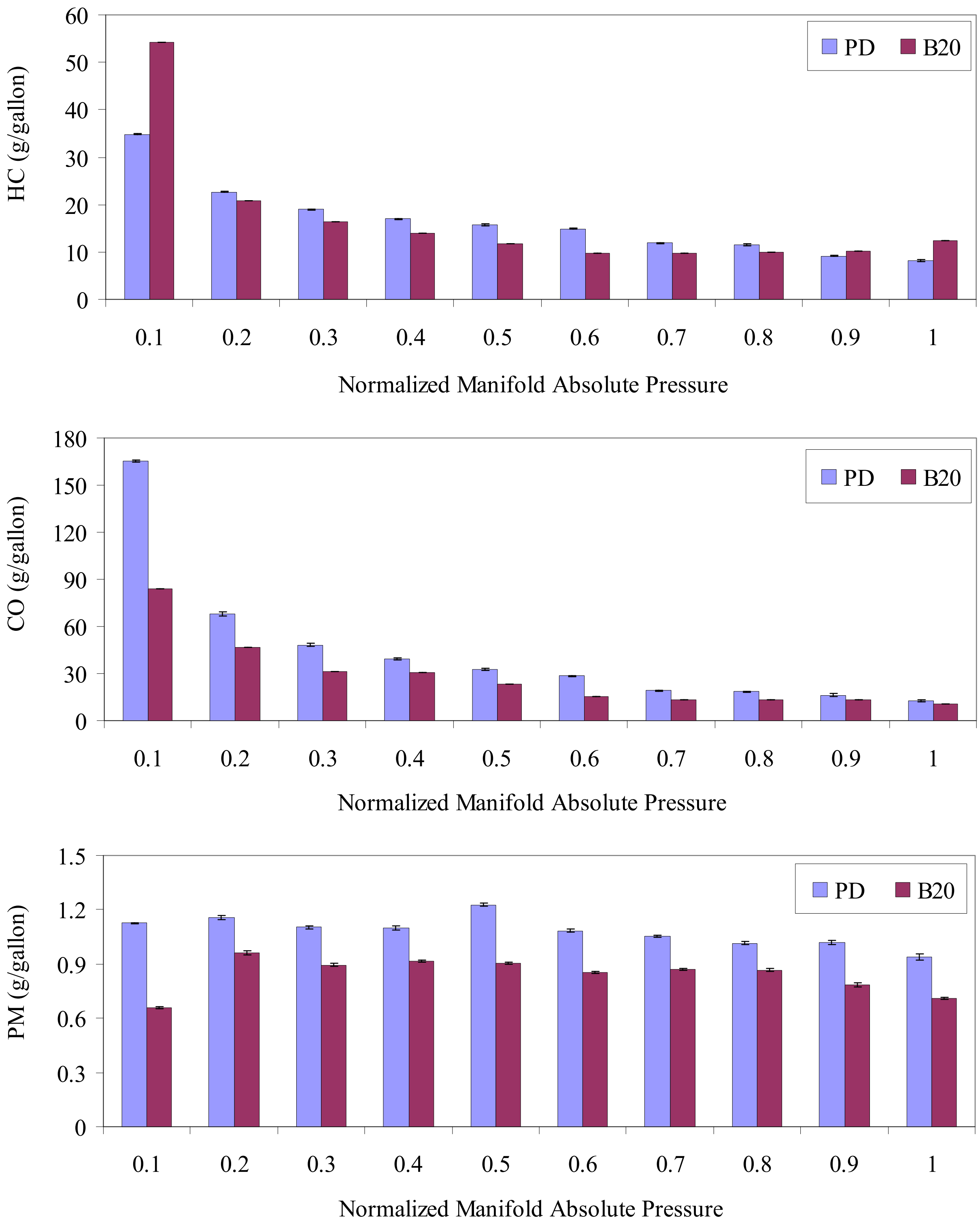
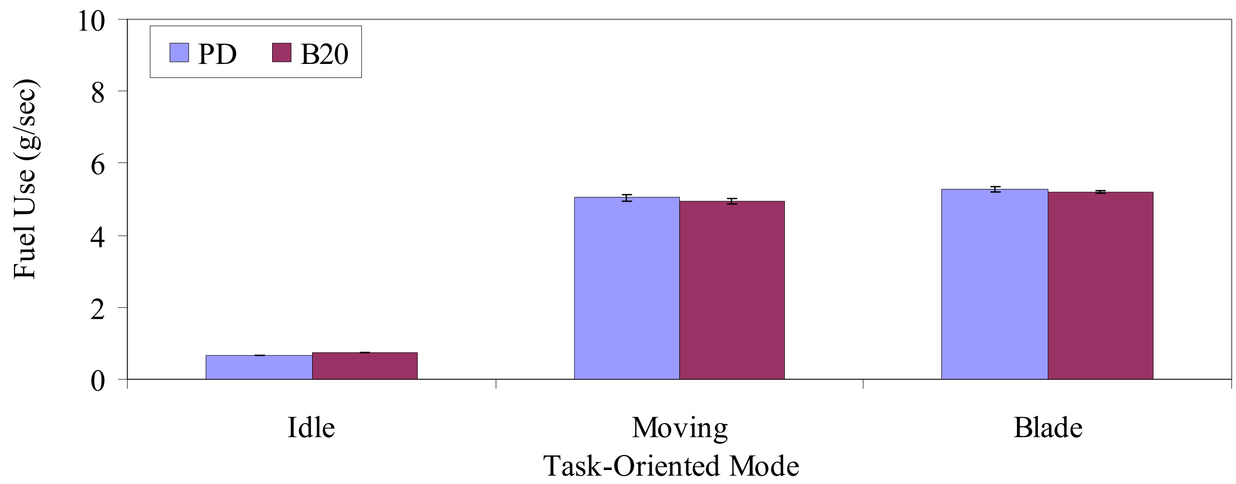
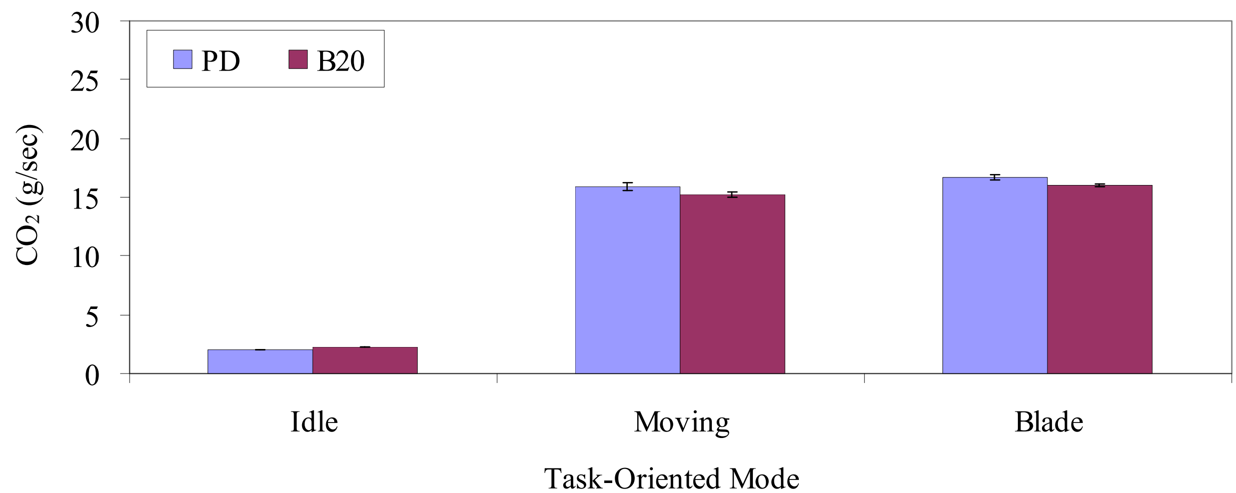


Figure A118. Continued

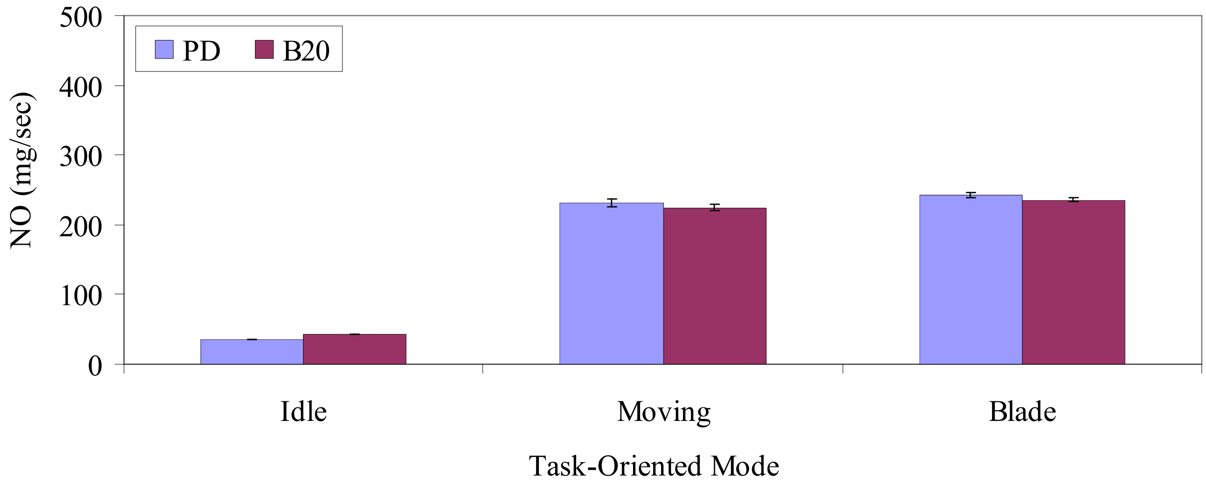


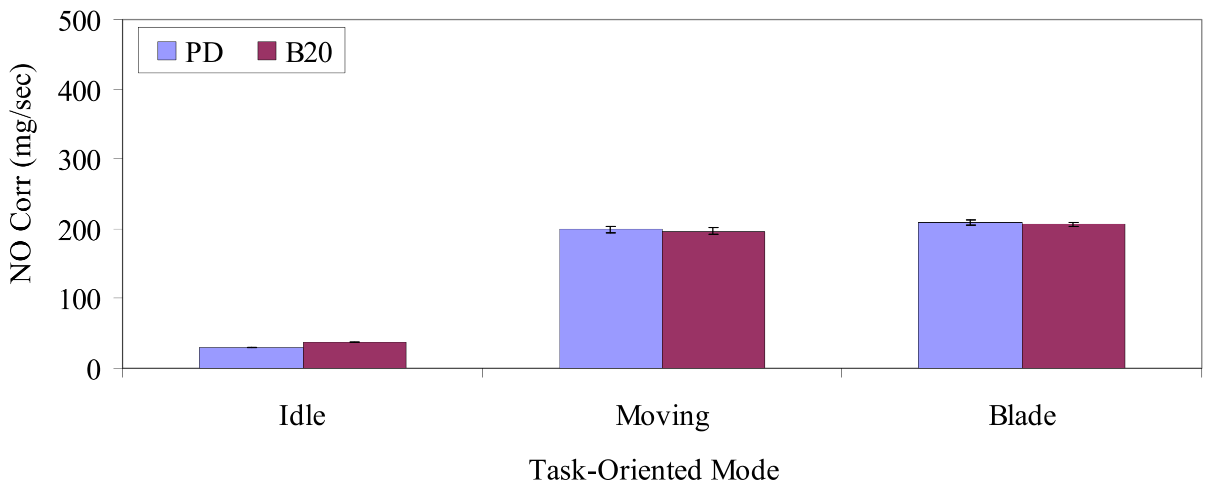


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 35 ^{o}F and the relative humidity was 39 %. For the B20 biodiesel test, the ambient temperature was 60 ^{o}F and the relative humidity was 72 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A119. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Motor Grader 5 (continued on next page)





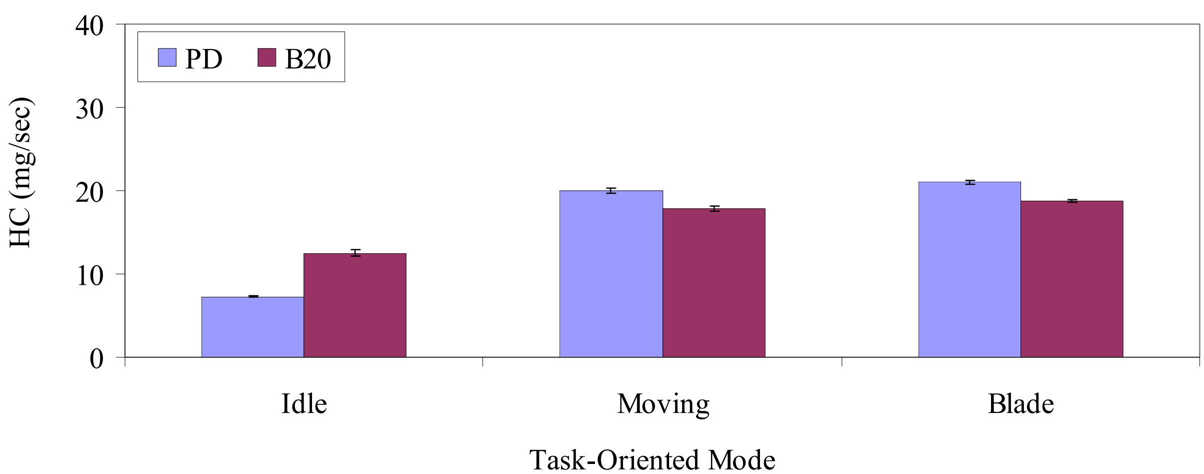
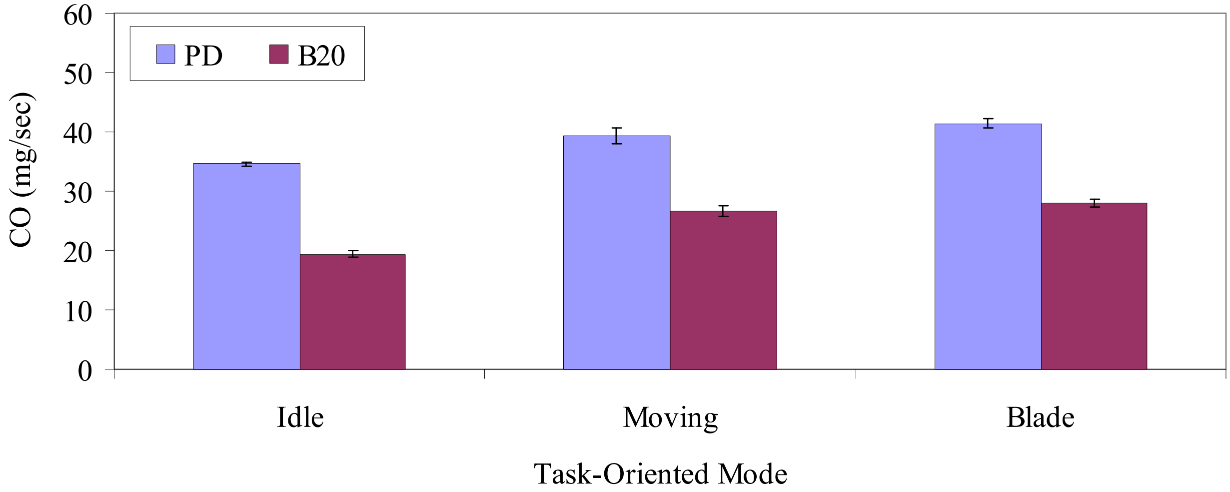


Figure A119. Continued



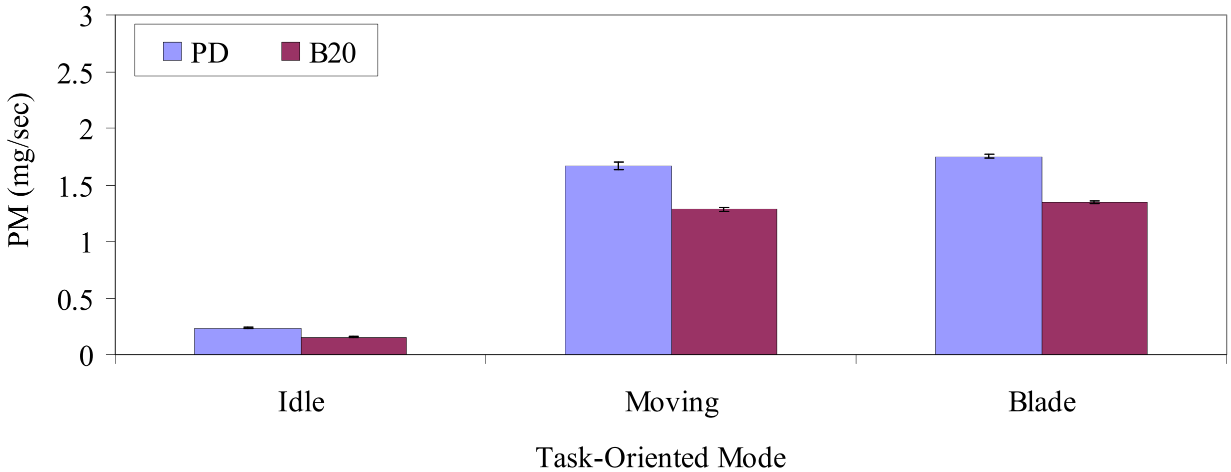
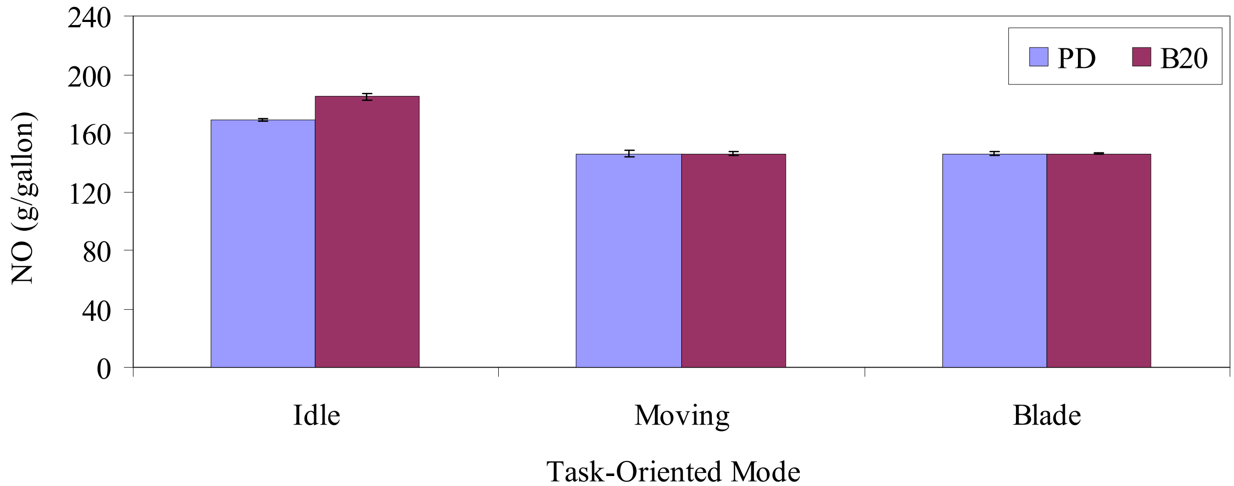
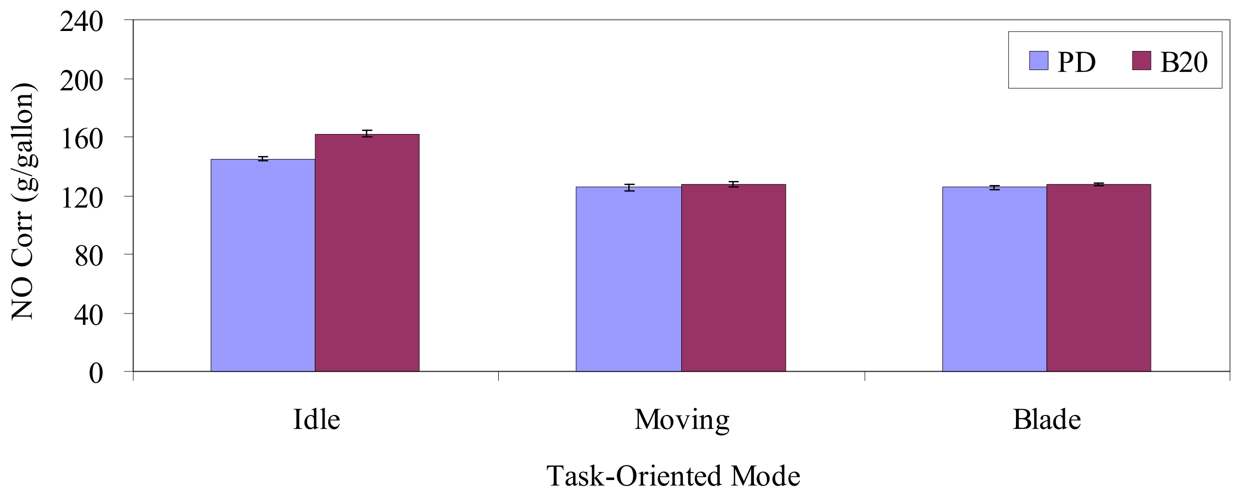


Figure A119. Continued

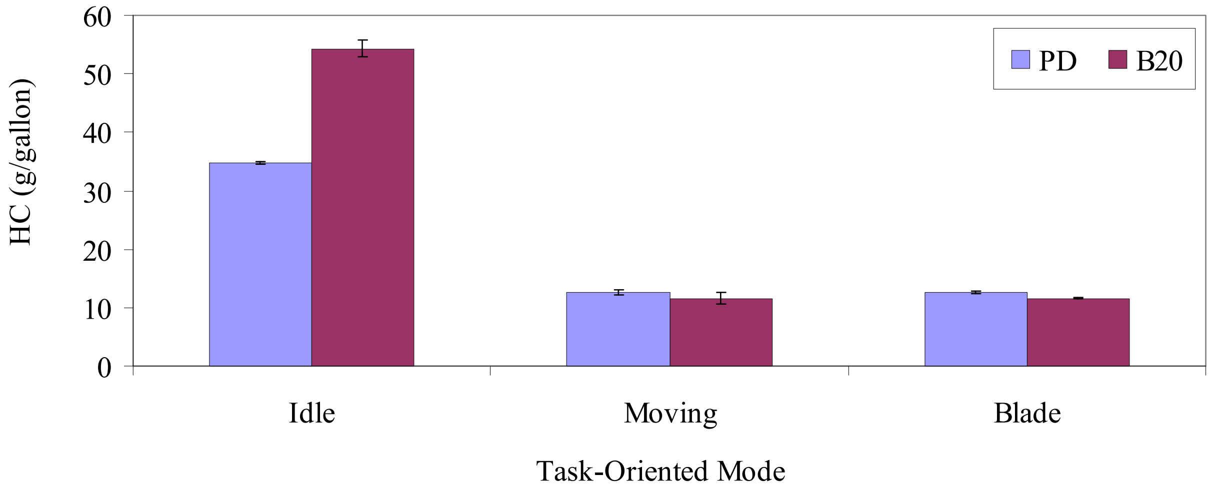


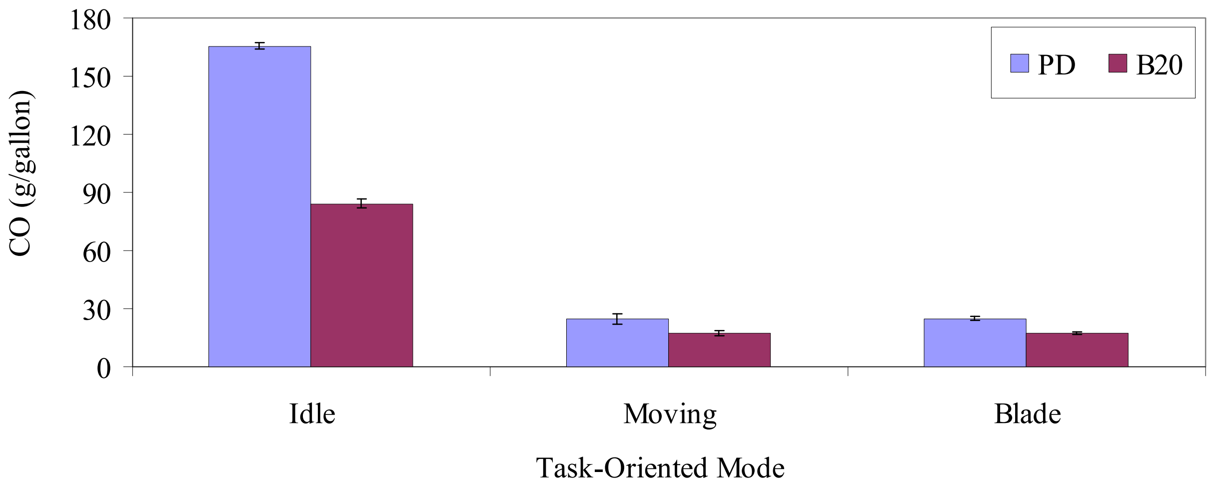


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 35 ^{o}F and the relative humidity was 39 %. For the B20 biodiesel test, the ambient temperature was 60 ^{o}F and the relative humidity was 72 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A120. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Motor Grader 5 (continued on next page)





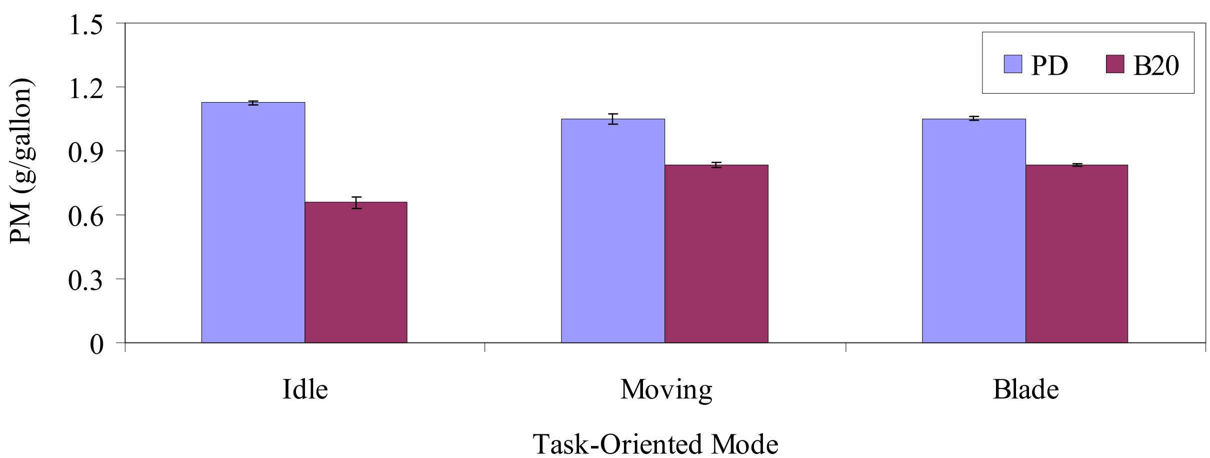
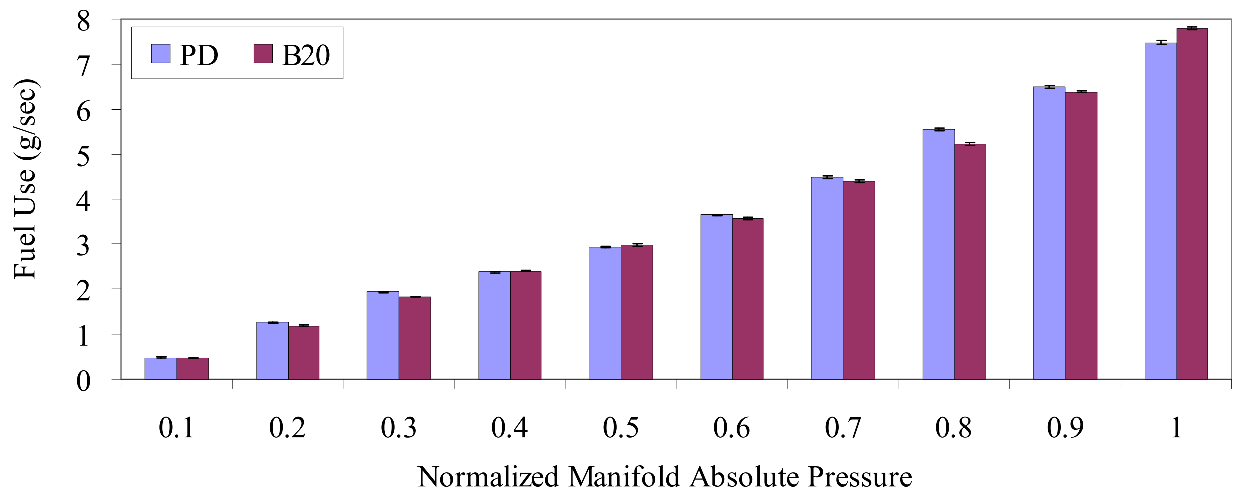
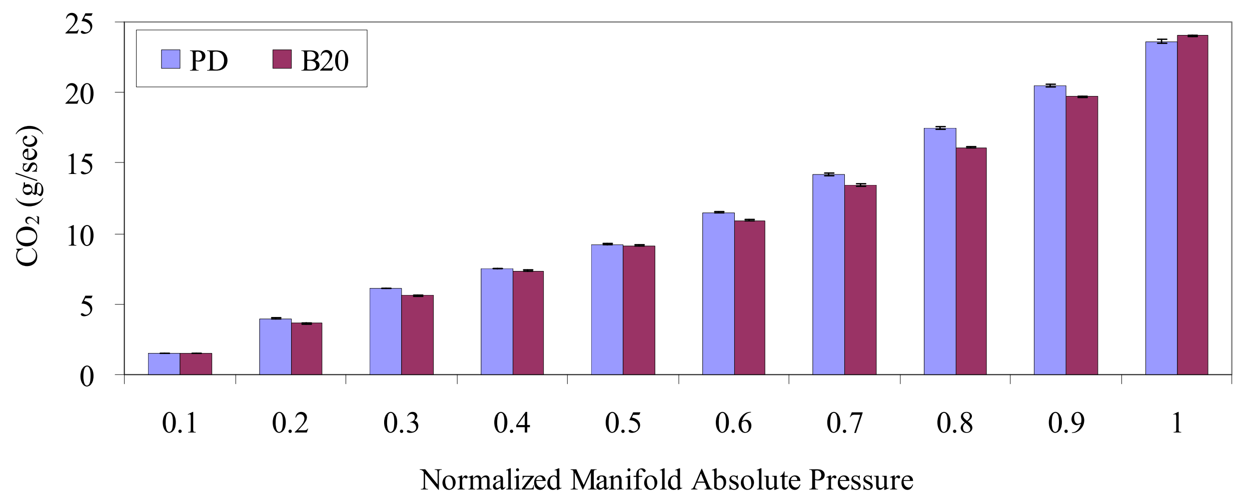


Figure A120. Continued

MOTOR GRADER 6

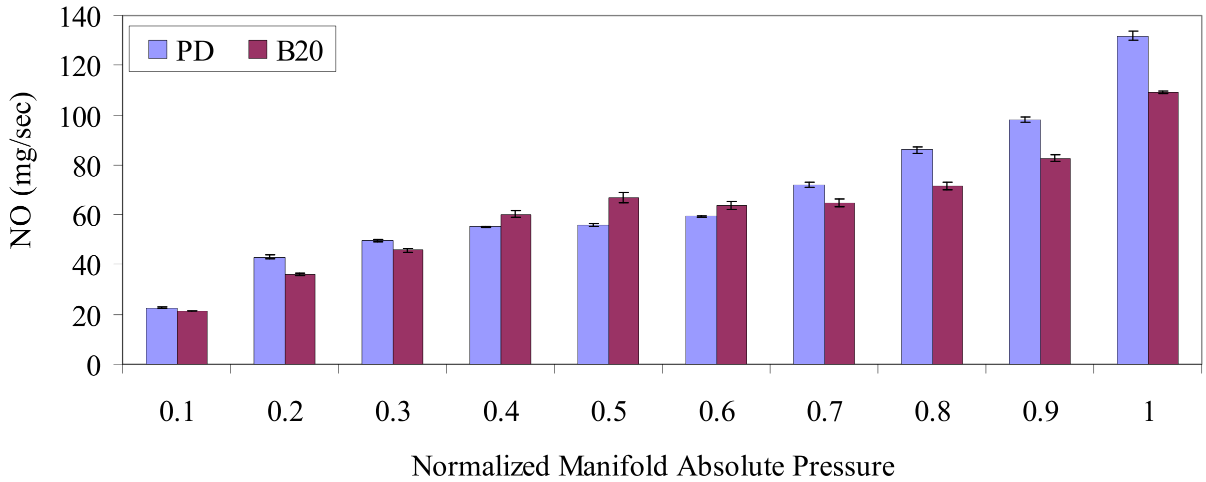


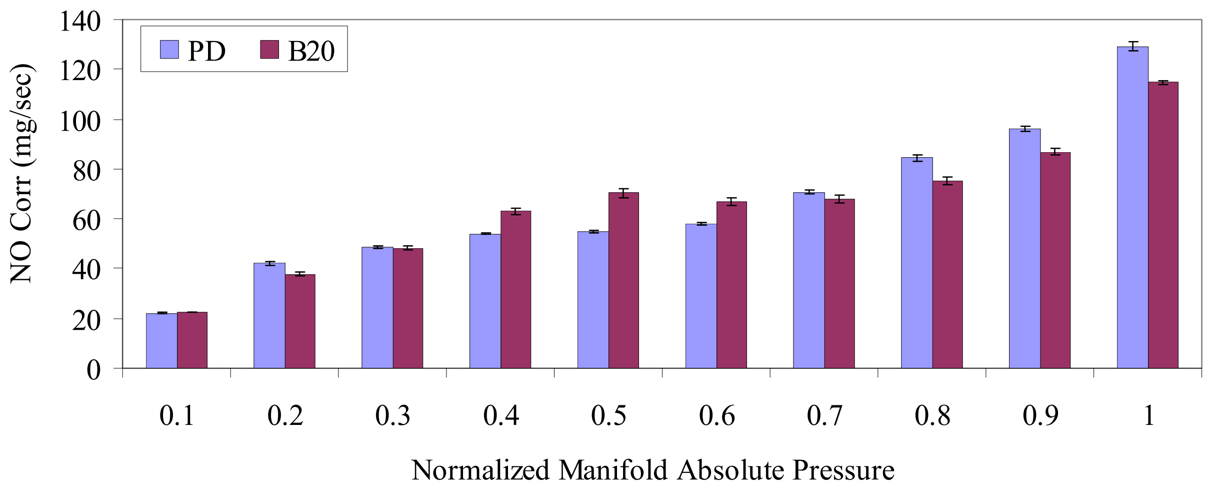


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 88 ^{o}F and the relative humidity was 56 %. For the B20 biodiesel test, the ambient temperature was 83 ^{o}F and the relative humidity was 42 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A121. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Motor Grader 6 (continued on next page)





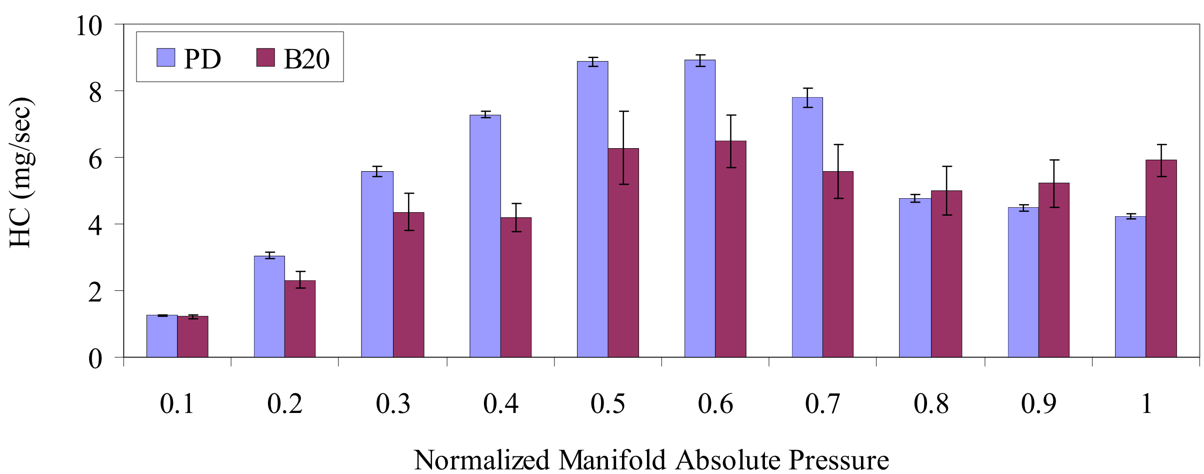
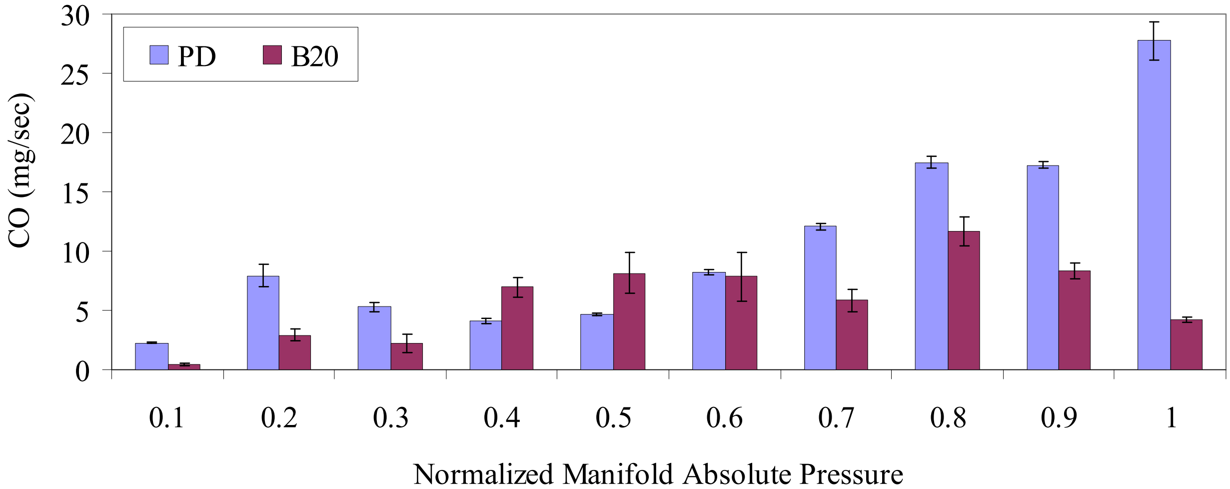


Figure A121. Continued



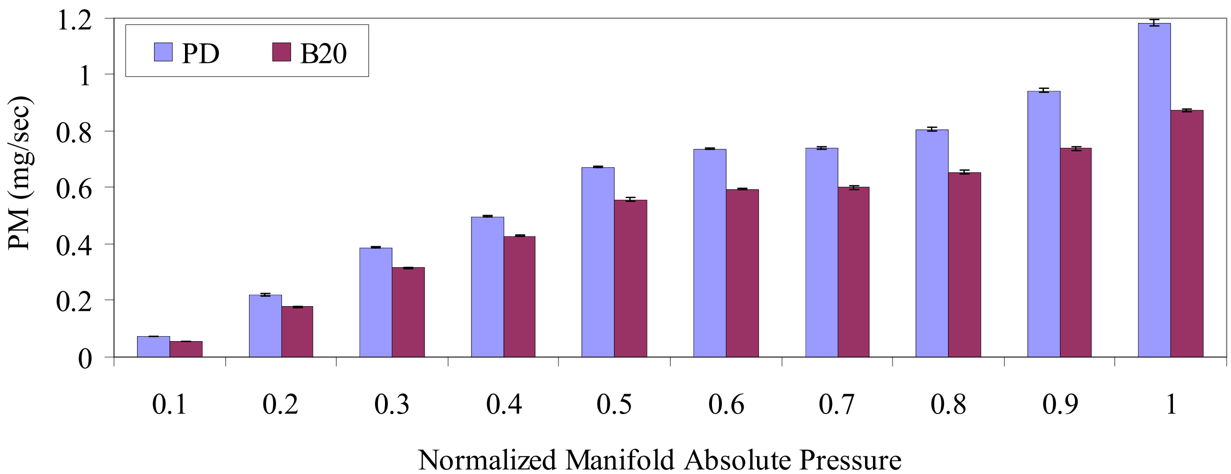
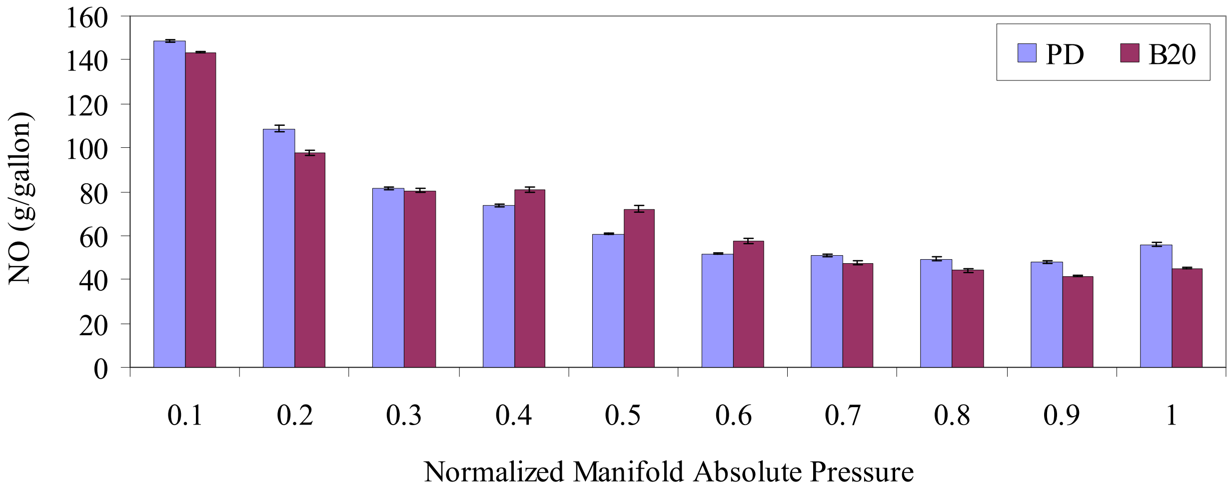
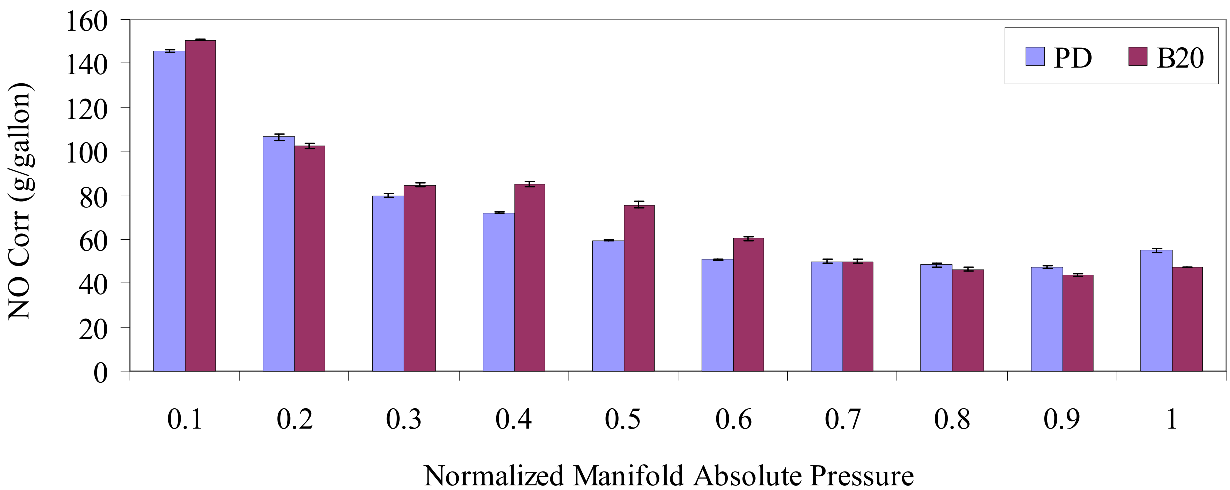


Figure A121. Continued

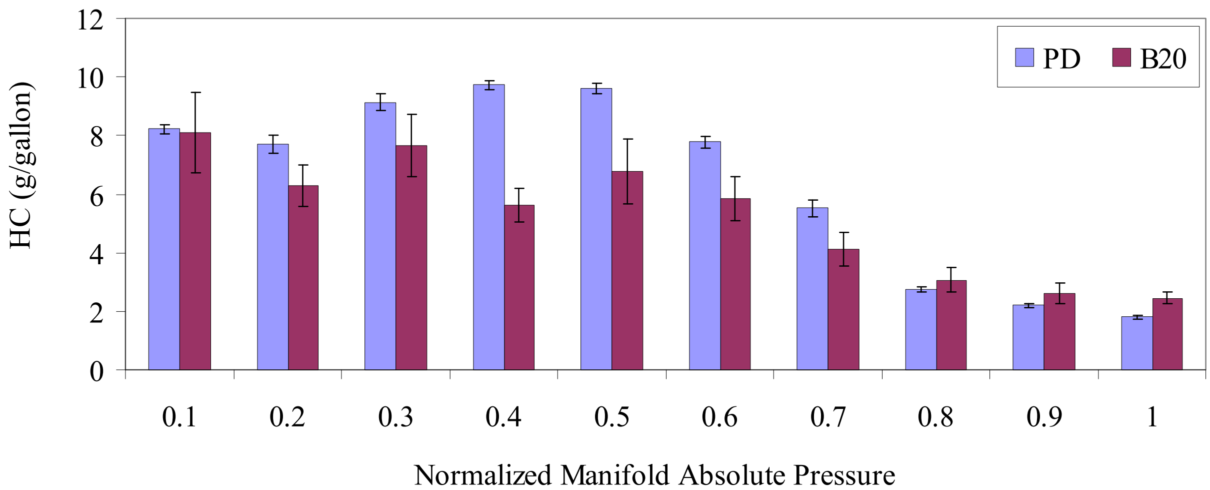


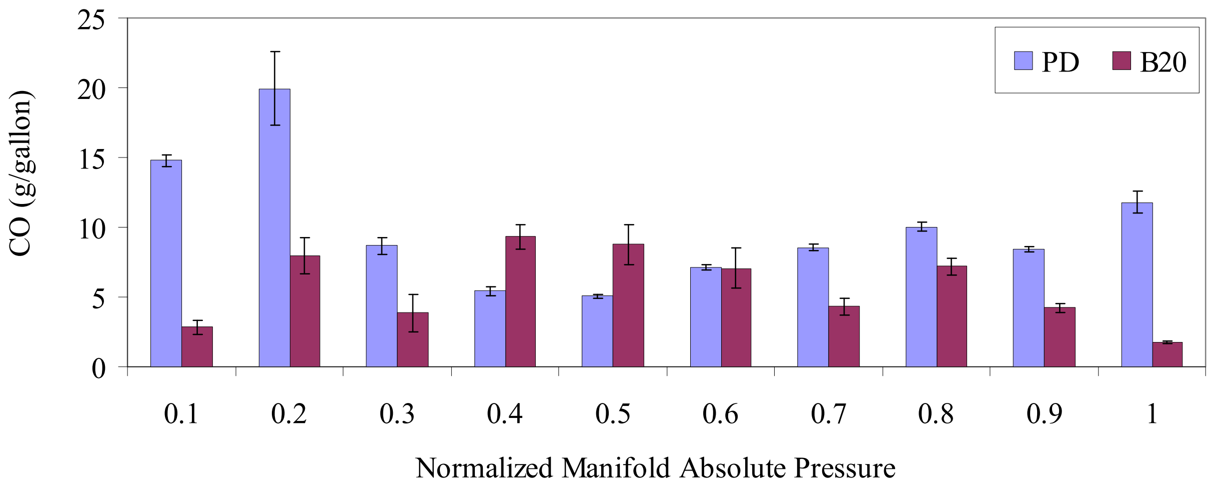


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 86 ^{o}F and the relative humidity was 56 %. For the B20 biodiesel test, the ambient temperature was 83 ^{o}F and the relative humidity was 42 %.

Values shown in the figure are the upper end of the range: "0.1" = 0 ≤ Normalized MAP < 0.1; "0.2" = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure A122. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes for Motor Grader 6 (continued on next page)





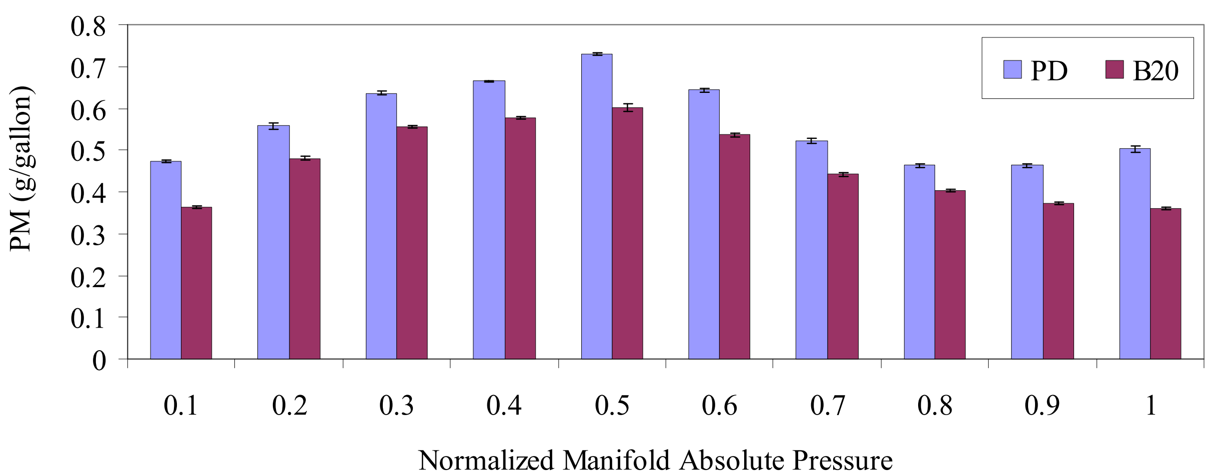
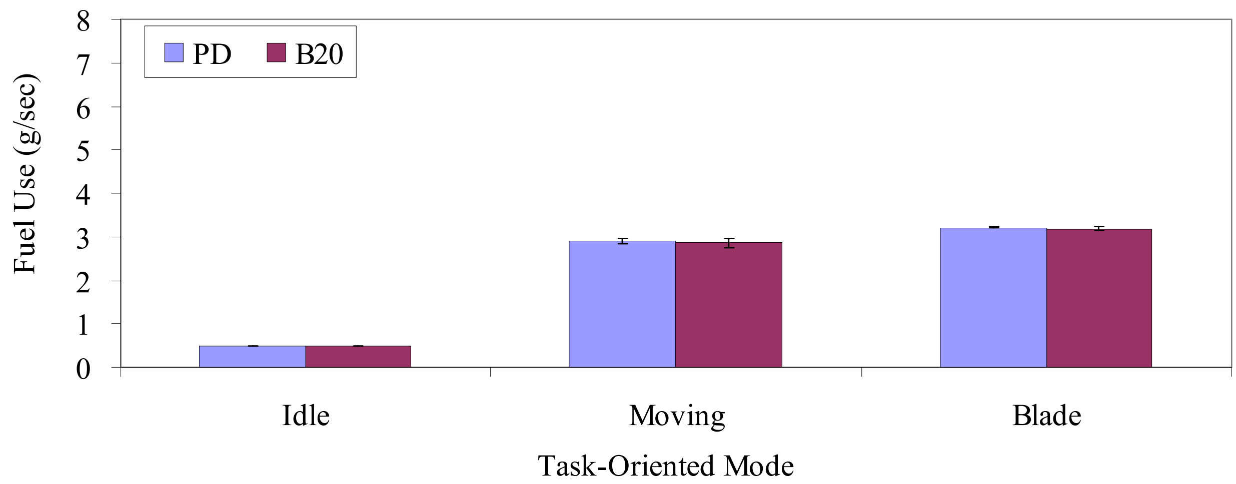
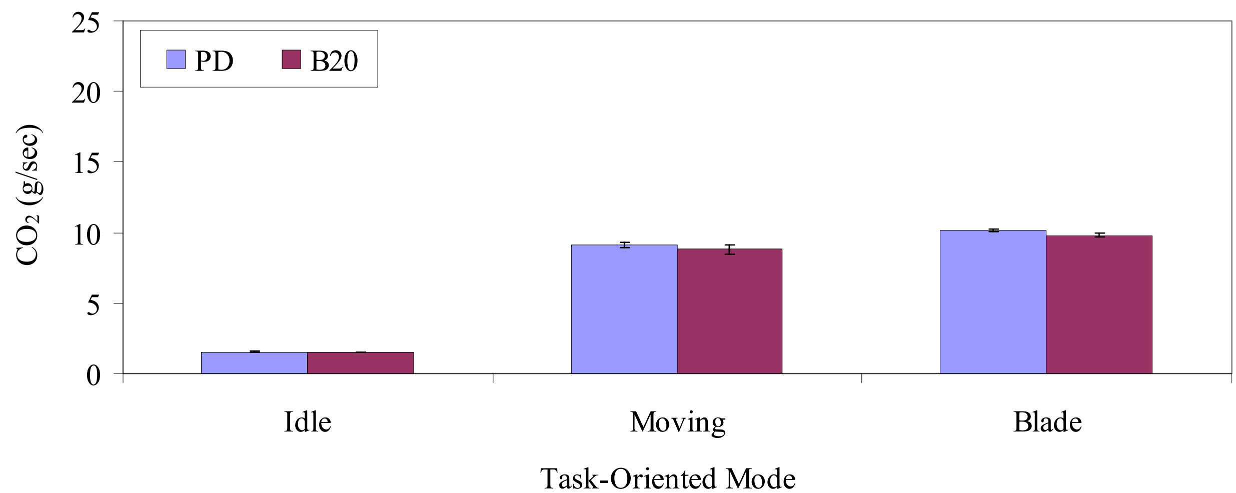


Figure A122. Continued

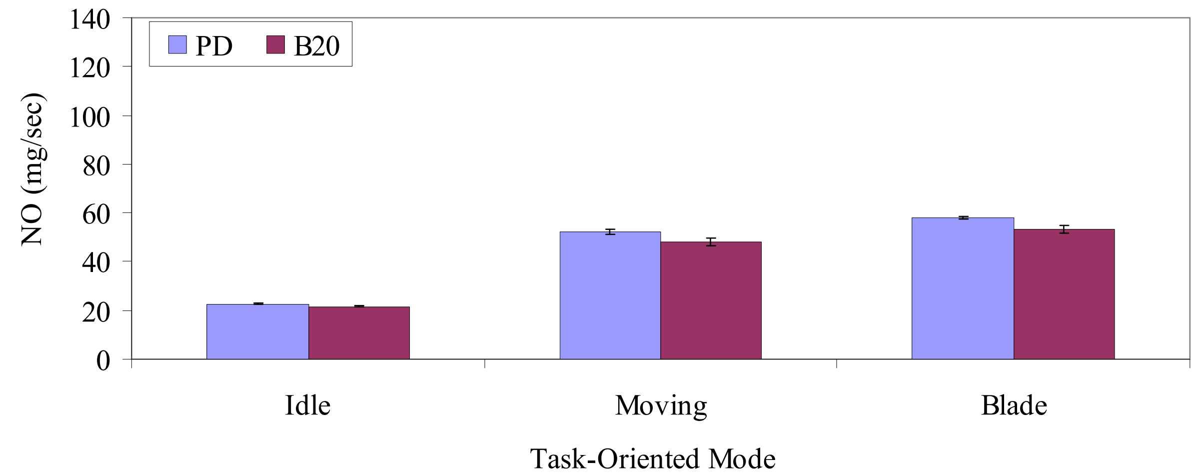


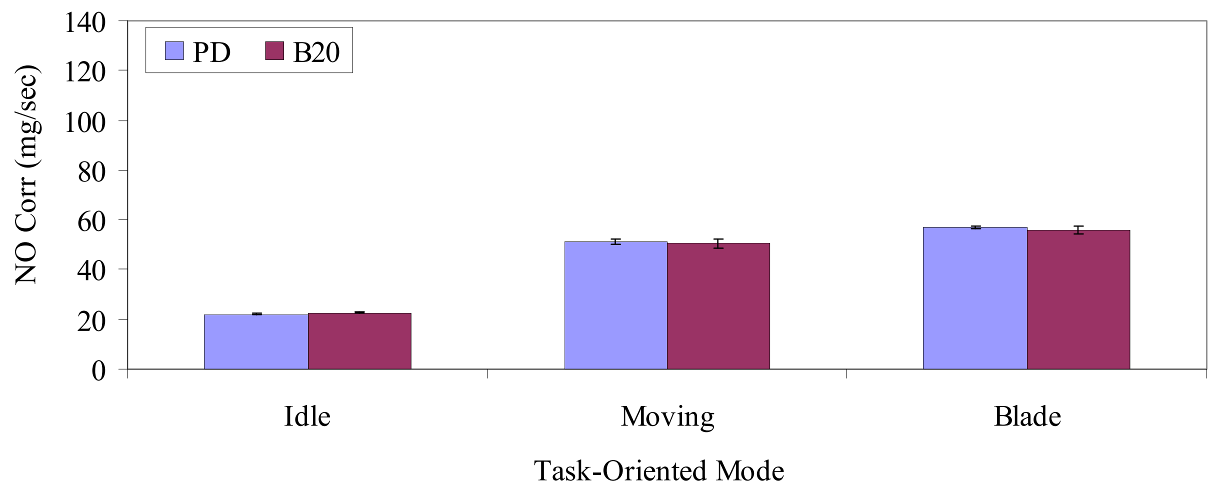


NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 86 ^oF and the relative humidity was 56 %. For the B20 biodiesel test, the ambient temperature was 83 ^oF and the relative humidity was 42 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A123. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Motor Grader 6 (continued on next page)





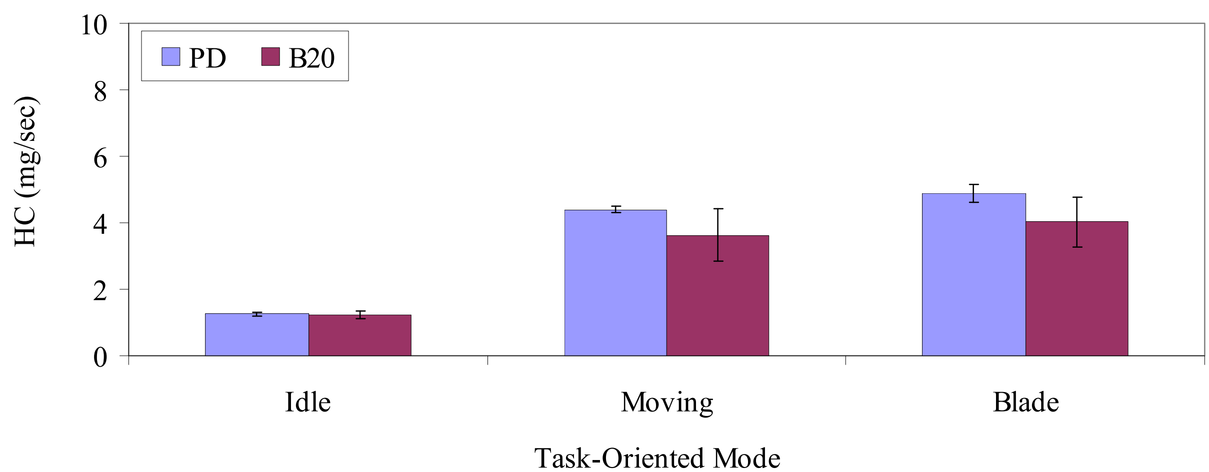
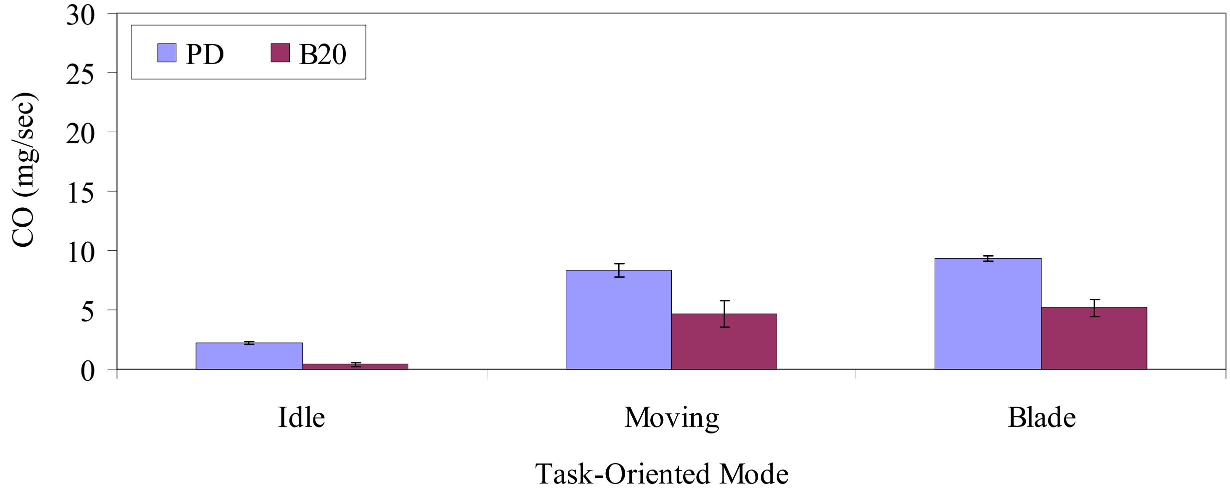


Figure A123. Continued



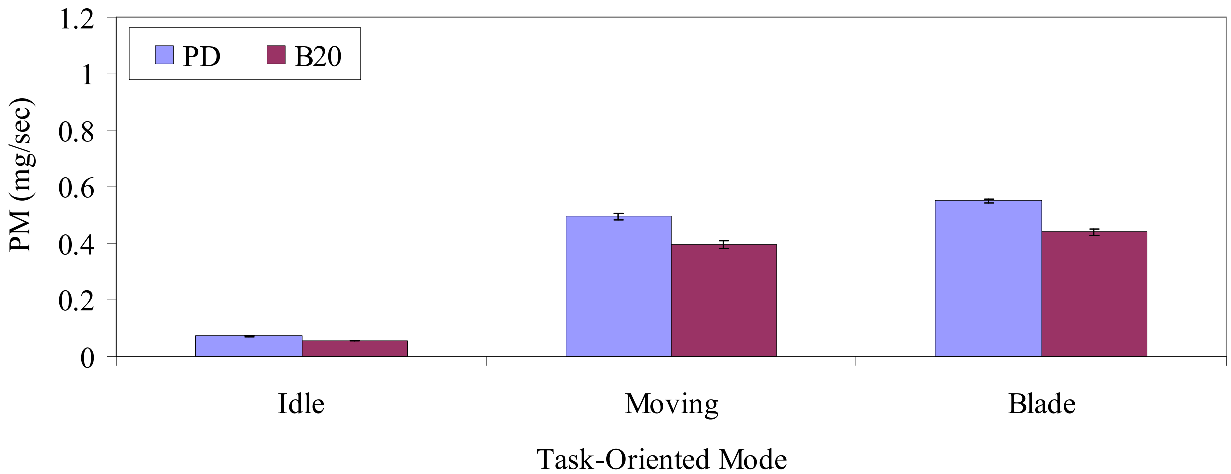
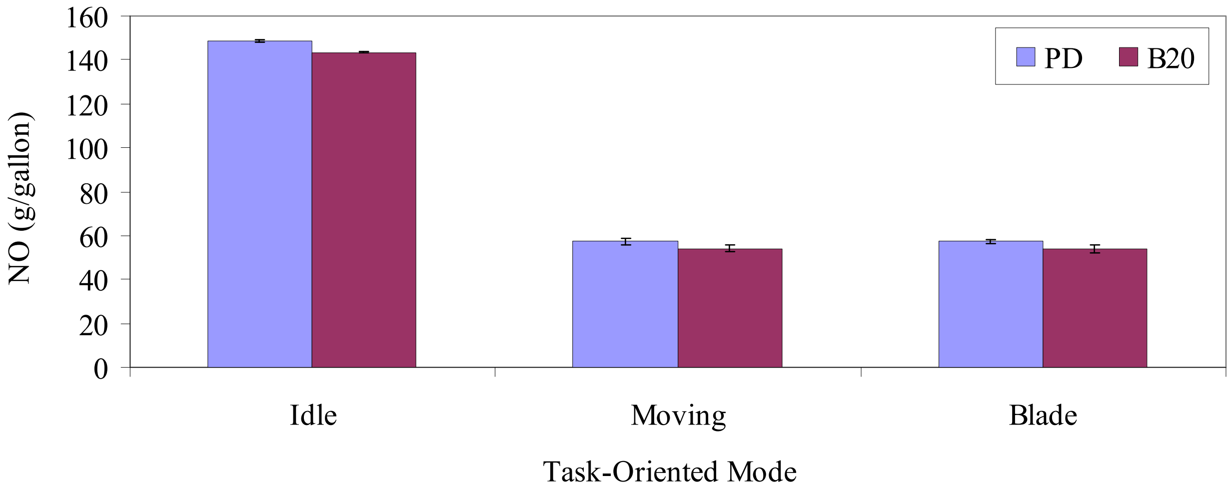
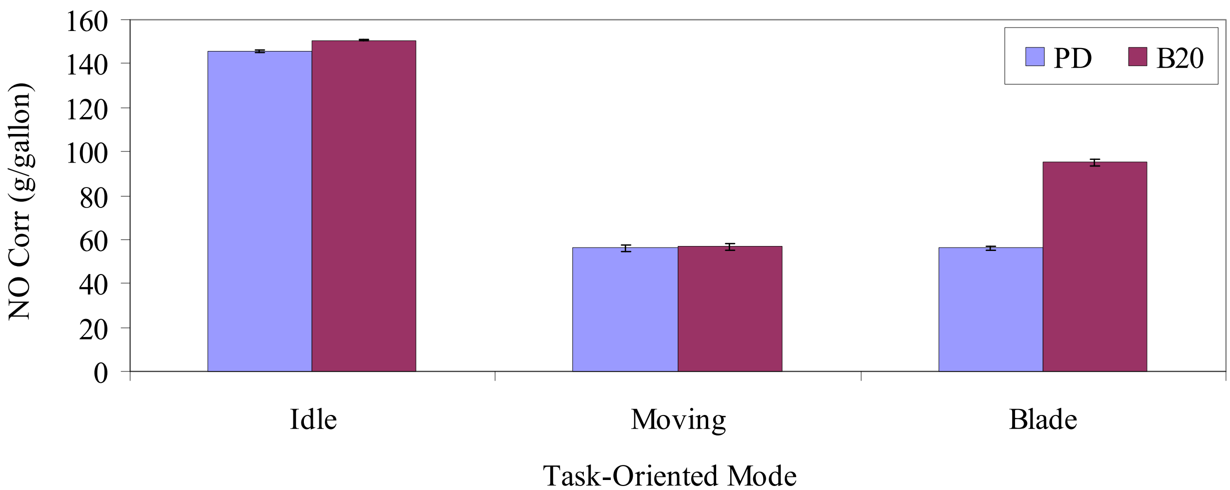


Figure A123. Continued





NO Corr: NO emissions are corrected based on ambient temperature and humidity. For the petroleum diesel test, the ambient temperature was 86 ^{o}F and the relative humidity was 56 %. For the B20 biodiesel test, the ambient temperature was 83 ^{o}F and the relative humidity was 42 %.

Task-oriented modes are: *idle*: engine on, but the vehicle is not working or moving; *moving*: movement of the motor grader when the blade is not in contact with the ground (forward or backward); *blade*: movement of the motor grader when the blade is in contact with the ground.

Figure A124. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Motor Grader 6 (continued on next page)

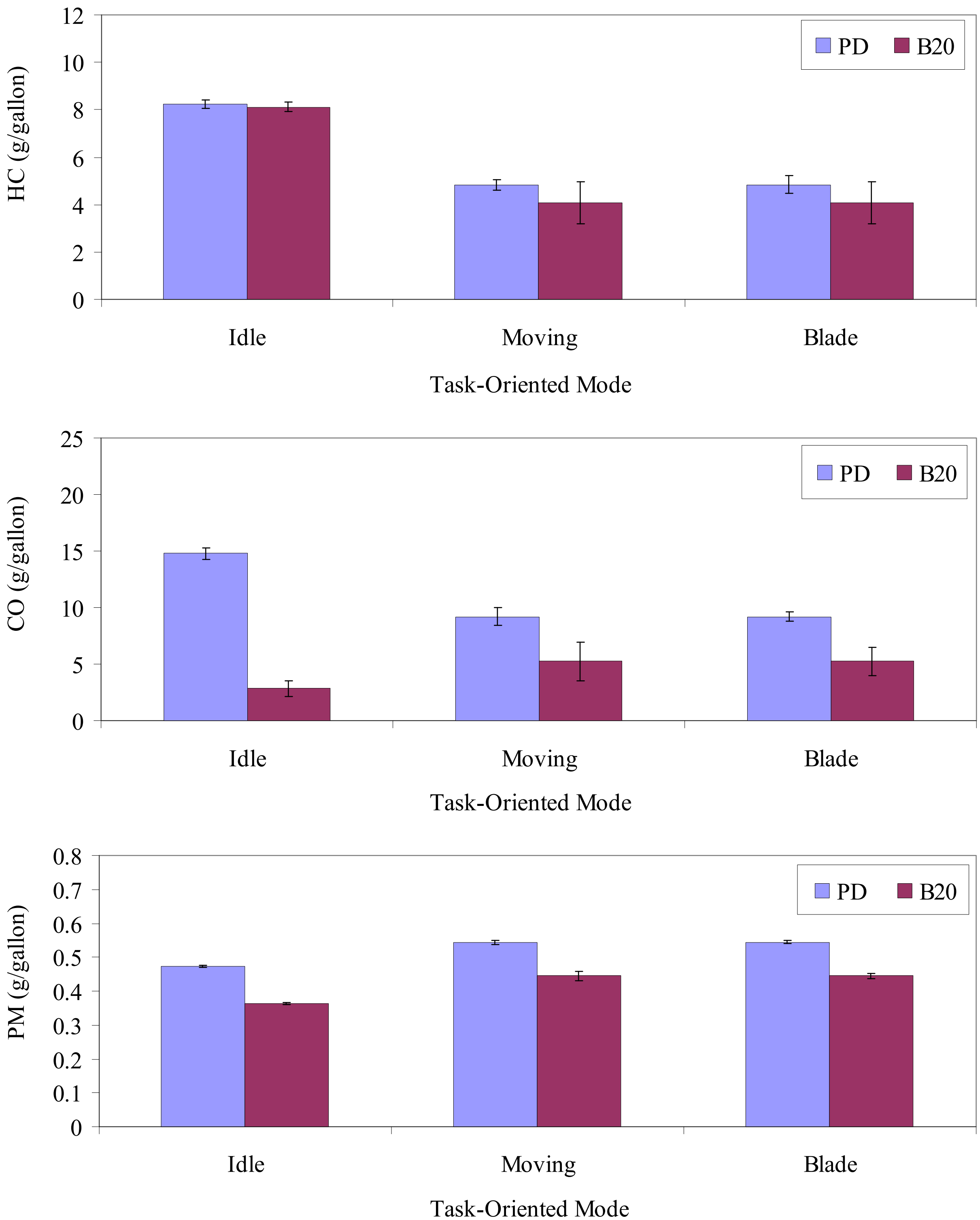


Figure A124. Continued

APPENDIX B. COEFFICIENTS OF PHYSICALLY REGRESSION MODELS FOR EACH TESTED VEHICLE

Appendix B provides coefficients of time-based and fuel-based regression models for each tested vehicle. Table B1 shows the coefficients of time-based regression models for fuel use, CO_2, HC, CO, and Opacity. Table B2 shows the coefficients of time-based regression models for NO. Table B3 shows the coefficients of fuel-based regression models for HC, CO, and Opacity. Table B4 shows the coefficients of fuel-based regression models for NO.

Table B1. Coefficients of Time-Based Regression Model for Fuel Use, CO_2, HC, CO, and Opacity

Equipment	Fuel Use		CO_2		HC		CO		Opacity	
	α	β	α	β	α	β	α	β	α	β
Front-End Loader 1	-4.102	0.046	-12.905	0.145	-0.0100	0.00013	-0.037	0.00046	-1.319	0.014
Front-End Loader 2	-5.470	0.058	-17.291	0.183	-0.0100	0.00017	0.007	0.00003	-1.935	0.020
Front-End Loader 3	-3.533	0.039	-11.158	0.122	-0.0074	0.00012	-0.0018	0.00007	-0.351	0.004
Front-End Loader 4	-5.209	0.057	-16.465	0.179	-0.0067	0.00012	-0.0065	0.00014	-1.772	0.019
Front-End Loader 5	-4.775	0.052	-15.085	0.164	-0.0029	0.00005	-0.0144	0.00016	-1.105	0.012
Dozer 1	-10.693	0.113	-33.748	0.357	-0.0076	0.00011	-0.0487	0.00059	-3.913	0.041
Dozer 2	-2.034	0.023	-6.425	0.073	-0.0075	0.00010	0.0034	0.00003	-0.813	0.008
Dozer 3	-10.870	0.115	-34.451	0.364	-0.0151	0.00019	0.0391	0.00012	-6.370	0.065
Dozer 4	-11.001	0.118	-34.644	0.370	-0.0187	0.00025	-0.0775	0.00095	-2.382	0.027
Dozer 5	-14.840	0.162	-46.996	0.511	-0.0005	0.00007	0.0137	0.00036	N/A	N/A
Excavator 1	-6.970	0.075	-22.053	0.237	-0.0050	0.00008	-0.0088	0.00015	-2.867	0.030
Excavator 2	-6.035	0.068	-19.054	0.214	-0.0125	0.00016	-0.0159	0.00328	-1.585	0.017
Excavator 3	-2.715	0.031	-8.594	0.097	-0.0030	0.00006	0.0012	0.00005	-0.664	0.007
Off-Highway Truck 1	-5.157	0.059	-16.097	0.185	-0.0096	0.00013	-0.1252	0.00129	-1.892	0.020
Off-Highway Truck 2	-10.465	0.115	-32.917	0.360	-0.0140	0.00017	-0.0855	0.00093	-3.005	0.033
Off-Highway Truck 3	-8.589	0.094	-27.116	0.298	-0.0092	0.00012	-0.0290	0.00040	-2.077	0.023
Backhoe 1	-3.870	0.042	-12.250	0.132	-0.0029	0.00006	0.0053	0.00001	-0.193	0.002
Backhoe 2	-9.099	0.100	-28.712	0.314	-0.0037	0.00006	-0.0496	0.00060	-5.920	0.062
Backhoe 3	-7.408	0.078	-23.355	0.246	-0.0101	0.00011	-0.0223	0.00025	-1.487	0.018
Backhoe 4	-2.750	0.030	-8.705	0.095	-0.0073	0.00008	-0.0081	0.00009	-0.622	0.007
Backhoe 5	-8.136	0.089	-25.016	0.275	-0.0123	0.00018	-0.4590	0.00476	-2.176	0.026
Backhoe 6	-6.776	0.073	-21.387	0.230	-0.0365	0.00038	-0.0697	0.00076	-2.661	0.028
Backhoe 7	-10.268	0.111	-32.269	0.348	-0.0061	0.00008	-0.1448	0.00158	-6.084	0.064
Backhoe 8	-2.674	0.029	-8.441	0.091	-0.0049	0.00006	-0.0114	0.00013	-0.670	0.007

(Continued on the next page)

Table B1. Continued.

Equipment	Fuel Use		CO_2		HC		CO		Opacity	
	α	β	α	β	α	β	α	β	α	β
Skid Steer Loader	-2.359	0.025	-7.450	0.080	-0.0056	0.00007	-0.0023	0.00006	-0.350	0.004
Motor Grader 1	-5.653	0.061	-17.866	0.193	-0.0095	0.00018	-0.0100	0.00017	-1.332	0.015
Motor Grader 2	-5.085	0.057	-16.041	0.180	-0.0113	0.00017	-0.0056	0.00013	-1.018	0.011
Motor Grader 3	-6.836	0.073	-21.416	0.229	-0.0239	0.00031	-0.0229	0.00028	-1.740	0.019
Motor Grader 4	-13.952	0.154	-43.952	0.483	-0.0248	0.00041	-0.0454	0.00070	-4.605	0.048
Motor Grader 5	-9.238	0.096	-29.241	0.303	-0.0238	0.00031	0.0183	0.00017	-3.051	0.032
Motor Grader 6	-3.511	0.037	-11.101	0.116	0.0001	0.00003	-0.0101	0.00010	-0.498	0.006
Track Loader	-7.029	0.074	-22.231	0.234	0.0002	0.00001	-0.0117	0.00020	-0.832	0.010

Table B2. Coefficients of Time-Based Regression Model for NO

Equipment	NO		
	α	β_1	β_2
Front-End Loader 1	49.071	16.720	1456.475
Front-End Loader 2	100.694	33.914	2673.598
Front-End Loader 3	41.345	13.749	1363.976
Front-End Loader 4	65.987	21.952	1927.226
Front-End Loader 5	91.546	30.880	2469.913
Dozer 1	122.100	41.119	3078.136
Dozer 2	44.728	15.290	1413.787
Dozer 3	262.616	89.800	5939.594
Dozer 4	39.244	12.596	1308.317
Dozer 5	26.124	7.867	1052.220
Excavator 1	3.095	0.744	491.197
Excavator 2	29.159	9.837	1018.020
Excavator 3	-7.114	-2.313	227.435
Off-Highway Truck 1	20.742	6.940	795.862
Off-Highway Truck 2	-10.073	-3.622	148.603
Off-Highway Truck 3	8.290	2.492	571.303
Backhoe 1	353.473	122.070	7698.026
Backhoe 2	609.924	212.665	12403.96
Backhoe 3	810.396	281.912	16606.48
Backhoe 4	89.629	30.567	2392.08
Backhoe 5	635.774	219.802	13381.98
Backhoe 6	202.943	69.130	4806.51
Backhoe 7	412.904	144.574	8334.49
Backhoe 8	91.321	31.148	2432.31
Skid Steer Loader	127.196	43.934	3104.59

(Continue on the next page)

Table B2. Continued.

Equipment	NO		
	α	β_1	β_2
Motor Grader 1	0.631	0.132	347.17
Motor Grader 2	24.255	8.073	899.790
Motor Grader 3	6.105	1.878	514.407
Motor Grader 4	61.980	20.481	1760.313
Motor Grader 5	84.355	27.876	2383.91
Motor Grader 6	-1.231	0.083	246.956
Track Loader	-13.431	-4.669	149.873

Table B3. Coefficients of Fuel-Based Regression Model for HC, CO, and Opacity

Equipment	HC		CO		Opacity	
	α	β	α	β	α	β
Front-End Loader 1	29.1	-0.122	62.1	-0.163	275.9	4.490
Front-End Loader 2	101.6	-0.604	176.5	-1.151	117.1	6.185
Front-End Loader 3	55.8	-0.247	71.9	-0.363	942.9	-2.839
Front-End Loader 4	61.2	-0.318	70.6	-0.361	882.4	0.477
Front-End Loader 5	31.8	-0.182	14.8	-0.0303	388.1	1.961
Dozer 1	27.4	-0.167	81.3	-0.440	1747.9	-4.444
Dozer 2	31.2	-0.090	88.3	-0.441	204.6	4.657
Dozer 3	38.2	-0.246	265.3	-1.964	-2896.9	36.617
Dozer 4	46.7	-0.252	96.9	-0.419	1259.4	-2.930
Dozer 5	34.1	-0.176	203.5	-1.025	N/A	N/A
Excavator 1	16.1	-0.065	51.6	-0.234	783.0	2.570
Excavator 2	28.1	-0.125	140.0	-0.734	42.6	4.223
Excavator 3	24.9	-0.094	109.3	-0.552	206.8	2.885
Off-Highway Truck 1	10.7	-0.013	-18.4	0.445	186.2	4.763
Off-Highway Truck 2	34.5	-0.211	74.6	-0.360	2223.6	-9.727
Off-Highway Truck 3	23.4	-0.109	77.8	-0.357	819.6	-0.0490
Backhoe 1	142.5	-1.084	322.5	-2.545	-261.3	3.317
Backhoe 2	68.5	-0.59	162.1	-1.204	378.4	8.0414
Backhoe 3	21.8	-0.133	55.0	-0.352	3775.8	-23.377
Backhoe 4	31.8	-0.163	9.9	-0.007	3775.8	-23.377
Backhoe 5	140.7	-1.100	-271.2	3.297	10949.4	-84.260
Backhoe 6	21.6	-0.060	44.1	-0.07	4039.4	-23.069
Backhoe 7	99.3	-0.865	258.3	-1.952	-6154.4	71.720
Backhoe 8	45.5	-0.271	36.2	-0.151	1024.3	-1.993
Skid Steer Loader	61.36191	-0.35659	161.0392	-1.06774	1355.7	-5.841

(Continue on the page)

Table B3. Continued

Equipment	HC		CO		Opacity	
	α	β	α	β	α	β
Motor Grader 1	35.5	-0.112	42.8	-0.155	973.3	-0.543
Motor Grader 2	34.6	-0.127	43.3	-0.169	520.7	0.790
Motor Grader 3	46.3	-0.170	47.6	-0.190	642.6	0.973
Motor Grader 4	113.9	-0.787	210.2	-1.492	-462.5	10.306
Motor Grader 5	73.8	-0.387	425.2	-2.586	1198.4	-0.696
Motor Grader 6	12.0	-0.024	13.7	-0.030	531.5	0.3817
Track Loader	9.7	-0.052	74.7	-0.358	1249.9	-4.177

Table B4. Coefficients of Fuel-Based Regression Model for NO

Equipment	NO		
	α	**β_1**	**β_2**
Front-End Loader 1	-9.37	-4.39	-421.12
Front-End Loader 2	18.25	4.80	225.77
Front-End Loader 3	-17.21	-7.12	-615.42
Front-End Loader 4	8.35	1.34	19.43
Front-End Loader 5	33.24	9.92	577.80
Dozer 1	-52.22	-19.41	-1294.4
Dozer 2	19.57	5.17	295.96
Dozer 3	-19.64	-8.44	-533.393
Dozer 4	-35.98	-13.82	-966.75
Dozer 5	-15.94	-7.08	-501.26
Excavator 1	-13.10	-5.87	-441.23
Excavator 2	-18.05	-7.37	-582.42
Excavator 3	-24.32	-9.58	-737.93
Off-Highway Truck 1	-0.904	-1.63	-232.10
Off-Highway Truck 2	-57.25	-20.72	-1428.32
Off-Highway Truck 3	-55.33	-19.92	-1461.71
Backhoe 1	192.27	65.33	3711.82
Backhoe 2	153.07	52.15	2846.06
Backhoe 3	256.08	88.37	4810.18
Backhoe 4	-57.66	-20.86	-1469.88
Backhoe 5	272.19	92.47	5499.71
Backhoe 6	1.05	-1.15	-99.57
Backhoe 7	-40.64	-14.62	-1206.01
Backhoe 8	-50.28	-18.37	-1304.66
Skid Steer Loader	-38.7933	-14.549	-1013.34

Table B4. Continued.

Equipment	NO		
	α	**β_1**	**β_2**
Motor Grader 1	-6.73471	-3.63448	-366.289
Motor Grader 2	0.152032	-1.27249	-212.98
Motor Grader 3	-20.5218	-8.16556	-700.316
Motor Grader 4	-72.356	-26.532	-1635.32
Motor Grader 5	7.577307	1.02052	9.648132
Motor Grader 6	-1.13798	-1.37497	-307.36
Track Loader	-34.5557	-12.8097	-966.255