Annual Report for Period: 09/2006 - 08/2007
Submitted on: 09/01/2007
Principal Investigator: Frey, H. Christopher .
Award ID: 0327731
Organization: North Carolina State U
Title:
Life Cycle Inventory and Impact Analysis Framework for Nonroad Construction Vehicles and Equipment Based Upon In-Use Measurements (TSE03-L)

Project Participants

Senior Personnel

Name: Frey, H. Christopher
Worked for more than 160 Hours: Yes
Contribution to Project:
H. Christopher Frey is the principal investigator. He has been involved in several key tasks during this reporting period. These key tasks include: (1) specification and procurement of the portable emissions monitoring system (PEMS); (2) identification of existing data regarding nonroad vehicle emissions based upon second-by-second in-use or real world measurements; and (3) identification and characterization of key types of nonroad equipment and their typical duty cycles.

Name: Rasdorf, William
Worked for more than 160 Hours: Yes
Contribution to Project:
William Rasdorf is the co-investigator of this project. His involvement during the reporting period has primarily been with respect to identification and characterization of key types of nonroad equipment and their typical duty cycles.

Post-doc

Graduate Student

Name: Kim, Kangwook
Worked for more than 160 Hours: Yes
Contribution to Project:
Mr. Kangwook Kim is a PhD student and a graduate research assistant. During the current reporting period he is working on a separate project sponsored by NCDOT pertaining to measurement of in-use emissions for onroad diesel vehicles. His involvement in this project has primarily been with respect to working with the Portable Emissions Monitoring System (PEMS) that is being procured in terms of communication and training with the vendor, Clean Air Technologies International, and verification of PEMS receipt and operational status. He has also performed a literature review pertaining to diesel fuel characteristics and factors pertaining to formation of selected air pollutants in diesel engines. His support is currently via the NCDOT funding but his work is synergistic with this project.

Name: Abolhasani, Saeed
Worked for more than 160 Hours: Yes
Contribution to Project:
Saeed worked on identifying other databases, evaluating existing data, developing modeling approaches for existing data, and developing protocols for field data collection.

Name: Pang, Shih-Hao
Worked for more than 160 Hours: Yes
Contribution to Project:
Shih-hao worked on development of the fuel cycle life cycle inventories for petroleum diesel and biodiesel, and also regarding existing tools used nationally for estimation of nonroad vehicle emissions.

Name: Lewis, Phil
Worked for more than 160 Hours: Yes
Contribution to Project:

Participates in scheduling of field data collection, characterization of construction activity, and development of field data summary information.

Undergraduate Student

Name: Dilmore, Beth

Worked for more than 160 Hours: Yes

Contribution to Project:

Student assisted in literature review regarding availability of second-by-second portable emissions measurement data for nonroad equipment, and identified some recent and ongoing activities in this area.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Clean Air Technologies International, In

Clean Air Technologies International, Inc. is the vendor of the portable emissions monitoring system (PEMS) that we purchased using funding on this project. The PEMS is referred to as the 'Montana system' and is capable of obtaining measurements on both electronically controlled and non-electronically controlled vehicles. Although our primary relationship with CATI is as a purchaser of their equipment, CATI has provided technical assistance toward our study and also has indicated a willingness to share data with us that they have collected regarding nonroad equipment.

U.S. Environmental Protection Agency

The U.S. Environmental Protection Agency is developing a new mobile source emissions model, referred to as MOVES. EPA is involved in collecting some data for nonroad vehicles. We are coordinating with EPA to obtain this data when possible. During this reporting period, EPA has provided us with second-by-second data files for several nonroad construction vehicles, which we have used as the basis for analysis of key explanatory variables.

Other Collaborators or Contacts

We have had collaborations from several local private construction contracting companies that have allowed us to instrument their vehicles for purposes of field data collection on bulldozers, excavators, backhoes, front end loaders, skid steer loaders, off-highway dump trucks, and generators.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Please see the attached Activities file.

Findings: (See PDF version submitted by PI at the end of the report)

Please see the attached Findings file.

Training and Development:

Examples of training and development of the graduate students working on this project include:

Introduction to air quality rules and regulations regarding nonroad construction vehicles including EPA's strategies.

Ability to categorize and describe methods of emissions measurement from construction vehicles including laboratory tests and on-board measurement.

Development of skills for programming by Visual Basic and coding macros into excel software.

Identification and description of protocols of obtaining data for both engine and exhaust.

Application of SAS software in statistical analysis of on-board emission data.

Identification and application of the NONROAD model in emission inventory studies.

Outreach Activities:

NC State University's 'RESULTS' magazine did a story that featured Dr. Frey and some of his students, including a photograph of data collection for a backhoe. The article is available at: http://www.ncsu.edu/research/results/vol11/6.html.

Journal Publications

Frey, HC, S. Abolhasani, "PROCEDURE FOR REAL-WORLD EMISSION DATA COLLECTION FROM NONROAD CONSTRUCTION VEHICLES: A CASE STUDY FOR EXCAVATORS", J. AWMA, p. , vol. , (2007). in final preparation,

Books or Other One-time Publications

Shih-Hao Pang, H. Christopher Frey, "Life Cycle Inventory for Nonroad Construction Equipment and Vehicles", (2005). Conference paper, accepted and presented at annual meeting
Collection: Air & Waste Management Association Annual Meeting, Student Paper Competition
Bibliography: Air & Waste Management Association, Pittsburgh, PA

Kangwook Kim, Saeed Abolhasani, Shih-Hao Pang, and H. Christopher Frey, "Real-world Data Collection Procedure for Non-road Construction Equipment: Problems, Solutions, and Data Quality Assurance", (2006). Conference Proceedings, Published
Collection: Proceedings, Annual Meeting of the Air & Waste Management Association
Bibliography: Extended Abstract #: 548

H.C. Frey, W. Rasdorf, S.-H. Pang, K. Kim, S. Abolhasani, and P. Lewis, "Methodology for Activity, Fuel Use, and Emissions Data Collection and Analysis for Nonroad Construction Equipment", (2007). conference proceedings, Published
Collection: Proceedings of the Annual Meeting of the Air & Waste Management Association
Bibliography: 2007-AWMA-447, Proceedings, 100th Annual Meeting of the Air & Waste Management Association, Pittsburgh, PA, June 26-28, 2007

H. C. Frey, W. J. Rasdorf, S-H. Pang, K. Kim, and P. Lewis, "Methodology for Activity, Fuel Use and Emissions Data Collection and Analysis for Nonroad Construction Equipment", (2007). conference proceedings, Published
Collection: Proceedings, 16th Annual International Emission Inventory Conference, U.S. Environmental Protection Agency, May 2007.
Bibliography: http://www.epa.gov/ttn/chief/conference/ei16/session4/frey.pdf

H. Christopher Frey
Shih-Hao Pang
William Rasdorf
, "Development of In-Use Energy Use and Emissions Models For Twelve Construction Vehicles", (2007). conference proceedings, Published
Collection: Proceedings, 17th CRC On-Road Vehicle Emissions Workshop
Bibliography: 119. ?Methodology for Light Duty Gasoline Vehicle-Specific Measurement and Modeling of On-Road Emissions and Energy Use,? On-Road Vehicle Emissions Workshop, held March 29-31, 2004

Web/Internet Site

URL(s):
http://www4.ncsu.edu/~frey/
Description:
Dr. Frey's web site, including summaries of research projects, publications, and related information.

Other Specific Products

Product Type:
Conference Presentation
Product Description:
?Measurement and Analysis of In-Use Emissions from Nonroad Construction Vehicles,? CRC On-Road Vehicle Emissions Workshop, San Diego, CA, March 30, 2006
Sharing Information:
This was presented at a conference and thus was shared with conference attendees

Product Type:
Conference Presentation
Product Description:
?Life Cycle Inventory Energy Use and Emissions for Biodiesel Versus Petroleum Diesel Fuels,? CRC On-Road Vehicle Emissions Workshop, San Diego, CA, March 29, 2006
Sharing Information:
Presented and shared at a conference.

Contributions

Contributions within Discipline:
Contributions of the project include the following, which pertain to fields of environmental engineering, construction engineering, and related disciplines such as mechanical and chemical engineering:
- Developing a tool for predicting energy use and emissions of construction equipment/vehicle life cycle
- Providing insight regarding fuel selection for construction equipment/vehicles
-- Identifying fuel cycle energy use and emissions and quantification of the portion of total energy use and emissions associated with specific stages of the fuel cycle
- Comparison of total emission rates and energy use for different vehicles/equipment and fuels taking into account the fuel cycle and direct vehicle emissions.
- Development and analysis of databases for nonroad vehicle energy use and emissions.
- characterization of micro-scale construction vehicle activity, fuel use, and emissions based on real world, in-use data.

Contributions to Other Disciplines:
The methods of this project contribute to other disciplines in terms of applications that are relevant to societal needs, such as the need to understand and manage air pollution from nonroad vehicles. Through a demonstration pilot data collection effort, we have demonstrated, for example, that vehicle emissions are episodic in nature and depend on specific aspects of the vehicle activity pattern. These insights have implications for pollution prevention and estimation of emissions. During the second year, we have compared different fuels and found that a promising fuel with lower tailpipe emissions also tends to have higher fuel cycle emissions, thereby implying the need for societal trade-offs and providing scientific information to inform a growing policy debate over the role of biofuels.

Contributions to Human Resource Development:
This project has contributed to human resource development with regard to developing the knowledge base and skills of the graduate students and faculty who are working on this project, in terms of ability to organize information, communicate, identify and use appropriate software tools, identify and implement field data collection procedures, and so on.
Specific areas of development include: (a) design of a field data collection study; (b) calibration and operation of the PEMS; (c) installation of the PEMS in a variety of types of vehicles; (d) execution of a field data collection study, including logistics of scheduling and deployment; (e)

data reduction and quality assurance of data; (f) statistical analysis of data using advanced software and methods; (g) development of models and inferences based upon the data; and (h) communication of results to stakeholders and other interested parties. The disciplinary areas of development are typically based upon environmental engineering, chemical engineering, and mechanical engineering concepts.

Contributions to Resources for Research and Education:

The main resources that we use for this project include the Portable Emissions Monitoring Systems (PEMS) that we have procured, and the Computational Laboratory for Energy, Air, and Risk (CLEAR) that we use for data reduction and analysis. The PEMS is a resource made possible via this grant.

Contributions Beyond Science and Engineering:

This project and its methods are motivated by considerations of emissions characterization and pollution prevention pertaining to an important emission source cateogory. The key findings to date imply the need for representative in-use information regarding construction vehicle/equipment emissions for high priority types of vehicles and equipment, insights regarding the sensitivity of emissions to the activity patterns of such vehicles, and trade-offs between tailpipe and fuel cycle emissions when comparing fuels such as petroleum diesel and biodiesel. All of these have implications for public welfare beyond science and engineering but informing the public as well as regulatory policy.

Special Requirements

Special reporting requirements: None

Change in Objectives or Scope: None

Unobligated funds: less than 20 percent of current funds

Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Summary of Activities

NSF Grant 0327731: Life Cycle Inventory and Impact Analysis Framework for Nonroad Construction Vehicles and Equipment Based Upon In-Use Measurements

Annual Report: August 2007

An overview of the major activities of the project is given here by task, supplemented by *Appendix A: Development of Physically-Based Microscale Energy Use and Emissions Model for Construction Equipment and Vehicles*.

Task 1. Acquisition and Measurement of Construction Vehicle/Equipment Activity, Energy Use, and Emissions Data

Table 1 provides a summary of the vehicles and equipment that have been tested to date. Approximately 61% (14 of 23) of the targeted tests have been completed. All of the targeted tests for the excavators and the generators have been completed. There are a total of nine tests remaining. It is anticipated that these tests will take approximately 3 - 5 weeks to complete during the final project year based on vehicle availability and scheduling.

To complete the remaining tests, several equipment owners have been contacted to request permission to access vehicles and equipment for testing. Contact was made by telephone calls, job site visits, or both. One of the owners that was contacted was an equipment rental company and the other owners were construction contractors that had the subject test vehicles in their equipment fleets. Although some of the owners that were contacted expressed no interest in participating in the study, there were three owners that were willing to participate. Other equipment owners will be contacted if necessary based on testing needs, vehicle availability, and owner cooperation.

Much of the work that has been completed thus far has been presented at various conferences, including the proceedings of the Annual Meeting of the Air & Waste Management Association (AWMA), the CRC On-Road Vehicle Emissions Workshop,, and the U.S. Environmental Protection Agency Emissions Inventory conference:

- "Methodology for Activity, Fuel Use, and Emissions Data Collection and Analysis for Nonroad Construction Equipment," Proceedings of the Air and Waste Management Association Annual Conference, AWMA, Pittsburgh, PA (June 2007).
- "Measurement and Analysis of In-Use Emissions for Non-Road Construction Vehicles," 16th CRC On-Road Vehicle Emissions Workshop, San Diego, CA (March 2006).
- "Methods for Measurement and Analysis of In-Use Emissions of Nonroad Construction Equipment," EPA Emissions Inventory Conference, Raleigh, NC (May 2007).

Table 1. Summary of Test Goals

VEHICLE	TEST GOALS Target	TEST GOALS Completed
Backhoe	3	2
Bulldozer	5	3
Excavator	3	3
Front-End Loader	3	1
Generator	3	3
Off-Road Truck	3	1
Skid-Steer Loader	3	1
	23	**14**

This work has been the source of information for many journal papers that are in progress. Topics for these papers include the following:

- Detailed methodology for field data collection;
- Regulatory issues and comparisons of sources of emissions data;
- Life cycle inventory energy consumption and emissions for biodiesel fuel versus petroleum diesel fuel; and
- Vehicle specific emissions model for nonroad construction equipment.

Task 2. Construction Equipment and Vehicle Energy Use and Emissions Model

The goal of this task is to develop a ***C**onstruction **I**n-Use **V**ehicle and **E**quipment emissions and energy use **M**odel* (CIVEM), based upon PEMS monitoring data.

During this year, we conducted an exploratory analysis of empirical data. The quality assured and synchronized second-by-second data obtained from field measurements using a portable emissions measurement system (PEMS) were analyzed in terms of the effect of engine activity on fuel use and emissions. Rank correlation was used to identify engine variables 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.

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), or the boost pressure, 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-oriented" approach. Therefore, four types of emission factors were developed: (1) engine-based modal mass of fuel use or emissions per time based on ranges of MAP; (2) engine-based mass of pollutant emitted per gallon of fuel consumed; (3) task-oriented modal mass of fuel use or emissions per time stratified with respect to different activity modes of a vehicle, such as use of a bucket to scoop dirt, lateral movement across a site, or idling; and, (4) task-oriented modal emission rates in units of mass of pollutant emitted per gallon of fuel consumed.

In order to develop engine-based modes, 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 strata represents 10 percent of the total duty cycle NO emissions.

Task-oriented 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-oriented 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 was estimated.

In addition to developing modal fuel use and emissions models, we developed regression models based on the second-by-second PEMS data. Regression models were developed based on a "calibration" data set and were verified based on a "validation" data set. The procedure for developing these two datasets is 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.

Using the calibration data, we developed physically-based regression models (***Please see Appendix A for details***) for each of the 14 vehicles or equipment 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). 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 variations in fuel use and emissions rates among different duty cycles were assessed. For each type of vehicle, we characterized typical duty cycles in terms of the percentage of time spent in each MAP-based mode. Based on a finding discussed later, fuel use and emission rates are highly correlated with MAP. Duty cycles were quantified based on the cumulative frequency distribution (CDF) of MAP for a given day of data collection. Multiple duty cycles were compared for the same type of vehicle (e.g., backhoes) based on data collected on different days for either the same vehicle or for different vehicles. This was done to determine whether duty cycles have significant differences in engine load.

Data from the CDF of MAP were used to estimate the fraction of total time spent in each MAP. An average emission rate for a duty cycle was estimated based on the coefficients of time-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 for which there were two or more vehicles tested (i.e. backhoes, excavators, bulldozers). Furthermore, comparisons were made for weighted averages of fuel use and emissions among different duty cycles for all of the tested engines.

To assess the validity of the measured emission rates, we compared emission factors based on the PEMS data to emission factors estimated using EPA's NONROAD model. In order to make the comparison, we had to convert both types of emission factors to a common basis. The PEMS-based emission factors can be reported in terms of mass of emissions per time or mass of emissions per gallon of fuel consumed. The mass per brake-horsepower-hour emission factors produced by the NONROAD model were converted to a fuel basis using brake specific fuel consumption (BSFC) factors. The NONROAD model provides 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. Therefore, there are expected to be some differences in the absolute values of the emission factors when comparing both approaches. However, the purpose of the comparison is to determine whether the magnitudes of the emission factors are similar.

APPENDIX A: DEVELOPMENT OF PHYSICALLY- BASED MICRO-SCALE ENERGY USE AND EMISSIONS MODEL FOR CONSTRUCTION EQUIPMENT AND VEHICLES

The purpose of this appendix is to explain the methodology used in the micro-scale Construction In-use Vehicle and Equipment energy use and emissions Model (CIVEM). In this Appendix, the background information of diesel engines and equations for developing statistical regression models are presented.

1.0 BACKGROUND

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. Due to the finite volume of the manifold, the pressure level in the manifold increases more slowly than would be the case if steady-state conditions prevailed at each throttle position. Actual results for the air flow rate and manifold pressure in response to an opening of the throttle (increase in throttle angle) are shown in Figure 1. The throttle is opening from 10 degrees to 18 degrees. The intake manifold pressure is linearly proportional to the throttle angle (defined as engine load). The total response time for intake manifold pressure is less than 0.2 second (shown in Figure 1).

When a construction vehicle operator pushes the pedal and changes the throttle position, there is theoretically an instantaneous response to the manifold absolute pressure of less than one second. Therefore, manifold absolute pressure can be a second-by-second indicator of the engine load.

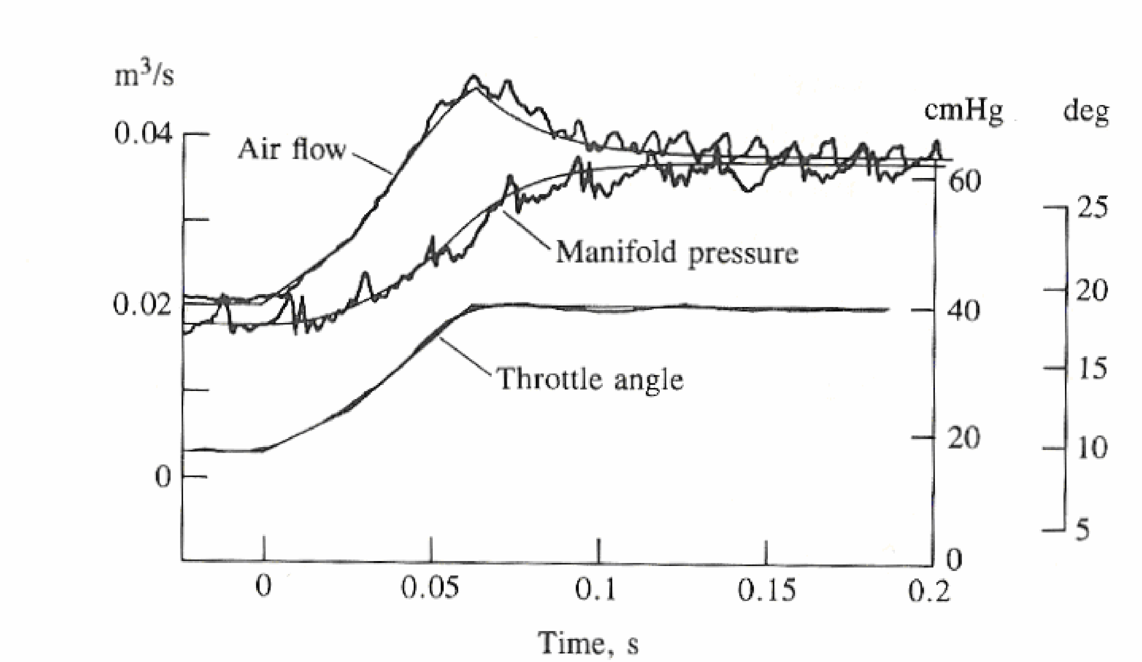


Figure 1. Throttle Angle, Intake Manifold Pressure, and Air Flow Rate Past the Throttle vs. Time for 10^o Part-Load Throttle Opening (Source: Heywood, 1988)

2.0 EQUATIONS FOR DEVELOPING PHYSICALLY-BASED MICRO-SCALE ENERGY USE AND EMISSIONS MODEL

The purpose of developing a predictive model is to estimate tailpipe emissions of nonroad construction equipment using engine data. Only engine variables can be used in the equations. Consecutive averaging times of 12 seconds are used to reduce the influence of instrument response time and autocorrelation in vehicle activity with respect to model formation.

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:

$$CH_{1.857} + u_t(0.21O_2 + 0.79N_2) \rightarrow b_tCO_2 + c_tCO + d_tC_6H_{14} + e_tNO + f_tH_2O + g_tO_2 + h_tN_2 \qquad (1)$$

where,

$CH_{1.857}$ = equivalent molecular formula of diesel
$u_t, b_t, c_t, d_t, e_t, f_t, g_t, h_t$ = stoichiometric coefficient of combustion for time t

When throttle is opened, more fuel is injected to the engine which corresponds to an increase of intake manifold absolute pressure. As shown in Figure 1, the engine load is a linear function of manifold absolute pressure. Fuel use and CO_2 emissions are intimately coupled with the throttle position which is defined as engine load. Thus, the functional form of the regression equation for fuel use and CO_2 can be shown as:

$$m_i = a_i \times MAP \qquad (2)$$

where,

m_i = Mass emission rate for specie i (fuel use and CO_2); (g/sec)
MAP = Manifold absolute pressure (kPa)
a_i = Model coefficient for specie i (fuel use and CO_2)

Air-to-fuel ratio (AFR) has been found to be a good explanatory variable for CO emissions in gasoline engines as shown in Figure 2. However, when the air-to-fuel ratio is greater than 16, CO emissions are very small and nearly constant. Diesel engines usually operate at AFR=25 to 150. Thus, AFR cannot explain the variation of CO emissions in diesel engines due to high AFR.

Another factor affecting CO emissions in diesel engines is the premixing process. With an imperfect mixture of air and fuel, CO emissions become higher. When engine load increases, more fuel is injected into the engine. Insufficiently premixed fuel results in higher CO emissions. Thus, engine loads can be the functional form of the regression equation for CO emissions. HC formation in diesel engines is similar to the CO formation mechanism. As mentioned before, the engine load is a linear function of manifold absolute pressure.

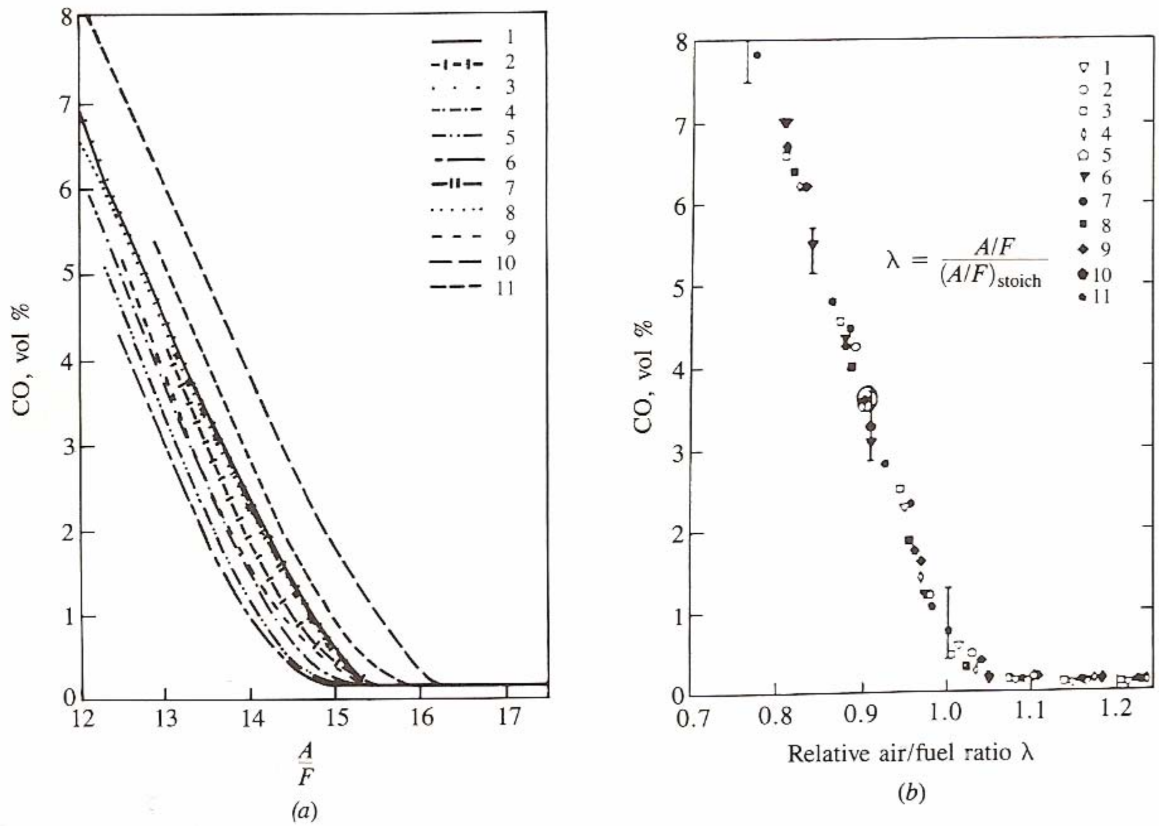


Figure 2. Variation of SI engine CO Emissions with 11 Fuels of Different H/C Ratio: (a) With Air-to-Fuel Ratio; (b) With Relative Air-to-Fuel Ratio λ (Heywood, 1988)

The functional form of the regression equation for CO and HC can be shown as:

$$m_i = a_i \times MAP \tag{3}$$

where,

m_i = Mass emission rate for specie i (CO and HC); (g/sec)
MAP = Manifold absolute pressure (kPa)
a_i = Model coefficient for specie i (CO and HC)

The PM emissions for diesel engines are mainly from unburned hydrocarbon and soot. Based on Sher (1998), the PM emissions in a diesel engine can be expressed as:

$$PM = 1.024 \times Soot + 0.277 \times HC \tag{4}$$

where,

PM	= Mass emission rate for PM; (g/sec)
$Soot$	= Mass emission rate for soot; (g/sec)
HC	= Mass emission rate for HC; (g/sec)

Soot formation is very complicated and it includes nucleation, surface growth, agglomeration, adsorption, and condensation. Based on Heywood (1988), soot formation increases with an increase of combustion temperature. For HC emissions, soot formation can be explained by engine load or manifold absolute pressure. The PM emissions in the diesel engine can be simplified as:

$$PM = 1.024 \times a_i MAP + 0.277 \times b_i MAP = c_i MAP \tag{5}$$

where,

PM	= Mass emission rate for PM; (g/sec)
$a_i MAP$	= Mass emission rate for soot; (g/sec)
$b_i MAP$	= Mass emission rate for HC; (g/sec)
c_i	= Model coefficient ($1.024 \times a_i + 0.277 \times b_i$)

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 (Heywood, 1988).

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

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 key factor affecting NO emissions is the combustion temperature. Combustion temperature (T) is linearly proportional to the fuel combustion in the diesel engine. When the fuel is combusted, the heating value of the fuel is released in the engine which results in an increase of combustion temperature. As mentioned before, combustion temperature is proportional to the engine load and engine load is a linear function of manifold absolute pressure. Thus, 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. In modern diesel engines, these variables are controlled by an electronic system. Because the PEMS does not actually measure the equilibrium concentrations of O_2 and N_2 in the engine, it is assumed that the equilibrium concentrations of O_2 and N_2 are equal to the concentrations in the exhaust. The PEMS reports the exhaust concentration of NO, HC, CO, CO_2, and O_2. The exhaust concentration of N_2 can be obtained through the mass balance of diesel combustion. Based on the results of a preliminary analysis, 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 can be simplified as:

$$Y_{t,NO} = \frac{C_1}{\left(MAP_t\right)^{0.5}} \exp\left(\frac{C_2}{MAP_t}\right) \tag{6}$$

where,

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

C_1, C_2 = Model coefficients;

The linear equation for NO is presented as:

$$\ln\left(Y_{t,NO}\right) = \alpha - \beta_1 \times 0.5 \ln\left(MAP_t\right) + \beta_2 \left(MAP_t\right)^{-1} + \varepsilon_t \tag{7}$$

where,

β_1 , β_2 = regression coefficient;

In order to illustrate the prediction capability of the micro-scale model, the analysis procedures include:

(1) Separate the data into a modeling dataset (75%) and a validation dataset (25%). The modeling dataset is used to build the micro-scale model. The validation dataset is used to validate the model.

(2) Draw the diagram of cumulative frequency versus MAP for the modeling dataset and the validation dataset.
   - If the diagrams for these two datasets are matched, these two datasets can be analyzed in Step (3).
   - If the diagrams for these two datasets have significant differences, the modeling and validation datasets need to be re-selected.

(3) Build the micro-scale model for fuel use, NO, HC, CO, CO_2, and PM using the modeling dataset based on Equations 2,3,5,7.

(4) Predict mass emissions rates for fuel use, NO, HC, CO, CO_2, and PM based on the developed model in Step (3).

(5) Draw the scatter plot of observed values versus predicted values.

References

John B. Heywood (1988). "Internal Combustion Engine Fundamentals", McGraw-Hill Inc.: New York, US.

Eran Sher (1998), "Handbook of Air Pollution from Internal Combustion Engines: Pollutant Formation and Control", Academic Press: San Diego, CA.

Summary of Findings

NSF Grant 0327731: Life Cycle Inventory and Impact Analysis Framework for Nonroad Construction Vehicles and Equipment Based Upon In-Use Measurements

Annual Report: August 2007

An overview of the major findings of the project is given here, supplemented by *Appendix B: Results of Construction Equipment And Vehicle Energy Use And Emissions Model.*

Findings from Task 1: Acquisition and Measurement of Construction Vehicle/Equipment Activity, Energy Use, and Emissions Data

Six equipment owners have cooperated thus far by providing access to their vehicles, which has allowed 14 of 23 scheduled tests to be completed. To complete the remaining tests, three other equipment owners have been contacted. By the completion of the project, it is anticipated that approximately nine different equipment owners will have participated in this study.

Of the three owners that are willing to participate in the remaining portion of the study, one is a local equipment rental company, one is a local general contractor, and one is a regional heavy highway contractor. The equipment rental company has already provided access to two generators that have been tested. The general contractor and the heavy highway contractor both have availability to all of the needed subject test vehicles and have agreed to provide access to these vehicles.

Findings from Task 2: Construction Equipment and Vehicle Energy Use and Emissions Model

Based on statistical analysis of the processed second-by-second data, MAP was typically found to be the engine parameter most highly correlated with 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 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. 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 fuel use and emission rates. The details are explained Appendix B Section 1.1, including tables of rank correlation of fuel use and emissions with respect to engine data and time series plots of manifold absolute pressure, fuel use, and NO emission rates.

Based on the exploratory analysis, MAP was used for developing engine-based modal models. The average (over all 14 tested vehicles) goodness-of-fits (R^2) for fuel use, CO_2, NO, HC, CO, and opacity rates is 0.91, 0.91, 0.85, 0.58, 0.39, 0.75, respectively, based on time-based engine-based modal models. The average goodness-of-fits (R^2) for NO, HC, CO, and opacity rates are

0.92, 0.58, 0.43, 0.77, 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. Further details are given in Appendix B Section 1.2, including parity plots of fuel use and NO emission rates for time-based engine-based modal models, and coefficients of determination (R^2) of time-based and fuel-based modal models for fuel use and emissions rates.

For task-oriented modal modes, the average (over all 14 tested vehicles) goodness-of-fits (R^2) for fuel use, CO_2, NO, HC, CO, and opacity rates are 0.55, 0.55, 0.57, 0.38, 0.26, 0.45, respectively, based on time-based task-oriented modal models. The average goodness-of-fits (R^2) for NO, HC, CO, and opacity rates are 0.89, 0.52, 0.37, 0.72, respectively, based on fuel-based task-oriented modal models. 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. Further details are given in Appendix B Section 1.2, including parity plots of fuel use and NO emission rates for task-oriented modal models, and coefficients of determination (R^2) of time-based and fuel-based task-oriented modal models for fuel use and emissions rates.

For physically-based regression models, the average (over all 14 tested vehicles) goodness-of-fits (R^2) for fuel use, CO_2, NO, HC, CO, and opacity rates are 0.96, 0.96, 0.88, 0.61, 0.41, 0.78, respectively, based on time-based regression models. The average goodness-of-fits (R^2) for NO, HC, CO, and opacity rates are 0.89, 0.51, 0.38, 0.78, 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. Further details are given in Appendix B Section 1.3, including coefficients of determination (R^2) of time-based and fuel-based regression models for fuel use and emissions rates.

In order to assess the variations of fuel use and emissions among different duty cycles, representative duty cycles for each type of construction vehicle were identified, based upon the distribution of MAP modes observed during each day of testing with each vehicle. For example, there is one duty cycle associated with the test on a front-end loader. For each of the three bulldozers, there are separate duty cycles. Thus, a total of 11 duty cycles are identified from the 11 vehicles. These cycles were observed during real world operation at a construction site. For purposes of benchmarking and comparison, an additional duty cycle was based on the ISO-C1 engine dynamometer test cycle used for diesel engines. The ISO-C1 test cycle is a basis for much of the data used in EPA's NONROAD model, and is represented here as Duty Cycle 12. Each of the duty cycles are listed below with a brief description:

Duty Cycle 1: Load a dump truck using a front-end loader

Duty Cycle 2: Clearing land using a bulldozer (Dozer 1)

Duty Cycle 3: Spreading material using a bulldozer (Dozer 2)

Duty Cycle 4: Spreading material using a bulldozer (Dozer 3)

Duty Cycle 5: Tree/Stump removal using an excavator (Excavator 1)

Duty Cycle 6: Moving objects using an excavator (Excavator 2)

Duty Cycle 7: Mass excavation using an excavator (Excavator 3)

Duty Cycle 8: Material hauling using an off-highway truck

Duty Cycle 9: Load a dump truck using a backhoe (Backhoe 1)

Duty Cycle 10: Mass excavation using a backhoe (Backhoe 2)

Duty Cycle 11: Material handling using a skid steer loader

Duty Cycle 12: ISO-C1 engine dynamometer test cycle

To assess key sources of variability in emission rates, comparisons are made between engines and between duty cycles. For a given duty cycle, the inter-engine variability is assessed. For a given engine, the inter-cycle variability is assessed. For purposes of general and somewhat stylized comparisons, average emission rates were estimated for each engine for each of the 12 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.

The inter-cycle variations among the 12 duty cycles are estimated for the engines of all vehicles and equipment, except for the generator engines. In Table 2, the ratios of the high versus low average fuel use and emissions rates are given based on comparison of the duty cycles. Similarly, Table 3 shows the ratios for high versus low fuel-based emission rates. For the generator engines, we do not have enough data for MAP-based modes and therefore cannot estimate average rates for duty cycles other than the one observed during testing. Thus, the generator engine was excluded from the inter-cycle and inter-engine comparison.

Table 2 Ratio of High versus Low Value for Cycle Average Time-Based Fuel Use and Emission Rates Based on Comparisons of 12 Duty Cycles for Engines of Each of 11 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	5.9	2.7	6.1	2.8	4.3	2.2	8.7	3.1	4.2	2.4	4.7	2.5
Engine 2	4.1	4.1	4.0	4.1	3.8	3.5	4.2	4.2	1.8	1.8	2.3	2.3
Engine 3	6.3	3.1	6.5	3.1	4.4	2.2	20.8	4.2	4.3	2.6	1.4	1.4
Engine 4	5.2	3.5	5.3	3.5	3.6	2.3	8.1	4.2	2.6	2.1	1.1	1.1
Engine 5	10.6	3.5	10.6	3.5	7.2	3.5	13.8	3.8	3.3	2.2	3.0	2.1
Engine 6	6.3	3.2	6.3	3.2	4.0	2.4	10.2	3.9	3.6	2.5	2.2	1.8
Engine 7	6.4	3.6	6.5	3.7	5.0	3.3	9.4	4.4	2.6	2.1	1.7	1.4
Engine 8	7.5	3.1	7.3	3.1	4.5	2.4	12.5	3.6	5.0	2.7	18.9	3.9
Engine 9	6.0	3.0	5.9	3.1	4.5	2.3	10.0	3.3	2.2	1.8	1.7	1.4
Engine 10	3.4	3.4	3.6	3.5	2.9	2.9	4.9	4.9	1.7	1.7	2.4	2.4
Engine 11	4.5	2.0	4.3	2.2	3.1	2.3	3.0	2.3	2.1	1.8	1.7	1.3
Average	**6.1**	**3.2**	**6.0**	**3.3**	**4.3**	**2.7**	**9.6**	**3.8**	**3.0**	**2.2**	**3.7**	**2.0**

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 3 Ratio of High versus Low Value for Cycle Average Fuel-Based Emission Rates Based on Comparisons of 12 Duty Cycles for Engines of Each of 11 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	1.5	1.1	1.0	1.2	1.0	1.1
Engine 2	1.2	1.2	1.0	1.0	1.0	2.4	1.0	1.8
Engine 3	1.1	1.6	3.3	1.3	1.0	1.2	1.0	2.2
Engine 4	1.2	1.7	1.6	1.2	1.0	1.7	1.0	3.6
Engine 5	1.0	1.2	1.3	1.1	1.0	1.6	1.0	1.7
Engine 6	1.0	1.3	1.6	1.2	1.0	1.3	1.0	1.7
Engine 7	1.0	1.2	1.3	1.2	1.0	1.7	1.0	2.5
Engine 8	1.0	1.3	1.7	1.1	1.0	1.2	2.5	1.2
Engine 9	1.3	2.4	1.8	1.2	1.0	1.5	1.0	2.1
Engine 10	1.0	3.0	1.3	1.4	1.0	2.0	1.0	1.4
Engine 11	1.0	1.2	1.0	1.2	1.0	1.4	1.0	2.0
Average	**1.1**	**1.6**	**1.6**	**1.2**	**1.0**	**1.6**	**1.1**	**1.9**

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

In Table 2, 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 12 cycles that represent variations in engine load.

For "Max vs. Idle," the average ratios of high versus low value for fuel use, CO_2, NO, Opacity, HC, and CO are 6.1, 6.0, 4.3, 9.6, 3.0, and 3.7, respectively. The highest average ratio is for opacity, because opacity rate is more sensitive to engine load. For example, when comparing the highest to the lowest engine-based opacity rate, the ratio between these two modes is 17.0 based on Engine 3 data. However, HC and CO has relatively lower average ratios compared to fuel use, CO_2, NO, and opacity. For example, when comparing the highest to the lowest engine-based HC and CO emission rates, the ratios between these two modes are 2.4 for HC and 3.9 for CO based on Engine 3 data.

For "Transient Cycle," the average ratios of high versus low value for fuel use, CO_2, NO, Opacity, HC, and CO are 3.2, 3.3, 2.7, 3.8, 2.2, and 2.0, 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 12 duty cycles for engines of each of 11 tested engines are shown in Table 3. For "Max vs. Idle," the average ratios for high versus low value for NO, Opacity, HC, and CO emission rates are 1.1, 1.6, 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, 3, 4 and 9. NO formation is a nonlinear function with respect to manifold absolute pressure (MAP). Figure 1 shows the fuel-based emission rates versus normalized MAP based on Engine 3 data. In Figure 1, the fuel-based NO emission rate for idling is not the highest value among different MAP. Thus, the nonlinear function results in some exceptions for fuel-based NO emission rates. For CO, there is one exception for Engine 8. A substantial proportion (79 percent) of the measured exhaust gas concentrations of CO are below the detection limit in Engine 8 data. 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 2. 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 4.3 for time-based emission rates and 1.1 for fuel-based emission rates.

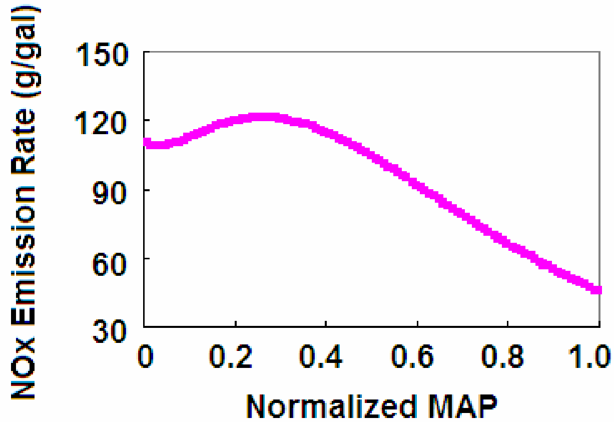


Figure 1. Fuel-based NO Emission Rates versus Normalized MAP Based on Engine 3

For "Transient Cycle," the average ratios of high versus low value for NO, Opacity, HC, and CO are 1.6, 1.2, 1.6, and 1.9, 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 2.7 for time-based emission rates and 1.6 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 2 data as an example. Based on an example of Engine 2, 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. Further details are given in Appendix B Section 2.0, including cumulative frequency distribution of normalized MAP for Twelve Duty Cycles, inter-cycle variations of fuel use, NO, opacity, HC, and CO emission rates.

The inter-engine variations among the 11 engines are estimated for the engines of all duty cycles. In Table 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 shows the ratios for high versus low fuel-based emission rates.

Table 4 Ratio of High versus Low Value for Cycle Average Time-Based Fuel Use and Emission Rates Based on Comparisons of 11 Engines for Each of 12 Duty Cycle [a]

Duty Cycle [b]	Fuel	CO_2	NO	Opacity	HC	CO
Duty Cycle 1	6.2	6.9	7.9	23.5	3.7	13.5
Duty Cycle 2	6.7	7.4	8.2	29.0	4.6	22.8
Duty Cycle 3	7.0	6.9	8.2	30.8	4.3	20.0
Duty Cycle 4	6.6	6.9	8.1	28.8	4.0	14.8
Duty Cycle 5	6.5	7.1	8.1	27.8	4.2	18.0
Duty Cycle 6	7.2	7.1	7.9	26.3	4.4	20.5
Duty Cycle 7	6.9	7.5	8.0	29.6	4.9	21.6
Duty Cycle 8	6.0	6.3	8.0	26.0	3.4	10.0
Duty Cycle 9	6.0	6.8	8.1	25.7	3.4	9.8
Duty Cycle 10	6.4	7.1	8.5	27.3	3.8	14.0
Duty Cycle 11	7.5	7.5	8.3	28.9	5.3	30.2
Duty Cycle 12	7.0	7.3	8.2	14.0	5.0	25.2
Average	**6.5**	**6.8**	**7.9**	**27.8**	**4.1**	**17.6**

a 11 engines were compared, including Front-End Loader, Dozer 1, Dozer 2, Dozer 3, Excavator 1, Excavator 2, Excavator 3, Off-Highway Truck, Backhoe 1, Backhoe 2, and Skid Steer Loader.

b Duty Cycle 1 is associated with the test on a Front-End Loader;
Duty Cycle 2 is associated with the test on Dozer 1;
Duty Cycle 3 is associated with the test on Dozer 2;
Duty Cycle 4 is associated with the test on Dozer 3;
Duty Cycle 5 is associated with the test on Excavator 1;
Duty Cycle 6 is associated with the test on Excavator 2;
Duty Cycle 7 is associated with the test on Excavator 3;
Duty Cycle 8 is associated with the test on Off-Highway Truck;
Duty Cycle 9 is associated with the test on Backhoe 1;
Duty Cycle 10 is associated with the test on Backhoe 2;
Duty Cycle 11 is associated with the test on Skid Steer Loader;
Duty Cycle 12 is associated with the test on ISO-CI test.

Table 5 Ratio of High versus Low Value for Cycle Average Fuel-Based Emission Rates Based on Comparisons of 11 Engines for Each of 12 Duty Cycle [a]

Duty Cycle [b]	NO	Opacity	HC	CO
Duty Cycle 1	1.9	11.2	3.4	4.4
Duty Cycle 2	1.9	13.1	4.2	5.8
Duty Cycle 3	1.9	13.8	4.0	5.5
Duty Cycle 4	1.8	12.2	3.5	4.5
Duty Cycle 5	1.9	12.7	3.8	5.1
Duty Cycle 6	2.2	11.1	4.1	5.6
Duty Cycle 7	2.3	13.3	4.6	6.1
Duty Cycle 8	2.7	11.7	3.0	3.6
Duty Cycle 9	2.5	11.3	2.9	3.6
Duty Cycle 10	1.9	12.1	3.2	4.2
Duty Cycle 11	4.5	12.7	4.8	7.1
Duty Cycle 12	3.5	13.4	4.7	6.9
Average	**2.4**	**12.7**	**3.9**	**5.1**

a 11 engines were compared, including Front-End Loader, Dozer 1, Dozer 2, Dozer 3, Excavator 1, Excavator 2, Excavator 3, Off-Highway Truck, Backhoe 1, Backhoe 2, and Skid Steer Loader.

b Duty Cycle 1 is associated with the test on a Front-End Loader;
Duty Cycle 2 is associated with the test on Dozer 1;
Duty Cycle 3 is associated with the test on Dozer 2;
Duty Cycle 4 is associated with the test on Dozer 3;
Duty Cycle 5 is associated with the test on Excavator 1;
Duty Cycle 6 is associated with the test on Excavator 2;
Duty Cycle 7 is associated with the test on Excavator 3;
Duty Cycle 8 is associated with the test on Off-Highway Truck;
Duty Cycle 9 is associated with the test on Backhoe 1;
Duty Cycle 10 is associated with the test on Backhoe 2;
Duty Cycle 11 is associated with the test on Skid Steer Loader;
Duty Cycle 12 is associated with the test on ISO-CI test.

For time-based emission rates shown in Table 4, the average ratios for fuel use, CO_2, NO, Opacity, HC, and CO are 6.5, 6.8, 7.9, 27.8, 4.1, and 17.6, respectively. The highest average ratio is for opacity, which means opacity rate is sensitive to not only different duty cycle, but also sensitive to different engines. The opacity rates for Engine 9 are substantially lower than other engines. Engine 9 is a backhoe equipped with a 4.0 liter and 88 horsepower engine. In order to assess the relation between opacity rate and engine size, Figure 2 shows an example of a scatter plot for time-based opacity rate versus engine displacement for 11 engines based on Duty Cycle 9. The R^2 is 0.69, which indicates the emission rates are approximately a linear function of engine displacement. Larger engines typically produce higher opacity rates.

For CO, the average ratio of high versus low value is also high. Engine 8 has the highest time-based CO emission rates, whereas Engine 11 has the lowest emission rates. Engine 8 is an off-highway truck equipped with a 9.6 liter and 306 horsepower engine and Engine 11 is the small skid steer loader equipped with a 2 liter and 44 horsepower engine. Figure 3 shows an example of a scatter plot for time-based CO emission rate versus engine displacement for 11 engines based on Duty Cycle 9. The R^2 is 0.54, which indicates the emission rates are somewhat linear with respect to engine displacement with some exceptions. For example, in Figure 3, Engine 5 is an excavator equipped with a 8.3 liter and 254 horsepower engine, but the CO emission rates for Engine 5 is lower than those for some small engines. Time-based CO emission rates show less variability among duty cycles in Table 2. Therefore, CO emission rate is more sensitive to different engines than duty cycles.

For HC, the average ratio of high versus low value is lower than Opacity, CO, and NO. Figure 4 shows an example of a scatter plot for time-based HC emission rate versus engine displacement for 11 engines based on Duty Cycle 9. The HC emission rates range from 2.0 mg/sec to 6.7 mg/sec. The ratio of high versus low value is only 3.4. The results indicate that time-based HC emission rate is not sensitive to either duty cycles or engines.

For fuel-based emission rates shown in Table 5, the average ratios for NO, Opacity, HC, and CO are 2.4, 12.7, 3.9, and 5.1, respectively. The highest average ratio is for opacity, which means fuel-based opacity rate is 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 for 11 engines based on Duty Cycle 9. The R^2 is 0.82 for time-based emission rate and 0.005 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.

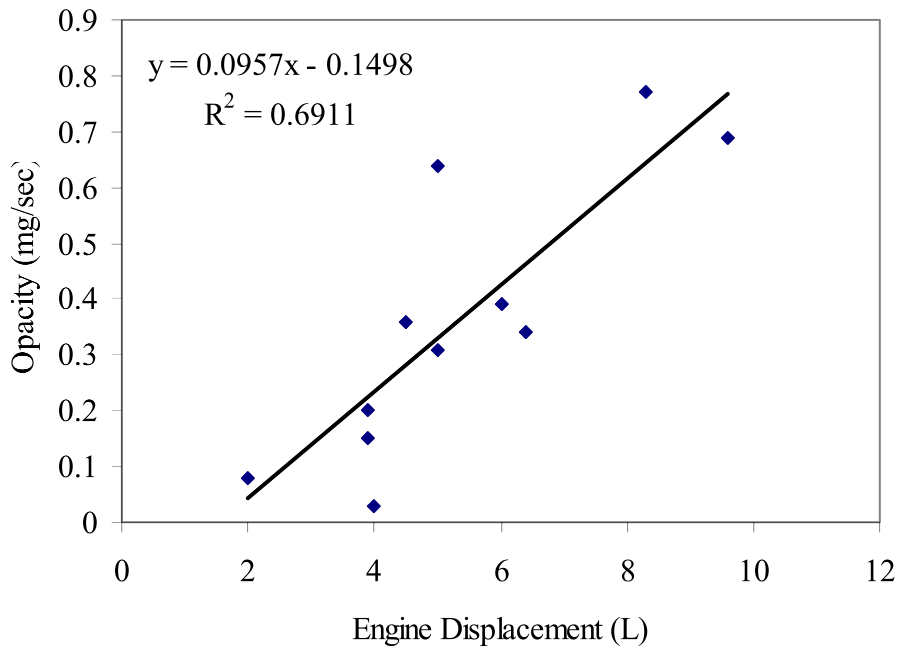


Figure 2. Scatter Plot of Time-Based Opacity Rate versus Engine Displacement Based on Duty Cycle 9

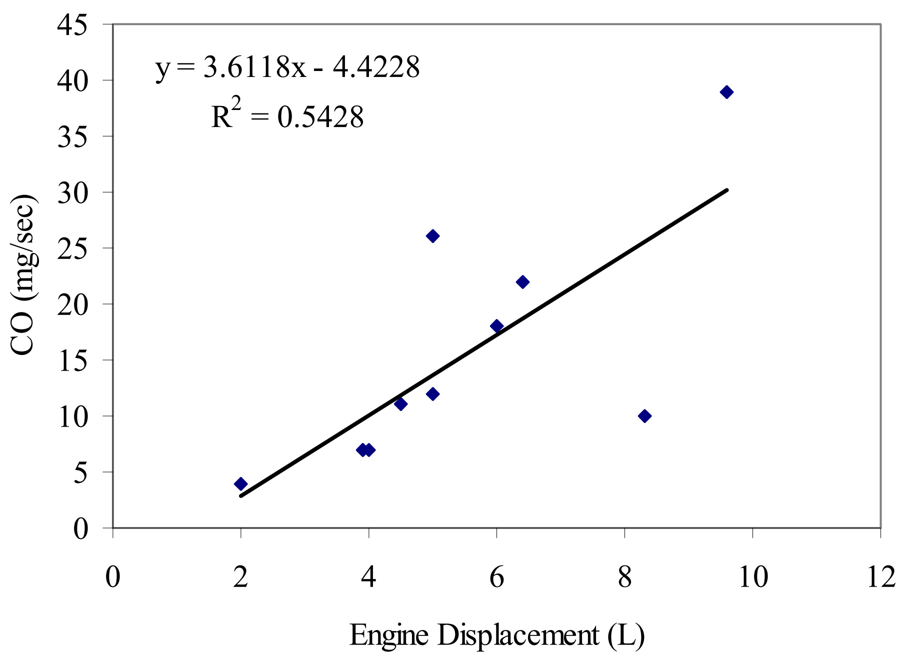


Figure 3. Scatter Plot of Time-Based CO Emission Rate versus Engine Displacement Based on Duty Cycle 9

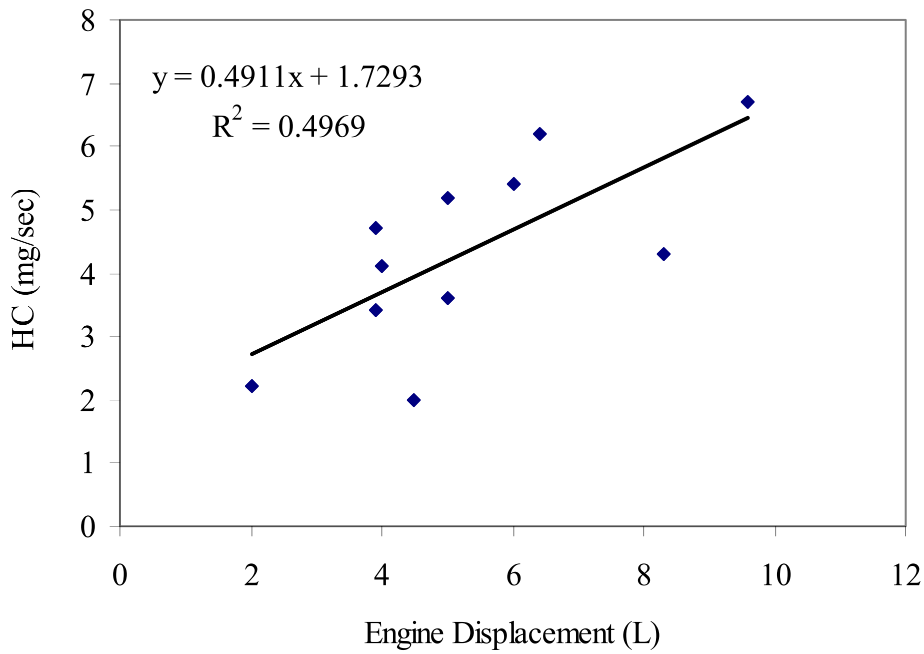


Figure 4. Scatter Plot of Time-Based HC Emission Rate versus Engine Displacement Based on Duty Cycle 9

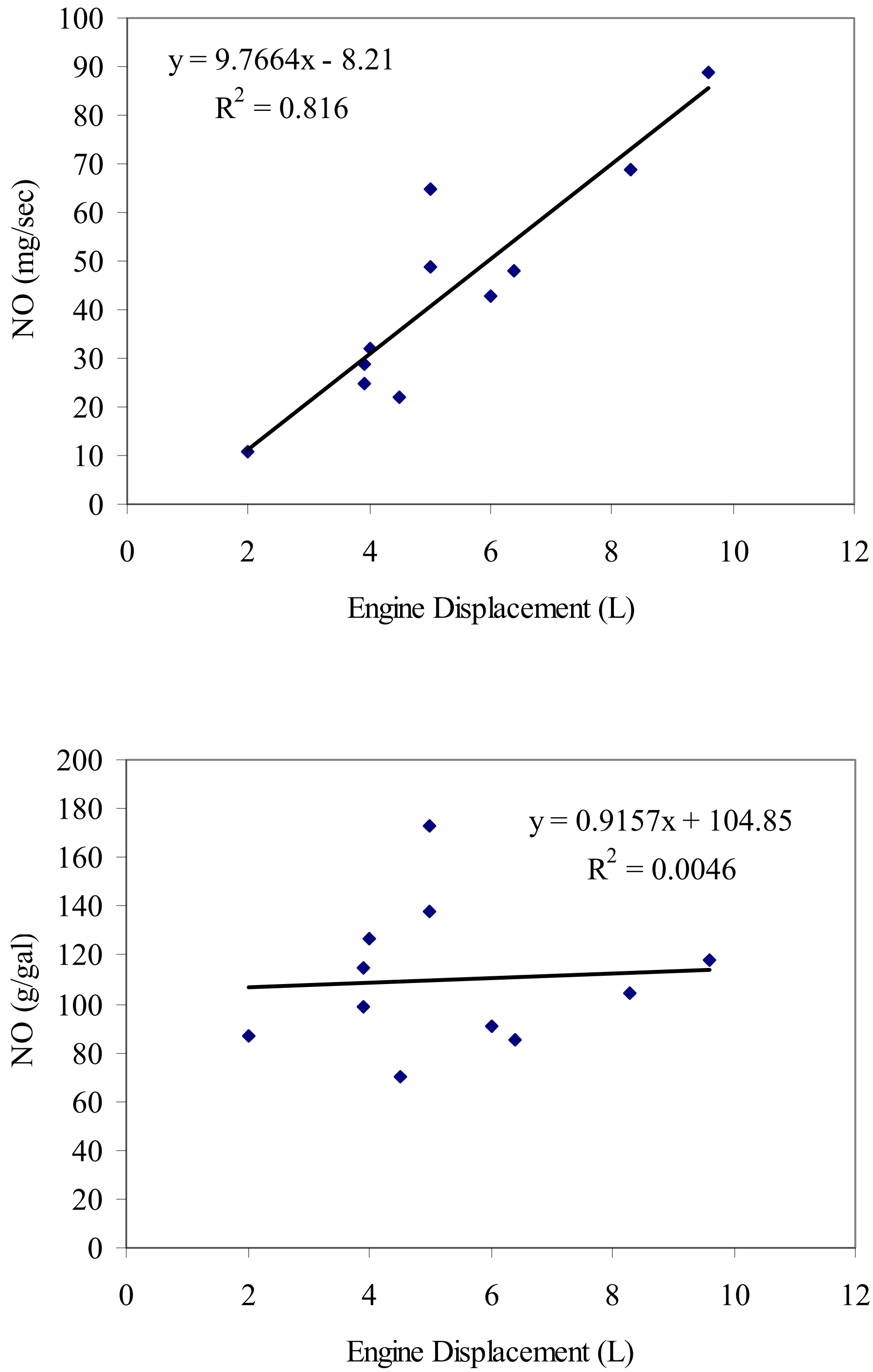


Figure 5. Scatter Plot of Time-Based and Fuel-Based NO Emission Rate versus Engine Displacement Based on Duty Cycle 9

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. For example, the excavator NO_x emission rates based on PEMS data ranged from 74 to 107 g/gallon, whereas the estimates for similar model years and engine sizes from the NONROAD model ranged from 81 to 102 g/gallon. Typically, there is substantial overlap in the ranges from both types of data for these three pollutants, with only a few exceptions. 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. Further details are given in Appendix B Section 3.0, including tables of steady-state emission factors and assumptions used in EPA's NONROAD model, and benchmarks of predicted emission rates.

The key findings from Task 2: Construction Equipment and Vehicle Energy Use and Emissions Model are summarized here:

- 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.
- Engine-based modal models perform better than task-oriented modal models.
- Regression-based models of intra-engine variability provide greater explanatory power than modal models. Time-based regression models have the best explanatory capability among all models.
- Time-based emission rates are highly correlated with fuel flow.
- Regression-based models can be used to estimate average cycle emissions for different duty cycles.
- 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.
- 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.

APPENDIX B: RESULTS OF CONSTRUCTION EQUIPMENT AND VEHICLE ENERGY USE AND EMISSIONS MODEL

The purpose of this appendix is to present the results of construction in-use vehicle and equipment emissions and energy use model (CIVEM), the variations of fuel use and emissions among different duty cycles, and benchmarks of predicted emission rates based on EPA's NONROAD model.

1.0 CONSTRUCTION IN-USE VEHICLE AND EQUIPMENT EMISSIONS AND ENERGY USE MODEL (CIVEM)

In order to develop construction in-use vehicle and equipment emissions and energy use model (CIVEM), 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.

1.1 Exploratory Analysis of Empirical Data

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 1 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.

The data were also analyzed in terms of the fuel use and average emission rate for activity modes. An activity mode can include idling, movement of the equipment for repositioning purposes, use of a blade or bucket, etc. These modes can vary depending on the type of vehicle. In Figure 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. 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. Activity modes are useful to explain the variations of fuel use and emissions among different work activities. 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 fuel use and emission rates.

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

	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

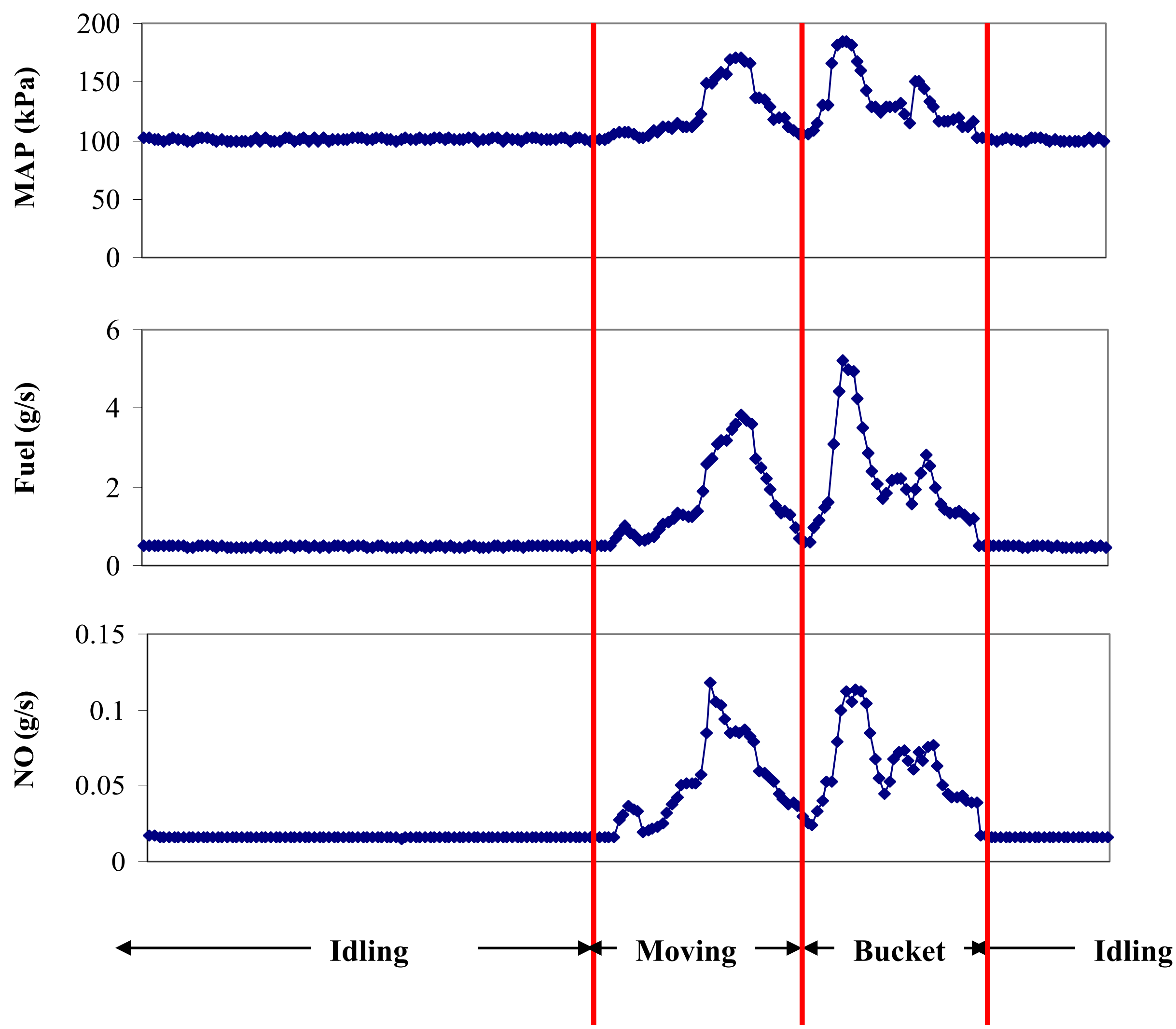


Figure 1. Example of a Time Series Plot of Manifold Absolute Pressure, Fuel Use, and NO Emission Rate for a Front-End Loader

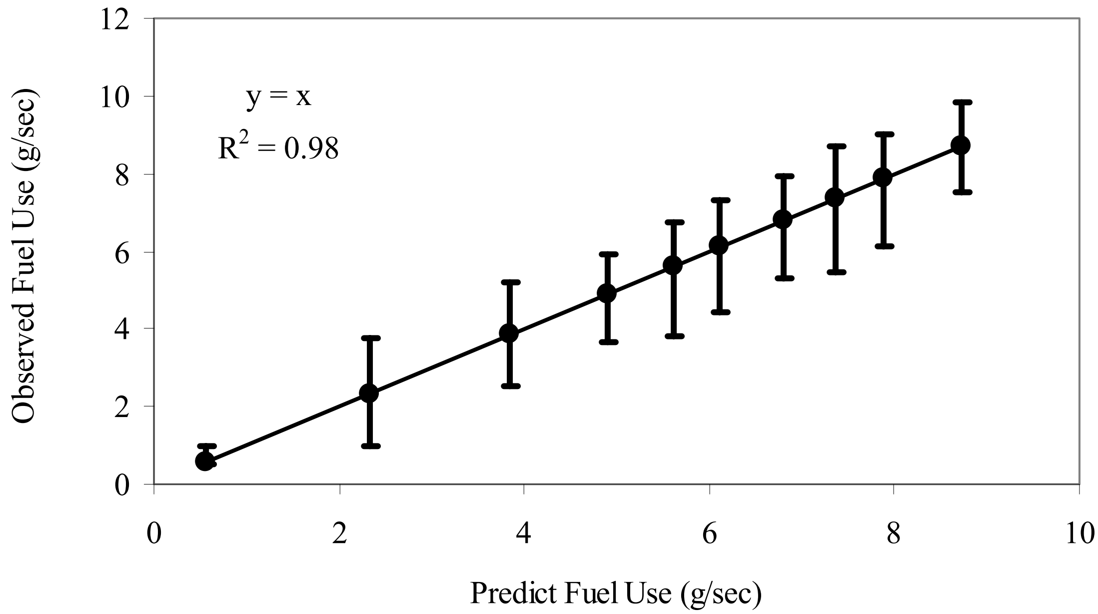
1.2 Engine-Based and Task-Oriented Modal Models

The raw data were carefully reviewed by the data screening and quality assurance procedures described in 2006 Annual Report. 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 rate for engine-based and task-oriented modes.

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. Thus, there are four modal models were developed based on engine-based and task-oriented modes:

1. Time-Based Engine-Based Modal Model
2. Fuel-Based Engine-Based Modal Model
3. Time-Based Task-Oriented Modal Model
4. Fuel-Based Task-Oriented Modal Model

For each engine-based and task-oriented mode, the average fuel use and emission rates are reported in 2006 Annual Report. Therefore, the second-by-second fuel use and emission rates can be predicted based on modal average emission rates. A parity plot was used to compare the observed and predicted fuel use and emission rates. Figures 2 and 3 show an example of the parity plots based on Excavator 1 data. For each mode, the 2.5 and 97.5 percentiles of fuel use and emission rates are also indicated in the figures. The slope for all parity plots is 1. Coefficients of Determination (R^2) for these four models are shown in Tables 2, 3, 4, and 5.



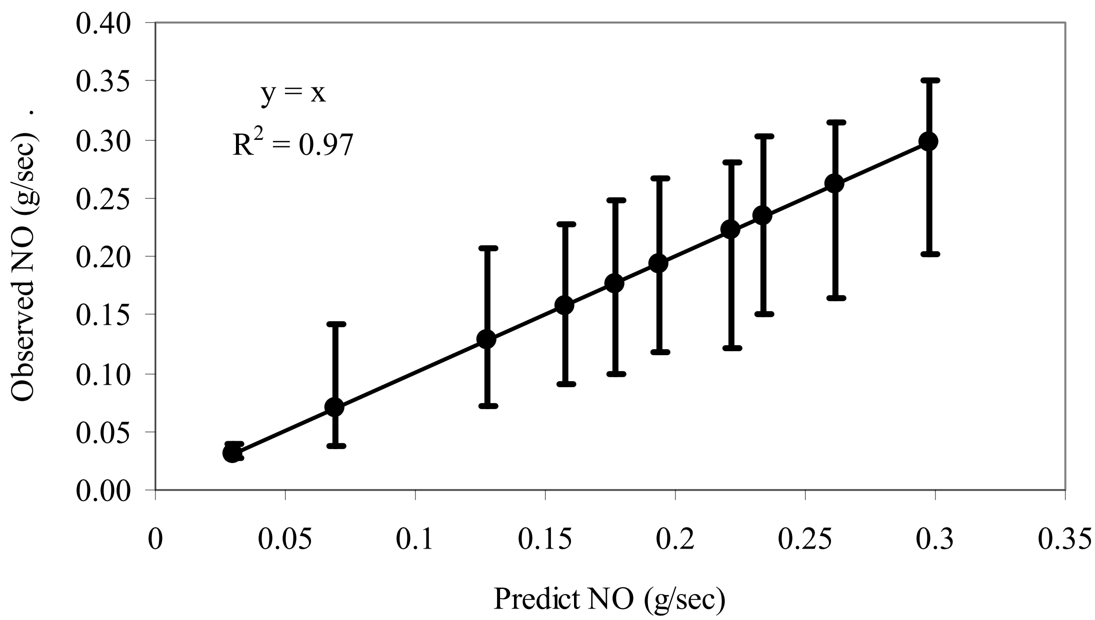
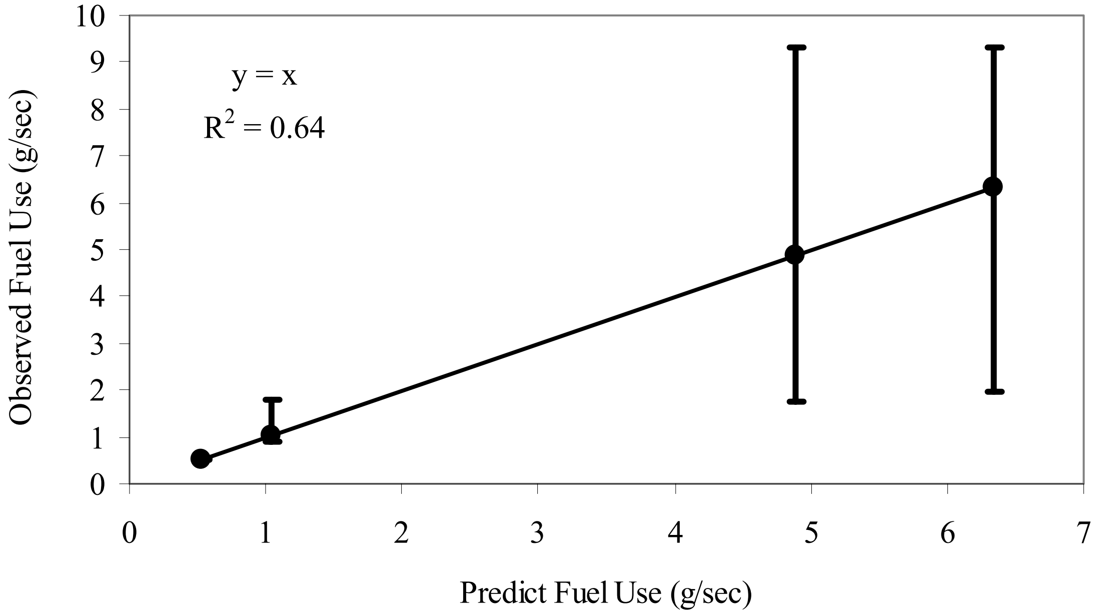


Figure 2. Observed Fuel Use and Emissions versus Predicted Fuel Use and Emissions Based on Time-Based Engine-Based Modal Models for Excavator 1



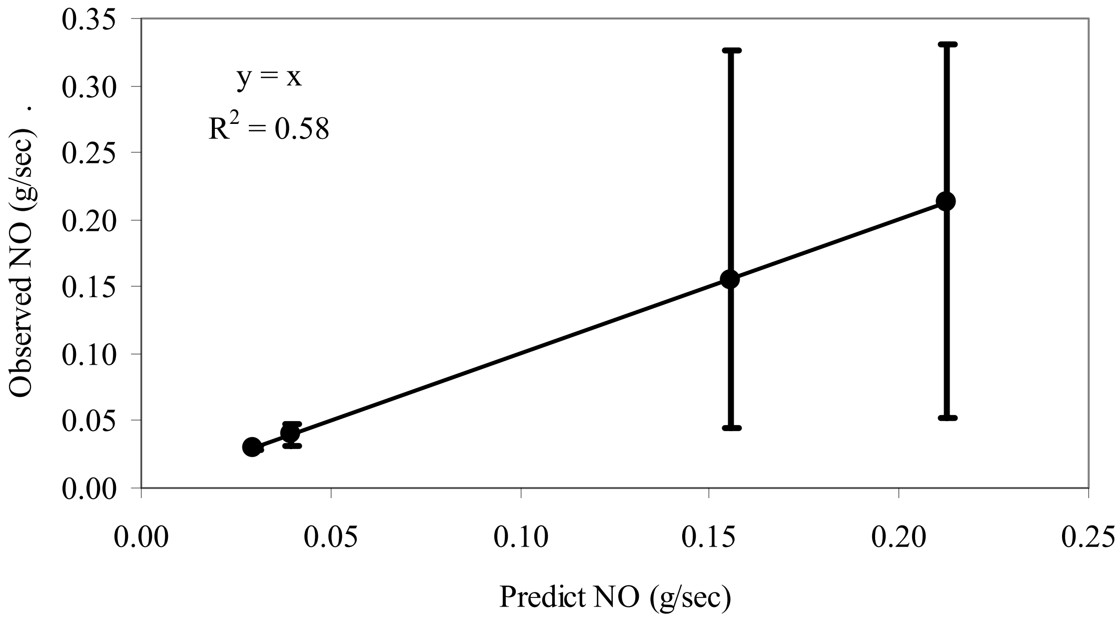


Figure 3. Observed Fuel Use and Emissions versus Predicted Fuel Use and Emissions Based on Time-Based Task-Oriented Modal Models for Excavator 1

Table 2 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
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	0.87	0.87	0.76	0.78	0.30	0.81
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
Front-End Loader	0.88	0.88	0.79	0.77	0.56	0.85
Skid Steer Loader	0.94	0.94	0.91	0.80	0.77	0.78
Average R^2	**0.91**	**0.91**	**0.85**	**0.58**	**0.39**	**0.75**

Table 3 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
Excavator 1	0.95	0.59	0.74	0.84
Excavator 2	0.94	0.7	0.48	0.92
Excavator 3	0.93	0.32	0.05	0.86
Off-Highway Truck	0.88	0.72	0.37	0.8
Backhoe 1	0.83	0.39	0.19	0.68
Backhoe 2	0.89	0.24	0.31	0.38
Front-End Loader	0.90	0.78	0.67	0.87
Skid Steer Loader	0.97	0.76	0.79	0.87
Average R^2	**0.92**	**0.58**	**0.43**	**0.77**

Table 4 Coefficient of Determination (R^2) of Time-Based Task-Oriented 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
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	0.46	0.46	0.38	0.36	0.22	0.43
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
Front-End Loader	0.35	0.35	0.31	0.12	0.25	0.34
Skid Steer Loader	0.61	0.61	0.65	0.68	0.55	0.54
Average R^2	**0.55**	**0.55**	**0.57**	**0.38**	**0.26**	**0.45**

Table 5 Coefficient of Determination (R^2) of Fuel-Based Task-Oriented 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
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	0.88	0.74	0.41	0.80
Backhoe 1	0.77	0.42	0.24	0.65
Backhoe 2	0.89	0.26	0.30	0.20
Front-End Loader	0.90	0.65	0.66	0.74
Skid Steer Loader	0.95	0.63	0.56	0.81
Average R^2	**0.89**	**0.52**	**0.37**	**0.72**

In Table 2, 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 0.91) and NO_x (with an average R^2 of 0.85). 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 3, 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 0.92) 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, the time-based task-oriented modal model was used for predicting fuel use and emission rates. Task-oriented 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-oriented modal models have less explanatory ability compared to engine-based modal models (10 modes). As expected, the R^2 shown in Table 4 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-oriented modal models in Table 5.

The main conclusions for the modal models are:

- Manifold absolute pressure (MAP) is a good explanatory variable for energy use and emission rates for engine-based modal model.
- Engine-based modal models perform better than task-oriented modal model.
- Fuel-based modal models perform similar or slightly better than time-based modal models.

1.3 Physically-based regression models

Linear regression models describe how the mean of the dependent variable varies with respect to changes in the corresponding explanatory variables. A linear regression model can be a linear combination of the basis functions described in Appendix A.

Emission rates in units of mass per time and in units of mass per gallon of fuel consumed are both considered in the physically-based regression model. As expected, the slope in each regression model is 1 for all vehicles. Coefficients of Determination (R^2) for time-based and fuel-based regression models are shown in Tables 6 and 7.

In Table 6, time-based regression model was used for predicting fuel use and emission rates for each piece of construction equipment. The goodness-of-fit is excellent for fuel use, CO_2 (with an average R^2 of 0.96), NO_x (with an average R^2 of 0.88), and opacity (with an average R2 of 0.78). The R^2 for HC and CO is 0.61 and 0.41, respectively.

In Table 7, fuel-based regression model was used for predicting fuel use and emission rates. The goodness-of-fit for NO, HC, CO, and opacity is similar or slightly lower than time-based regression models.

The time-based regression model is recommended in order to predict fuel use and emission rate from construction equipment. The main conclusions for the regression models are:

- Physically-based regression models for these vehicles perform well and manifold absolute pressure (MAP) is a good explanatory variable for fuel use and emission rates.
- The R^2 for fuel use, CO_2, and NO_x are high for all vehicles.
- 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.
- Time-based regression model has the best explanatory capability among all models.

Table 6 Coefficient of Determination (R^2) of Time-Based Regression Models for Fuel Use and Emission Rates (Validation Dataset)

	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
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	0.95	0.95	0.82	0.78	0.44	0.90
Backhoe 1	0.91	0.91	0.86	0.27	0.002	0.84
Backhoe 2	0.95	0.95	0.77	0.08	0.25	0.33
Front-End Loader	0.90	0.90	0.79	0.79	0.60	0.85
Skid Steer Loader	0.95	0.95	0.91	0.80	0.80	0.76
Average R^2	**0.96**	**0.96**	**0.88**	**0.61**	**0.41**	**0.78**

Table 7 Coefficient of Determination (R^2) of Fuel-Based Regression Models for Fuel Use and Emissions (Validation Dataset)

	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
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	0.82	0.77	0.37	0.86
Backhoe 1	0.76	0.12	0.001	0.71
Backhoe 2	0.80	0.04	0.24	0.33
Front-End Loader	0.76	0.59	0.62	0.84
Skid Steer Loader	0.94	0.83	0.45	0.76
Average R^2	**0.89**	**0.51**	**0.38**	**0.78**

2.0 ASSESS THE VARIATIONS OF FUEL USE AND EMISSIONS AMONG DIFFERENT DUTY CYCLES

In order to assess the variations of fuel use and emissions among different duty cycles, the representative duty cycles for each type of construction equipment were identified in the construction site. As mentioned in Section 1.3, time-based regression model has the best explanatory capability among all models. Based on the cumulative frequency of normalized MAP for duty cycle, the fuel use and emission rates can be predicted for each duty cycle using the regression model. Therefore, inter-cycle and inter-engine variability can be assessed for different duty cycles and engines.

2.1 Representative Duty Cycles for Each Type of Construction Equipment

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. For example, the duty cycle for a front-end loader performing material handling typically includes the components of load bucket, carry loaded, dump, and return empty; one complete cycle of these components comprises the duty cycle of material handling for a front-end loader.

In order to determine representative duty cycles for construction equipment, the data collection team went to the job site and observed the tasks for these vehicles prior to data collection. Representative duty cycles for each type of construction equipment were developed. The duty cycles were observed in the construction site.

The observed duty cycle for a front-end loader was “load truck.” “Load truck” is the typical duty cycle for a front-end loader to load material with the bucket in a dump truck. The duty cycle components for “load truck” typically include load bucket, maneuver loaded, dump, and maneuver empty.

The observed duty cycles for a bulldozer included “clearing land,” and “spreading material.” The duty cycle components for “clearing land” include pushing and maneuvering. The duty cycle components for “spreading material” are pushing and returning.

The observed duty cycles for an excavator included “Tree/Stump Removal,” “Moving Objects,” and “Mass Excavation.” The “Tree/Stump Removal” cycle does not have specific defined duty cycle. The duty cycle components for “Moving Objects” include lifting, carrying, loaded, setting, and returning empty. The duty cycle components for “Mass Excavation” include digging, swing loaded, dumping, and swing empty.

The only observed duty cycle for an off-highway truck is “Material Hauling.” The duty cycle components for “Material Hauling” include receiving load (Idling), hauling loaded, dumping, and returning empty.

There were two observed duty cycles for backhoes. These duty cycles were defined as "load truck," and "mass excavation." The "load truck" cycle for a backhoe is similar to the cycle for a front-end loader. In addition to loading trucks, a backhoe also performs the duty cycles of "mass excavation." "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. 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. The backhoes observed employed a front bucket with a 1.25 cubic yard capacity and a rear bucket with a 0.24 cubic yard capacity. Therefore, the front bucket is approximately five times larger than the rear bucket, meaning that "load truck" was usually the most power-demanding duty cycle for a backhoe.

The only observed duty cycle for a skid steer loader is "Material Handling." The duty cycle components for "Material Handling" include loading bucket, carrying load, dumping, and returning empty. The generator has only one duty which is idling.

The representative duty cycles for construction equipment and vehicles are summarized below. The cumulative frequency of normalized MAP for all duty cycles is shown in Figure 4.

Duty Cycle 1: Load a dump truck using a front-end loader

Duty Cycle 2: Clearing land using a bulldozer (Dozer 1)

Duty Cycle 3: Spreading materials using a bulldozer (Dozer 2)

Duty Cycle 4: Spreading materials using a bulldozer (Dozer 3)

Duty Cycle 5: Tree/Stump removal using an excavator (Excavator 1)

Duty Cycle 6: Moving objects using an excavator (Excavator 2)

Duty Cycle 7: Mass excavation using an excavator (Excavator 3)

Duty Cycle 8: Material hauling using an off-highway truck

Duty Cycle 9: Mass excavation using a backhoe (Backhoe 1)

Duty Cycle 10: Load a dump truck using a backhoe (Backhoe 2)

Duty Cycle 11: Material handling using a skid steer loader

Duty Cycle 12: ISO-C1 engine dynamometer test cycle

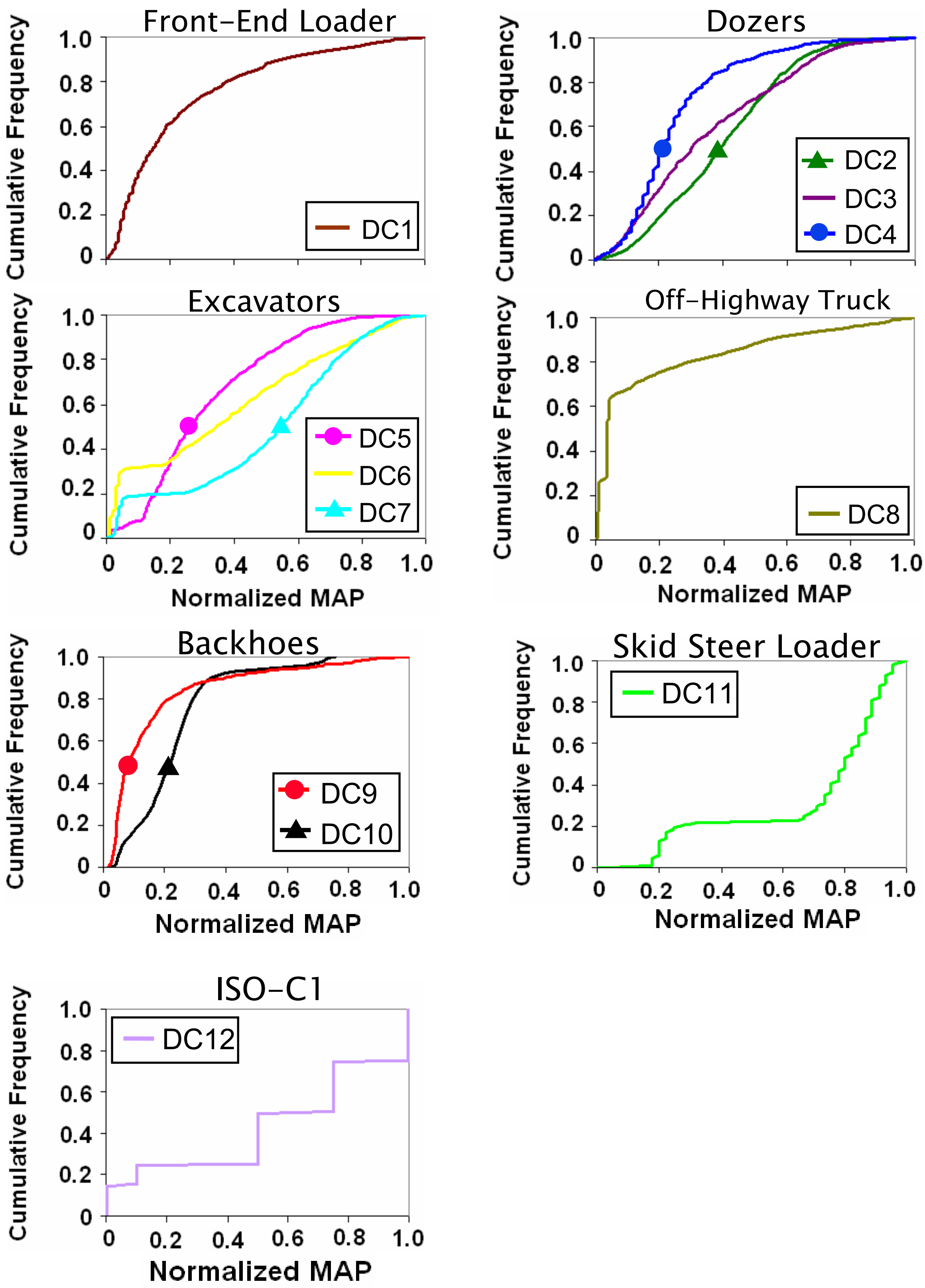


Figure 4 Cumulative Frequency Distribution of MAP for Twelve Duty Cycles

2.2 Inter-Cycle and Inter-Engine Variability

In Section 2.1, each duty cycle is characterized by a frequency distribution of normalized manifold absolute pressure (MAP). The average fuel use and emission rates for each duty cycle are predicted based on the distributions of normalized MAP using time-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, CO_2, NO_x, opacity, HC, and CO emission rates are shown in Tables 8, 9 10, 11, 12, and 13.

In Table 8, for one specific vehicle, fuel use rates are estimated for each duty cycle. Duty cycles 2, 3, and 4 are estimated based on bulldozer activities. In order to show the inter-cycle and inter-engine variations among the same type of equipment, Engines 2, 3, and 4 are grouped together (Engine 2, 3, and 4 represent Dozer 1, 2, and 3, respectively). Similarly, Engines 5, 6, and 7 are grouped together to show the inter-cycle and inter-engine variations for excavators. Table 8 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) range from 0.7 g/sec to 4.1 g/sec among 12 duty cycles. This is a 486% difference between the high versus low values. Among same type of equipment, the inter-cycle and inter-engine variations are less but still significant. For bulldozers, the fuel use rates for Engines #2, 3, 4 and Duty Cycles 2, 3, and 4 range from 1.1 g/sec to 3.2 g/sec. This is a 191% difference between the high versus low values. Time-based emission factors for CO_2 emission rates are shown in Table 9. As expected, the results for CO_2 emission rates are similar to those for fuel use rates because CO_2 emission rates are highly correlated with fuel use.

In Table 10, the inter-cycle and inter-engine variations of time-based NO emission rates are shown. In general, 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 #5 (Excavator 1) range from 33 to 239 mg/sec. This is a 624% difference between the high versus low values. Among same type of equipment, the inter-cycle and inter-engine variations are less but still significant. For bulldozers, the time-based NO emission rates for Engines #2, 3, 4 and Duty Cycles 2, 3, and 4 range from 38 mg/sec to 153 mg/sec. This is a 303% difference between the high versus low values.

In Table 11, 12, and 13, the inter-cycle and inter-engine variations are shown for time-based opacity, HC, and CO emission rates. A similar trend of the inter-cycle and inter-engine variations was observed for opacity, HC, and CO. Time-based emission factors have significant inter-cycle and inter-engine variations for all vehicles, but less variations were observed among same type of vehicles.

Table 8 Inter-Engine and Inter-Cycle Variations of Fuel Use Rates (g/sec)

Duty Cycle	Engine [a]											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	1.8	1.3	1.0	2.0	2.8	2.3	1.1	3.1	1.0	1.3	0.5	
DC2	2.7	**2.2**	**1.6**	**3.2**	4.5	3.6	1.8	4.7	1.6	2.1	0.7	
DC3	2.4	**1.9**	**1.4**	**2.9**	4.0	3.2	1.6	4.2	1.4	1.9	0.6	
DC4	1.9	**1.4**	**1.1**	**2.2**	3.0	2.5	1.2	3.3	1.1	1.4	0.5	
DC5	2.2	1.7	1.3	2.6	**3.6**	**2.9**	**1.4**	3.9	1.3	1.7	0.6	
DC6	2.5	2.0	1.4	2.9	**4.1**	**3.3**	**1.6**	4.3	1.4	1.9	0.6	
DC7	3.1	2.6	1.8	3.8	**5.3**	**4.2**	**2.1**	5.5	1.8	2.5	0.8	
DC8	1.5	0.9	0.8	1.5	2.1	1.8	0.8	2.4	0.8	1.0	0.4	
DC9	1.5	0.9	0.8	1.5	2.1	1.8	0.8	2.4	**0.8**	**1.0**	0.4	
DC10	1.9	1.3	1.1	2.1	2.9	2.4	1.1	3.2	**1.1**	**1.3**	0.5	
DC11	4.1	3.7	2.5	5.2	7.4	5.7	2.9	7.5	2.4	3.4	0.9	
DC12	3.5	3.1	2.1	4.4	6.2	4.8	2.4	6.3	2.1	2.9	0.9	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 9 Inter-Engine and Inter-Cycle Variations of CO_2 Emission Rates (g/sec)

Duty Cycle	Engine [a]											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	5.7	4.0	3.2	6.3	8.9	7.2	3.4	9.6	3.2	4.1	1.4	
DC2	8.4	**6.8**	**4.9**	**10.1**	14.3	11.2	5.5	14.7	4.9	6.6	2.0	
DC3	7.6	**6.0**	**4.4**	**9.0**	12.7	10.1	4.9	13.2	4.4	5.9	1.9	
DC4	6.1	**4.4**	**3.4**	**6.8**	9.6	7.8	3.6	10.3	3.4	4.4	1.5	
DC5	7.0	5.4	4.1	8.2	**11.5**	**9.2**	**4.4**	12.1	4.0	5.3	1.7	
DC6	7.7	6.1	4.5	9.2	**13.0**	**10.3**	**5.0**	13.5	4.5	6.0	1.9	
DC7	9.7	8.2	5.8	11.9	**16.9**	**13.1**	**6.6**	17.2	5.7	7.8	2.3	
DC8	4.6	2.8	2.5	4.8	6.7	5.7	2.5	7.6	2.6	3.1	1.2	
DC9	4.6	2.8	2.5	4.7	6.6	5.6	2.4	7.5	**2.5**	**3.1**	1.2	
DC10	5.8	4.1	3.3	6.5	9.2	7.5	3.5	9.9	**3.3**	**4.2**	1.4	
DC11	12.8	11.6	7.8	16.4	23.3	17.8	9.1	23.3	7.7	10.8	3.0	
DC12	11.0	9.6	6.7	13.8	19.6	15.1	7.6	19.7	6.5	9.1	2.7	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 10 Inter-Engine and Inter-Cycle Variations of NO_x Emission Rates (mg/sec)

Duty Cycle	Engine [a]											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	52	64	33	89	89	60	38	110	42	33	14	
DC2	76	**103**	**51**	**153**	139	89	58	163	67	60	20	
DC3	68	**92**	**44**	**130**	125	80	52	147	57	49	18	
DC4	57	**67**	**38**	**105**	93	65	39	122	52	42	15	
DC5	65	82	43	123	**112**	**75**	**47**	138	57	49	17	
DC6	67	97	41	120	**132**	**79**	**54**	143	49	42	18	
DC7	81	127	50	154	**170**	**98**	**69**	175	58	52	22	
DC8	42	52	24	64	73	48	31	88	29	21	11	
DC9	43	49	25	65	69	48	29	89	**32**	**22**	11	
DC10	56	63	37	102	88	63	38	119	**52**	**41**	14	
DC11	94	172	53	148	239	117	95	208	47	35	25	
DC12	83	144	47	134	202	101	80	181	46	38	22	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 11 Inter-Engine and Inter-Cycle Variations of Opacity Rates (mg/sec)

Duty Cycle	Engine [a]											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	0.51	0.45	0.29	0.92	1.05	0.48	0.22	0.94	0.04	0.55	0.09	
DC2	0.77	**0.78**	**0.49**	**1.58**	1.74	0.80	0.39	1.52	0.06	1.00	0.12	
DC3	0.70	**0.68**	**0.43**	**1.39**	1.54	0.70	0.34	1.35	0.05	0.87	0.11	
DC4	0.54	**0.49**	**0.31**	**1.01**	1.15	0.52	0.25	1.01	0.04	0.61	0.09	
DC5	0.64	0.61	0.39	1.24	**1.39**	**0.63**	**0.30**	1.22	0.05	0.77	0.11	
DC6	0.71	0.70	0.44	1.42	**1.58**	**0.72**	**0.35**	1.38	0.06	0.90	0.12	
DC7	0.90	0.94	0.59	1.90	**2.07**	**0.95**	**0.47**	1.81	0.07	1.22	0.14	
DC8	0.40	0.32	0.21	0.66	0.78	0.35	0.16	0.70	0.03	0.37	0.08	
DC9	0.39	0.31	0.20	0.64	0.77	0.34	0.15	0.69	**0.03**	**0.36**	0.08	
DC10	0.52	0.46	0.30	0.96	1.09	0.49	0.23	0.97	**0.04**	**0.58**	0.09	
DC11	1.22	1.33	0.83	2.68	2.89	1.33	0.66	2.50	0.10	1.76	0.18	
DC12	1.04	1.10	0.69	2.23	2.41	1.11	0.55	2.10	0.08	1.45	0.15	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 12 Inter-Engine and Inter-Cycle Variations of HC Emission Rates (mg/sec)

Duty Cycle	Engine [a] 1	2	3	4	5	6	7	8	9	10	11	12
DC1	6.4	4.0	5.7	6.0	5.0	7.4	4.0	8.2	4.5	2.2	2.5	
DC2	8.9	**4.9**	**8.2**	**7.9**	6.8	10.4	5.2	11.9	5.6	2.6	3.0	
DC3	8.2	**4.6**	**7.5**	**7.3**	6.3	9.5	4.8	10.8	5.3	2.5	2.9	
DC4	6.8	**4.1**	**6.1**	**6.2**	5.3	7.8	4.1	8.7	4.7	2.2	2.5	
DC5	7.6	4.4	6.9	6.9	**5.9**	**8.8**	**4.6**	10.0	5.1	2.4	2.7	
DC6	8.3	4.7	7.6	7.4	**6.3**	**9.6**	**4.9**	11.0	5.4	2.5	2.9	
DC7	10.1	5.3	9.3	8.8	**7.6**	**11.8**	**5.8**	13.6	6.1	2.8	3.3	
DC8	5.5	3.6	4.8	5.3	4.3	6.3	3.5	6.8	4.1	2.0	2.2	
DC9	5.4	3.6	4.7	5.2	4.3	6.2	3.4	6.7	**4.1**	**2.0**	2.2	
DC10	6.6	4.0	5.9	6.1	5.1	7.6	4.0	8.4	**4.6**	**2.2**	2.5	
DC11	13.0	6.3	12.1	11.0	9.6	15.2	7.3	18.0	7.4	3.4	4.0	
DC12	11.3	5.7	10.5	9.7	8.5	13.2	6.4	15.4	6.7	3.1	3.6	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 13 Inter-Engine and Inter-Cycle Variations of CO Emission Rates (mg/sec)

Duty Cycle	Engine [a]											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	22	14	8	26	11	24	7	54	7	13	4	
DC2	32	**19**	**9**	**26**	15	30	9	91	8	18	4	
DC3	29	**18**	**8**	**26**	14	29	8	80	8	16	4	
DC4	24	**15**	**8**	**26**	12	25	8	59	7	13	4	
DC5	27	17	8	26	**13**	**27**	**8**	72	8	15	4	
DC6	29	18	8	26	**14**	**29**	**8**	82	8	17	4	
DC7	36	21	9	25	**17**	**33**	**9**	108	9	20	5	
DC8	19	12	7	26	10	22	7	40	7	11	4	
DC9	18	12	7	26	10	22	7	39	**7**	**11**	4	
DC10	23	14	8	26	12	25	7	56	**7**	**13**	4	
DC11	47	27	10	25	21	40	10	151	10	26	5	
DC12	40	24	10	25	18	36	10	126	9	23	5	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

In addition, there are inter-cycle and inter-engine variations when predicting fuel-based emission factors. The predicted fuel-based NO, opacity, HC, and CO emission rates are shown in Tables 14, 15, 16, and 17.

In Table 14, the inter-cycle and inter-engine variations of fuel-based NO emission rates are shown.

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 #5 (Excavator 1) range from 96 to 150 g/gal. This is a 56% difference between the high versus low values, as compared to 624% for time-based NO emission rates. Similar trends were observed for fuel-based opacity, HC, and CO emission rates shown in Tables 15, 16, and 17.

The main conclusions for the inter-cycle and inter-vehicle variations are:

- Time-based inter-cycle and inter-engine variations of fuel use and emissions are significant.
- Fuel-based emission rates are less sensitive to differences in duty cycles.

Table 14 Inter-Engine and Inter-Cycle Variations of NO_x Emission Rates (g/gal)

Duty Cycle	Engine [a]											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	92	157	105	142	101	83	110	113	134	81	89	
DC2	90	**149**	**101**	**152**	98	79	102	110	133	91	91	
DC3	90	**154**	**100**	**143**	99	80	103	111	129	82	95	
DC4	95	**152**	**110**	**152**	99	83	103	118	150	95	95	
DC5	94	153	105	150	**99**	**82**	**107**	113	139	92	90	
DC6	85	154	93	132	**102**	**76**	**107**	106	111	70	95	
DC7	83	155	88	129	**102**	**74**	**104**	101	102	66	87	
DC8	89	184	95	136	111	85	123	117	115	67	87	
DC9	91	173	99	138	104	85	115	118	**127**	**70**	87	
DC10	94	154	107	154	96	83	110	118	**150**	**100**	89	
DC11	73	148	67	91	103	65	104	88	62	33	80	
DC12	75	148	71	97	104	67	106	91	70	42	78	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 15 Inter-Engine and Inter-Cycle Variations of Opacity Rates (g/gal)

Duty Cycle	Engine [a]											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	0.90	1.10	0.92	1.46	1.19	0.66	0.64	0.96	0.13	1.35	0.57	
DC2	0.91	**1.13**	**0.97**	**1.57**	1.23	0.71	0.69	1.03	0.12	1.51	0.55	
DC3	0.93	**1.14**	**0.98**	**1.52**	1.22	0.70	0.68	1.02	0.11	1.46	0.58	
DC4	0.90	**1.11**	**0.90**	**1.46**	1.22	0.66	0.66	0.97	0.12	1.39	0.57	
DC5	0.93	1.14	0.95	1.52	**1.23**	**0.69**	**0.68**	0.99	0.12	1.44	0.58	
DC6	0.90	1.11	1.00	1.56	**1.23**	**0.69**	**0.70**	1.02	0.14	1.51	0.64	
DC7	0.92	1.15	1.04	1.59	**1.24**	**0.72**	**0.71**	1.05	0.12	1.55	0.56	
DC8	0.85	1.13	0.83	1.40	1.18	0.62	0.64	0.93	0.12	1.18	0.64	
DC9	0.83	1.10	0.80	1.36	1.17	0.60	0.60	0.91	**0.12**	**1.14**	0.64	
DC10	0.87	1.13	0.87	1.45	1.20	0.65	0.66	0.96	**0.12**	**1.42**	0.57	
DC11	0.95	1.14	1.06	1.64	1.24	0.74	0.72	1.06	0.13	1.65	0.57	
DC12	0.94	1.13	1.04	1.61	1.24	0.74	0.73	1.06	0.12	1.59	0.53	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 16 Inter-Engine and Inter-Cycle Variations of HC Emission Rates (g/gal)

Duty Cycle	Engine [a] 1	2	3	4	5	6	7	8	9	10	11	12
DC1	11.3	9.8	18.1	9.5	5.7	10.2	11.6	8.4	14.3	5.4	15.9	
DC2	10.5	**7.1**	**16.3**	**7.9**	4.8	9.2	9.2	8.1	11.1	3.9	13.6	
DC3	10.9	**7.7**	**17.0**	**8.0**	5.0	9.4	9.5	8.2	12.0	4.2	15.4	
DC4	11.4	**9.3**	**17.6**	**9.0**	5.6	9.9	10.9	8.4	13.6	5.0	15.9	
DC5	11.0	8.2	16.9	8.4	**5.2**	**9.6**	**10.4**	8.2	12.5	4.5	14.3	
DC6	10.6	7.5	17.3	8.1	**4.9**	**9.3**	**9.7**	8.1	12.3	4.2	15.4	
DC7	10.4	6.5	16.4	7.4	**4.6**	**8.9**	**8.8**	7.9	10.8	3.6	13.1	
DC8	11.7	12.7	19.1	11.2	6.5	11.1	13.9	9.0	16.3	6.4	17.5	
DC9	11.4	12.7	18.7	11.0	6.5	11.0	13.5	8.9	**16.3**	**6.4**	17.5	
DC10	11.0	9.8	17.1	9.2	5.6	10.1	11.6	8.3	**13.3**	**5.4**	15.9	
DC11	10.1	5.4	15.4	6.7	4.1	8.5	8.0	7.6	9.8	3.2	12.7	
DC12	10.3	5.8	15.9	7.0	4.4	8.7	8.5	7.8	10.1	3.4	12.7	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

Table 17 Inter-Engine and Inter-Cycle Variations of CO Emission Rates (g/gal)

Duty Cycle	Engine [a]											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	38.9	34.2	25.4	41.3	12.5	33.2	20.2	55.4	22.3	31.8	25.4	
DC2	37.7	**27.5**	**17.9**	**25.8**	10.6	26.5	15.9	61.6	15.9	27.3	18.2	
DC3	38.4	**30.1**	**18.2**	**28.5**	11.1	28.8	15.9	60.6	18.2	26.8	21.2	
DC4	40.2	**34.1**	**23.1**	**37.6**	12.7	31.8	21.2	56.9	20.2	29.5	25.4	
DC5	39.0	31.8	19.6	31.8	**11.5**	**29.6**	**18.2**	58.7	19.6	28.1	21.2	
DC6	36.9	28.6	18.2	28.5	**10.9**	**27.9**	**15.9**	60.6	18.2	28.5	21.2	
DC7	36.9	25.7	15.9	20.9	**10.2**	**25.0**	**13.6**	62.4	15.9	25.4	19.9	
DC8	40.3	42.4	27.8	55.1	15.1	38.9	27.8	53.0	27.8	35.0	31.8	
DC9	38.2	42.4	27.8	55.1	15.1	38.9	27.8	51.7	**27.8**	**35.0**	31.8	
DC10	38.5	34.2	23.1	39.4	13.2	33.1	20.2	55.7	**20.2**	**31.8**	25.4	
DC11	36.5	23.2	12.7	15.3	9.0	22.3	11.0	64.0	13.3	24.3	15.9	
DC12	36.3	24.6	15.1	18.1	9.2	23.9	13.3	63.6	13.6	25.2	17.7	

[a] Engine 1 = Front-End Loader;
Engine 2 = Dozer 1;
Engine 3 = Dozer 2;
Engine 4 = Dozer 3;
Engine 5 = Excavator 1;
Engine 6 = Excavator 2;
Engine 7 = Excavator 3;
Engine 8 = Off-Highway Truck;
Engine 9 = Backhoe 1;
Engine 10 = Backhoe 2;
Engine 11 = Skid Steer Loader.

3.0 Benchmarks of Predicted Emission Rates Based on EPA's NONROAD Model

Fuel based emission factors from PEMS data were compared with fuel-based emission factors estimated using EPA's NONROAD model for the same model year, chassis type, and engine Tier. The NONROAD 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. Therefore, there are expected to be some differences in the absolute values of the emission factors when comparing both approaches. However, the purpose of the comparison is to determine whether the magnitudes of the emission factors are similar.

The EPA's NONROAD emission inventory model produces exhaust emission factors for nonroad diesel engines. 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.

For the deterioration of the engine and the variation of chassis, the NONROAD model uses two correction factors: the transient adjustment factors (TAF) and the deterioration factor (DF). TAF represents the variation of equipment type, and DF is for the representation of engine type and age. TAFs and DFs used in NONROAD model are shown in Tables 18 and 19.

The emission factors used in the NONROAD model were developed based on engine dynamometer measurements in the units of grams per brake horsepower-hour shown in Table 20. However, in real-world measurements, the emission factors are obtained in the units of grams per second or grams per gallon of fuel consumed. Thus, in order to enable comparisons with the PEMS data, the emission factors in the NONROAD model need to be converted to the units of grams per gallon of fuel using an assumed brake-specific fuel consumption rate.

Table 18 Transient Adjustment Factors (TAF) in NONROAD Model

Equipment	Tier	TAF				
		HC	CO	NO_X	PM	BSFC
Front End Loader	Tier 2	1.05	1.53	0.95	1.23	1.01
Dozer 1	Tier 0	1.05	1.53	0.95	1.23	1.01
Dozer 2	Tier 2	1.05	1.53	0.95	1.23	1.01
Dozer3	Tier 1	1.05	1.53	0.95	1.23	1.01
Excavator 1	Tier 1	1.05	1.53	0.95	1.23	1.01
Excavator 2	Tier 2	1.05	1.53	0.95	1.23	1.01
Excavator 3	Tier 1	1.05	1.53	0.95	1.23	1.01
Hauler	Tier 2	1.05	1.53	0.95	1.23	1.01
Backhoe 1	Tier 1	2.29	2.57	1.10	1.97	1.18
Backhoe 2	Tier 1	2.29	2.57	1.10	1.97	1.18
Skid Steer Loader	Tier 1	2.29	2.57	1.21	1.97	1.18
Generator	Tier 1	1.00	1.00	1.00	1.00	1.00

Table 19 Relative Deterioration Factors (DF) in NONROAD Model

Pollutant	Relative Deterioration Factor (A)			
	Base/Tier 0	Tier 1	Tier 2	Tier 3+
HC	0.047	0.036	0.034	0.027
CO	0.185	0.101	0.101	0.151
NO_X	0.024	0.024	0.009	0.008
PM	0.473	0.473	0.473	0.473

Table 20 Zero-Hour Steady-State Emission Factors in NONROAD Model

Equipment	Tier	Emission Factor (g/bhp-hr)				BSFC (lb/bhp-hr)
		HC	CO	NO_X	PM	
Front-End Loader	Tier 2	0.34	0.87	4.41	0.24	0.367
Dozer 1	Tier 0	0.99	3.49	6.90	0.72	0.408
Dozer 2	Tier 2	0.37	2.37	4.70	0.24	0.408
Dozer 3	Tier 1	0.52	2.37	5.60	0.47	0.408
Excavator 1	Tier 1	0.31	0.75	5.58	0.25	0.367
Excavator 2	Tier 2	0.34	0.87	4.41	0.24	0.367
Excavator 3	Tier 1	0.52	2.37	5.60	0.47	0.408
Hauler	Tier 2	0.17	0.89	4.50	0.14	0.367
Backhoe 1	Tier 1	0.52	2.37	5.60	0.47	0.408
Backhoe 2	Tier 1	0.52	2.37	5.60	0.47	0.408
Skid Steer Loader	Tier 1	0.43	1.88	4.95	0.39	0.408
Generator	Tier 1	0.34	0.87	5.65	0.28	0.367

The emission factors are calculated in units of grams per gallon as follows:

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

Where,

EF_{conv} = Corrected Emission Factor (*g/gal*)
EF = Emission Factor used in EPA's NONROAD model (*g/hp-hr*)
TAF = Transient Adjustment Factor (*unitless*)
DF = Deterioration Factor (*unitless*)
CF = Conversion *Factor* (*lb/gal*)

In addition, the emission factors used in the NONROAD model were developed based on fleet average emission rates. Those emission factors may not represent inter-vehicle variations within one specific engine tier. Thus, there could be some disagreement between the NONROAD emission factors and the data from the PEMS.

The fuel based emission factors from the PEMS data are of comparable magnitude to fuel-based emission factors estimated from the NONROAD model for NO, HC, and CO shown in Table 21. The PEMS emission factors are estimated based on the regression model described in Section 1.3.

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. For example, based on the NONROAD model, the average emission rate for NO varies from approximately 81 to 114 g/gallon, compared to ranges of approximately 70 to 154 g/gallon from the PEMS data. The two sources of 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.

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.

Table 21 Benchmarks of Weighted Average Emission Rates Based on NONROAD Model

	Duty Cycle	NO_x (g/gal)		HC (g/gal)		CO (g/gal)	
		PEMS	NONROAD Model	PEMS	NONROAD Model	PEMS	NONROAD Model
Front End Loader	DC1	92	81	11.3	6.8	38.9	25.5
Dozer 1	DC2	149	114	7.1	18	27.5	92.4
	DC3	154		7.7		30.1	
	DC4	152		9.3		34.1	
Dozer 2	DC2	101	81	16.3	6.2	17.9	40.7
	DC3	100		17		18.2	
	DC4	110		17.6		23.1	
Dozer 3	DC2	152	92	7.9	9.5	25.8	62.7
	DC3	143		8		28.5	
	DC4	152		9		37.6	
Excavator 1	DC5	99	102	5.2	6.2	11.5	22
	DC6	102		4.9		10.9	
	DC7	102		4.6		10.2	
Excavator 2	DC5	82	81	9.6	6.8	29.6	25.5
	DC6	76		9.3		27.9	
	DC7	74		8.9		25	
Excavator 3	DC5	107	92	10.4	9.5	18.2	62.1
	DC6	107		9.7		15.9	
	DC7	104		8.8		13.6	
Hauler	DC8	117	82	9	6.2	53	21.9
Backhoe 1	DC9	127	91	16.3	17.7	27.8	40.6
	DC10	150		13.3		20.2	
Backhoe 2	DC9	70	95	6.4	19.1	35	43.7
	DC10	100		5.4		31.8	
Skid Steer Loader	DC11	80	89	12.7	14.6	15.9	71.6
Generator	DC12	118	98	11.4	9.1	68.1	41.4