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Real-World In-Use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators

Saeed Abolhasani, H. Christopher Frey, Kangwook Kim, William Rasdorf, Phil Lewis, and Shih-Hao Pang
Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC

ABSTRACT
A study design was developed and demonstrated for deployment of a portable emission measurement system (PEMS) for excavators. Excavators are among the most commonly used vehicles in construction activities. The PEMS measured nitric oxide, carbon monoxide, hydrocarbons, carbon dioxide, and opacity-based particulate matter. Data collection, screening, processing, and analysis protocols were developed to assure data quality and to quantify variability in vehicle fuel consumption and emissions rates. The development of data collection procedures was based on securing the PEMS while avoiding disruption to normal vehicle operations. As a result of quality assurance, approximately 90% of the attempted measurements resulted in valid data. On the basis of field data collected for three excavators, an average of 50% of the total nitric oxide emissions was associated with 29% of the time of operation, during which the average engine speed and manifold absolute pressure were significantly higher than corresponding averages for all data. Mass per time emission rates during non-idle modes (i.e., moving and using bucket) were on average 7 times greater than for the idle mode. Differences in normalized average rates were influenced more by intercycle differences than intervehicle differences. This study demonstrates the importance of accounting for intercycle variability in real-world in-use emissions to develop more accurate emission inventories. The data collection and analysis methodology demonstrated here is recommended for application to more vehicles to better characterize real-world vehicle activity, fuel use, and emissions for nonroad construction equipment.

IMPLICATIONS
Emissions from nonroad vehicles are becoming of increasing importance as emissions from other sources are reduced. There is a need for a methodology for measuring, analyzing, and reporting real-world fuel use and emissions from nonroad vehicles such as excavators. A procedure for field data collection, quality assurance, and analysis is demonstrated that can be applied to nonroad vehicles. The results indicate that it is possible to obtain new insight regarding the effect of intervehicle and intercycle variability in fuel use and emissions from these data. Such methods and data should be used to improve nonroad emission factor and inventory models.

INTRODUCTION
In the past decade, nonroad engine emissions have increasingly become the focus of regulatory action and air quality improvement strategies.[1] Nonroad sources include construction, farm, industrial, lawn and garden, recreational, marine, locomotives, aviation, and others.[2] Construction vehicles are estimated to contribute nearly half (48%) of nitrogen oxide (NO_x) emissions from all nonroad sources.[1]

Most emissions tests of construction, farm, and industrial equipment have been done using steady-state engine dynamometer test cycles that involve operating the engine at one or more settings of constant load and engine speed.[3–9] The U.S. Environmental Protection Agency's NONROAD model, which is widely used for development of emissions inventories, is based on such data for a limited number of such cycles measured in the laboratory for nonroad engines of different sizes.[10,11] Adjustment factors are applied to the test cycle data to represent emissions for various applications that are intended to represent specific types of equipment, such as bulldozers, front-end loaders, excavators, and so on. However, the empirical basis for such adjustments, if any, is limited.

An alternative method for measuring emissions is to collect data in the field during actual operations. Formerly, on-board emission measurement was prohibitively expensive and involved the use of bulky and expensive laboratory grade instrumentation that was permanently mounted inside a vehicle.[12–16] However, lower-cost portable instruments have recently been developed. For example, the U.S. Environmental Protection Agency (EPA) supported development of portable emissions measurement systems (PEMS) for both light- and heavy-duty vehicles, including nonroad equipment.[17–19] Commercial PEMS are available for both light- and heavy-duty vehicle applications, for either gasoline or diesel vehicles.[20–24]

There is a lack of real-world data for construction equipment. Limited data have been collected by Clean Air Technologies International (CATI), Inc. at the World Trade Center site for a loader, a large Caterpillar excavator, a small Komatsu excavator, and a crane for the purpose of evaluating the benefits of ultra-low sulfur and diesel particulate filter technologies.[25] West Virginia University (WVU) collected PEMS data for a street sweeper, a rubber-tire loader, and an excavator to generate transient test cycles that could be used to simulate real-world operating conditions for exhaust emissions research.[26] EPA used a specialized PEMS, the Simple Portable On-Board Test (SPOT) instrument, to collect engine and exhaust data for 50 construction vehicles in 2002.[27,28] However, not all of these data are quality assured or publicly available. Some projects to measure in-use emissions of nonroad vehicles are recently starting, such as a study by the University of California–Riverside.[29]

A key question is whether there is significant intercycle variability in fuel use and emission rates for a given type of vehicle. A duty cycle is a sequence of tasks that is repeated to produce a unit of output. A unit of output can be cubic yards of dirt removed, carried, or dumped per use of a bucket, such as for an excavator, front-end loader, or backhoe. A hypothesis is that variability in in-use duty cycles leads to variability in energy use and emissions that should be accounted for when developing an energy and emissions assessment framework. There is a critical need to analyze real-world, on-board data to understand the relationship between construction equipment duty cycles with respect to energy use and emissions.[12] The main focus of this paper is on excavators, which are commonly used equipment in construction activities.[30]

The objectives of this study were to: (1) document a procedure for collecting real-world emissions and fuel use data from excavators, (2) develop a procedure for data quality assurance, (3) demonstrate a conceptual analytical methodology for analyzing on-board data, (4) demonstrate the episodic nature of the vehicle activity and emissions data and the influence of vehicle duty cycle on the average emission rates, and (5) develop recommendations for future construction vehicle on-board emissions testing strategies.

THE ROLE OF EXCAVATORS IN CONSTRUCTION AND THEIR EMISSIONS

On the basis of results obtained using EPA's NONROAD model, excavators are estimated to contribute 11% of NO_x, 7.4% of carbon monoxide (CO), and 8.6% of coarse particulate matter (PM_{10}) emissions produced by construction equipment in 2005.[31] In 2005, there were an estimated 139,000 diesel excavators, according to the NONROAD model's engine population estimates. Excavators are powered by diesel engines ranging from 17 to 2,000 hp; however, 87% of all excavators are in the range of 50–600 hp.[32]

Excavators consist of three major components: (1) a carrier, which provides mobility and stability for the equipment; (2) a revolving deck, which contains the power and control units; and (3) a front-end attachment, which serves various operational functions, known as the "bucket." The bucket can be used to dig, but also to lift and transport heavy objects such as riprap. Excavators can lift equipment such as generators or mixers, typically using chains or belts attached to a hook on the underside of the bucket. Excavators are classified as either track- or wheel-type. Unless the application calls for significant travel to, from, and around the construction site, a track-type of excavator is preferred and is currently more common.[33,34]

Various factors that affect the emissions produced by excavator engines include the vehicle weight, duty cycle, and the terrain traveled (which, in turn, affects engine power demand), age, and ambient conditions. In addition, engine controls such as injection timing strategies can affect emissions.[35,36] In recent years, EPA has set Tier 1–Tier 4 emission standards for engines used in most construction vehicles. Tiers 1–3 have been phased-in from 1996 to 2006 and are met through advanced engine design with no use of exhaust gas aftertreatment. The most stringent of these standards, Tier 4, are to be phased-in during 2008–2015. The Tier 4 standards require that emissions of PM and NO_x be further reduced by approximately 50 and 90%, respectively, compared with the current Tier 3 emission standard. Compliance with the Tier 4 standards is expected to require the use of aftertreatment control technologies.[37,38] However, because nonroad vehicles often remain in service for 10 yr or more, total nonroad emissions will continue to be influenced by pre-Tier and low-Tier vehicles for some time.[39]

COMPARISON OF EMISSIONS MEASUREMENT METHODS

Current approaches for estimating construction equipment emissions are based upon testing only the engine, not the entire chassis, on an engine dynamometer and estimating average emissions for a weighted combination of steady-state modes.[40,41] A mode involves operation of the engine at a specified constant engine speed and/or load. The most common test procedures, such as the 8-, 13-, and 21-mode tests, involve multiple modes. EPA has primarily used data from the 8-mode test, known as ISO-C1, as the basis for the NONROAD model. For this test procedure, the engine is run at rated revolutions per minute (rpm) for four levels of torque (100, 75, 50, and 10% of maximum torque), at an intermediate rpm level while similarly varying the percent of maximum torque, and once at idle.[40]

To improve the representativeness of engine dynamometer tests, EPA and the Engine Manufacturers Association have jointly developed some nonregulatory transient test cycles for agricultural tractors, backhoe loaders, crawlers, tractors, excavators, arc welders, skid steer loaders, and wheeled loaders.[11,42] However, these cycles are not yet used as the basis for the NONROAD model and there are no reported plans to use such cycles.

On-board emission measurement enables data collection under real-world in-use conditions at a job site.[43,44] In-use data collection captures the effects of the chassis (e.g., vehicle weight) and actual duty cycle. However, because in-use measurement is essentially an observational, rather than controlled, experiment, there can be more variability in results from one test to another.

METHODOLOGY

The methodology includes: (1) study design, (2) instrumentation, (3) installation of instrumentation, (4) field data collection, (5) data quality assurance, and (6) data analysis.

Study Design

The design of on-board in-use data collection for excavators is subject to controllable and uncontrollable factors. The controllable factors include scheduling and, in principle, also include the choice of vehicle, duty cycle, and site. However, the latter factors require cooperation from vehicle operators. Access to a vehicle, its duty cycle, and the site of data collection depended on the work schedule of the contractor and their willingness to allow their vehicle to be instrumented and observed. Uncontrollable factors include ambient conditions and operator behavior. The data were collected during normal duty cycles.

The characteristics of the three excavators that were tested are given in Table 1. These excavators range from 93 to 254 hp, corresponding to NONROAD model engine size categories of 76–100 hp, 101–175 hp, and 176–300 hp. These three categories represent 77% of the estimated number of excavators in the United States. Although the engines have different model years, they were all produced under the same Tier 1 emission standard.

Data were collected at two sites and each site included flat and hilly terrain. The soil at both sites was mostly muddy. All three excavators performed similar tasks, including excavating dirt and lifting heavy objects. Excavator 1 was used at site 1 to transport foundation casting frames and excavate in preparation for a building foundation. Excavator 2 was used at site 2 to install constructed riffles, which are stone structures used as velocity dissipaters in stream beds to help prevent erosion and scour of embankments. Excavator 3 was used at site 2 for loading dump trucks at two locations over the site.

PEMS

The PEMS used here is the Montana Universal System manufactured by CATI.[24,45,46] The system is comprised of two identical five-gas analyzers, a particulate matter (PM) measurement device, an engine diagnostic scanner or sensor array (both are available, but only the sensor array is used here), a global positioning system (GPS), and an on-board computer. All data were recorded on a second-by-second basis. A schematic of the interface of the PEMS with the vehicle is given in Figure 1. The main unit of the PEMS is the size of a carry-on suitcase and weights approximately 35 lb.

Each of the five-gas analyzers measures exhaust gas concentrations of hydrocarbons (HCs), CO, and carbon dioxide (CO_2) using nondispersive infrared (NDIR); concentrations of nitric oxide (NO) and oxygen (O_2) were measured using electrochemical sensors. PM concentrations were estimated based on light scattering, and thus are approximately comparable to an opacity type of measurement. Water vapor is separated from the sample before the sample enters the electrochemical cells and NDIR chambers.

Although many newer model construction vehicles have an electronic control unit (ECU) with an engine diagnostic link, unlike light-duty gasoline vehicles these interfaces are not standardized. The software needed to decode ECU data, when available, is proprietary. The

Table 1. Characteristics, emission test, and construction site information for the selected excavators.

Characteristics	Excavator 1	Excavator 2	Excavator 3
Chassis			
Size	Small	Medium	Large
Manufacturer	Kobelco	Caterpillar	Komatsu
Model	SK130	320C	PC300-7
Year	1998	2002	2001
Engine			
Rated horsepower (hp)	93	138	254
ES at rated horsepower (rpm)	2200	1900	1900
Displacement (L)	3.9	6.37	8.27
Number of cylinders	4	6	6
Fuel type	Diesel	Diesel	Diesel
Emission standard	Tier 1	Tier 1	Tier 1
Construction site			
Location	Site 1: NCSU campus, Western Boulevard	Site 2: NCSU campus, Cates Avenue	Site 2: NCSU campus, Cates Avenue
Terrain	Flat/hill[a]	Flat/hill	Flat/hill
Soil condition	Muddy	Muddy/rock	Muddy
Activity	Carrying heavy objects/digging	Moving ripraps/digging	Carrying heavy objects/ digging
Data collection summary			
Date of data collection	January 16, 2006	November 2, 2005	August 24–26, 2005
Seconds of raw data (sec)	22,515	23,593	53,487
Ambient temperature (°F)	31–62 (average 47)	40–68 (average 54)	65–85 (average 75)
Relative humidity (%)	20–72 (average 46)	26–96 (average 61)	46–94 (average 70)
Barometric pressure (in. Hg)	29.85–30.00 (average 29.90)	30.00–30.30 (average 30.12)	30.07–30.20 (average 30.14)

Notes: [a]The site area includes both hilly and flat terrain. NCSU = North Carolina State University.

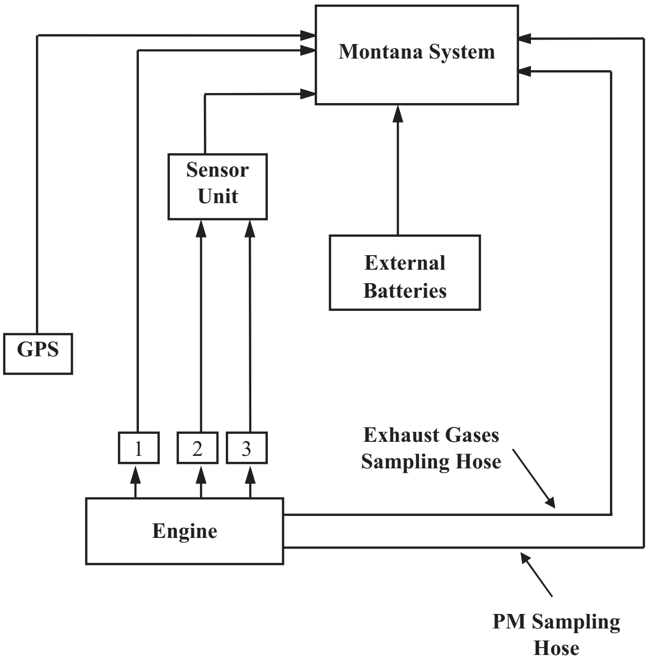

Figure 1. Conceptual diagram for installation of PEMS on nonroad construction equipment. The sensor array comprises: (1) the MAP sensor, connected directly to the Montana System main unit; (2) the ES sensor connected to a sensor unit; (3) the IAT sensor connected to a sensor unit; and (4) a sensor unit that is connected to the Montana System main unit.

sensor array can be used with any make or model of vehicle and therefore provided flexibility. The sensor array included sensors that are temporarily installed on an engine compartment for measuring engine speed (ES), intake air temperature (IAT), and manifold absolute pressure (MAP). No modification to the engine was needed.

On the basis of the engine data, exhaust concentration data for CO_2, engine displacement, and an estimate of the engine volumetric efficiency, the mass exhaust flow rate was calculated on a second-by-second basis.[44]

The system operates on 13 V dc power. To avoid imposing a power load on the vehicle, two batteries independent of the vehicle were used as a power supply.

CATI conducted studies to compare the PEMS with dynamometer measurements at the New York Department of Environmental Conservation (NYDEC) and EPA's National Fuel and Vehicle Emissions Laboratory in Ann Arbor.[25] The coefficient of determination (R^2) values for comparisons of cycle total emissions for the Montana system versus the dynamometer were in the range of 0.90–0.99, which indicates good precision. Furthermore, the slopes of the parity plots of cycle total emissions for a given pollutant were not significantly different from those for CO_2, CO, and NO, indicating good accuracy. For HC, it is well known that NDIR responds accurately to short-chain alkenes but has less than full response for other types of compounds (e.g., alkenes, aromatics, and others).[47] Therefore, the total response of the HC measurement is typically approximately 50% of the total actual HC levels in the exhaust. PM is measured using light scattering, with measurements ranging from ambient levels to low double-digit opacity. The PM measurements are semiquantitative. To clarify that the measurements are not intended to represent accurate mass emission rates, the term "opacity" is used rather than "PM."

The fuel consumption levels reported by the Montana system have been verified based on measurements for 12 dump trucks that were tested for one day each on petroleum diesel fuel and one day each on B20 biodiesel fuel.[48] When comparing the measured to actual fuel consumption for each of the 24 days of testing, the R^2 was 0.999 and the slope of the parity plot was 0.996. Thus, the fuel consumption data were deemed to be of good precision and accuracy.

The Montana system was calibrated before each test using a span gas mixture containing 200 ppm propane (C_3H_8), 0.5 vol % CO, 6 vol % CO_2, and 300 ppm NO.[24] The Montana system performs zero calibration automatically every 10 min. Zero calibration involves using ambient air as a reference to prevent drift of the signal.

Installation of PEMS

A procedure for field data collection was developed taking into account four key factors: (1) applicability to any vehicle and site, (2) avoidance of disruption of the normal operation of the vehicle, (3) placement of the PEMS so as to avoid limiting the operational performance of the vehicle, and (4) installation of the PEMS system so as to avoid damage during data collection.

On the basis of these considerations, the field data collection procedure was divided into steps of preinstallation, installation, data collection, and decommissioning. The PEMS components that are time consuming to install are preinstalled on the vehicle during off-hours the afternoon or evening before data collection. The final installation occurs early the morning of data collection for the more expensive and sensitive system components.

Preinstallation includes placement of the engine sensors, sensor unit, exhaust sampling probes and hoses, external batteries, and a safety cage. The latter was fabricated for the purpose of protecting the main unit of the Montana system from damage. Installation includes securing the main unit of the Montana system inside the safety cage, mounting the GPS system on the chassis, and connecting cables routed from the sensors and hoses from the tailpipe to the main unit of the Montana system.

Placement of the ES and MAP sensors was the most challenging aspect of preinstallation. The ES sensor must be secured to a stationary metal object that allows an unobstructed view of reflective tape attached to the flat section of the harmonic balancer. The MAP sensor must be connected to an existing boost pressure port located between the turbocharger and the engine intake manifold. Proper functioning of the sensors was verified during preinstallation by temporarily connecting them to the Montana system main unit and observing that the measured values were within valid ranges (e.g., ES between ~600 and 2000 rpm; MAP between ~101 and 300 kPa). Exhaust sample probes were secured to the exhaust pipe using radiator pipe clamps. Cables and hoses were routed to the location of the safety cage using plastic ties placed at strategic points along their path, so that they did not come loose during vehicle operation.

The safety cage was secured to the roof or hood of the vehicle using heavy-duty adjustable cargo straps. For excavator 1, the safety cage was mounted on the cab roof. For excavators 2 and 3, the cage was mounted on a flat area of the engine hood. Before installation of the main unit, rubber and foam pads were placed in the safety cage to as to reduce transmission of vibration from the vehicle. Furthermore, the main unit was shielded from direct sunlight by a tarp secured over the top of the cage. Air was allowed to flow through the sides of the safety cage.

The main unit was warmed up for 30–45 min before data collection. Installation was scheduled to be finished before the excavator was needed for its normal duty cycle. On average, preinstallation required two people and took about 2.5 hr, whereas installation also required two people and took about 1.5 hr. The time-consuming aspects of installation include installing the sensor array and warming up the instrument. The consumables include replacement sensors for NO and O_2, filters, and calibration gas.

Field Data Collection

Data collection was comprised of two main activities. The first was monitoring the operation of the PEMS and the second was recording additional data regarding site conditions and vehicle modes of operation.

During data collection, the status of the PEMS was periodically monitored by checking the screen of the main unit during operator work breaks. The objectives of this action were to make sure that the sensor array is properly communicating with the computer of the Montana system and both analyzers are properly measuring exhaust gas.

Site conditions were recorded on a standard form. An example of the vehicle activity at the site was recorded for approximately 15 min using a camcorder so that there was a visual record of the site conditions and the typical vehicle activity. A research assistant who was observing the vehicle from a safe distance recorded the timing of specific modes of operation using a laptop computer. The modes of operation, also referred to as task-oriented modes, are activities that the equipment routinely performs to accomplish a specific task. For the excavators tested, the task-oriented modes include idling, moving, and using the bucket. Moving refers to lateral transport of the excavator from one location to another at the site. Using the bucket refers to any activity in which the bucket was lowered, filled, raised, or emptied. The bucket was also used to lift heavy equipment and objects.

Data Quality Assurance

The goal of quality assurance was to develop a database that contains valid data. The procedure included identification of whether any errors or problems exist in the data, correction of such errors or problems when possible, and removal of invalid data if errors or problems cannot be corrected.

The types of errors or problems that may be encountered include data flagged as "invalid" by the Montana system, missing MAP values, unusual ES, unusual IAT, interanalyzer discrepancy, zero calibration procedure of the Montana system, negative values of pollutant concentrations, leakage in the exhaust gas sampling system, gas analyzer freezing, and incorrect synchronization of engine and emissions data. "Freezing" refers to a situation in which there is no reported change in emission concentrations for a period of several seconds while engine data are changing. Criteria for detecting and correcting errors associated with missing MAP values, unusual IAT, and synchronization of engine and emissions data are briefly explained. For the other errors and problems, procedures developed previously were used.[45,48,49]

On occasion, communication between the sensor array and Montana system might have been lost, leading to loss of MAP data. In this case, an error code of −34 was reported in the data file. Typically, when a MAP value was missing, other simultaneously measured data, such as engine rpm and pollutant concentrations, were valid. Missing MAP data were imputed when the absolute relative difference (ARD) between MAP values that occurred before and after missing values was less than 5%. After estimating missing MAP values, emission rates were recalculated. MAP data were missing for 3.9% of the 23,893 sec of data for excavator 3. However, this error was not observed for excavators 1 and 2.

IAT should be greater than ambient temperature and typically changes gradually over time. On the basis of previous field data collection, when the absolute difference of IAT values between two consecutive seconds is greater than 1 °F, there may be some problems with the IAT sensor. IAT was checked for all seconds of data and no unusual values or rapid changes were found for any excavator.

Synchronization of engine and emissions data was evaluated after other quality checks were completed. For this purpose, segments of second-by-second data were selected in which ES changed by greater than 200 rpm in one second and by greater than 500 rpm for a short-term event that may have occurred over several seconds. Temporal trends of CO_2 and CO concentrations were compared with the change in engine rpm. On the basis of analysis of time traces, the concentrations of CO_2 and CO were found to be more responsive to changes in ES than for other pollutants. The time difference between the corresponding initial rise (or initial decrease) in ES versus the corresponding change in CO_2 concentration, CO concentration, or both, is referred to as synchronization time (T_{synch}). If T_{synch} is not zero, then the engine data must be shifted earlier or later compared with gas analyzer data and the second-by-second emission rates must be recalculated using the proper pairing of engine and concentration data. For each of the test excavators, the raw emissions data reported by the PEMS were found to be 1 sec earlier than engine data. This error was corrected for all data files.

A high proportion (i.e., 91%) of measurement attempts resulted in valid vehicle activity and emission files for excavators 2 and 3. However, for excavator 1, for which vehicle vibrations were more severe, only 82.5% of the data were valid because several times there was a loss of power to the Montana system. For all excavators, interanalyzer discrepancy and analyzer freezing were the most frequent errors observed. To reduce the effects of these errors, the NDIR of both analyzers should be cleaned before the test and efforts should be made to reduce the transmission of vibration transferred to the Montana system, such as through the use of foam pads around the system.

The screened and quality-assured data files include: (1) time stamps for each second; (2) measured values of engine rpm, IAT, MAP, and pollutant concentrations; (3) estimated rates of intake air mass flow, exhaust gas mass flow, fuel consumption, and emissions; (4) GPS data; and (5) modes of operation recorded separately and combined with the PEMS data file.

RESULTS

The results include: (1) benchmark comparison of measured emissions rates of the excavators to estimates based on the NONROAD model, (2) exploratory analysis of variation in emission rates with respect to engine variables, (3) characterization of the effect of microscale events (e.g., short-term events such as use of the bucket) during real-world operation on real-world emission rates, and (4) quantification of variability in fuel consumption and emission rates with respect to variability in duty cycles.

Comparison of Measured and Modeled Emission Rates

The average emission rates obtained from measurements using PEMS are compared with estimates obtained using the NONROAD model to assess similarities and for benchmarking purposes. The comparisons were done on a mass of pollutant per unit of fuel consumed basis. Because the NONROAD models report emission factors in units of g/bhp·hr, a brake-specific fuel consumption (BSFC) rate of 0.367 lb/bhp·hr was used for conversion.[41] To correspond as closely as possible to the tested excavators, NONROAD model results were obtained for excavators for the closest matching model years and engine size ranges. The results of the comparison are given in Table 2.

The average emission rates for NO based on the PEMS measurements ranged from 77 to 110 g/gal versus values of approximately 97.6–106 g/gal estimated from the NONROAD model. These numbers agree well in terms of magnitude and also imply substantial similarity in fuel-based NO emission rates for different vehicles. The PEMS data are based on NO (reported as equivalent nitrogen dioxide [NO_2]) whereas the NONROAD estimates include both NO and NO_2. The substantial agreement is not surprising because for diesel vehicles without postcombustion controls, total NO_x is typically approximately 90–95% NO, with the balance NO_2.[50]

For excavators 1 and 3, the magnitudes of the average HC emission rates agreed to within 40% for both the PEMS and NONROAD-based estimates. The difference in the estimates for excavator 2 was approximately 25%.

The average CO emission rates agreed to within 25% for the PEMS and NONROAD-based estimates for excavators 1 and 3. The average difference was 60% for excavator 2.

The PEMS-based averages of inferred PM concentration based on the light-scattering (opacity) measurement were within an order of magnitude of the estimates from the NONROAD model, but the latter are consistently larger than the former. Thus, the opacity data from the PEMS are not likely to be useful for estimating the magnitude of total PM emissions, but might be useful for assessing relative differences among vehicles (or among modes for a given vehicle).

Exploratory Analysis

Exploratory analysis was conducted to quantify the intravehicle variability of emissions and identify trends with respect to engine variables. The strength of the linear relationship between either fuel use or emission rates to each explanatory variable is reported in Table 3. Fuel use and emission rates typically have a stronger linear association with MAP compared with the other engine variables. There was relatively weak relationship between emissions rates and IAT. ES had high correlation with MAP based on R^2 values ranging from 0.67 to 0.75 among the excavators.

NO emission rates were strongly correlated with fuel use rate, with coefficient of determination (R^2) values ranging from 0.91 to 0.97. The relationship between each of HC, CO, and PM emission rates with respect to fuel consumption rate was much weaker, with an average R^2 value 0.14.

Table 2. Comparison of average normalized emissions rates for selected excavators based on on-board data vs. estimates from EPA's NONROAD model.

Vehicle	Emission Estimation Method	Pollutants: NO (g/gal)	HC (g/gal)	CO (g/gal)	Opacity-Based PM (g/gal)
Excavator 1	PEMS[a]	108	4.5	12.8	1.14
	NONROAD[b]	97.6	9.09	17.3	8.11
Excavator 2	PEMS	77	8.9	31.0	0.73
	NONROAD	106	6.78	19.2	5.53
Excavator 3	PEMS	110	10.2	14.1	0.79
	NONROAD	105	6.01	14.2	5.09

Notes: [a]PEMS: the average emission rates estimated by data measured by the PEMS; [b]NONROAD: the average emission rates estimated using the NONROAD model. Because the NONROAD models reports emission factors in units of g/bhp·hr, a BSFC rate of 0.367 lb/bhp·hr was used for conversion. To correspond as closely as possible to the tested excavators, NONROAD model results were obtained for excavators for specific model years and engine size ranges.

Table 3. Coefficients of determination (R^2) of ordinary least square regression of second-by-second emission and fuel consumption rates vs. individual engine variables.[a]

Excavator	Emission Rate (g/sec)	R^2 MAP (kPa)	ES (rpm)	IAT (°C)
1	NO	0.62	0.55	0.16
	HC	0.16	0.17	0.11
	CO	0.20	0.50	0.06
	CO_2	0.61	0.58	0.13
	Opacity-based PM[b]	0.20	0.18	0.13
	Fuel	0.61	0.58	0.13
2	NO	0.52	0.57	0.20
	HC	0.31	0.36	0.10
	CO	0.20	0.31	0.08
	CO_2	0.49	0.50	0.16
	Opacity-based PM	0.39	0.32	0.10
	Fuel	0.49	0.50	0.16
3	NO	0.46	0.31	0.19
	HC	0.43	0.52	0.30
	CO	0.49	0.68	0.30
	CO_2	0.49	0.37	0.18
	Opacity-based PM	0.57	0.33	0.15
	Fuel	0.49	0.37	0.18

Notes: [a]R^2 values are based on univariate regressions as follows: for MAP, fuel or emission rate = constant + slope (MAP) on a second-by-second basis. Similarly, ES and IAT are used as explanatory variables in univariate linear regression models. All of the [a]R^2 values are statistically significant at a 0.05 significance level; [b]The term "opacity-based PM" is used here rather than PM because PM is detected using a light-scattering method, which is a semiquantitative approach for characterizing the particle loading in the exhaust.

Microscale Activity and Emissions

To characterize episodic nature of microscale events during a duty cycle and to gain insight into the temporal variation in vehicle activity, fuel use, and emissions, an example for excavator 1 of a time trace of ES, MAP, fuel use rate, and emission rates for selected pollutants is given in Figure 2.

For the example, the excavator performs two cycles of operation that include idle, moving, and use of the bucket. The temporal profiles of ES are similar each time the bucket is used, which occurs between 0 and 3.5 elapsed minutes and between 7.5 and 11 elapsed minutes. During these times, ES varies between approximately 960 and 2150 rpm. Likewise, the ES profile is similar for the two time periods when the excavator is moving.

Most of the large peaks in fuel consumption and emissions rates, on a mass per time basis, coincided with peaks in ES and MAP. For example, at an elapsed time of approximately 1.8 min, engine rpm increased from approximately 1500 to 2000. MAP increased simultaneously. Fuel use increased from approximately 2.3 to 3.8 g/sec, and the NO emission rate increased from 0.07 to 0.11 g/sec. On average, 99.8% of the carbon in the fuel is emitted as CO_2. Therefore, CO_2 emissions are a good surrogate for fuel consumption.

For NO, 50% of the total emissions were produced in 29, 23, and 32% of the total duty cycle for excavators 1, 2, and 3, respectively. In 50% of the duty cycle time, these excavators produced between 78 and 81% of the total NO. The average ES and MAP values for episodes that contributed disproportionately (with respect to time) to the total emissions were higher compared with the average values for the observed duty cycles. Thus, short-term episodes can substantially affect average emissions.

Task-Oriented Modes

PEMS data were analyzed with respect to task-oriented modes. The purpose of this analysis was to explore variability in emissions with respect to variability in modes of operation.

For excavators, idling is comprised of four submodes that include low idle, high idle, and two transients, as illustrated in Figure 3 for excavator 2. In low idle, the engine runs at 900 rpm or less. Before the operator is ready to start using the bucket, the operator uses the ES control unit to manually increase the engine idle speed to a high idle, at approximately 1000–1100 rpm. The two types of idles, as well as the transitions between low and high idle, and between high idle and use of the bucket, are assessed individually with respect to their effect on fuel use and emissions.

A comparison of the average modal rates for fuel consumption and each of the five pollutants is shown in Figure 4. Typically, for a given quantity, the rate for low idle was the lowest; high idle had a higher rate than low idle. The transient (1) mode had comparable or higher rates than high idle in most cases. The transient (2) mode was highly variable among the vehicles. For excavator 1, transient (2) had average rates comparable to the other idling modes, whereas for excavator 2 and, especially, excavator 3, these rates are typically significantly higher. The bucket and moving modes tend to have similar average rates compared with each other for a given quantity and vehicle. In most cases, the bucket and moving modes have higher average rates than the transient (2) mode. Overall, it appears that there is not much benefit to separately quantifying the bucket and moving modes, because their rates are similar. Thus, these two modes can be combined into one "non-idle" mode.

The task-oriented modes were also analyzed on the basis of mass of emissions per gallons of fuel consumed. NO and HC emission rates per gallon of fuel consumed were highest for idling for all of the excavators and were approximately similar when comparing the bucket and moving modes.

To evaluate the relative importance of each of the operation modes, the distributions by mode of total time, fuel consumption, and emissions are given in Figure 5. On average, all idle and transient modes accounted for 12% of time, but only 2% of fuel consumption. The distribution of pollutants by mode was approximately similar to that of the distribution of fuel use, except for HC and CO, for which there was typically a larger proportional contribution from the idling modes.

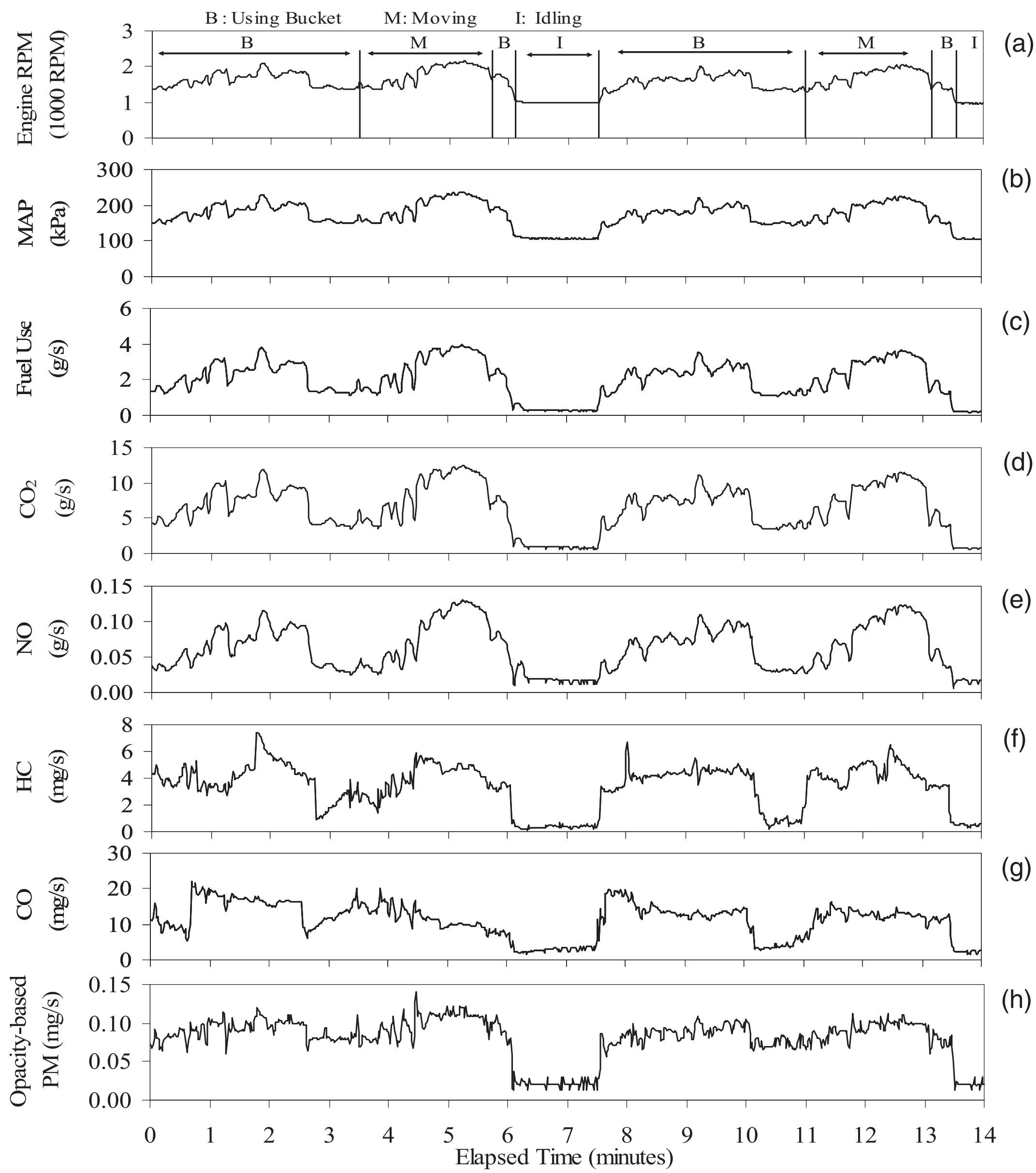

Figure 2. Example time traces for (a) engine rpm, (b) MAP, (c) fuel use, (d) CO_2, (e) NO, (f) HC, (g) CO, and (h) opacity-based PM for excavator 1 tested on January 16, 2006.

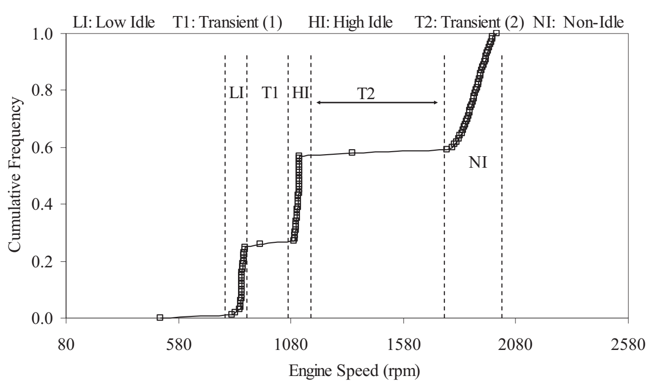

Figure 3. Cumulative distribution function of the frequency of ES data for excavator 2, with modes of operation indicated.

Engine-Based Modes

An engine-based modal analysis was performed. One purpose of this analysis was to determine whether there are consistent trends in the relationship between fuel consumption or emissions rates and engine activity. Because these rates were highly correlated with MAP, modes were defined based on MAP ranges. To enable comparisons between vehicles, all second-by-second MAP values were normalized based on maximum and minimum observed values for each vehicle. Fuel consumption and emission rates were normalized with respect to their observed maximum values. Table 4 presents modal average values of normalized MAP and normalized NO emission rates for each excavator. These normalized modal average rates increased monotonically with MAP from modes 1 to 10 for each vehicle.

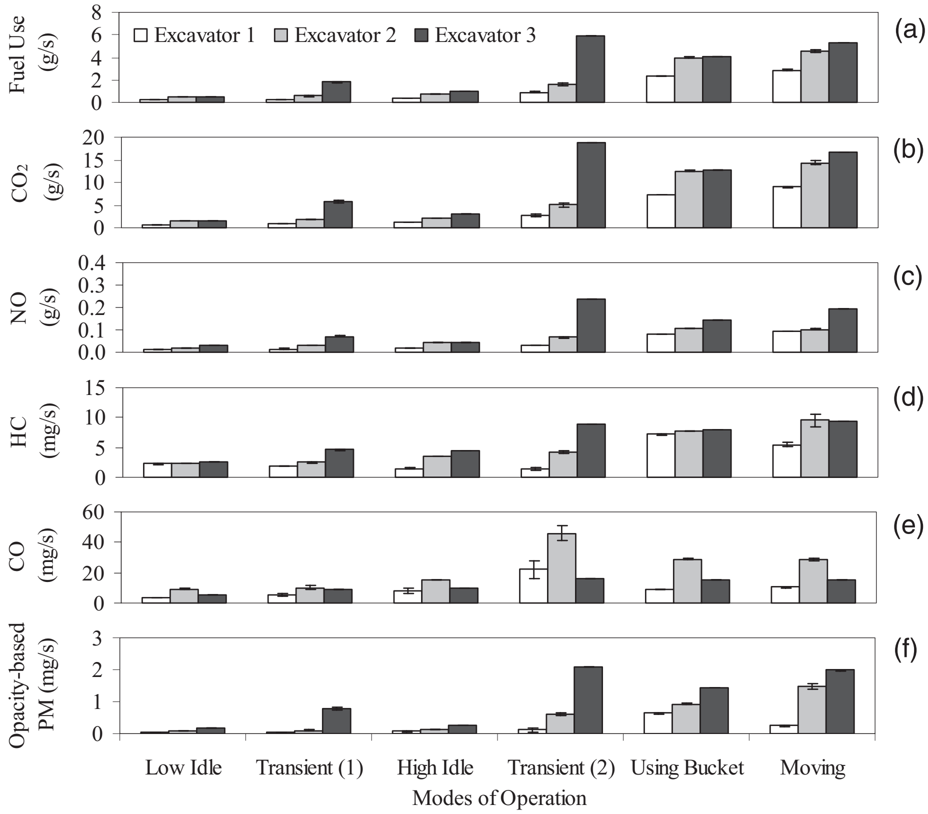

Figure 4. Comparison of average mass per time fuel use and emission rates along with 95% confidence intervals of mean values for task-oriented modes for (a) fuel use, (b) CO_2, (c) NO, (d) HC, (e) CO, and (f) opacity-based PM.

Figure 6 presents an example of results of average modal rates for fuel consumption and emissions on a mass per time basis, and for emission rates on a fuel basis. With only minor exceptions for HC and CO, the modal mass per time rates increased monotonically with MAP, and the lowest rates were associated with engine idling in the lowest MAP range.

In contrast, the emissions per gallon of fuel consumed were highest at idle for NO, HC, and CO. For higher values of MAP, the fuel-based emission rates of these pollutants were approximately constant.

Duty Cycles

The effect of differences in duty cycles on average emission rate is explored here. The excavators performed repetitive operations. A unit of productivity for excavators 1 and 3 was cubic yards of dirt removed or dumped and for excavator 2 was the cubic yard of riprap installed. A duty cycle can be subdivided into either task-oriented or engine-based modes.

To illustrate the spatial aspects of duty cycles, maps of excavator locations for each second of operation for two examples are shown in Figure 7 on the basis of GPS data. Excavator 1 traveled more extensively around the site than did excavator 2.

The duty cycles were compared in terms of the cumulative distribution function of second-by-second MAP values for the engines of each of the three excavators, as shown in Figure 8. MAP fluctuated with the throttle position and the engine load.[50] Excavator 1 spent a higher proportion (nearly 85%) of time in the higher engine load mode (i.e., using bucket) than the other two (see Figure 5), and thus had a higher average MAP than the other excavators. In contrast, excavators 2 and 3 had duty cycles that were similar to each other, particularly for the nonidle modes, as indicated by similar frequency distributions of MAP for values greater than 117 kPa. However, all of the duty cycles were significantly different from each other.

To evaluate the effect of duty cycle on average emission rate for a given vehicle, three duty cycles were compared for each of the three excavators. The duty cycles were characterized based on the CDFs of normalized MAP observed on a given day of data collection with a given vehicle. For a given duty cycle (e.g., from site 1 on January 16, 2006), the percentage of time in each mode was estimated for each of the three vehicles separately, using normalized modal MAP cutoff values in each mode, as shown for NO emissions in Table 4. The average emission rate for the cycle was estimated based upon the time-weighted average of the normalized modal emission rates. The results are given in Table 5.

For a given vehicle, the average normalized fuel use and emission rates varied substantially when comparing engine duty cycles 2 and 3, with the exception of CO. For example, the normalized average fuel consumption rate for excavator 2 was 0.53 and 0.33 for these two cycles, respectively. On average, there was a 63% reduction

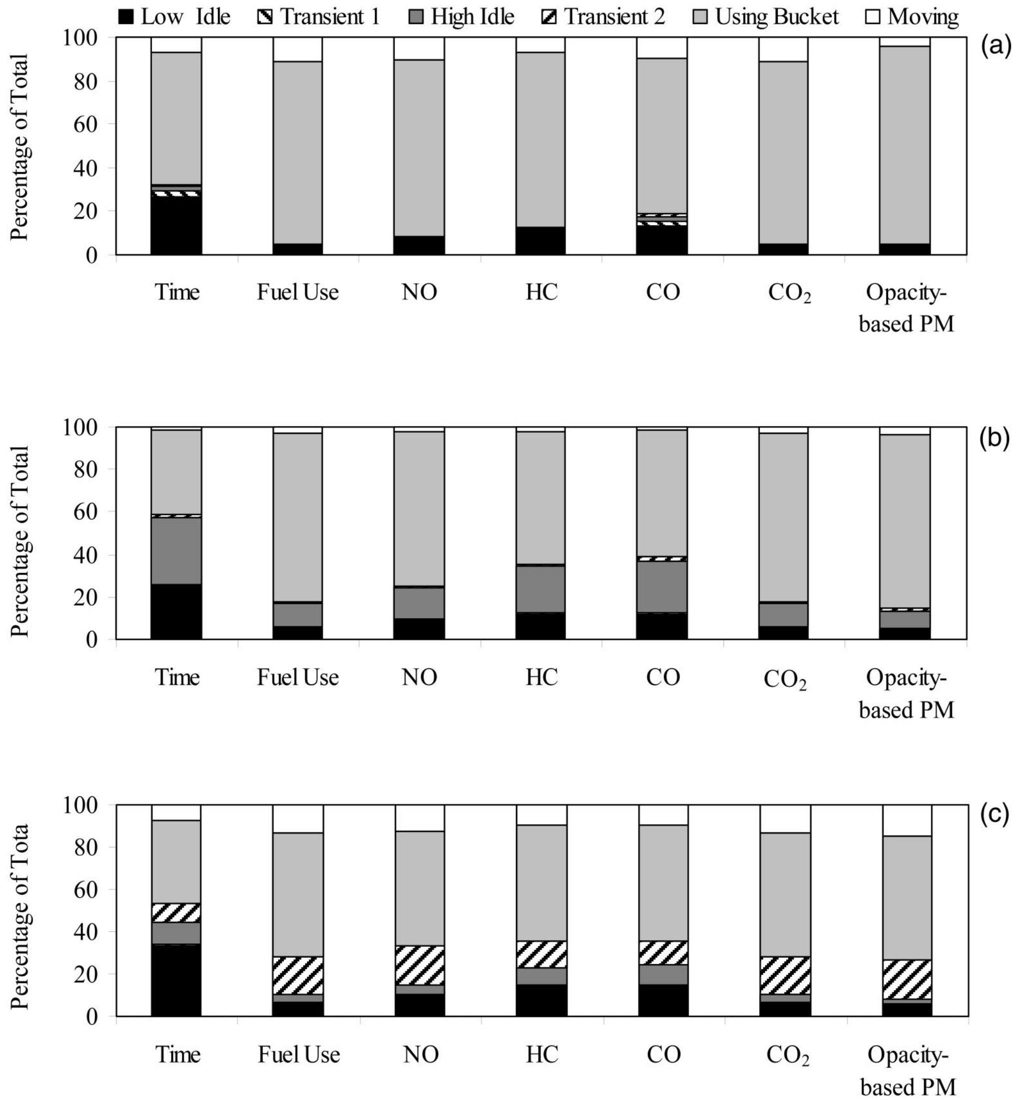

Figure 5. Distribution of task-oriented modes with respect to (a) total operation time, (b) fuel use, and (c) emissions for the test excavators.

(except for CO) in normalized fuel consumption and emissions rates when comparing these two cycles. However, engine duty cycles 1 and 2 are similar to each other, and the average normalized rates for a given vehicle and quantity differ by less than 0.06 in most cases when comparing these two cycles. On average, there is 2.5% increase (except for CO) in normalized fuel use and emissions rates when comparing these two cycles.

For a given duty cycle, the average normalized rates were similar when comparing different vehicles. For example, the average normalized NO emission rate had a range of only 0.34–0.45 for duty cycle 3. The normalized intervehicle differences for a given duty cycle and quantity were less than or equal to 0.035 in all cases (except for CO), corresponding to relative differences of approximately 8%.

Overall, for the examples given here, there were larger differences in normalized average emission rates because of intercycle differences than because of intervehicle differences.

CONCLUSIONS

The key lessons learned from development of procedures for real-world data collection on nonroad vehicles were the critical need to properly secure the PEMS and protect it from vibration, and the need to avoid interference with the operator's normal work schedule and tasks. The implementation of a standardized procedure for data collection and quality assurance produced valid data for approximately 90% of the attempted data collection effort. Lessons learned from identification of key sources of data quality assurance problems can be used to improve the data collection procedure.

The results of the PEMS data were evaluated based on a comparison of the average emission rates estimated from PEMS data to estimates inferred from the NONROAD model. Because the NONROAD model is based on different data collected under different conditions from the PEMS field data, the estimates are not expected to agree strongly. Nonetheless, the PEMS-based emission factors are of similar magnitude and thus are approximately comparable to those

Table 4. Modal values of average normalized MAP, average normalized NO emission rate, and fraction of time for each excavator.

Mode Based on Normalized MAP	Excavator 1 Average Normalized MAP[a]	Excavator 1 Average Normalized NO[b]	Excavator 1 Fraction of Time (%)	Excavator 2 Average Normalized MAP	Excavator 2 Average Normalized NO	Excavator 2 Fraction of Time (%)	Excavator 3 Average Normalized MAP	Excavator 3 Average Normalized NO	Excavator 3 Fraction of Time (%)
0.000–0.100	0.045	0.129	13.3	0.019	0.144	12.4	0.020	0.094	13.6
0.110–0.200	0.163	0.225	0.4	0.255	0.359	4.5	0.159	0.201	26.5
0.210–0.300	0.279	0.274	4.3	0.461	0.453	13.8	0.253	0.313	19.9
0.310–0.400	0.362	0.392	9.4	0.657	0.534	13.6	0.358	0.402	13.7
0.410–0.500	0.464	0.548	14.0	0.863	0.595	14.4	0.461	0.491	9.2
0.510–0.600	0.562	0.634	21.4	0.160	0.653	10.8	0.559	0.580	8.1
0.610–0.700	0.659	0.707	17.4	0.453	0.710	9.9	0.649	0.655	4.9
0.710–0.800	0.754	0.773	12.0	0.595	0.755	8.6	0.756	0.699	3.0
0.810–0.900	0.853	0.848	7.1	0.710	0.818	8.8	0.839	0.815	1.0
0.910–1.00	0.932	0.925	0.7	0.818	0.849	3.2	0.946	0.967	0.1

Notes: [a]For a given excavator, MAP values were normalized based on $(MAP_i - MAP_{min})/(MAP_{max} - MAP_{min})$, where MAP_{min} is the observed minimum value, MAP_{max} is the observed maximum, and MAP_i is the measured value in a given second. These values are determined based on all second-by-second data for an individual excavator; [b]For a given excavator NO emission rates were normalized with respect to the observed maximum value. The average modal emission rates were significantly different from each other when comparing pairwise combinations of modes for a given excavator.

from the NONROAD model, while enabling more detailed insight regarding the relationship between emissions, transient episodes during duty cycles, and averages for different duty cycles.

Fuel use and emissions rates of excavators are episodic, with relative short periods of time contributing disproportionately to total fuel consumption and emissions. The microscale trends in fuel use and emission rates

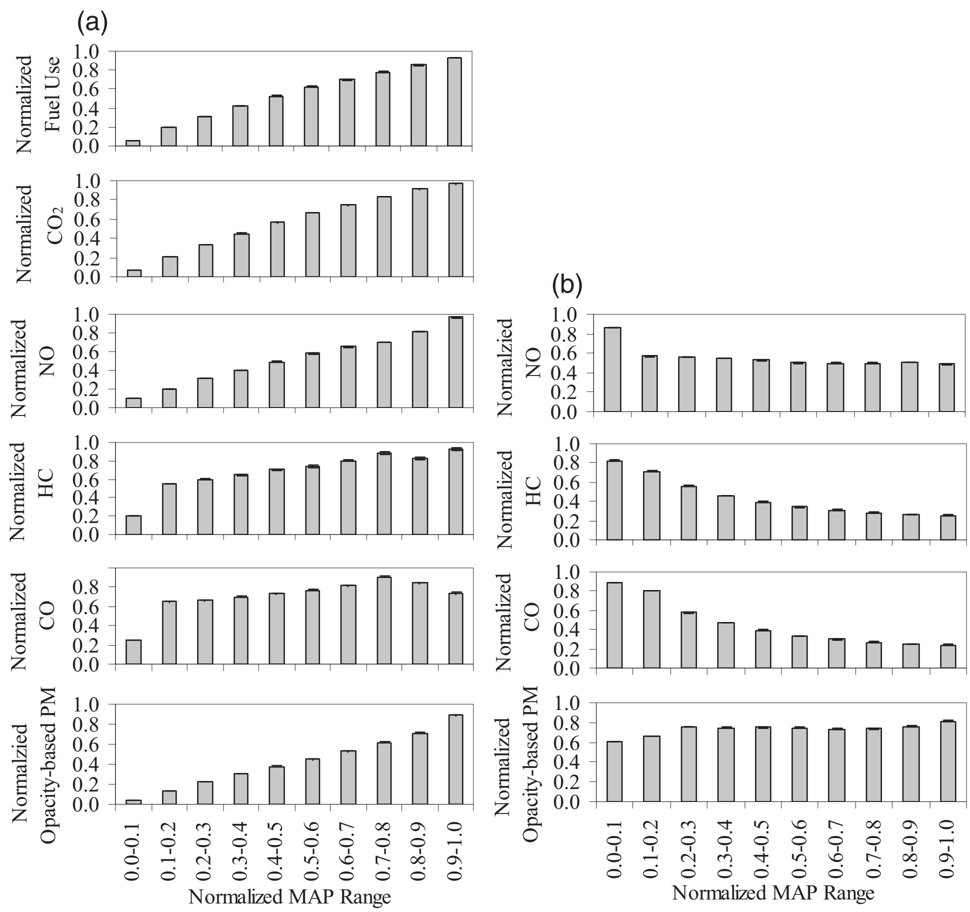

Figure 6. (a) Average modal normalized fuel consumption and mass emission rates, and (b) average emissions per gallon of fuel consumed for engine-based modes for excavator 3.

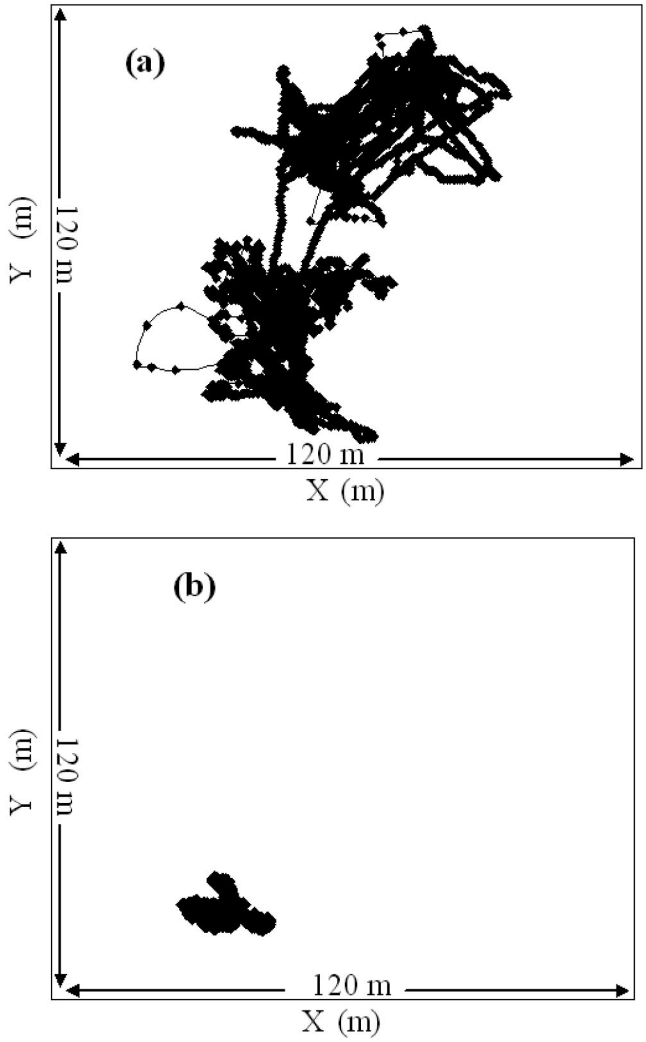

Figure 7. Examples of spatial patterns associated with duty cycles based on GPS data: (a) excavator 1 at site 1 transported foundation casting frames at a site near Western Boulevard on the North Carolina State University campus, (b) excavator 2 at site 2 installed constructed riffles at a site near Cates Avenue on the North Carolina State University campus.

were highly correlated with engine MAP, which is a practical although not perfect surrogate for engine load. Because consistent trends were identified for fuel use and

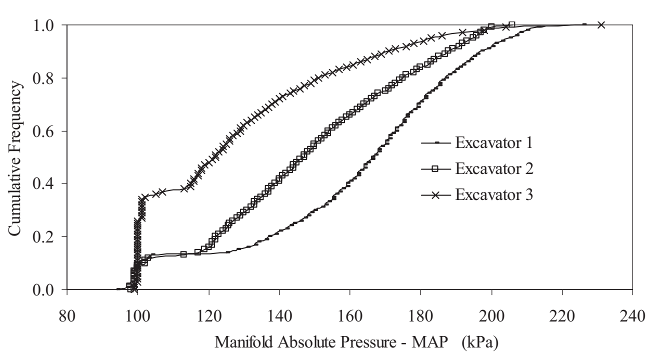

Figure 8. Cumulative distribution function of the frequency of MAP data for the three excavators.

Table 5. Comparison of average normalized fuel use and emission rates of three excavators with respect to engine duty cycles.

Quantity	Engine Duty Cycle[a]	Average Normalized Fuel Use and Emission Rates by Excavator[b]		
		Excavator 1	Excavator 2	Excavator 3
Fuel Use	1	0.53	0.52	0.55
	2	0.49	0.49	0.50
	3	0.33	0.36	0.35
CO_2	1	0.53	0.58	0.59
	2	0.48	0.53	0.54
	3	0.33	0.39	0.37
NO	1	0.56	0.59	0.52
	2	0.51	0.56	0.48
	3	0.35	0.45	0.34
HC	1	0.63	0.66	0.69
	2	0.62	0.63	0.66
	3	0.53	0.55	0.59
CO	1	0.67	0.80	0.71
	2	0.73	0.86	0.69
	3	0.80	0.99	0.64
Opacity-based PM	1	0.42	0.40	0.42
	2	0.40	0.37	0.38
	3	0.30	0.23	0.25

Notes: [a]The engine duty cycle from a given excavator was estimated based upon the cumulative distribution function (CDF) of normalized MAP based upon field data. Engine duty cycle 1 was observed in site 1 on January 16, 2006. Engine duty cycle 2 was observed in site 2 on November 2, 2005. Engine duty cycle 3 was observed in site 2 on August 24–26, 2005. These duty cycles are shown in Figure 8. [b]The average normalized fuel use or emission rates were estimated based on the CDF of MAP for a given engine duty cycle, from which the fraction of time in each mode for a given excavator was estimated. The average normalized fuel use or emission rate is a time-weighted modal average.

emission rates versus MAP, distributions of MAP were used to characterize duty cycles, and ranges of MAP were used to estimate modal emission rates.

However, an attempt to define "task-oriented" modes merely provided insight that emission rates are substantially different for idle versus non-idle, but was not able to explain variability in emission rates when the vehicle was using a bucket or moving laterally over a site. Instead, the use of distributions of MAP was found to be more useful for characterizing variability in emissions during nonidling vehicle operations.

For the three vehicles tested, there was more variability in emission rates associated with estimates of average emissions for different duty cycles than there was among different vehicles (engines) for the same duty cycle. Although this result may not be generalizable because of the small number of vehicles and duty cycles observed here, it implies a need to consider intercycle variability as a quantifiable factor when developing nonroad vehicle emission inventories.

The data collection and analysis methodology developed here is recommended for application to larger numbers and different types of nonroad vehicles, such as bulldozers, front-end loaders, backhoes, motor graders, off-road dump trucks, and others. Data collection on nonroad vehicles should include characterization of various duty cycles for each type of vehicle, and their implications for fuel use and emission inventories.

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About the Authors

Saeed Abolhasani participated in this work as a graduate research assistant in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University and is now Engineering Director at Emisstar, LLC. Within the Department of Civil, Construction, and Environmental Engineering at North Carolina State University, Dr. H. Christopher Frey is a professor of environmental engineering, Dr. William Rasdorf is a professor in the construction and computer aided engineering groups, and Phil Lewis is a Ph.D. student. Dr. Kangwook Kim and Dr. Shih-Hao Pang participated in this work as Ph.D. students in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. Dr. Kim is now with the Department of Sanitation of the City of New York. Dr. Pang is now with the California Air Resources Board in El Monte, CA. Please address correspondence to: Dr. H. Christopher, Frey, Department of Civil, Construction, and Environmental Engineering, Campus Box 7908, Mann Hall, 2501 Stinson Avenue, Raleigh, NC 27695-7908; phone: +1-919-515-1155; fax: +1-919-515-7908; e-mail: frey@eos.ncsu.edu.