Comparison of Real World Emissions of Backhoes, Front-End Loaders, and Motor Graders for B20 Biodiesel vs. Petroleum Diesel and for Selected Engine Tiers

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Abstract

Field data for in-use fuel consumption and emission rates were collected for 15 nonroad vehicles using a portable emission measurement system (PEMS). Each vehicle, including 5 backhoes, 4 front end loaders, and 6 motor graders, were tested once on petroleum diesel and once on B20 biodiesel. The vehicles include different model years and thus represent a variety of engine certification tiers. A methodology was developed for study design, field data collection, data screening and quality assurance, data analysis, and benchmarking of the data. The average rate of loss of data due to data quality issues was 6.9 percent. On average, over 3 hours of valid data were collected in each test. Time-based emission factors were found to increase monotonically with respect to engine manifold absolute pressure. Fuel-based emission factors were mainly sensitive to differences between idle and non-idle engine operation. Typical duty cycles were quantified in terms of frequency distributions of manifold absolute pressure (MAP) and used to estimate cycle average emission factors. On average, the use of B20 instead of petroleum diesel lead to an insignificant 1.8 percent decrease in NO emission rate and significant decreases of 18, 26, and 25 percent for opacity, HC, and CO, respectively. Emission rates were also found to decrease significantly when comparing newer, higher tier vehicles to older ones. Fuel use, NO, HC, and CO data were found to be of similar magnitude as independent benchmark data. Specific recommendations are made for future work.

INTRODUCTION

Diesel vehicles, including both onroad and nonroad vehicles, emit significant amounts of nitrogen oxides (NO_x) and particulate matter. In 2005, nonroad diesel construction vehicles were estimated to emit annual U.S. national totals of 657,000 tons of NO_x and 63,000 tons of PM_{10} (*1*). In recent years, the U.S. Environmental Protection Agency (EPA) has set Tier 1 to Tier 4 emission standards for the engines used in most construction, agricultural, and industrial vehicles.

The North Carolina Department of Transportation (NCDOT) has been using B20 biodiesel in its inventory of diesel vehicles, including onroad and nonroad, in order to comply with the Energy Policy Act. Based on engine dynamometer testing, B20 biodiesel leads to a small increase (i.e. 2 percent) in tailpipe NO_x emission rate, but decreases of 10 percent for PM, 11 percent for CO, and 21 percent for hydrocarbon (HC) tailpipe emission rates (*2*). In previous work, we have assessed the effect of B20 versus petroleum diesel with respect to tailpipe emissions of selected Tier 1 and Tier 2 dump trucks, including both single rear axle and tandem chassis configurations (*3*). The average NO emission rate, among 12 vehicles tested, decreased by approximately 10 percent. The observed average decreases in CO, HC, and PM emission rates were similar to those of the dynamometer tests.

Emissions from nonroad construction equipment are typically quantified based on steady-state engine dynamometer tests. However, such tests do not represent actual duty cycles. There is a need for more representative data based on real-world vehicle activity. There has been limited in-use testing of nonroad vehicles using a variety of instruments (*4-6*). Some of these data are proprietary, some are limited in scope (e.g., measurement of only two pollutants), and some are reported only in summary form. Furthermore, these data do not address the desired scope of comparison of multiple Tiers of engine regulations nor comparison of B20 versus petroleum diesel fuel.

The purpose of this project was to conduct field measurements of selected nonroad vehicles in the NCDOT equipment inventory in order to gain insight into the real world implications for emissions of increasingly stringent Tiers of engine regulations and of the substitution of soy-based B20 biodiesel for petroleum diesel. The parent B100 blend stock meets ASTM standards. Ultra-low sulfur diesel was used for both petroleum diesel and in the B20 blend. Such insights are useful when evaluating the benefits of replacing older vehicles with newer ones or of purchasing an alternative fuel for which there is currently a cost premium compared to conventional fuel. The specific research objectives include:

- Measure real-world, in-use duty cycles in North Carolina for specific types of nonroad vehicles, including backhoes, front-end loaders, and motor graders;
- Simultaneously measure real-world, in-use emissions;
- Develop modal emission factors;
- Develop representative duty cycles;
- Compare engine Tiers and B20 versus petroleum diesel based on real-world data; and,

- Conduct benchmark comparisons of average emission factors;

METHODOLOGY

The key elements of the methodology include study design, instrumentation, data collection procedures, quality assurance procedures, techniques for analyzing data, and benchmark comparisons to independent data sources.

Study Design

Real world vehicle activity and emissions were measured using a portable emission measurement system (PEMS). The key elements of study design are briefly described:

- **Study Location** – The study areas included NCDOT Division 4 in Nash County and NCDOT Division 5 in Wake County.
- **Vehicle Selection** – The tested vehicles included five backhoes, four front-end loaders, and six motor graders. The selected backhoes included Tier 0 to Tier 2 certified engines. The selected front end loaders included Tier 1 and Tier 2 certified engines. The selected motor graders included Tier 0 to Tier 3 certified engines.
- **Vehicle Activities** – Data collection typically occurred at field sites where the instrumented vehicles conducted normal road maintenance tasks.
- **Data Collection Scheduling** – Each of the 15 vehicles was tested during one day on B20 biodiesel and one day on petroleum diesel. The field tests were scheduled based on coordination with a maintenance yard supervisor.
- **Fueling** – There was an interval of typically 1 to 6 weeks between the tests on the two fuels for a given vehicle, during which NCDOT would refill the fuel tank at least twice in order to purge the first fuel.
- **Data Collection Duration** –As a result of analysis of data from some of the early tests, a determination was made that 3 hours of processed field data would be adequate for characterizing emission rates.
- **Operator** – The operator was assigned by the NCDOT supervisor. Typically, the operator performed normal tasks as required by NCDOT's road maintenance work schedule. The operators cooperated with the study team in allowing periodic access to the PEMS in order to verify that it was collecting valid data.
- **Flexibility in Scheduling** – On occasion, the operator might alter their work schedule because of maintenance project needs, or there may be unanticipated problems with the nonroad vehicle or the PEMS that resulted in delays.

Instrumentation

The PEMS is the OEM-2100 "Montana" system manufactured by Clean Air Technologies International, Inc. (*7*), which is comprised of two parallel five-gas analyzers, a PM measurement system, an engine sensor array, a global position system (GPS), and an on-board computer. The engine sensor array is used for vehicles that either do not have an on-board diagnostic interface or for which the interface is not standardized or is proprietary. The sensor array includes sensors for measuring manifold absolute pressure (MAP), engine RPM, and intake air temperature. The on-board computer synchronizes the incoming second-by-second emissions, engine, and GPS data. Intake airflow, exhaust flow, and mass emissions are estimated from engine operating data, engine and fuel properties, and exhaust gas concentrations.

HC, CO and CO_2 are measured using non-dispersive infrared (NDIR). Measurements of CO and CO_2 are accurate to within 10 percent when compared to a dynamometer lab *(8)*. The accuracy of the HC measurement depends on type of fuel used (*9*). NO is measured using electrochemical cell. For diesel vehicles, total NO_x is typically approximately 90 to 95 percent NO, with the balance NO_2 (*10*). The PM measurements are semi-quantitative are are used for relative comparisons. Because they are based on a light scattering method, they are analogous to opacity. The gas analyzers are calibrated periodically based on a cylinder gas and also self-calibrate periodically using ambient air as a reference, referred to as “zeroing.”

Data Collection Field Procedures

Data collection procedures include four steps: (1) pre-installation; (2) installation; (3) field data collection; and (4) decommissioning.

Pre-installation occurs during the afternoon before data collection, takes approximately two hours to complete, and includes:

- Installation of a safety cage on the vehicle. The safety cage securely holds the PEMS during the data collection process and protects it from damage, such as from overhanging tree branches.
- Installation of sensor array on the engine.
- Installation of external batteries on the vehicle in order to provide power to the PEMS independent of the vehicle’s power system.
- Installation of power cable, GPS receiver and wire, and exhaust gas sampling lines.

Installation is performed two hours prior to data collection and includes: placement of the PEMS main unit into the safety cage; connection of the power cable, GPS receiver, and exhaust gas hoses to the PEMS; and setup of an auxiliary laptop and a video camera. The main unit must be warmed up for 45 minutes before data collection. An auxiliary laptop is used by a research assistant to record time stamps when vehicle activity changes from one task-oriented mode (e.g., dumping, use of a blade, moving, idling) to another. A research assistant uses a video camera to record approximately 15 minutes of vehicle activity in order to have a record of the vehicle, site conditions, and the duty cycle.

Data collection includes: (1) assessing and recording field conditions; (2) recording vehicle characteristics; (3) operating the PEMS; (4) periodically checking the PEMS to identify and correct (if possible) data collection and quality assurance problems; (5) recording modes of vehicle activity on a separate laptop; and (6) recording video.

Decommissioning includes reversing all of the installation and pre-installation steps, which takes approximately 30 minutes.

Data Screening and Quality Assurance

Data screening and quality assurance are procedures for reviewing data collected in the field, determining whether any errors exist in the data, correcting such errors where possible, and removing invalid data.

A number of possible errors have been previously identified in previous work that involved downloading engine control unit data (*11,12*). However, here, engine data are obtained using a sensor array instead of an engine scanner. Thus, the procedures required modification.

The procedure includes: (a) initial screening based on error flags generated automatically by the Montana system; (b) reviewing and correcting (if necessary) the synchronization of engine, GPS, and exhaust concentration data; (c) identifying and correcting (if possible) problems associated with the sensor array, such as missing or invalid values of MAP, engine RPM, and IAT; (d) identifying problems associated with the gas analyzers, such as large discrepancies between the two gas analyzers, "freezing" of the analyzers (failure to update data), occurrences of zero calibration during which data should not be used, and occurrence of negative values of emissions that are statistically significantly different from zero; (e) identifying potential problems with air leakage into the sampling system based on assessment of the air-to-fuel ratio. For short periods of missing data, such as one or two seconds of missing MAP values, missing values are imputed. For long periods of missing data, the data are flagged as incomplete and are not used for estimating emission rates. If the data have to be resynchronized or if any values have to be corrected, the mass emission rates are recalculated. A 19-step data screening and quality assurance process has been automated using Visual Basic macros in Excel. Details of the procedure and of the macros are available (*13*).

Exploratory Analysis of Data

The raw data were analyzed in terms of the effect of engine activity on fuel use and emissions. Rank correlation was used to identify engine variables highly correlated with variations in fuel use and emission rates. Time series plots were used to represent the variation of fuel use and emission rates in terms of different real-world activities. The fuel use and emission rates were found to be highly correlated with the manifold absolute pressure (MAP) of the engine. MAP is a surrogate for engine load.

Emission Factors Based on Real-World Data

Emission factors are the ratios of emissions to vehicle activity. Nonroad vehicle activity can be quantified with respect to time or fuel consumption. Furthermore, emission factors vary with respect to engine load as well as components of duty cycles. Thus, emission factors were developed for each of several modes based either on an "engine-based" or a "task-oriented approach. Therefore, four types of emission factors were developed: (1) "engine-based" modal mass of fuel use or emissions per time based on ranges of MAP; (2) engine-based mass of pollutant emitted per gallon of fuel consumed; (3) "task-oriented" modal mass of fuel use or emissions per time stratified with respect to different operational modes of a vehicle, such as use of a bucket to scoop dirt, lateral movement across a site, or idling; and (4) task-oriented modal emission rates in units of mass of pollutant emitted per gallon of fuel consumed.

Whereas the exhaust gas concentrations of NO and CO_2 were well above the gas analyzer detection limits, for some vehicles the concentrations of HC and CO were comparable to or less than their respective detection limits. Furthermore, the NDIR method used for detecting HC and CO appears to be sensitive to vibration (*14-15*). Nonroad vehicles, and especially those with shorter chassis that operate on rough terrain (such as backhoes and front end loaders, compared to motor graders), are particularly subject to vibrations as they pitch and yaw over uneven surfaces. The real-world detection limits for HC and CO were inferred by statistical analysis of comparisons of the parallel gas analyzers. Linear regression was used on progressively larger ranges of data, starting with the smallest observed values, until the slope of the regression line was statistically significant. For HC concentrations less than 20 ppm, there is no statistically significant association between the concentrations of one gas analyzer versus the other. Likewise, for CO, the inferred detection limit was 0.02 volume percent.

Based on previous detailed statistical modeling using bootstrap simulation (*16*), a detection limit does not significantly affect a mean emission rate unless the detection limit is greater than the mean emission rate. Footnotes are used in later tables to indicate when an average emission rate may be subject to uncertainty because of a high proportion of exhaust gas concentration data that are below the detection limit.

Determination of Representative Duty Cycles

A duty cycle is defined as the sum of activities that a vehicle performs on a job site to complete a particular task, such as mass excavation or material handling. We observed real-world duty cycles during field data collection; hence, the observed cycles are representative of real-world activity. Based on a finding, as discussed later, that fuel use and emission rates are highly correlated with MAP, duty cycles were quantified based on the cumulative frequency distribution (CDF) of normalized MAP for a given day of data collection. Multiple duty cycles were compared for the same type of vehicle (e.g., backhoes) based on data collected on different days for the same vehicle or for difference vehicles, in order to identify duty cycles that have significant differences in average engine load and in variability in engine load. Data from the CDF are used to estimate the fraction of total time spent in each engine-based mode. An average emission rate for a duty cycle is estimated based on the weighted average of the modal emission rates.

Benchmark Comparisons

Fuel based emission factors from PEMS data were compared with fuel-based emission factors estimated using EPA's NONROAD model for the same model year, chassis type, and engine Tier. The mass per brake-horsepower-hour emission factors produced by NONROAD were converted to a fuel basis using brake specific fuel consumption (BSFC). The NONROAD model produces fleet average emission estimates based on engine dynamometer data. Therefore, some differences are expected in the emission factors when comparing both approaches. However, the purpose of the comparison is to determine whether the magnitudes of the emission factors are similar.

Second-by-second and average fuel consumption rates are estimated from the PEMS data. NCDOT maintains an electronic database of the annual hours of engine operation and the gallons of fuel consumed for vehicles in its equipment inventory. Thus, average fuel consumption rates measured during field testing were compared with annual average fuel consumption rates from NCDOT's database.

RESULTS

The results from field data collection of 15 nonroad vehicles are given here. These results include an overview of the data collection effort, a summary of the outcome of quality assurance, characterization of emission factors that are influenced by high proportions of non-detected exhaust concentration measurements, exploratory analysis of the data to identify useful explanatory variables for emission rates, modal emission rates, representative duty cycles, cycle-average emission factors, comparisons between fuels and engine tiers, and benchmark comparisons,.

Data Collection

The five backhoes were of 1999 to 2004 model year, with gross vehicle weights (GVW) ranging from 16,000 to 22,000 lbs. They have engines of approximately 4 liters and 90 to 100 horsepower. The four front-end loaders included 2002 and 2005 model years, all were approximately 29,000 lb GVW, and all had similarly sized engines of approximately 5.9 liter displacement and 130 horsepower. The six motor graders ranged in model year from 1990 to 2007. While all had GVW of 37,000 lb, the engines ranged from 7.1 to 8.3 liters and 160 to 200 horsepower.

On average, for each vehicle there were 3 hours and 25 minutes of raw second-by-second data per test, and each vehicle was tested once on petroleum diesel and once on B20 biodiesel. Idling accounted for 44 percent of the observed raw data. For backhoes, moving, use of the front bucket, and use of the rear bucket accounted for 15 percent, 27 percent, and 16 percent of time, respectively. For front end loaders, moving and use of the bucket accounted for 22 percent and 29 percent of time, respectively. For motor graders, moving and use of the blade each accounted for 29 percent of time.

Vibration, dust, and mud were associated with failures of the PEMS system that required time consuming repairs. Solutions to these problems included restricting data collection in the latter stages of the project to sites with less severe terrain, use of additional foam padding under and around the PEMS main unit within its safety cage, and use of a fine mesh fabric cover over the safety cage to reduce the amount of dust that deposits on or in the PEMS. Scheduling was subject to cancellation depending on the NCDOT field work load or vehicle or instrument problems. Thus, continuous communication was required in order to confirm or reschedule data collection.

Quality Assurance

On average, 6.9 percent of raw second-by-second data were removed in order to create a final database for use in emissions estimation. The error rate varied among the 30 tests from as low as 0.8 percent to as high as 17 percent. The leading causes for loss of data included analyzer "freezing," large discrepancies between the two parallel gas analyzers, and unacceptably high air-to-fuel ratios. Other types of errors occurred at average rates of 0.23 percent or lower), including missing values of MAP, unusual (out-of-range) values of engine RPM, unusual values of IAT, and negative exhaust concentrations that were statistically different from zero. Of the 102.5 hours of total raw data collected, there were 95.4 hours of valid processed data.

Non-Detected Measurements

The modal average exhaust gas concentrations for HC were below the detection limit for tests on petroleum diesel for five or more modes for three backhoes, one front-end loader, and two motor graders. Typically, these were for vehicles of the most recent engine tiers that tend to have the lowest average emission rates compared to older vehicles of lower engine tiers. For example, the Tier 2 and Tier 3 motor graders had a large proportion of non-detected HC and CO measurements when tested on both fuels.

The proportion of non-detects tended to be higher for B20 than petroleum diesel tests, because emission rates of HC and CO tend to be lower for B20 than petroleum diesel. For tests conducted on B20, the same three backhoes and two motor graders that had a high proportion of non-detects on petroleum diesel also had a high proportion of non-detects; however, all four motor graders had a high proportion of non-detects when tested on B20 compared to only one when tested on petroleum diesel. For CO, all four front end loaders had a high proportion of non-detects when tested on both fuels. The Tier 2 backhoes and the Tiers 2 and 3 motor graders also had a high proportion of nondetects on both fuels.

Exploratory Analysis

MAP was typically found to be the engine parameter most highly correlated with fuel use and emission rates. The rank correlation of MAP with each of these rates often exceeded 0.95, except for NO and opacity for which the rank correlation was typically approximately 0.8. While engine RPM is also highly correlated with these rates, the correlations were slightly weaker than those for MAP. Thus, MAP was used as the basis for defining engine-based modes.

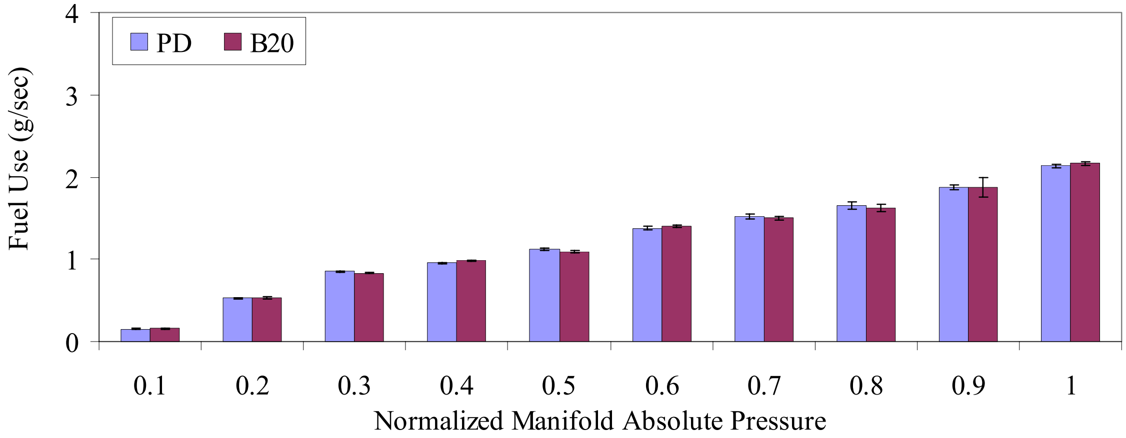
Time series plots of engine data, fuel use rate, and emission rates were used to visualize the association between these rates and engine data. Typically, a peak in MAP is associated with a corresponding peak in fuel use and emission rates.

Modal Emission Rates

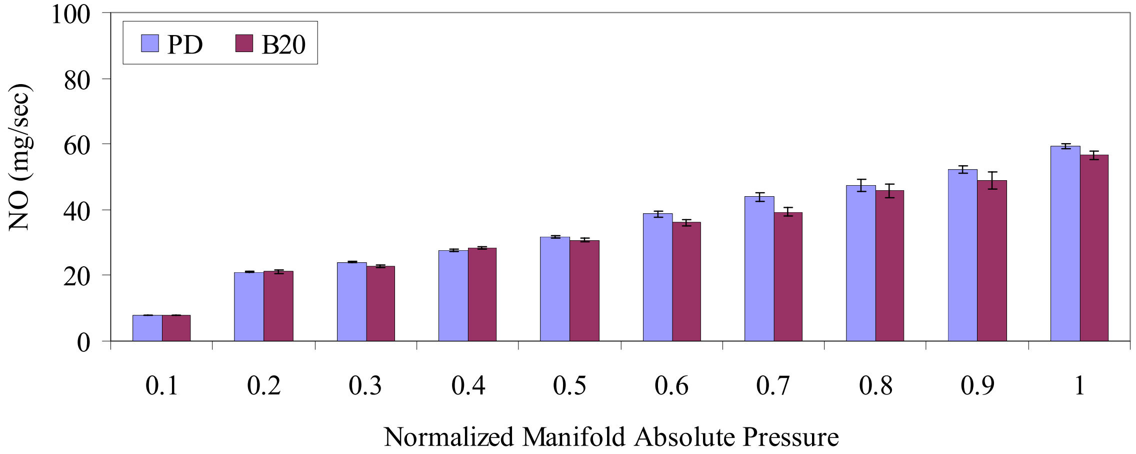
Modal emission rates were estimated for each vehicle. An example is shown for Backhoe 1 in Figure 1 for engine-based modal fuel use and NO emission rates and in Figure 2 for task-oriented modal rates. The NO emission rates are shown on a per time and per gallon basis. The NO emission rates have been corrected to a standard temperature and humidity based on a regulatory methodology (*17*). The engine-based modal rates are estimated with respect to normalized MAP. Normalized MAP is calculated on a second-by-second basis based on the minimum and maximum values of MAP observed during a test, as (actual MAP – minimum MAP)/(maximum MAP – minimum MAP). The ranges of MAP observed in tests of B20 and petroleum diesel for a particular vehicle were very similar, and the cut-off points for the MAP-based modes were the same for both fuels for a given vehicle.

The mass fuel use and CO_2 emissions per unit of energy in the fuel are expected to be slightly higher for B20 because it has slightly less energy and carbon density than does petroleum diesel. However, these differences are only a few percent and are within the precision of the measurements. Figure 1 shows that fuel usage rate for B20 is approximately the same as that for petroleum diesel, as expected. The comparison of CO_2 emission rates (not shown) is similar, since over 99 percent of the carbon in the fuel is emitted as CO_2. The time-based fuel use and NO emission rates increase monotonically with normalized MAP. The NO emission rates for modes with lower MAP tend to be similar for the two fuels. For higher MAP, the NO emission rate for B20 is slightly lower than for petroleum diesel. The fuel-based NO emission rate tends to decrease with MAP, and is substantially higher for the two lowest MAP modes compared to all others. The first MAP mode is associated with engine idling. For situations in which the engine is under load, there is less variability in the fuel-based emission rates than the time-based emission rates. Although not shown in Figures 1 and 2, as expected, the emission rates of HC, CO, and PM are substantially lower for B20 versus petroleum diesel. Results for all pollutants are shown in Table 1, 2, and 3 for backhoes, front-end loaders, and motor graders, respectively.

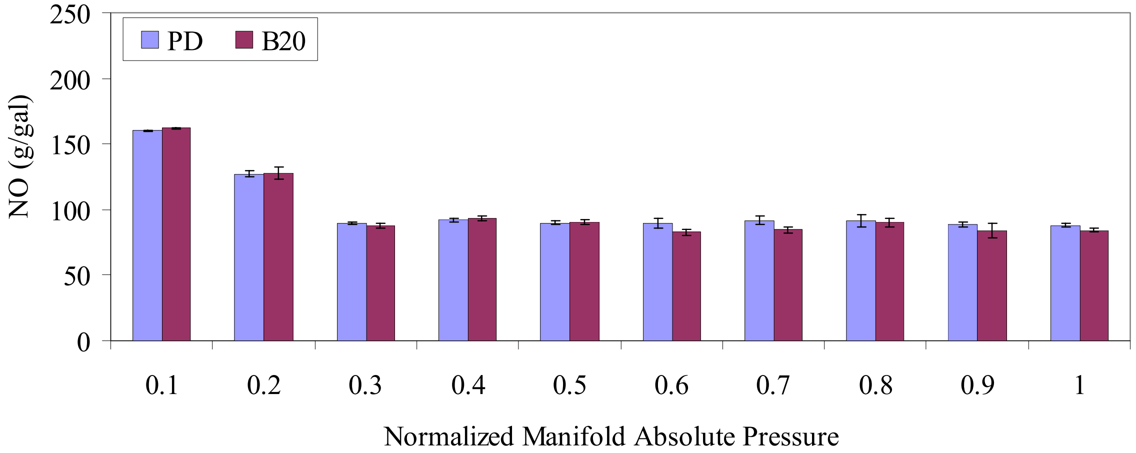
The example results in Figure 2 indicate that fuel use and emission rates are substantially different during idling compared to other modes. However, the differences among the three non-idle modes are relatively minor. Furthermore, the variability in fuel use and emission rates captured by these task-oriented modes is much less than that of the engine-based modes. For example, the engine-based modal fuel use rates vary from approximately 0.2 to 2 g/sec, whereas the task-oriented modal rates vary from 0.2 to 1.3 g/sec.



(a) Time-based fuel use rate

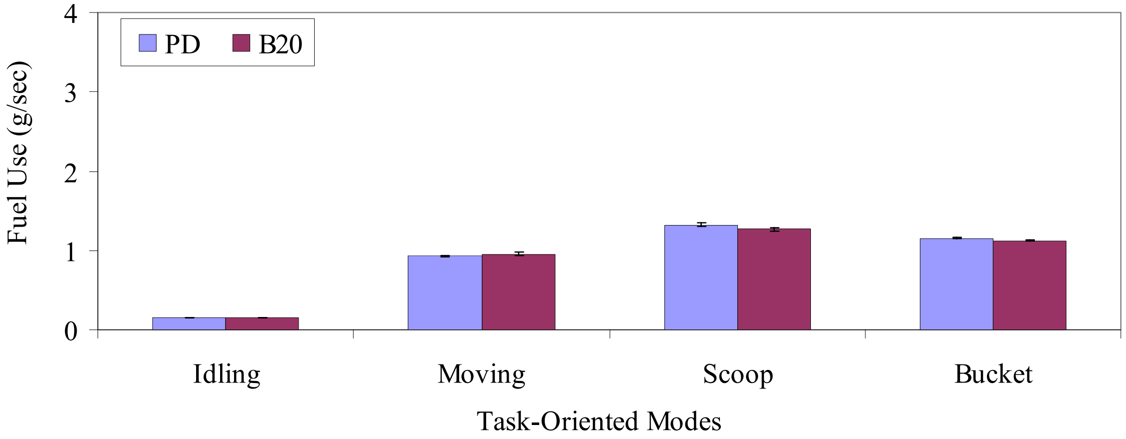


(b) Time-based NO emission rate, corrected for ambient temperature and humidity

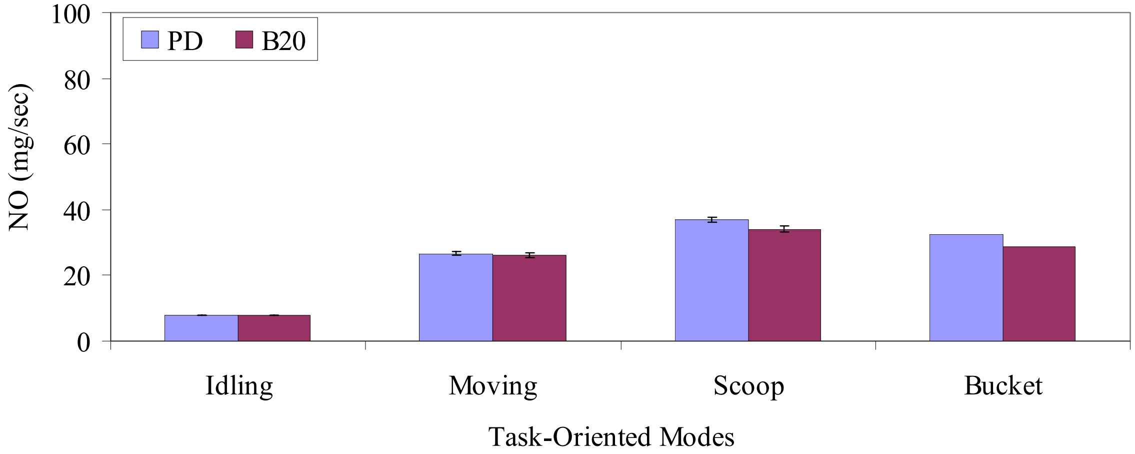


(c) Fuel-based NO emission rate, corrected for ambient temperature and humidity

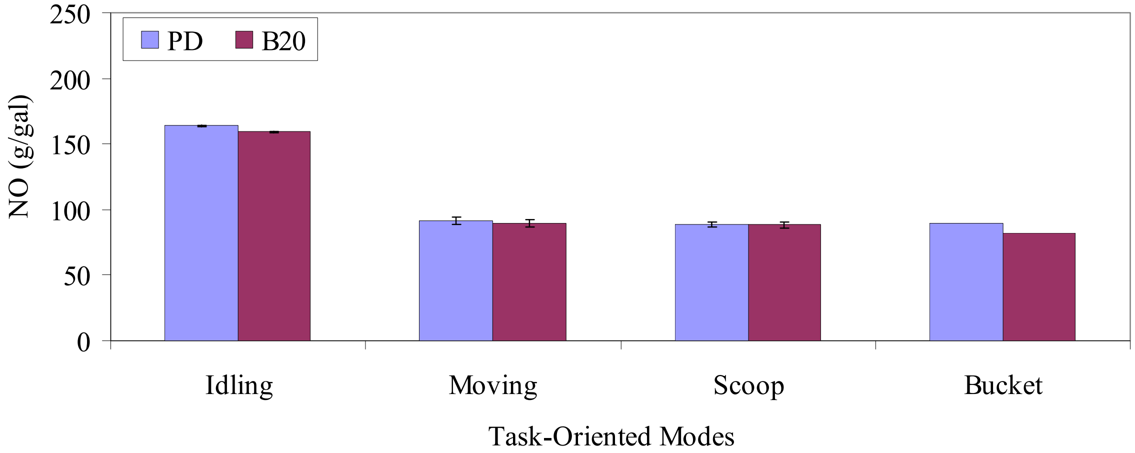
Figure 1. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and NO Emission Rates for Engine-Based Modes for Backhoe 1



(a) Time-based fuel use rate



(b) Time-based NO emission rate, corrected for ambient temperature and humidity



(c) Fuel-based NO emission rate, corrected for ambient temperature and humidity

Figure 2. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and NO Emission Rates for Task-Oriented Modes for Backhoe 1

Representative Duty Cycles

In order to estimate average emission rates, several duty cycles were developed. For backhoes, three cycles were identified that represent mass excavation, material handling, and loading a truck with dirt. These cycles have significant differences in engine load. For front end loaders, three cycles were identified, including rock handling, soil handling, and loading a truck. However, unlike the backhoes, there was less difference in average engine load among these three cycles. For motor graders, two cycles were observed, including resurfacing an unpaved road and regarding the shoulders of a road. These two cycles have significant differences in average engine load, as shown in Figure 3.

Average Emission Factors

Cycle average emission factors for backhoes are given in Table 1 for three duty cycles, two fuels, and three engine tiers, with data shown for all five tested vehicles. For each tier and fuel, an overall average emission rate is indicated. For NO, the emission rates are approximately similar for the two fuels. The emission rates do not vary significantly by engine tier. For opacity, the emission rates are significantly lower for B20 versus petroleum diesel especially for the higher tiers, and the emissions rates decrease significantly for higher tiers. The trend for HC is similar to that of opacity. For CO, the emission rates decrease modestly for B20 versus petroleum diesel but substantially with respect to engine tier.

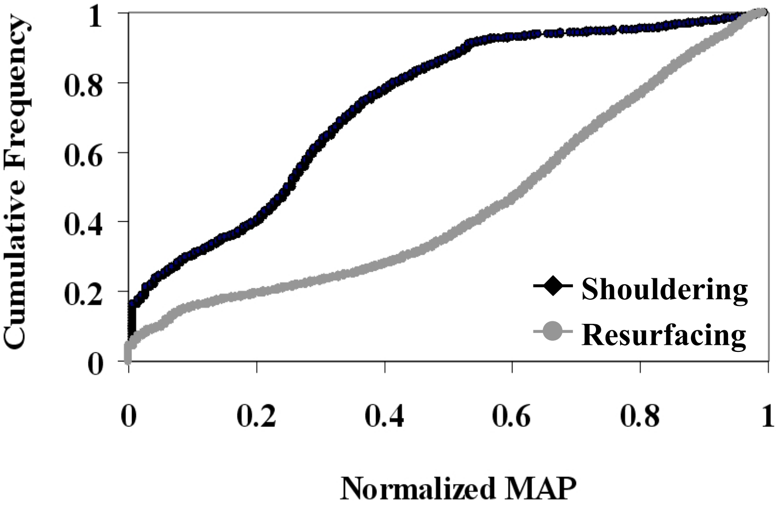


Figure 3. Cumulative Frequency of Normalized Manifold Absolute Pressure (MAP) for Shouldering and Resurfacing Duty Cycles for Motor Graders

For front-end loaders, as shown in Table 2, the NO emission rates are similar for the two fuels but are lower for the higher tier vehicle. For opacity, HC, and CO, the emission rates are significantly lower for B20 versus petroleum diesel and are lower for the Tier 2 engine versus the Tier 1 engines.

Results for motor graders are shown in Table 3. The NO emission rates are comparable for the two fuels, but decrease with increase engine tier. For example, the Tier 3 vehicle has emission rates approximately 50 percent lower than the tier 0 vehicles. For opacity, HC, and CO, the emission rates are lower for B20 versus petroleum diesel for all tiers, and the emission rates decrease monotonically as the tiers increase.

On average over all 15 vehicles tested, NO emission rates are 2 percent lower for B20 than petroleum diesel, which is not a statistically significant result. However, emission rates are lower by 18, 26, and 25 percent for opacity, HC, and CO, respectively, which are significant.

Although there is not a large sample of vehicles in each tier, the results suggest that emission rates tend to decrease as the engine tier increases. The reductions in emissions that accrue from replacement of older (i.e. Tier 0) vehicles with newer Tier 2 or Tier 3 vehicles is on the order of 8 to 86 percent for backhoes, depending on the pollutant, and 41 to 76 percent from motor graders, depending on the pollutant.

Benchmark Comparisons

The fuel based emission factors from the PEMS data are of comparable magnitude to fuel-based emission factors estimated from the NONROAD model for NO, HC, and CO. For example, for motor graders, the emission rates based on PEMS data range from 59 to 139 g/gallon, whereas the estimates for similar model years and engine sizes from the NONROAD model range from 45 to 159 g/gallon. Typically, there is substantial overlap in the ranges from both types of data for these three pollutants, with a few exceptions. For example, for CO emission rates from front-end loaders, the estimates based on PEMS data are 11 to 18 g/gallon versus 26 to 28 g/gallon based on NONROAD results. However, in all of these cases, the emission factors are of similar magnitude.

The NONROAD model provides PM emission factors. The opacity measurements from the PEMS are substantially lower than the PM emission rates provided in the NONROAD model. For example, for motor graders, the inferred range from PEMS data is 0.5 to 1.1 g/gallon versus 1.8 to 18 g/gallon based on the NONROAD model results. While the opacity measurements may be adequate for relative comparisons between fuels or vehicles, they are not considered to be accurate with respect to estimation of the absolute magnitude of PM emission rates.

Table 1. Measured Fuel-Based Emission Factors for Backhoes: Comparison of Tiers, Fuels and Duty Cycles

Pollutant	Engine Type	Test ID	Vehicle ID	B20			Petroleum Diesel		
				LTC[a]	MEC[b]	MHC[c]	LTC[a]	MEC[b]	MHC[c]
NO (g/gallon)	Tier 0	BH2	803-0242	118	104	102	115	101	98
		Average		**108**			**105**		
	Tier 1	BH3	803-0241	83	84	88	99	100	103
		BH4	808-0214	87	104	119	93	109	120
		Average		**94**			**104**		
	Tier 2	BH5	FDP22085	96	92	108	100	96	110
		BH1	FDP20882	94	92	104	96	92	105
		Average		**97**			**99**		
Opacity (g/gallon)	Tier 0	BH2	803-0242	1.2	1.1	1.2	1.3	1.1	1.3
		Average		**1.2**			**1.2**		
	Tier 1	BH3	803-0241	1.23	1.0	1.1	1.2	0.91	1.2
		BH4	808-0214	1.3	0.71	0.98	1.6	1.7	1.3
		Average		**1.1**			**1.3**		
	Tier 2	BH5	FDP22085	0.70	0.51	0.62	0.79	0.69	0.74
		BH1	FDP20882	0.50	0.46	0.47	0.70	0.66	0.66
		Average		**0.54**			**0.71**		
HC (g/gallon)	Tier 0	BH2	803-0242	12	14	15	13	16	17
		Average		**14**			**15**		
	Tier 1	BH3	803-0241	15	9.0	11	15	11	13
		BH4[d]	808-0214	4.3	5.9	6	5.6	6.7	9.1
		Average		**8.5**			**10**		
	Tier 2	BH5[e]	FDP22085	3.3	3.2	3.9	8.6	11	10
		BH1[f]	FDP20882	8.3	7.1	8.8	11	10	12
		Average		**5.8**			**10**		
CO (g/gallon)	Tier 0	BH2	803-0242	86	62	67	106	77	82
		Average		**72**			**88**		
	Tier 1	BH3	803-0241	32	36	32	36	39	36
		BH4	808-0214	43	36	46	54	45	53
		Average		**38**			**44**		
	Tier 2	BH5[e]	FDP22085	13	10	14	16	16	17
		BH1[f]	FDP20882	7.9	7.1	7.7	9.1	8.4	9.3
		Average		**10**			**13**		

[a] LTC: Load Truck Cycle; [b] MEC: Mass Excavation Cycle; [c] MHC: Material Handling Cycle

[d,e,f] The average emission factor is based on a high proportion of data below the gas analyzer detection limit

Table 2. Measured Fuel-Based Emission Factors for Front-End Loaders: Comparison of Tiers, Fuels and Duty Cycles

Vehicle Type	Engine Type	Test ID	Vehicle ID	B20			Petroleum Diesel		
				RHC[a]	SDHC[b]	LTC[c]	RHC[a]	SDHC[b]	LTC[c]
NO (g/gallon)	Tier 1	FL1	010-0249	109	112	112	109	113	108
		FL2	010-0301	120	124	118	128	131	127
		FL3	010-5074	130	133	132	127	129	125
		Average		**121**			**122**		
	Tier 2	FL4	010-0388	92	95	91	94	96	95
		Average		**93**			**95**		
Opacity (g/gallon)	Tier 1	FL1	010-0249	0.65	0.66	0.64	1.0	1.0	1.0
		FL2	010-0301	0.42	0.42	0.43	0.49	0.51	0.49
		FL3	010-5074	0.74	0.76	0.75	0.91	0.89	0.94
		Average		**0.61**			**0.81**		
	Tier 2	FL4	010-0388	0.57	0.54	0.60	0.62	0.62	0.66
		Average		**0.57**			**0.63**		
HC (g/gallon)	Tier 1	FL1[d]	010-0249	7.2	7.3	7.6	17	18	19
		FL2[e]	010-0301	8.2	8.3	8.9	16	17	17
		FL3[f]	010-5074	9.5	9.8	11	13	13	13
		Average		**8.6**			**16**		
	Tier 2	FL4[g]	010-0388	4.9	5.1	5.1	5.4	5.6	5.8
		Average		**5.0**			**5.6**		
CO (g/gallon)	Tier 1	FL1[d]	010-0249	12	13	15	15	16	18
		FL2[e]	010-0301	9.8	10	11	12	13	14
		FL3[f]	010-5074	8.5	8.7	9.1	15	15	16
		Average		**11**			**15**		
	Tier 2	FL4[g]	010-0388	8.9	9.1	8.9	11	11	1
		Average		**9.0**			**11**		

[a] RHC: Rock Handling Cycle; [b] SDHC: Soil and Dirt Handling Cycle; [c] LTC: Load Truck Cycle

[d,e,f] The average emission factor is based on a high proportion of data below the gas analyzer detection limit

Table 3. Measured Fuel-Based Emission Factors for Motor Graders: Comparison of Tiers, Fuels and Duty Cycles

Pollutant	Engine Type	Test ID	Vehicle ID	B20 Biodiesel		Petroleum Diesel	
				RC[a]	SC[b]	RC[a]	SC[b]
NO (g/gallon)	Tier 0	MG 4	948-6647	125	121	134	126
		MG 5	955-0277	140	136	136	139
		Average		**131**		**134**	
	Tier 1	MG 1	955-0515	99	109	104	113
		MG 3	955-0516	111	114	105	115
		Average		**108**		**109**	
	Tier 2	MG 2	955-0606	94	110	90	106
		Average		**102**		**98**	
	Tier 3	MG 6	955-0633	57	82	58.6	77.4
		Average		**69**		**68**	
Opacity (g/gallon)	Tier 0	MG 4	948-6647	0.81	0.69	0.93	0.77
		MG 5	955-0277	0.88	0.86	1.0	1.1
		Average		**0.81**		**0.96**	
	Tier 1	MG 1	955-0515	0.72	0.78	0.86	0.90
		MG 3	955-0516	0.66	0.56	0.80	0.80
		Average		**0.68**		**0.84**	
	Tier 2	MG 2	955-0606	0.44	0.55	0.62	0.65
		Average		**0.50**		**0.63**	
	Tier 3	MG 6	955-0633	0.43	0.52	0.53	0.61
		Average		**0.47**		**0.57**	
HC (g/gallon)	Tier 0	MG 4	948-6647	13	17	16	21
		MG 5	955-0277	12	17	12	17
		Average		**15**		**17**	
	Tier 1	MG 1	955-0515	12	11	13	17
		MG 3	955-0516	12	17	17	19
		Average		**13**		**16**	
	Tier 2	MG 2[c]	955-0606	7.6	9.7	9.2	15
		Average		**8.7**		**12**	
	Tier 3	MG 6[d]	955-0633	4.0	6.0	4.5	7.9
		Average		**5.0**		**6.2**	
CO (g/gallon)	Tier 0	MG 4	948-6647	23	33	27	34
		MG 5	955-0277	17	30	26	46
		Average		**26**		**33.1**	
	Tier 1	MG 1	955-0515	12	15	12	15
		MG 3	955-0516	12	16	15	16
		Average		**14**		**15**	
	Tier 2	MG 2[c]	955-0606	8.1	14	8.5	15
		Average		**10.8**		**12**	
	Tier 3	MG 6[d]	955-0633	4.9	5.8	9.3	8.7
		Average		**5.4**		**9.0**	

[a] RC: Resurfacing Cycle; [b] SC: Shouldering Cycle

[c,d] The average emission factor is based on a high proportion of data below the gas analyzer detection limit

Fuel usage rates observed based on PEMS data were compared to NCDOT maintenance records for 12 of the 15 vehicles. Two of the tested backhoes were rental vehicles for which NCDOT did not have historical fuel consumption data. One of the tested motor graders was a 2007 model year Tier 3 vehicle for which no historical data are yet available. The observed fuel usages rates were, on average, 6 percent lower than the historical data. These rates are not expected to agree exactly because the field data are for a period of approximately 3 to 4 hours and thus may not be the same as an annual average. Based on these comparisons, the fuel consumption estimates from the PEMS are deemed to be reasonable. The variability in fuel use rate among the vehicles was 1.4 to 5.7 gallons per hour based on the PEMS data.

CONCLUSIONS AND RECOMMENDATIONS

A number of lessons were learned that were used to improve the field data collection, data screening, quality assurance, and data analysis procedures. A formal methodology was developed for pre-installation, installation, data collection, and decommissioning. The scheduling of data collection is influenced by extreme ambient conditions during which PEMS operation is infeasible. Furthermore, site characteristics can lead to situations with high vibration that challenge the durability of the instrument. These challenges led to adaptations of the field procedures, such as collecting data in the morning prior to the onset of a hot afternoon, or use of additional padding and protection for the PEMS.

As a result of substantial attention to data quality as part of data collection, the overall frequency of problems that lead to loss of data was only 6.9 percent. MAP was found to be highly associated with variability in fuel use and emission rates and thus is a useful practical basis for developing modal emission rate on a per time basis. On a fuel-basis, emission rates are highly sensitive to idle versus non-idle operation. However, fuel-based emission factors are less sensitivity to engine load for non-idle than are time-based emission factors. Therefore, fuel-based emission factors are likely to be a more robust basis for estimating emission inventories, if fuel consumption data are available.

Emission rates for use of B20 versus petroleum diesel were approximately the same for NO but decreased significantly for opacity, HC, and CO. These results are approximately as expected.

Although limited in terms of the number of vehicles, the data suggest substantial emission benefits from the use of newer vehicles subject to higher tier engine standards than older vehicles in the equipment inventory. Thus, an agency such as NCDOT can claim tailpipe emissions benefits from the combination of usage of B20 and of replacing older vehicles with newer ones.

The emission factors for NO, HC, and CO are comparable to those from other data sources. The opacity measurements are useful for relative comparisons but are not accurate for absolute determinations of the level of emission rates.

This work has demonstrated the feasibility of collecting data for a substantial number of nonroad vehicles using a commercially available PEMS. The methodology developed here can be applied to further studies. Examples include: (a) measurement of a larger number of vehicles of each tier in order to develop more refined comparisons of emission rates among different tiers; (b) evaluation of alternative fuels, such as different suppliers of B20, different proportions of biofuel blend stock (e.g., B30), and evaluation of fuel additives; (c) evaluation of future vehicles as they become available (e.g, Tier 3 for backhoes and front end loaders, Tier 4 for all vehicles); (d) evaluation of additional types of nonroad vehicles; and (e) development of methodologies for controlled experiments in which activity is quantified in terms of metrics typically used for a given activity, such as cubic yards of dirt moved.

DISCLAIMER

The contents of this paper reflect the views of the authors and not necessarily the views of the University. The authors are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the North Carolina Department of Transportation, the Federal Highway Administration, or the Center for Transportation and the Environment at the time of publication. This report does not constitute a standard, specification, or regulation.

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