RESULTS OF A COMPREHENSIVE FIELD STUDY OF FUEL USE AND EMISSIONS OF NONROAD DIESEL CONSTRUCTION EQUIPMENT

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ABSTRACT

There is limited field data that can be used for fuel use and emissions analyses of nonroad diesel construction equipment. This paper summarizes the results of field research that used a portable emission monitoring system (PEMS) to collect fuel use and emissions data from eight backhoes, six bulldozers, three excavators, four generators, six motor graders, three off-road trucks, one skid-steer loader, three track loaders, and five wheel loaders while they performed various duty cycles. These tests produced approximately 119 hours of field data for petroleum diesel and approximately 48 hours for B20 biodiesel. Engine attribute data including horsepower, displacement, model year, engine tier, and engine load were measured to determine their influence on fuel use rates and emission rates of NO_x, HC, CO, CO_2, and opacity. Mass per time fuel use rates were developed for each item of equipment as well as mass per time and mass per fuel used emission rates for each pollutant. For petroleum diesel, fuel use and emission rates of each pollutant were found to increase with engine displacement, horsepower, and load, and to decrease with model year and engine tier. The results were qualitatively similar for B20. Fuel-based emission rates were found to have less variability and less sensitivity to engine size and load than time-based emission rates. Hence, where possible, development of emission inventories based on fuel consumed, rather than time of activity, is preferred.

INTRODUCTION

There are over two million items of diesel construction and mining equipment in the United States that consume almost 6 billion gallons of diesel fuel per year *(1)*. This equipment emits nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), and carbon dioxide (CO_2). Fuel use and emissions estimates for construction equipment are typically based on steady-state engine dynamometer tests using uninstalled stationary engines in a laboratory; these tests, however, do not represent in-use equipment activity. Thus, there is a need to determine fuel use and emission rates based on in-use measurements. Field data can be used to quantify construction equipment activity and the influence of equipment duty cycles on fuel use and emissions.

North Carolina State University (NCSU) recently completed two field studies that quantified the fuel use, emissions, and engine performance data of 39 items of diesel-powered construction equipment as they performed common construction duty cycles on job sites *(2, 3)*. The equipment includes eight backhoes, six bulldozers, three excavators, four generators, six motor graders, three off-road trucks, one skid-steer loader, three track loaders, and five wheel loaders. These items were tested while fueled with petroleum diesel. Furthermore, five of the backhoes, all six motor graders, and four of the wheel loaders were also tested with B20 biodiesel. Thus, a total of 54 field measurements were conducted. This research has produced an unprecedented database of real-world fuel use and emissions field data for diesel construction equipment. Although portions of this data are published in specific case studies, there has not yet been a comprehensive overview of trends within these extensive data.

The objective of this paper is to report and assess trends in this large body of field data. The results include engine size, engine model year, and engine tier; engine performance data related to engine load; representative duty cycles of the work performed by the equipment at the job site; and the related fuel use rates and emission rates of NO_x, HC, CO, CO_2, and PM. These data can be used to develop and improve diesel emission inventories, evaluate diesel emissions reduction programs and regulations, model diesel equipment fuel use and emissions, assess air quality impacts of alternative fuels, estimate CO_2 emissions from diesel construction equipment, and develop fuel and emission inventories for construction projects.

RELATED WORK

There has been a lack of field data for in-use fuel consumption and emissions characteristics of construction equipment. The Environmental Protection Agency (EPA), West Virginia University (WVU), and Clean Air Technologies International, Inc (CATI) have conducted on-board in-use measurements of emissions from construction equipment *(4 - 6)*. Not all of these data were quality assured nor are they all available for public use. Furthermore, it is not possible to investigate the relationship between the activity duty cycles versus fuel use and emissions based on these data.

Abolhassani *et al. (7)* evaluated the fuel use and emissions of excavators performing duty cycles in the field. Frey *et al. (8)* performed a comparison of petroleum diesel versus B20 biodiesel emissions from backhoes, motor graders, and wheel loaders performing field activities based on field data. Frey *et al. (9)* characterized the field activity, fuel use, and emissions of selected motor graders fueled with petroleum diesel and B20 biodiesel. Lewis *et al. (10)* examined requirements and incentives for reducing emissions from construction equipment and also advocated the use of field emissions data versus emissions data obtained from engine dynamometer tests. Lewis *et al. (11)* discussed the development and use of an emissions inventory for a fleet of backhoes, front-end loaders, and motor graders to make fleet management decisions related to replacing older equipment with newer equipment. Pang *et al. (12)* quantified the tailpipe emissions and fuel cycle energy use for petroleum diesel and B20 biodiesel to support a comprehensive comparison of the difference in total fossil energy use, greenhouse gas emissions, and air pollutant emissions for substitution of B20 in place of petroleum diesel.

Frey and Bammi *(13)* developed probabilistic emission factors for NO_x and HC based on engine dynamometer data from nonroad mobile sources including construction, farm, and industrial engines. Frey *et al. (14)* used field data from dump trucks to develop link-based emission factors for NO_x, HC, CO, and PM. Although these were highway vehicles, this type of equipment is used extensively in construction and can be used to estimate the overall impact of emissions from construction activities.

METHODOLOGY

This section provides a brief overview of the field data collection and analysis process.Detailed documentation of these procedures is provided by Frey *et al. (3)* and Rasdorf *et al. (15)*.

Field Data Collection

An on-board portable emissions monitoring system (PEMS) was used to gather engine, fuel use, and emissions data directly from in-use construction equipment. The PEMS used was the Montana System manufactured by CATI *(16)*. The PEMS was secured to the body of the equipment. Sensors were connected to the engine to collect engine performance data related to engine speed, intake air temperature, and engine load. Tailpipe exhaust amples were drawn continuously to measure exhaust concentrations of NO_x, HC, CO, CO2, and PM. These data were collected on a second-by-second basis, typically for three hours or more.

The original field data (referred to as “raw data”) underwent a rigorous quality assurance process to determine whether any errors or problems existed. This process is documented in detail by Frey et al *(3)*. If any errors were found, they were corrected when possible. If the errors could not be corrected, the affected data were removed. The purpose of the quality assurance process was to produce a valid set of data (referred to as “processed data”).

Engine Attributes

Engine attributes that affect performance, fuel use, and emissions include engine size, engine age, engine tier, and engine load. Engine size is quantified based on rated horsepower and displacement. This information was collected in the field and verified with the engine manufacturer’s specifications, found in publications such as the Caterpillar Performance Handbook *(17)*.

As engines increase in age, their performance may deteriorate *(18)*. Consequently, engines may produce more emissions as they get older. Engine age was represented by the engine model year. Engine hours of operation are another attribute that can be used to measure engine age; however, insufficient data was collected for engine hours and therefore is not reported.

In 1994, EPA adopted an engine tier classification system for all new nonroad diesel engines. Engine tiers are emission standards that require diesel engines manufactured after a specified date to meet the performance levels specified in the standards. The EPA engine tier classifications include successive Tier 1, Tier 2, Tier 3, Tier 4 Transitional, and Tier 4 Final, which are effective in reducing emissions in a phased sequence from 1996 to 2013. Engine tiers are essentially a hybrid engine attribute based on engine size (horsepower rating) and engine age (model year). The engine tier of each item of equipment was recorded.

Engine load affects the fuel use and emission rates of construction equipment. The variables that were monitored by the PEMS include engine speed measured in revolutions per minute (RPM), engine intake air temperature (IAT) measured in °C, and pressure-based engine load measured by manifold absolute pressure (MAP) in units of kPa.

Of the variables that were monitored, MAP has been consistently identified as highly correlated with fuel use and emission rates *(3)* and is often used as a surrogate for engine load. Since the equipment had various ranges of MAP values, the values were normalized on a consistent basis to enable comparisons between engines. The recorded second-by-second MAP values for a specific item of equipment were normalized according to:

$$\mathrm{MAP}_{\mathrm{nor}} = \frac{\mathrm{MAP} - \mathrm{MAP}_{\mathrm{min}}}{\mathrm{MAP}_{\mathrm{max}} - \mathrm{MAP}_{\mathrm{min}}}$$

where,

$\mathrm{MAP}_{\mathrm{nor}}$ = Normalized MAP for a measured MAP for a specific item of equipment
MAP = Measured MAP for a specific item of equipment
$\mathrm{MAP}_{\mathrm{min}}$ = Minimum MAP for a specific item of equipment
$\mathrm{MAP}_{\mathrm{max}}$ = Maximum MAP for a specific item of equipment

Normalized MAP values range from zero to one, thus representing a percentage of in-use engine loads.

Representative Duty Cycles

The duty cycle of the equipment used for a construction activity has its own distinct sequence of activities that affect the engine performance, fuel use, and emissions characteristics. A representative duty cycle for each item of equipment that was monitored during field data collection was defined. Although it is possible to describe the equipment's duty cycle in great detail, these representative duty cycles were intended only to provide the general nature of the work being performed by the equipment. Each duty cycle was subdivided into activity modes, including idling, moving, or working with an attachment such as a bucket or a blade. The representative duty cycles were used to evaluate relationships among equipment activity, engine performance data, and fuel use and emission rates.

Average Fuel Use and Emission Rates

Second-by-second equipment fuel use was computed on a mass per time basis of grams per second (g/s), based on the measured engine variables and exhaust composition. The average fuel use for each item of equipment is reported in units of gallons of fuel used per hour (gal/hr). The PEMS also measured the second-by-second emission rate of each pollutant on a mass per time basis of grams per second (g/s). The average mass per time emission rate of each pollutant for each item of equipment is reported in units of grams per hour (g/hr).

Fuel-based emission rates, which quantify the mass of emissions per unit of fuel consumed, were estimated based on a carbon balance based on the exhaust composition and the fuel properties. The average of the mass per fuel used emission rates for each item of equipment is reported in units of grams per gallon of fuel used (g/gal).

The term "fuel-based emission factors" only refers to estimating emissions per unit of fuel consumed (grams of pollutant per gallon of fuel consumed), as opposed to estimating emissions per unit of engine shaft output (grams per brake horsepower-hour) as has been the typical practice based on engine dynamometers. It is not possible to measure engine shaft output during actual operations; therefore, g/bhp-hr emission factors are not a convenient basis for developing practical emission inventories. Furthermore, the results of this research will indicate that fuel-based emission factors have less variability than time-based (gram of pollutant emitted per hour of operation) emission factors. Since one objective of this work is to support improved emission inventories, the most convenient form of an emission factor can be selected, irrespective of the regulatory framework used for engine certification testing.. A fuel-based emission factor can be developed for any fuel, and thus does not imply or exclude any particular regulatory approach.

The average fuel use and emission rates of each pollutant were measured for all 39 items of equipment while they were fueled with petroleum diesel. Furthermore, five backhoes, six motor graders, and four wheel loaders were tested a second time while fueled with B20 biodiesel, thus providing a basis for comparison of fuel use and emission rates of construction equipment while using different types of fuel. The methodology used to collect the data was the same for each fuel type.

RESULTS

This section provides the results of the field data collection for the equipment that was tested. These results include engine attributes, representative duty cycles, and average fuel use and emission rates. Analyses of trends in the data are also provided.

Field Data Collection

The 54 tests yielded over 665,000 seconds (185 hours) of raw data. After the quality assurance process, nearly 604,000 seconds (168 hours) of processed data remained. Approximately 9% of the raw data were deemed invalid by the quality assurance process and were not included in the final processed dataset; thus, approximately 91% of the data collected in the field were available for use. Of the processed data, approximately 119 hours were associated with equipment fueled with petroleum diesel and approximately 48 hours were associated with B20 biodiesel.

The PEMS estimated accurate emissions data for NO_x, CO, and CO_2. The emission rates of these pollutants are of the same magnitude of those found in other data sources, such as the EPA NONROAD model *(1)*. The HC data tend to be biased low. The PM detection method for the PEMS is analogous to opacity. The field measurements are useful for relative comparisons of PM emission rates for different fuels or equipment types, but not for characterization of the absolute magnitude of PM emissions. The PM data reported here could be low by an order of magnitude according to previous comparisons of the opacity-based measurements to other PM data. Batelle *(20)* provides a detailed evaluation of the reporting accuracy of the PEMS.

Engine Attributes

Table 1 summarizes the engine attributes of the tested equipment. The rated horsepower of the equipment ranged from 44 hp for a skid-steer loader to 306 hp for an off-road hauler truck. The engine displacement ranged from 2.0 liter for a skid-steer loader to 14.2 liter for a bulldozer. The engine model years ranged from 1988 to 2007, with one engine from the 1980's, 12 engines from the 1990's, and 26 engines from the 2000's; thus, the majority of the engines were less than ten years old when they were tested. Engine Tiers 0 through 3 were represented in the dataset, with six Tier 0 engines, 19 Tier 1 engines, 13 Tier 2 engines, and one Tier 3 engine. The latter was a new motor grader that recently had been placed into service. Engine loads and their relationship to duty cycles are discussed in the following section.

Representative Duty Cycles

The representative duty cycle for each item of tested equipment is summarized in Table 2 for the equipment fueled with petroleum diesel and in Table 3 for the equipment fueled with B20 biodiesel. These duty cycles were related to grading and earthwork activities commonly performed on construction sites such as moving soil, moving rock, moving building materials, loading trucks, rough grading, fine grading, excavating soil, clearing and grubbing, and shaping soil stockpiles. For motor graders, the "Resurface" duty cycle refers to a dirt road maintenance activity that involved smoothing ruts in the road surface while using the full length of the motor grader's blade; the "Shoulder" duty cycle refers to a highway maintenance activity that involved grading roadway shoulders and ditches while using only the end portion of the motor grader's blade. The primary duty cycle of the generators was to provide a temporary source of electricity at a jobsite. Overall, there were 12 observed representative duty cycles during the 54 tests.

The average engine loads based on the normalized MAP values are summarized in Table 2 for the equipment fueled with petroleum diesel and in Table 3 for the equipment fueled with B20 biodiesel. The average engine loads correspond to each duty cycle.

For the equipment fueled with petroleum diesel, the skid-steer loader and generators have the highest overall average engine loads of 54% and 53%, respectively. The skid-steer loader average engine load, however, is based on one observation only; thus, there is no basis for comparison with other skid-steer loaders. Furthermore, generators are stationary equipment that does not move around a jobsite, thus there is limited variability in engine load.

The lowest overall average engine load is 8% for the off-road hauler trucks; however, such a low average engine load should be interpreted with caution. The duty cycles observed for these off-road trucks included long idle times while the trucks were waiting to be loaded and then moving at low speeds for very short haul distances. Off-road trucks frequently operate at high speeds over long distances while hauling heavy payloads and can therefore generate very high engine loads. Thus, the overall average engine load for off-road trucks presented here are not representative of all off-road truck duty cycles.

Backhoes and wheel loaders have similar overall average engine loads of 19% and 17%, respectively. Both types of equipment are wheel-mounted tractors with comparable body styles and front-loader buckets that are used to perform similar duty cycles, including loading trucks, moving soil, and moving building materials. Bulldozers and track loaders also have similar overall average engine loads of 24% and 29%, respectively. These are track-type tractors with comparable body styles and work attachments that perform similar duty cycles including rough grading, fine grading, stockpile shaping, and moving building materials. Although the average engine loads for these four types of equipment can be higher under extreme conditions, such as moving maximum payloads on an adverse grade, the average engine loads presented here are typical for the observed duty cycles.

Each of the three excavators was observed performing a separate duty cycle that had its own distinct average engine load. Based on this data, it is apparent that excavators can operate under a wide range of engine loads. For example, the average engine load of 21% for clearing and grubbing involved removing small-to-medium sized trees that did not require much effort from the engine. Conversely, the average engine load of 52% involved moving heavy rock which required significant effort. For the excavating soil duty cycle, an average engine load of 40% was observed for the excavator while digging in common earth; however, the soil type may affect the engine load. A lower engine load would be expected for an excavator digging in sandy topsoil and a higher engine load would be expected for an excavator digging in hard-packed clay, although there was no opportunity to measure the engine loads for an excavating soil duty cycle for various soil types.

Motor graders were observed performing two separate duty cycles, including resurfacing and shouldering. Resurfacing had an average engine load of 39% and shouldering had an average engine load of 24%. The resurfacing duty cycle had a higher average engine load because the motor grader engaged the full length of its blade and thus had a higher resistance imposed by the ground. The shouldering duty cycle had a lower average engine load because only a fraction of the blade was engaged with the ground and thus had less resistance.

For the equipment fueled with B20 biodiesel, the overall average engine loads were quantitatively similar to the equipment fueled with petroleum diesel. Backhoes and wheel loaders had an overall average engine load of 22% and 19%, respectively (19% and 17%, respectively for petroleum diesel). For motor graders, the overall average engine load for resurfacing was 39%, the same as petroleum diesel, and 22% for shouldering (24% for petroleum diesel). Thus, as expected, fuel type has no significant impact on average engine loads and the slight variability in average engine loads based on fuel type shown here can be attributed to the variation in the individual duty cycles that were measured.

Average Fuel Use and Emission Rates

The average time-based fuel use and emission rates and the average fuel-based emission rates are summarized in Table 2 for the equipment fueled with petroleum diesel and in Table 3 for the equipment fueled with B20 biodiesel. The average fuel use and emission rates for each item of equipment correspond to the duty cycle and engine attribute data including horsepower, displacement, model year, engine tier, and engine load. Furthermore, the correlation coefficients for fuel use and emission rates versus engine attributes are presented in Tables 4 and 5 for the equipment fueled with petroleum diesel and B20 biodiesel, respectively.

Based on Table 4, the time-based fuel use and emission rates of each pollutant have a strong positive relationship with displacement and a moderate positive relationship with horsepower; thus, engine size has the greatest impact on time-based petroleum diesel fuel use and emission rates of NO_x, HC, CO, CO_2 and opacity. As examples, scatterplots for the relationships of fuel use and NO_x emission rates versus displacement are presented in Figure 1. These plots represent the linear increase in fuel use and NO_x emission rates as displacement increases. Although not shown, similar trends exist in the emission rates of the other pollutants.
Based on Table 5, the time-based fuel use and emission rates of NO_x, HC, CO_2, and opacity have a strong positive relationship with engine load; CO emission rates have a strong negative relationship with model year. Fuel use and NO_x, HC, and CO_2 emission rates also have a strong positive relationship with horsepower and displacement. Overall, engine load has the most significant impact on B20 biodiesel time-based fuel use and emission rates of NO_x, HC, CO_2, and opacity; model year has the most significant impact on CO emission rates.

Engine displacement was the most highly correlated factor for petroleum diesel fuel use and emission rates in part because there was large variability of a factor of more than 6, from 44 to 306 hp, in displacement among those data. For the equipment tested using B20 fuel, displacement varied by only a factor of approximately 2, from 90 to 198 hp. However, for the tests on B20 fuel, engine load varied by a factor of 4, from 12 to 48 percent. Hence, the identification of engine load as most highly correlated with fuel use rate and most of the emission rates for B20 is in part an artifact of the range of variation of this factor in the sample data set. As examples, scatterplots for the relationships of fuel use and NO_x versus engine load are presented in Figure 2. These plots represent the linear increase in fuel use and NO_x emissions with an increase in engine load. Although not shown, there are similar trends in the data for HC, CO_2, and opacity with respect to engine load; however, CO emission rates decrease as the model year increases.

Based on Tables 4 and 5, there is a negative relationship of fuel use and emission rates versus model year and engine tier, regardless of fuel type. Although these relationships are relatively weak, they still imply that newer model engines and engine tier standards have been effective at reducing fuel use and emissions.

Based on Tables 4 and 5, fuel-based emission rates have relatively weak relationships with the measured engine attributes of horsepower, displacement, model year, engine tier, and engine load. This does not mean, however, that fuel-based emission rates are unreliable. In fact, fuel-based emission rates tend to have less variability than time-based emission rates and therefore are effective for emissions analyses. Based on the data in Table 2, the petroleum diesel fuel-based emission rates have coefficients of variation (standard deviation divided by the mean) that are lower than the time-based emission rates' by approximately 73% for NO_x, 34% for HC, 14% for CO, and 42% for opacity; the average fuel-based emission rate of CO_2 for all equipment that was measured using petroleum diesel is approximately 9,900 g/gal ± 2%. Based on the data in Table 3, the B20 biodiesel fuel-based emission rates have coefficients of variation that are lower than the time-based emission rates' by approximately 65% for NO_x, 8% for HC, 51% for CO, and 32% for opacity; the average fuel-based emission rate CO_2 for all equipment that was measured using B20 biodiesel is approximately 9,700 g/gal ± 5%. Overall, the relative range of variation for fuel-based emission rates is lower than time-based emission rates.

A comparison of results between B20 and petroleum diesel for the 15 vehicles that were measured using both fuels needs to be done on a consistent basis for the same duty cycles for each type of equipment, in order to avoid the confounding effect of inter-test variability in duty cycle. Frey et al. (*8*) developed and applied engine load-based modal models of fuel use and emission rates, and for each equipment item used the same distribution of engine load, to enable comparison between the two fuels for the same duty cycle. On average over all 15 vehicles tested, time-based NO emission rates were 2 percent lower for B20 than petroleum diesel, which is not a statistically significant result. However, time-based emission rates were lower by 18, 26, and 25 percent for PM, HC, and CO, respectively, which are significant.

CONCLUSIONS & RECOMMENDATIONS

There is a need for accurate fuel use and emissions data for in-use nonroad diesel construction equipment. This type of data can be used to assess the environmental impacts of construction activities, particularly with regard to energy use and air quality. The work presented here provides a solid foundation for developing comprehensive datasets of fuel use and emissions information; however, more research needs to be done. The research that produced these results should be continued to observe more equipment of the same type in order to refine the current data and also gather data from other non-represented equipment types.

Fuel use and emissions field data collected by an on-board PEMS has an advantage over laboratory dynamometer testing in that the field data represents actual in-use conditions for the equipment as opposed to simulated conditions. Thus, PEMS data are useful for developing emission inventories that are representative of actual vehicle operations in the field; however, the methods and results presented here are not intended as a certification test or to replace existing certification tests. The field data results presented here have been quality assured and benchmarked to independent data, and are considered valid. These data should be used as a complement to existing emissions data, including the EPA NONROAD emission factors, in order to provide in-depth analyses of nonroad emission sources, including construction equipment.

The construction activities being performed by the equipment presented here were characterized by representative duty cycles; therefore, the corresponding fuel use and emissions for the construction activity itself can be compared to the quantity of work completed by the equipment. By linking construction quantities to fuel use and emissions, it is possible to establish fuel use and emission factors based on construction quantities, such as the cubic yards of excavation per gallon of fuel used by an excavator or the grams of pollutant emitted per mile of roadway shoulder scraped by a motor grader. These emission factors can then be used to estimate the fuel use requirements and the pollutants emitted for a construction project based on a quantity takeoff from a set of construction plans and specifications.

Petroleum diesel and B20 biodiesel fuel use and time-based emission rates, in most cases, have a strong positive relationship with engine displacement, horsepower, and load. For both fuels, time-based fuel and emission rates were inversely proportional to model year and engine tier. These types of trends should be investigated further and used for modeling fuel use and emissions as a function of equipment type, engine size, engine load, and model year or engine tier.

Fuel-based emission rates tend to have less variability than time-based emission rates. Hence, development of emissions inventories based on quantifying fuel consumed, rather than time of operation, is preferred where possible.

The data presented here may be used to evaluate fuel use and emission rates based on equipment type, fuel type, and engine attributes including horsepower, displacement, model year, engine tier, and engine load. These comparisons permit fuel use and emissions considerations to be used when making fleet management decisions such as selecting equipment for a specific activity or evaluating the equipment’s useful life and deterioration rates. Fleet managers should consider the impact of fuel use and emissions when determining which equipment to use on a project and also when to retire, replace, or retrofit existing equipment.

The results presented here may be used as a basis for establishing emissions inventories of construction projects to help determine their emissions footprint. These types of emission inventories may be used to assess the environmental impact of construction projects at the local, state, regional, and national levels. Environmental planners and policy-makers should consider such emissions inventories when developing pollution reduction strategies and regulations, particularly for the construction industry.

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REFERENCES

1. EPA. *User's Guide for the Final NONROAD2005 Model*. EPA-420-R-05-013, U.S. Environmental Protection Agency, Office of Transportation and Air Quality, Ann Arbor, MI, 2005.

2. Frey, C., W. Rasdorf, K. Kim, S. Pang, P. Lewis, and S. Abolhassani. *Life Cycle Inventory and Impact Analysis Framework for Nonroad Construction Vehicles and Equipment (TSE03-L)*. Research Project for National Science Foundation, Arlington, VA, 2007.

3. Frey, C., W. Rasdorf, K. Kim, S.H. Pang, P. Lewis, and S. Abolhassani. *Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina*. FHWA/NC/ 2006 – 55, Prepared by North Carolina State University for North Carolina Department of Transportation, Raleigh, NC, 2008.

4. May, D.; L. Fisher, C. Tennis, and T. Parrish. *Simple, Portable, On-vehicle Testing (SPOT) Final Report.* Contract number 86-C-01-106, Prepared by Analytical Engineering, Inc. for the U.S. Environmental Protection Agency, Columbus, IN, 2002.

5. Gautam, M., D. Carder, N. Clark, and D. Lyons. *Testing for Exhaust Emissions of Diesel Powered Off-Road Engines*. APB contract number 98-317, Prepared by West Virginia University for the California Air Resources Board and the California EPA, Sacramento, 2002.

6. Vojtisek-Lom, M. *Real-World Exhaust Emissions from Construction Equipment at the World Trade Center #7 Site*. Prepared by Clean Air Technologies International, Inc. for Northeast States for Coordinated Air Use Management, Buffalo, NY, 2003.

7. Abolhasani, S., C. Frey, K. Kim, S. Pang, W. Rasdorf, and P. Lewis. Real-World In-Use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators, *Journal of the Air & Waste Management Association*, Vol. 58, No. 8, pp. 1033-1046, 2008.

8. Frey, C., W. Rasdorf, K. Kim, S. Pang, and P. Lewis. Comparison of Real World Emissions of Backhoes, Front-End Loaders, and Motor Graders for B20 Biodiesel vs. Petroleum Diesel and for Selected Engine Tiers. In *Transportation Research Record*: *Journal of the Transportation Research Board*, No. 2058, Transportation Research Board of the National Academies, Washington, D.C., pp. 33-42, 2008.

9. Frey, C., K. Kim, W. Rasdorf, S. Pang, and P. Lewis. Characterization of Real-World Activity, Fuel Use, and Emissions of Selected Motor Graders Fueled with Petroleum Diesel and B20 Biodiesel. *Journal of the Air & Waste Management Association*, Vol. 58, No. 10, pp 1274-1287, 2008.

10. Lewis, P., W. Rasdorf, C. Frey, K. Kim, and S. Pang. Requirements and Incentives for Reducing Construction Vehicle Emissions and Comparison of Nonroad Diesel Engine Emissions Data Sources, *Journal of Construction Engineering and Management*, Vol. 135, No. 5, pp. 341-351, 2009.

11. Lewis, P., C. Frey, and W. Rasdorf. Development and Use of Emissions Inventories for Construction Vehicles. In *Transportation Research Record*: *Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington, D.C., 2009, (In Press TRB09-1485).
12. Pang, S., C. Frey, and W. Rasdorf. Life Cycle Inventory Energy Consumption and Emissions for Biodiesel versus Petroleum Diesel Fueled Construction Vehicles, *Environmental Science and Technology*, Vol. 43, No. 16, pp. 6398-6405, 2009.
13. Frey, C. and S. Bammi. Probabilistic Nonroad Mobile Source Emission Factors. *Journal of Environmental Engineering*, Vol. 129, No. 2, pp. 162-168,2003.
14. Frey, C., N. Rouphail, and H. Zhai. Link-Based Emission Factors for Heavy-Duty Diesel Trucks Based on Real-World Data. In *Transportation Research Record*: *Journal of the Transportation Research Board*, No. 2058, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 23 – 32.
15. Rasdorf, W., C. Frey, P. Lewis, K. Kim S. Pang, and S. Abolhassani. Field Procedures for Real-World Measurements of Emissions from Diesel Construction Vehicles. *Journal of Infrastructure Systems*, Submitted October 2008.
16. CATI. *OEM-2100 Montana System Operation Manual*, Clean Air Technologies International, Inc., Buffalo, NY, 2003.
17. CAT. *Caterpillar Performance Handbook, Edition 35*, Caterpillar, Inc., Peoria, IL, 2004.
18. Nichols, H. and D. Day. *Moving the Earth: The Workbook of Excavation*, The McGraw-Hill Companies, Inc., New York, NY, 2005.
19. EPA. *Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling - Compression-Ignition*. EPA-420-P-04-009, NR-009c, U.S. Environmental Protection Agency, Ann Arbor, MI, 2004.
20. Battelle. Environmental Technology Verification Report: Clean Air Technologies International, Inc. REMOTE On-Board Emissions Monitor, Prepared by Battelle for the U.S. Environmental Protection Agency, Columbus, OH, 2003.

LIST OF TABLES AND FIGURES

TABLE 1 Summary of Engine Attributes

Equipment	Horsepower (HP)	Displacement (Liters)	Model Year	Engine Tier
Backhoe 1	88	4.0	2004	2
Backhoe 2	88	4.2	1999	1
Backhoe 3	88	4.2	2000	1
Backhoe 4	97	3.9	2004	2
Backhoe 5	90	4.2	1997	0
Backhoe 6	90	4.2	2001	1
Backhoe 7	99	4.5	1999	1
Backhoe 8	97	4.5	2004	2
Bulldozer 1	89	5.0	1988	0
Bulldozer 2	95	3.9	2002	1
Bulldozer 3	90	5.0	2003	1
Bulldozer 4	175	10.5	1998	1
Bulldozer 5	285	14.2	1995	0
Bulldozer 6	99	4.2	2005	2
Excavator 1	254	8.3	2001	1
Excavator 2	138	6.4	2003	2
Excavator 3	93	3.9	1998	1
Generator 1	90	4.5	2002	1
Generator 2	150	6.8	2004	2
Generator 3	200	6.8	2004	2
Generator 4	177	6.8	2003	2
Motor Grader 1	195	8.3	2001	1
Motor Grader 2	195	7.1	2004	2
Motor Grader 3	195	8.3	2001	1
Motor Grader 4	167	8.3	1990	0
Motor Grader 5	160	8.3	1993	0
Motor Grader 6	198	7.2	2007	3
Off-Road Truck 1	306	9.6	2005	2
Off-Road Truck 2	285	10.3	1998	1
Off-Road Truck 3	285	10.3	1998	1
Skid Steer Loader 1	44	2.0	2003	1
Track Loader 1	121	7.2	1998	1
Track Loader 2	70	4.5	1997	0
Track Loader 3	127	7.2	2006	2
Wheel Loader 1	149	5.9	2004	2
Wheel Loader 2	130	5.9	2002	1
Wheel Loader 3	130	5.9	2002	1
Wheel Loader 4	126	5.9	2002	1
Wheel Loader 5	133	6.0	2005	2
Maximum	**306**	**14.2**	**2007**	**3**
Minimum	**44**	**2.0**	**1988**	**0**

TABLE 2 Summary Data for Petroleum Diesel

LEGEND

BH = Backhoe
BD = Bulldozer
EX = Excavator
GE = Generator
MG = Motor Grader
OT = Off-Road Truck
SS = Skid-Steer Loader
TL = Track Loader
WL = Wheel Loader

			Avg. Time-Based Fuel & Emission Rates						**Avg. Fuel-Based Emission Rates[1]**			
Equipment	**Duty Cycle**	**Load (%)**	**Fuel (gal/hr)**	**NO$_x$ (g/hr)**	**HC (g/hr)**	**CO (g/hr)**	**CO$_2$ (g/hr)**	**Opacity (g/hr)**	**NO$_x$ (g/gal)**	**HC (g/gal)**	**CO (g/gal)**	**Opacity (g/gal)**
BH 1	Load Truck	5	0.5	60	14	25	4,791	0.1	124	34	65	0.2
BH 2	Move Material	16	1.1	112	9	35	10,535	1.1	99	12	38	1.1
BH 3	Move Soil	19	0.8	73	7	15	8,360	1.3	82	10	23	2.1
BH 4	Move Soil	20	0.5	64	6	5	4,611	0.3	172	14	11	0.8
BH 5	Load Truck	23	1.8	206	27	154	18,175	2.1	111	15	80	1.1
BH 6	Load Truck	30	2.1	222	24	73	20,795	2.2	106	12	35	1.1
BH 7	Move Soil	19	0.8	112	7	52	8,035	0.7	164	13	61	0.8
BH 8	Move Soil	19	0.5	69	6	10	4,764	0.4	168	17	27	0.9
	Average	*19*	*1.0*	*115*	*13*	*46*	*10,008*	*1.0*	*128*	*16*	*43*	*1.0*
BD 1	Rough Grade	23	1.7	252	16	63	16,658	2.3	180	17	59	1.3
BD 2	Fine Grade	14	0.9	92	14	28	8,540	0.7	119	22	52	0.6
BD 3	Fine Grade	14	1.4	228	18	91	14,221	2.3	165	19	123	1.5
BD 4	Rough Grade	27	3.4	613	39	131	34,311	2.9	214	18	51	1.0
BD 5	Stockpile	48	10.1	1,913	33	240	100,647	NA[2]	204	9	56	NA[2]
BD 6	Stockpile	18	1.1	104	24	44	11,166	0.9	94	24	41	0.8
	Average	*24*	*3.1*	*534*	*24*	*100*	*30,924*	*1.8*	*163*	*18*	*64*	*1.0*
EX 1	Clear & Grub	21	2.8	319	13	37	28,503	3.2	145	9	23	1.0
EX 2	Move Rock	52	2.5	189	19	71	25,077	1.7	73	7	27	0.7
EX 3	Excavate Soil	40	1.9	214	20	27	19,401	1.5	132	16	26	0.8
	Average	*38*	*2.4*	*241*	*17*	*45*	*24,327*	*2.1*	*117*	*11*	*25*	*0.8*
GE 1	Generate	62	0.8	92	9	54	7,589	0.6	120	12	71	0.8
GE 2	Generate	46	1.1	72	19	137	10,533	0.9	67	18	128	0.9
GE 3	Generate	NA[2]	1.4	90	24	238	13,320	1.8	65	18	170	1.3
GE 4	Generate	50	1.4	121	19	121	13,532	1.6	88	14	88	1.2
	Average	*53*	*1.2*	*94*	*18*	*138*	*11,244*	*1.2*	*85*	*16*	*114*	*1.1*

(Continued on next page).

TABLE 2 Continued

			Avg. Time-Based Fuel & Emission Rates						Avg. Fuel-Based Emission Rates[1]			
Equipment	**Duty Cycle**	**Load (%)**	**Fuel (gal/hr)**	**NO_x (g/hr)**	**HC (g/hr)**	**CO (g/hr)**	**CO_2 (g/hr)**	**Opacity (g/hr)**	**NO_x (g/gal)**	**HC (g/gal)**	**CO (g/gal)**	**Opacity (g/gal)**
MG 1	Resurface	53	5.5	643	53	67	54,615	4.9	129	16	17	1.0
MG 2	Shoulder	10	1.7	192	50	48	16,956	1.0	148	43	29	0.5
MG 3	Shoulder	42	2.5	275	152	29	25,085	2.8	131	77	20	1.1
MG 4	Resurface	27	2.9	596	95	141	28,845	2.3	215	43	72	0.7
MG 5	Shoulder	20	2.6	423	26	134	26,013	1.9	179	15	113	0.7
MG 6	Resurface	38	2.5	163	21	17	24,893	1.8	86	10	7	0.7
	Average	*32*	*3.0*	*382*	*66*	*73*	*29,401*	*2.5*	*148*	*34*	*43*	*0.8*
OT 1	Haul Soil	14	2.4	298	22	121	23,543	2.2	155	13	32	0.9
OT 2	Haul Soil	4	1.7	246	15	41	16,904	1.5	181	13	27	0.9
OT 3	Haul Soil	6	1.9	268	17	59	19,080	1.6	179	13	44	0.9
	Average	*8*	*2.0*	*271*	*18*	*74*	*19,842*	*1.8*	*172*	*13*	*34*	*0.9*
SS 1	Move Material	54	0.9	74	12	17	8,721	0.5	97	17	29	0.6
	Average	*54*	*0.9*	*74*	*12*	*17*	*8,721*	*0.5*	*97*	*17*	*29*	*0.6*
TL 1	Fine Grade	30	2.9	169	29	67	29,297	2.3	67	14	30	0.8
TL 2	Move Material	44	2.9	514	22	38	28,738	2.1	159	10	17	1.0
TL 3	Stockpile	46	3.7	216	7	58	37,241	2.2	71	5	26	0.7
	Average	*29*	*2.1*	*237*	*17*	*55*	*21,343*	*1.6*	*131*	*13*	*30*	*0.8*
WL 1	Move Soil	18	1.7	179	19	73	17,399	1.5	114	14	44	0.9
WL 2	Load Truck	18	1.6	195	33	38	15,534	1.5	132	30	42	0.9
WL 3	Load Truck	17	0.9	131	8	18	9,250	0.4	179	14	38	0.6
WL 4	Load Truck	25	1.2	156	15	12	11,691	1.1	145	22	13	1.0
WL 5	Move Soil	9	0.8	78	8	23	7,819	0.5	104	13	36	0.6
	Average	*17*	*1.2*	*148*	*17*	*33*	*12,339*	*1.0*	*135*	*19*	*35*	*0.8*
	Maximum	**62**	**10.1**	**1,913**	**152**	**240**	**100,647**	**4.9**	**215**	**77**	**170**	**2.1**
	Minimum	**4**	**0.5**	**60**	**6**	**5**	**4,611**	**0.1**	**65**	**5**	**7**	**0.2**

[1] Average fuel-based CO_2 emission rate for all equipment is 9,939 g/gal ± 2%

[2] Data not available

TABLE 3 Summary Data for B20 Biodiesel

LEGEND

BH = Backhoe
BD = Bulldozer
EX = Excavator
GE = Generator
MG = Motor Grader
OT = Off-Road Truck
SS = Skid-Steer Loader
TL = Track Loader
WL = Wheel Loader

			Avg. Time-Based Fuel & Emission Rates						**Avg. Fuel-Based Emission Rates[1]**			
Equipment	**Duty Cycle**	**Load (%)**	**Fuel Use (gal/hr)**	**NO_x (g/hr)**	**HC (g/hr)**	**CO (g/hr)**	**CO_2 (g/hr)**	**Opacity (g/hr)**	**NO_x (g/gal)**	**HC (g/gal)**	**CO (g/gal)**	**Opacity (g/gal)**
BH 4	Move Soil	23	0.6	77	9	6	5,994	0.3	181	56	NA[2]	1.8
BH 5	Load Truck	29	1.8	213	25	125	18,290	2.0	114	14	66	1.1
BH 6	Move Soil	23	2.0	178	19	64	19,575	2.1	91	10	33	1.1
BH 7	Move Soil	20	1.2	111	42	105	11,388	1.6	139	33	73	1.2
BH 8	Move Soil	15	0.4	69	2	6	4,346	0.3	202	3	16	0.5
	Average	*22*	*1.2*	*129*	*19*	*61*	*11,919*	*1.3*	*145*	*23*	*47*	*1.1*
MG 1	Resurface	48	5.1	561	62	64	49,997	4.2	129	15	22	0.9
MG 2	Shoulder	14	1.7	233	16	34	17,102	0.5	173	13	24	0.3
MG 3	Shoulder	31	3.8	364	47	53	36,710	2.1	122	18	22	0.4
MG 4	Shoulder	12	1.3	201	36	NA[2]	12,658	0.0	131	32	NA[2]	0.8
MG 5	Shoulder	30	3.4	600	47	92	33,443	1.9	195	24	57	0.6
MG 6	Resurface	30	2.7	166	55	28	26,869	1.4	100	34	12	0.5
	Average	*28*	*3.0*	*354*	*44*	*54*	*29,463*	*1.7*	*142*	*23*	*27*	*0.6*
WL 2	Move Soil	17	1.0	126	8	28	9,637	0.7	151	19	53	1.8
WL 3	Move Soil	16	1.2	166	22	16	11,735	0.6	170	27	22	0.6
WL 4	Move Soil	22	2.2	253	30	38	21,130	1.6	132	21	29	0.7
WL 5	Move Soil	20	1.5	137	8	37	14,495	1.0	103	8	33	0.6
	Average	*19*	*1.5*	*171*	*17*	*30*	*14,249*	*1.0*	*139*	*19*	*34*	*0.9*
	Maximum	**48**	**5.1**	**600**	**62**	**318**	**49,997**	**4.2**	**202**	**56**	**313**	**1.8**
	Minimum	**12**	**0.4**	**69**	**2**	**6**	**4,346**	**0.0**	**100**	**3**	**12**	**0.3**

[1] Average fuel-based CO_2 emission rate for all equipment is 9,749 g/gal ± 5%

[2] Data not available

Table 4 Correlation Coefficients for Fuel Use and Emissions vs. Engine Attributes (Based on Petroleum Diesel)

		Horsepower	Displacement	Model Year	Engine Tier	Engine Load
Time-Based	**Fuel (gal/hr)**	0.50	0.72	-0.32	-0.33	0.39
	NO_x (g/hr)	0.45	0.70	-0.45	-0.47	0.26
	HC (g/hr)	0.26	0.34	-0.24	-0.22	0.18
	CO (g/hr)	0.40	0.53	-0.29	-0.23	0.23
	CO_2 (g/hr)	0.50	0.72	-0.32	-0.34	0.39
	Opacity (g/hr)	0.40	0.54	-0.31	-0.31	0.28
Fuel-Based	**NO_x (g/gal)**	0.29	0.40	-0.55	-0.52	-0.33
	HC (g/gal)	0.04	0.04	-0.06	-0.05	-0.10
	CO (g/gal)	0.00	0.04	-0.13	-0.10	-0.01
	Opacity (g/gal)	-0.02	-0.02	-0.20	-0.25	0.03

Table 5 Correlation Coefficients for Fuel Use and Emissions vs. Engine Attributes (Based on B20 Biodiesel)

		Horsepower	Displacement	Model Year	Engine Tier	Engine Load
Time-Based	**Fuel (gal/hr)**	0.66	0.68	-0.13	-0.19	0.87
	NO$_x$ (g/hr)	0.56	0.71	-0.41	-0.44	0.71
	HC (g/hr)	0.61	0.65	-0.31	-0.21	0.70
	CO (g/hr)	0.10	0.32	-0.85	-0.64	-0.13
	CO$_2$ (g/hr)	0.66	0.68	-0.13	-0.18	0.87
	Opacity (g/hr)	0.24	0.26	-0.06	-0.24	0.91
Fuel Based	**NO$_x$ (g/gal)**	-0.09	-0.03	-0.08	-0.02	-0.29
	HC (g/gal)	-0.01	-0.05	-0.10	0.08	-0.02
	CO (g/gal)	0.04	0.26	-0.77	-0.52	-0.34
	Opacity (g/gal)	-0.54	-0.52	-0.05	-0.16	-0.02

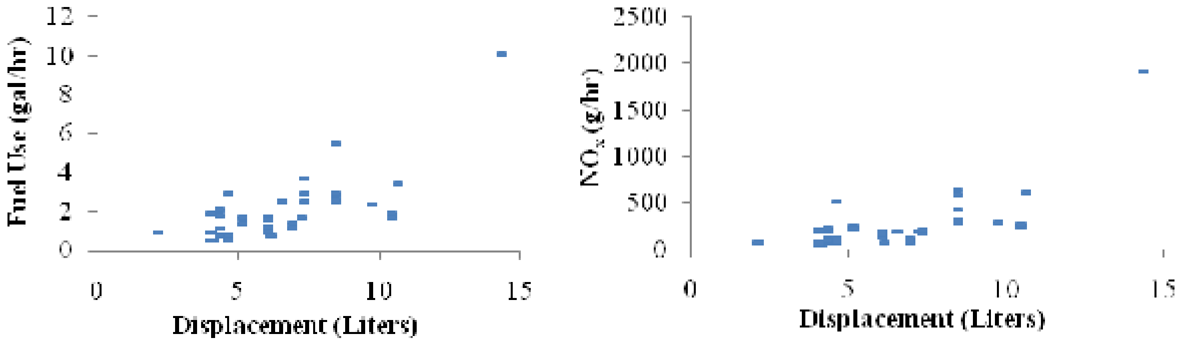

Figure 1 Time-Based Fuel Use and Emission Rates vs. Displacement (Based on Petroleum Diesel)

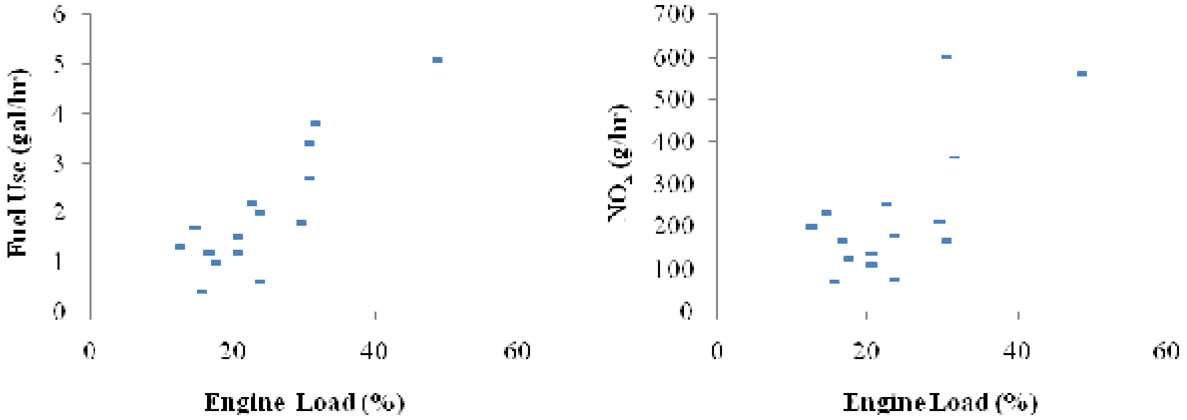

Figure 2 Time-Based Fuel Use and Emission Rates vs. Engine Load (Based on B20 Biodiesel)