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Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina

**Prepared
for
North Carolina Department of Transportation**

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16. 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 included 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%. 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% decrease in NO emission rate and significant decreases of 18, 26, and 25% for opacity, HC, and CO, respectively. Emission rates were also found to decrease significantly when comparing newer, higher tier vehicles to lower ones. Fuel use rate, and NO, HC, and CO emission factors, were found to be of similar magnitude as independent benchmark data. An emissions inventory was developed for these vehicles. The current fuel mix of B20 and petroleum diesel is estimated to produce 0.4 to 6.4 percent lower emissions, depending on the pollutant, than usage of 100 percent petroleum diesel. If NCDOT were to use 100% B20 in the same vehicles, then additional reductions in emissions of each pollutant would be approximately 2.0% to 36.9% lower than for the current fuel mix of B20 and petroleum diesel. Although higher tier engines have lower emissions factors for each pollutant than lower tier engines, their annual average emissions tend to be higher because of greater utilization. Specific recommendations are made for future work, including expansion of the use of B20 to further reduce tailpipe emissions in the NCDOT inventory, replacement of older vehicles with newer ones, field data for larger sample sizes of vehicles for each Tier in order to improve confidence in the emissions factors and inventories, assessment of Tier 4 vehicles as they become available using improved instrumentation, evaluation of fuel formulations, evaluations of other vehicle types, and others.

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DISCLAIMER

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EXECUTIVE SUMMARY

Diesel vehicles, including both onroad and nonroad vehicles, emit significant amounts of nitrogen oxides (NO_x) and particulate matter (PM). 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}. 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, the typical expectation is that the use of B20 biodiesel leads to a small increase (i.e. 2%) in tailpipe NO_x emission rates, but decreases of 10% for PM, 11% for CO, and 21% for hydrocarbon (HC) tailpipe emission rates.

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. The average NO emission rate, among 12 vehicles tested, decreased by approximately 10%. The observed average decreases in CO, HC, and PM emission rates were very 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. 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 do they address a 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 increasing stringent Tiers of engine regulations and of the substitution of soy-based B20 biodiesel for petroleum diesel. Such insights are useful when evaluating the benefits of replacing older vehicles with newer ones or when purchasing an alternative fuel for which there is currently a cost premium compared to conventional fuel. The specific research objectives of the project 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.
- 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, benchmark comparisons to independent data sources, and development of an emissions inventory.

Study Design

Real world vehicle activity and emissions were measured using a portable emission measurement system (PEMS). The key elements of the 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 NCDOT used the instrumented vehicles to conduct normal road maintenance tasks. For backhoes, such tasks included loading dump trucks with dirt, mass excavation, and material handling. For front-end loaders, typical tasks included rock handling, soil and dirt handling, and loading dump trucks. Motor graders were typically used for resurfacing unpaved roads or for grading of road shoulders. It should be noted that as a result of some damage sustained to the PEMS as a result of extreme vibrations, particularly for backhoes and front end loaders, some of the data collection on these vehicles was conducted at the equipment maintenance yard for the same kinds of duty cycles but for less severe terrain.
- **Data Collection Scheduling –** Each vehicle was on both B20 biodiesel on petroleum diesel. Thus, there were a total of 30 field tests on the 15 tested vehicles. The field tests were scheduled based on anticipated equipment use 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 based by the NCDOT maintenance yard supervisor. Typically, the operator performed normal tasks as required by the NCDOT 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 the work schedule because of maintenance project needs, or there may be unanticipated problems with the vehicle, the PEMS, or the weather that resulted in data collection delays.

Instrumentation

The PEMS used here is the OEM-2100 "Montana" system manufactured by Clean Air Technologies International, Inc., 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. None of the vehicles tested had a diagnostic interface; thus, the sensor array was always used. 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% when compared to a dynamometer lab. The accuracy of the HC measurement depends on the type of fuel used. NO is measured using electrochemical cell. For diesel vehicles, total NO_x is typically approximately 90% to 95% NO, with the balance NO_2. The PM measurements are semi-quantitative are used for relative comparisons. Because they are based on a light scattering method, they are analogous to opacity.

The gas analyzers are calibrated periodically based on a cylinder gas and also self-calibrated periodically using ambient air as a reference, referred to as "zeroing." Two gas analyzer modules are used in parallel in order to have continuous data even when one goes off-line for periodic "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 the 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 a 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, placement of the GPS receiver, connection of exhaust gas hoses to the PEMS; setup of an auxiliary laptop computer, and setup of 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 typical vehicle activity, the 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 computer; and, (6) recording video.

Decommissioning includes reversing all of the installation and pre-installation steps, which takes approximately 30 minutes. The PEMS is returned to the laboratory and is cleaned and prepared for the next data collection session. The data from both the PEMS and the separate laptop are saved to multiple copies for storage and backup. The video is archived.

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. However, in the current study, engine data are obtained using a sensor array instead of with an engine scanner. Thus, the data screening and quality assurance procedures required modification.

The procedures include: (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; and, (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.

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. Nonroad vehicles, and especially those with a shorter chassis that operate on rough terrain (such as backhoes and front end loaders, compared to motor graders) are particularly subject to severe 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, 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

Based on a finding discussed later, fuel use and emission rates are highly correlated with MAP. Duty cycles were quantified based on the cumulative frequency distribution (CDF) of MAP for a given day of data collection. Multiple duty cycles were compared for the same type of vehicle (e.g., backhoes) based on data collected on different days for either the same vehicle or for different vehicles, 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

Two benchmarking comparisons were made. The first compared the emissions results with the EPA NONROAD model predictions. The second compared the fuel consumption results from this study with historical fuel use by NCDOT vehicles.

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) factors. The NONROAD model produces fleet average emission estimates based on engine dynamometer data that are not representative of the real world duty cycles observed in the field data collection. Therefore, there are expected to be some differences in the absolute values of the emission factors when comparing both approaches. However, the purpose of the comparison is to determine whether the magnitudes of the emission factors are similar.

A second type of benchmark comparison was for fuel consumption rates. 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 the NCDOT database.

Development of Emissions Inventory

An emissions inventory was developed to estimate the levels of air pollutants that were emitted by NCDOT backhoes, front-end loaders, and motor graders. Emissions were estimated for NO_x, opacity, HC, and CO.

The emissions inventory was determined by applying the appropriate emission factors to the vehicle fleet inventory information that was provided by NCDOT. This information included an itemized list of all backhoes, front-end loaders, and motor graders that are on record for NCDOT. For example, the vehicle fleet inventory information provided fuel usage data for 2005 and 2006, as well as the model year and engine horsepower for each vehicle. The fuel usage data included the gallons of petroleum diesel and B20 biodiesel that were used by each vehicle. These data were averaged over two years to estimate an annual average.

The average annual emissions were calculated based on the average annual fuel use and the emission factor for each type of vehicle for the appropriate engine tier and fuel. Three scenarios were considered: (a) the current mix of B20 and petroleum diesel; (b) 100% usage of petroleum diesel; and (c) 100% usage of B20. The latter two were bounding cases for comparison with the status quo.

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 including comparisons between fuels and engine tiers, benchmark comparisons, and emissions inventory.

Data Collection

The five backhoes were of 1999 to 2004 model years, with gross vehicle weights (GVW) ranging from 16,000 to 22,000 lbs. GVW. 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 lbs 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 lbs, 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% of the observed raw data. For backhoes, moving, use of the front bucket, and use of the rear bucket accounted for 15%, 27%, and 16% of time, respectively (58% total). For front-end loaders, moving and use of the bucket accounted for 22% and 29% of time, respectively (51% total). For motor graders, moving and use of the blade each accounted for 29% of time (58% total).

When testing nonroad vehicles, the PEMS is located on an exterior surface of the vehicle and thus is subject to ambient temperatures. The PEMS overheats if the ambient temperature exceeds 90^{o}F. Furthermore, vapor in the exhaust gas sample line can freeze if ambient temperatures are below freezing. Thus, data could be collected only when ambient temperatures were between 32 and 90^{o}F. 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 time periods with acceptable ambient temperatures, 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 schedule, confirm, or reschedule data collection.

Quality Assurance

On average, 6.9% of raw second-by-second data were because of errors 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% to as high as 17%. 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. Also, other types of errors occurred at very low frequency (0.23% 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 highest 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 Tier 2 and Tier 3 motor graders also had a high proportion of non-detects on both fuels.

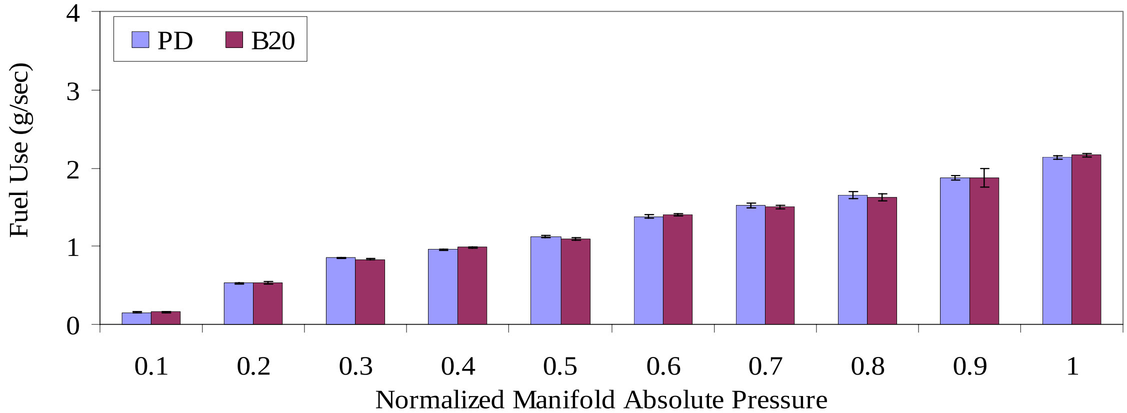
Exploratory Analysis

Based on statistical analysis of the processed second-by-second data, MAP was typically found to be the engine parameter most highly correlated with fuel use and emission rates. The rank correlation of MAP with each of these rates often exceeded 0.95, except for NO and opacity for which the rank correlation was 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.

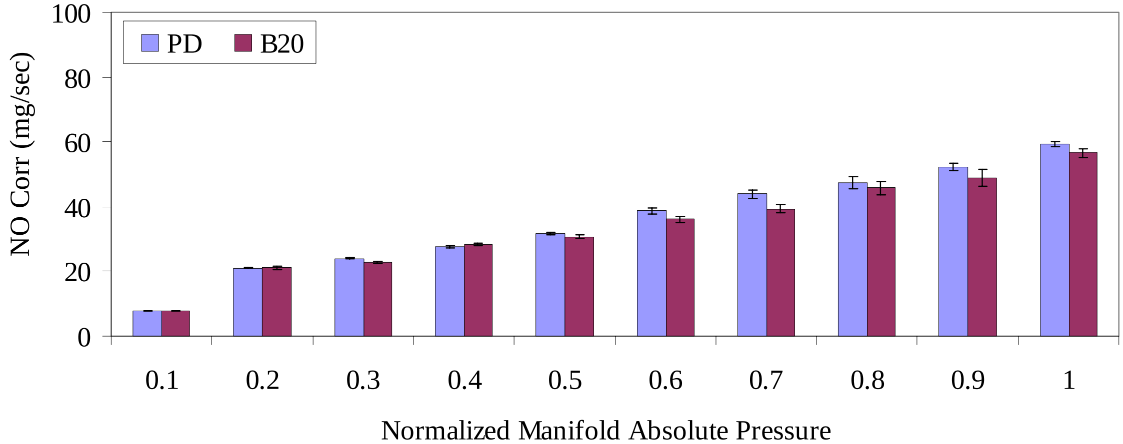
Time series plots of engine data, fuel use rate, and emission rates were used to visualize the association between these rates and engine data. Typically, a peak in MAP is associated with a corresponding peak in fuel use and emission rates.

Modal Emission Rates

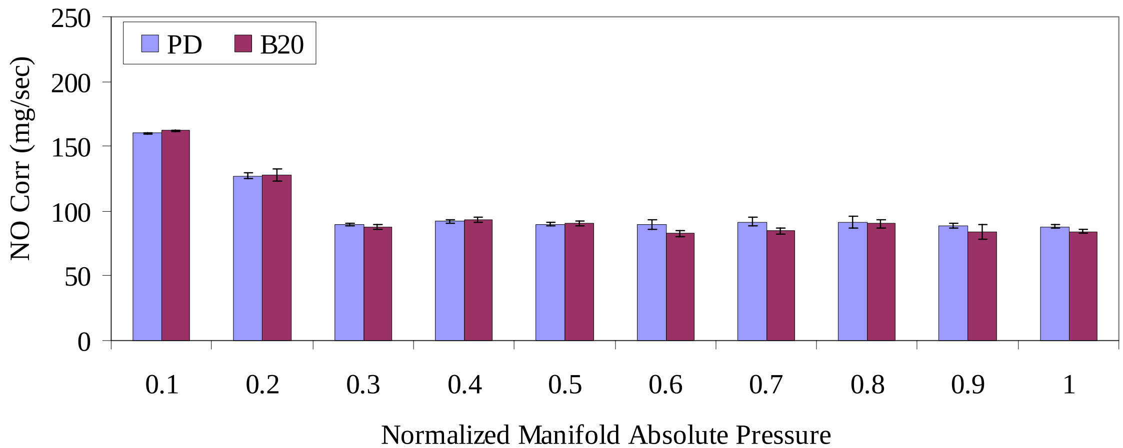
Modal emission rates were estimated for each vehicle. An example is shown for Backhoe 1 in Figure ES-1 for engine-based modal fuel use and NO emission rate and in Figure ES-2 for task-oriented modal rates. The NO emission rates are shown on a per time and per gallon basis. The NO emission rates have been corrected to a standard temperature and humidity based on a regulatory methodology. 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, calculated 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.



(a) Time-based fuel use rate

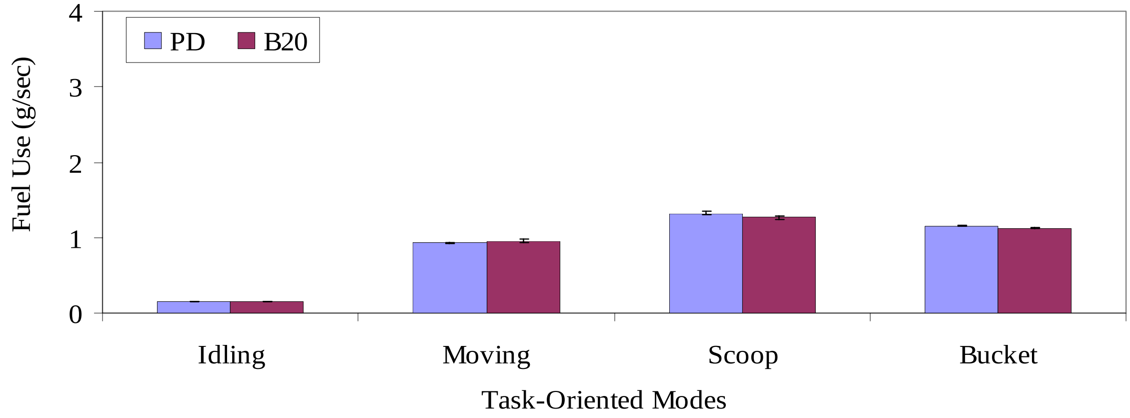


(b) Time-based NO as equivalent NO_2 emission rate, corrected for ambient temperature and humidity

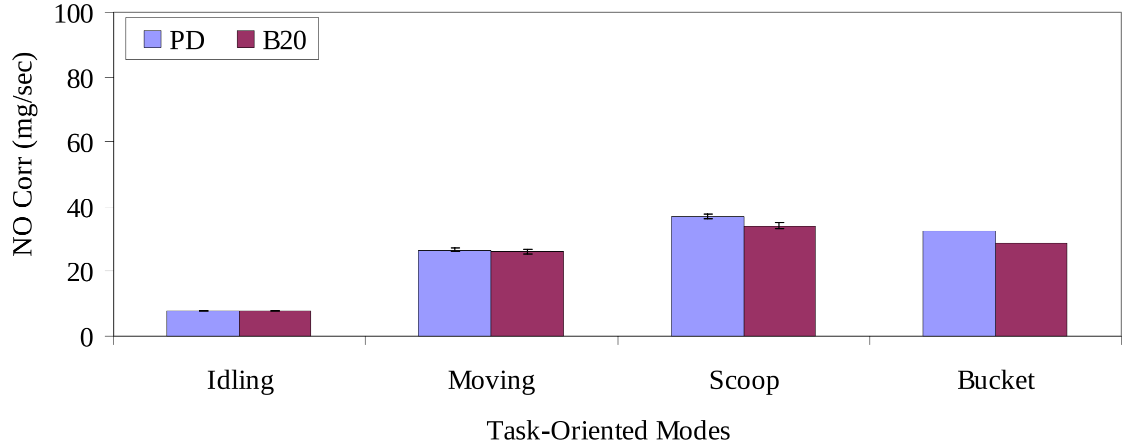


(c) Fuel-based NO as equivalent NO_2 emission rate, corrected for ambient temperature and humidity

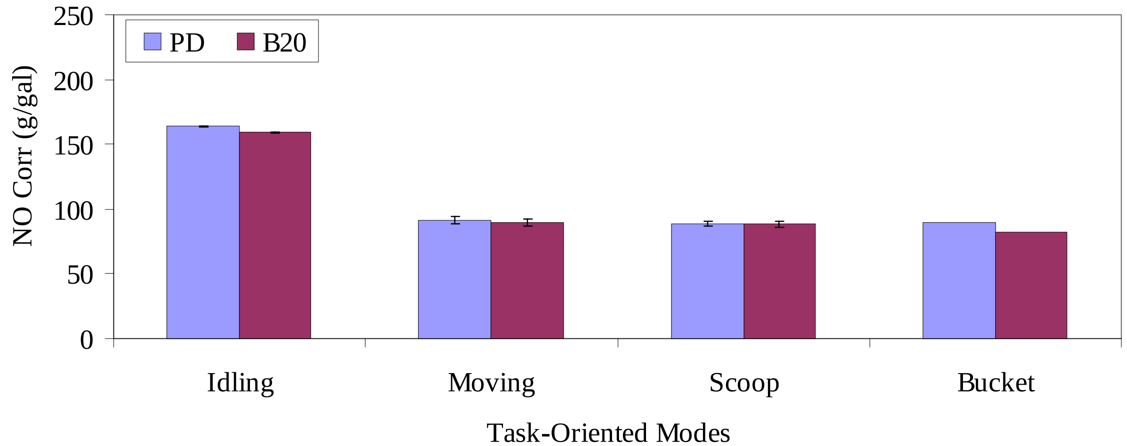
Figure ES-1. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and NO as Equivalent NO_2 Emission Rates for Engine-Based Modes for Backhoe 1



(a) Time-based fuel use rate



(b) Time-based NO as equivalent NO_2 emission rate, corrected for ambient temperature and humidity



(c) Fuel-based NO as equivalent NO_2 emission rate, corrected for ambient temperature and humidity

Figure ES-2. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and NO as Equivalent NO_2 Emission Rates for Task-Oriented Modes for Backhoe 1

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. As shown in Figure ES-1, the 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% 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. On a fuel-basis, the 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 here, the emission rates of HC, CO, and PM are substantially lower for B20 versus petroleum diesel (see main body of report).

The example results in Figure ES-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.

Representative Duty Cycles

In order to estimate average emission rates, representative 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 re-grading the shoulders of a road. These two cycles have significant differences in average engine load, as shown in Figure ES-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.

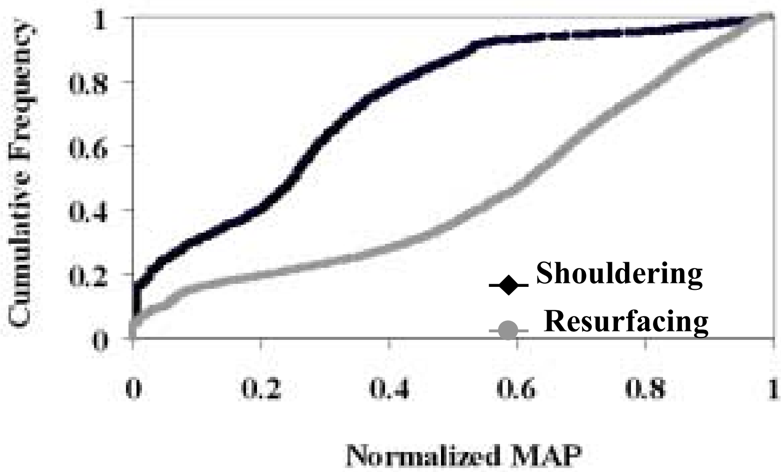


Figure ES-3. Cumulative Frequency of Normalized Manifold Absolute Pressure (MAP) for Shouldering and Resurfacing Duty Cycles for Motor Graders

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 an increase in engine tier. For example, the Tier 3 motor grader has emission rates approximately 50% 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 for all 15 vehicles tested, NO emission rates are 2% lower for B20 than petroleum diesel, which is not a statistically significant result. However, emission rates are lower by 18%, 26%, and 25% 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 emission rates 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% for backhoes, depending on the pollutant;15 – 57% for front-end loaders, depending on the pollutant (for Tier 1 to Tier 2 comparisons only); and 41% to 76% for 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, the motor grader 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 only a few exceptions.

Table ES-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 as Equivalent NO_2 (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 ES-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]	SHC[b]	LTC[c]	RHC[a]	SHC[b]	LTC[c]
NO as Equivalent NO_2 (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] SHC: Soil 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 ES-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 as Equivalent NO_2 (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

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 nearly all the comparisons between the results of the study and the NONROAD results, the emission factors are of similar magnitude.

In contrast, for the opacity measurements from the PEMS, the inferred emission rates are substantially lower than the PM emission rates based on 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.

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 that was placed in service in May 2007 and for which no historical data were available. The observed fuel usages rates were, on average, 6% 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 1.1 to 4.8 gallons per hour based on the PEMS data.

Emissions Inventory

The emissions inventory showed that the current fuel mix of B20 biodiesel and petroleum diesel that was used in the tested vehicle types produced slightly lower levels of emissions, by approximately 0.4% to 6.4% depending on the pollutant and the vehicle type, than the use of petroleum diesel only. However, if NCDOT were to use 100% B20 biodiesel in the same vehicle types instead of the current fuel mix, then emissions reductions would be approximately 2.0% to 36.9% lower than emissions from the current fuel mix of B20 biodiesel and petroleum diesel, depending on the pollutant.

Although higher tier vehicles have lower emission factors, they tend to be utilized more extensively than lower tier vehicles and, therefore, may have higher total emissions even though their emission rates are lower. For example, the estimated average annual emissions of NO_x for motor graders with Tier 0, Tier 1, and Tier 3 engines are 253 lbs/yr, 445 lbs/yr, and 524 lbs/yr, respectively.

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 activities that are influenced by extreme ambient conditions that affect 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, the use of additional foam padding and protection for the PEMS, or collecting data in the maintenance yard where less extreme conditions prevail.

As a result of substantial attention to data quality with respect to data collection, the overall frequency of problems that lead to a loss of data was only 6.9%.

MAP was found to be highly associated with variability in fuel use and emission rates and thus is a useful and practical basis for developing modal emission rates 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 sensitive 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 by 18 to 24 percent 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 with lower tier engines in the equipment inventory. Thus, an agency such as NCDOT can claim tailpipe emissions benefits from the combining the use of B20 with the replacement of 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 vehicle activity is quantified in terms of metrics typically used for a given activity, such as cubic yards of dirt moved. The results here support recommendations to expand the use of B20 throughout the NCDOT inventory of backhoes, front-end loaders, and motor graders, and to replace older vehicles with newer ones, in order to reduce tailpipe emissions.

1.0 INTRODUCTION

According to the U.S. Environmental Protection Agency (EPA), most Americans living in urban areas breathe air that does not meet National Ambient Air Quality Standards (NAAQS) for either ozone or particulate matter. Heavy duty diesel vehicles, including both onroad and nonroad vehicles, emit significant amounts of nitrogen oxides (NO_x) which is a precursor to ozone formation and particulate matter. In North Carolina, 30 counties are within 8-hour ozone non-attainment areas and 3 counties are within particulate matter (PM-2.5) non-attainment area as of June 2007. Heavy duty diesel vehicles contribute substantially to statewide emissions of nitrogen oxides (NO_x) and particulate matter, including particulate matter less than 2.5 microns in aerodynamic diameter. The proper management of emissions will become increasingly critical to the economic growth of North Carolina because effective control measures will be needed in order to come into attainment of the National Ambient Air Quality Standards.

Unlike emissions trends for on-road vehicles, emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and VOC (volatile organic compounds) from nonroad engines and vehicles increased steadily from 44 percent to 110 percent, depending on the pollutant, from 1970 to 2006 (EPA, 2007). In 2005, nonroad diesel construction vehicles were estimated to emit annual U.S. national totals of 657,000 tons of NO_x, 1,100,000 tons of CO, 63,000 tons of PM_{10}, and 94,000 tons of SO_2 (Environ, 2005).

Over time, increasingly stringent regulations have been implemented to reduce tailpipe emissions of NO_x and particulate matter from diesel vehicles. Onroad diesel vehicles have been subject to increasingly stringent regulation over the years. Nonroad diesel equipment is now coming under increased scrutiny. 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 most stringent of these standards, Tier 4, are to be phased-in over the period of 2008-2015. The Tier 4 standards require that emissions of PM and NO_x be further reduced by about 50% and 90%, respectively, compared to the current emission standard of Tier 3 (EPA, 2004; CARB 2004). However, the existing vehicle fleet will emit pollutants at higher rates than Tier 3 and Tier 4.

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

On-board emissions measurement is widely recognized as a desirable approach for measuring emissions from vehicles, since data are collected under real-world conditions in the driving environment (Cicero-Fernandez and Long, 1997; Gierczak et al., 1994; Tong et al., 2000). Compared to dynamometer-based measurement methods, the advantage of on-board measurement is that it is possible to obtain real-world in-use data that is representative of actual operation and emissions. On-board measurement systems have had limited applicability because of high cost. However, in the last few years, efforts have been underway to develop lower-cost instruments capable of measuring both vehicle activity and emissions (e.g., Scarbro, 2000; Vojtisek-Lom and Cobb, 1997). On-board Portable Emissions Measurement Systems (PEMS) are relatively simple and inexpensive. These systems are designed for measuring in-use emissions during real-world operations under any ambient conditions, traffic conditions, and operational/duty cycles. Initially, PEMS have had the capability to measure HC, NO, CO, and CO_2 emissions using repair-grade gas analyzers (Kihara and Tsukamoto, 2001). More recently, PM measurement capabilities have been added to some PEMS systems (CATI, 2003). The key advantage of a PEMS over a more complex on-board measurement system is that it can be installed more easily in a wide variety of vehicles. Thus, it is possible to collect on-board, in-use, real-world emissions data during actual duty cycles. Whereas the complex systems can weigh hundreds or thousands of pounds, the portable systems might typically weigh 30 to 100 pounds, and can typically be installed in about an hour or less. The connections of the portable system to the vehicle are typically reversible and no modifications are necessary in many cases.

There is a substantial lack of real-world representative data from which to accurately estimate construction vehicle emissions. The EPA, West Virginia University (WVU), and Clean Air Technologies International, Inc. (CATI), have separately conducted on-board in-use measurements to characterize emissions from construction vehicles (May *et al*, 2002; Gautam *et al.*, 2002; Vojtisek-Lom, 2003). However, not all of these data were quality assured or publicly available. It was not possible to investigate the relationship between vehicle's activity patterns and emissions and fuel consumption. Therefore, there is a need to quantify energy use and emissions from construction equipment based on in-use measurement methods. NCDOT is using biodiesel fuel (B20) and buying new vehicles to replace old ones. There is a need to assess the differences in exhaust pipe emissions when using B20 biodiesel versus petroleum diesel and the benefits of newer vehicles versus older vehicles with respect to exhaust emission rates.

Petroleum diesel fuel is a complex mixture of many different hydrocarbons with carbon numbers in the range of C9 to C28 and with a distillation range of 350 to 640°F. The hydrocarbon composition influences many of the fuel's properties, including ignition quality, heating value, volatility, and oxidation stability (Flagan and Seinfeld, 1998). The petroleum diesel that was used in the vehicles that were tested in this study was ultra-low sulfur diesel fuel (ULSD), which has a sulfur content of 15 parts per million (ppm) or less.

Biodiesel is a naturally oxygenated and possibly cleaner burning diesel replacement fuel made from natural, renewable sources such as new and used vegetable oils or animal fats. It can be used directly in diesel engines without major modifications to the engines and vehicles (EPA, 2002). Biodiesel can be blended with petroleum diesel fuel in any ratio. A common blend rate is 20% renewable source and 80% petroleum diesel. Biodiesel is registered as a fuel and fuel additive with the U.S. EPA (Bockey, 2004; Coltrain, 2002). The biodiesel that was used in the vehicles that were tested in this study was soy-based B20. The B20 fuel composition included 80% ULSD and 20% ASTM-compliant B100 blend stock. These two components were splash-mixed to achieve the B20 biodiesel fuel.

However, use of biodiesel fuel can lead to clogging of a fuel filter. Biodiesel fuel has a strong solvent action, and thus can dissolve residues in the fuel tank and fuel line. These dissolved residues can cause clogging of the fuel filter (Tyson, 2001). Thus, a typical need is to replace or enlarge fuel filters when switching from petroleum diesel to biodiesel.

Comparing B20 biodiesel versus petroleum diesel, a review of available engine dynamometer test data for a variety of diesel engines indicates that there is a reduction in the emission rate of PM, CO, and HC and an increase in the emission rate of NO_x. These results are based upon analysis of a database compiled by the U.S. EPA. EPA has analyzed the data by general categories of engine types. An overall average among all engine types is that emissions decreased for B20 biodiesel versus petroleum diesel by 10% for PM, 11% for CO, and 21% for HC, but increased by 2% for NO_x. Fuel quality has been shown to be important with respect to NO_x emissions in diesel engines (Sluder *et al*., 2006). Therefore, there is a need to further evaluate the differences in emissions for B20 biodiesel versus petroleum diesel under real world conditions.

1.1. Motivation

The key problems addressed by this work are the following:

- Lack of quantification of real-world, representative duty cycles for specific types of construction equipment used in North Carolina;
- Lack of ability to accurately estimate real-world emissions for construction equipment because of lack of emissions data that can be correlated with specific characteristics of duty cycles;
- Lack of baseline duty cycles and emissions estimates that can be used as a basis for evaluating operations (e.g., to improve fuel use or reduce emissions) and to develop emissions inventories; and
- Lack of a case study to provide a method for developing a vehicle emissions inventory.

1.2. Research Objectives

The primary objectives of this work are as follows:

- Measure real-world, in-use duty cycles in North Carolina for specific types of construction vehicles;
- Simultaneously measure real-world, in-use emissions;
- Develop recommended duty cycles and emissions estimates (for individual equipment) to use as a basis for evaluating operational procedures (e.g., with respect to fuel use and emissions) and as a basis for developing emissions inventories; and
- Develop a case study to demonstrate how real-world duty cycles and emissions estimates, as well as existing emissions data, should be used to develop emissions inventories for the NCDOT fleet.

1.3. Overview of the Document

In this document, a methodology for collecting and analyzing real-world in-use data from nonroad construction equipment is presented. The methodology presented here is being used to measure the in-use activity and emissions of construction vehicles such as backhoes, front-end loaders, and motor graders. The findings and conclusions will improve the characterization of in-use activity and emissions of these vehicles, which can further support development of improved emissions inventories and approaches to air quality management.

Supplemental information is provided in the report Appendices. The following is a brief summary of the information included in each appendix:

Appendix A: Specifications for Tested Backhoes, Front-End Loaders, and Motor Graders
This appendix provides information about the vehicles that were monitored. This information includes the identity of the vehicle, the characteristics of its chassis and engine, and who was in charge of the use of and access to the vehicle. Information about the owner of the vehicle is also included in this appendix.

Appendix B: Summaries of Quantity of Data and Site Conditions for Each Tested Vehicle
This appendix provides information related to the amount of time that data were collected for each vehicle. This appendix provides quantities for the amount of raw data that was collected in the field for each task-oriented activity mode and the amount of raw data that has been processed through quality assurance. The amount of raw data and processed data for each activity mode is given for each vehicle that was tested.

Another necessary part of the data collection process was to assess and record the field conditions at the site where the construction vehicle was working and to record the nature of that work. This appendix includes site condition information such as location, weather conditions, and terrain that was gathered for each test. This appendix also contains information about the work activity being performed by the vehicle, as well as a brief description of the modes that were recorded during the work activity.

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

Appendix D: Data Screening and Quality Assurance
This appendix provides details and explains the data screening and quality assurance procedures. Data screening and quality assurance procedures were developed to review data collected in the field to determine whether any errors or problems exist in the data, to correct such errors or problems where possible, and to remove invalid data if errors or problems cannot be corrected. The goal of data screening and quality assurance is to produce a database that contains valid data.

Appendix E: Description of Macros Developed for Data Screening and Quality Assurance of On-Board Data Collected from Nonroad Construction Equipment
The objective of this appendix is to explain the algorithms and computer programs developed for quality checks and preliminary analyses of data. This appendix describes the user interface used to view inputs and outputs of the quality check and analysis programs. All programs were

written in Visual Basic. The programs can be used as the macros incorporated with Microsoft Excel.

Appendix F: Measured Time-Based Modal Fuel Use and Emission Rates and Fuel-Based Emission Rates for Engine and Task Oriented Modes for All Tested Vehicles

Appendix F provides supplementary Figures and Tables for Section 3.6. Emission rates results for five backhoes, four front-end loaders, and six motor graders are summarized in this appendix. Summaries of the test ID, vehicle ID, engine type of tested vehicles, and test date for each fuel are provided. The pollutants for which emission rates are reported include CO_2, CO, HC, NO as Equivalent NO_2, and PM.

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

- Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes
- Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Based Modes
- Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes
- Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes

Based on engine-based MAP bins, modal emission rates for fuel use, CO_2, HC, CO, and opacity are presented on a time basis for both petroleum diesel and B20 biodiesel. Also, a comparison of engine-based average modal emission rates for CO, HC, NO as Equivalent NO_2, and PM for the two fuels on a per unit of fuel consumed basis is given. A comparison of the two fuels with respect to fuel use and emission rates for the task-oriented modes is given for a time basis and for a fuel consumed basis.

Appendix G: Evaluation of Non-Detected Measurements of HC and CO Exhaust Gas Concentrations On Modal Average Emission Rates For Engine-Based Modes

This appendix documents the modal average concentrations of each pollutant for each of the engine-based modes. Cases in which the average modal concentration is below a detection limit are indicated.

Appendix H: Supplementary Tables for Emissions Inventory

The tables in this appendix document the intermediate data that was used to make the comparisons of emissions based on fuel type and engine tiers reported in Section 3.12 of this report. These tables show the average annual fuel use for petroleum diesel and B20 biodiesel, the emission factors for petroleum diesel and B20 biodiesel, and the resulting estimated average annual emissions for petroleum diesel and B20 biodiesel. This data is classified by engine tier for the backhoes, front-end loaders, and motor graders and results are provided for NO as equivalent NO_2, opacity, HC, and CO.

2.0 METHODOLOGY

This chapter describes the methodology that was used to collect emissions and equipment data in the field and the methods used to prepare the collected data for analysis. This section addresses the following topics:

1. Development of the study design.
2. Instrumentation.
3. Field Data collection procedures.
4. Data collection problems and solutions.
5. Data screening and quality assurance.
6. Description of macros developed for data screening and quality assurance of on-board data collected from nonroad construction equipment.
7. Exploratory analysis of data.
8. Determination of representative duty cycles for backhoes, front-end loaders, and motor graders.
9. Emission factors for B20 biodiesel and petroleum diesel based on representative duty cycles.
10. Non-detected measurements of HC and CO.
11. Benchmarks of measured emission rates based on the NONROAD model.
12. Benchmarks of observed fuel use rates versus NCDOT maintenance data.
13. Development of emissions inventory.

2.1 Development of the Study Design

The key elements of a study design for field data collection of in-use activity and emissions are briefly summarized here:

- **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 NCDOT used the instrumented vehicles to conduct normal road maintenance tasks. For backhoes, such tasks included loading dump trucks with dirt, mass excavation, and material handling. For front-end loaders, typical tasks included rock handling, soil handling, and loading dump trucks. Motor graders were typically used for resurfacing unpaved roads or for grading of road shoulders. However, as a result of damage sustained to the PEMS as a result of extreme vibrations, particularly for backhoes and front end loaders, some of the data collection on these vehicles was conducted at the equipment maintenance yard for the same kinds of duty cycles but for less severe terrain.
- **Data Collection Scheduling –** Each vehicle was tested during one day on B20 biodiesel and one day on petroleum diesel. Thus, there were a total of 30 field tests of the 15 tested vehicles. 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 maintenance yard supervisor. Typically, the operator performed normal tasks as required by the NCDOT 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 the work schedule because of maintenance project needs, or there may be unanticipated problems with the nonroad vehicle or the PEMS that resulted in data collection delays.

2.2 Instrumentation

The PEMS used here was the Montana system manufactured by CATI, Inc. The Montana measures second-by-second mass emissions from vehicles with electronically controlled sparked ignition and diesel engines. For vehicles with diesel engines, the Montana collects emissions data (using a sample probe inserted into the tailpipe) for the following pollutants:

- Nitric Oxide (NO)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO_2)
- Hydrocarbons (HC)
- Particulate Matter (PM)

The Montana has two gas analyzers and a particulate matter (PM) sensor. The gas analyzers monitor the emissions from the vehicle and the information they collect is recorded on a portable disc. This enables the data to be transferred to the laboratory for analysis.

The Montana is contained in a carry-on luggage-sized case and weighs approximately 44 pounds. It may be powered by the battery of the vehicle's electrical system or by an external battery mounted on the vehicle by the research team. Figure 1 shows the components of the Montana system.

- Computer
- Power Panel
- Main Housing Unit
- Gas Analyzers and Sensors Inside of Main Housing Unit
- Cables and Sampling Hoses

Figure 1. Montana System Components

The Montana uses a sensor array that connects to the vehicle's engine to obtain engine data. The variables of most interest are manifold absolute pressure, intake air pressure, and revolutions per minute. The sensor array is connected to the engine during the pre-installation phase.

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

Because the NO and O_2 sensors deteriorate slowly with use, they have to be calibrated at a frequency between once per week and once per month during data collection. After pre-installation, the main unit of the Montana system is brought to the laboratory and calibrated with a standard cylinder gas mixture. When performing calibration, the PEMS must be warmed up for 45 minutes. The calibration procedure is (Vojtisek-Lom and Allsop, 2001; Vojtisek-Lom, 2003):

1. To access the calibration function for gas analyzer number 1, press the "shift" key and the "1" key simultaneously. From the Service and Calibration Menu select the "C" key to enter the calibration subroutine.
2. Follow the on-screen instructions to perform the calibration.
3. The program will report either a failed calibration or that the test has been completed.
4. The "calibration completed" notification is the only indication that the calibration has passed.
5. This process must then be repeated for gas analyzer number 2. To access the calibration function for gas analyzer number 2, press the "shift" key and the "2" key simultaneously. From the Service and Calibration Menu select the "C" key to enter the calibration subroutine.
6. Follow the on-screen instructions to perform the calibration.

The calibration gas mixture recommended when data is to be collected from diesel engines is 200 ppm propane (C_3H_8), 0.5 *vol*-% carbon monoxide (CO), 6.0 *vol*-% carbon dioxide (CO_2) and 300 ppm nitric oxide (NO). There is no O_2 in the calibration mixture gas. During calibration, neither of the gas analyzer benches should detect O_2. If the O_2 concentration is higher than zero, then some leakage may have occurred inside the Montana system. There is some trade-off in that the PEMS measurement methods may not be as accurate or precise as those of the more complex and expensive equipment used in more permanent on-board installations, such as the large tractor trailers at EPA or UCR. However, PEMS have been compared with dynamometer measurements on the same test cycles and have been found to have adequate accuracy and precision (Vojtisek-Lom, 2003; Cowen et al., 2001)

2.3 Field Data Collection Procedures

This section describes a general description of the methods that were used to collect emissions and vehicle data during field tests. A more detailed description of these procedures and the instrumentation used for data collection is included in Appendix C.

The study team usually consisted of two or three individuals. There were four chronological components of the overall data collection process. These components were:

1. Pre-installation
2. Installation
3. Data Collection
4. Decommissioning

2.3.1 Pre-Installation

Pre-installation occurred the day before the data is actually collected from the construction vehicle. The purpose of pre-installation was to perform the following tasks:

- Install the safety cage on the vehicle. The safety cage securely holds the (PEMS) during the data collection process and helps to protect the PEMS from damage.
- Install the PEMS sensor array on the vehicle's engine. The sensor array is used to collect engine data such as manifold absolute pressure (MAP), intake air temperature (IAT), and revolutions per minute (RPM).
- Install the external battery on the vehicle. A separate battery is provided to power the PEMS so that the vehicle's battery is not required to provide power to the PEMS.
- Install various cables, hoses, and sampling lines on the vehicle. These items are used to gather emissions data and transmit it to the PEMS.

These steps are performed the day before data collection because each individual step takes approximately 10 – 30 minutes to complete and they cannot be completed during the morning that the vehicle is placed into service. Furthermore, additional steps need to be completed during the morning of data collection. Table 1 shows the typical time period and range of time needed to complete the pre-installation procedures for each type of vehicle that was tested.

2.3.2 Installation

On the day that data was to be collected, the research team typically arrived at the construction site approximately two hours before data collection was to begin in order to prepare the PEMS. The difference between pre-installation and installation is that installation is done before the vehicle operator starts working on the test day, whereas pre-installation is done the day before the test. When the installation is done, the PEMS is ready to collect data from the construction vehicle. Table 2 shows the typical time period and range of time needed to complete the installation procedure for each type of vehicle that was tested. There are three tasks that must be completed during the installation procedure:

1. Install and use the Montana system
2. Prepare and use the laptop computer
3. Prepare and use the video camera

Table 1. Typical Time Period for Pre-installation Based on Vehicle Type

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

Table 2. Typical Time Period for Installation Based on Vehicle Type

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

2.3.2.1 Montana System

The main unit of the Montana is typically mounted on the roof of the vehicle in the safety cage so that it will not interfere with the operation of the vehicle. The purpose of the safety cage is to protect the Montana from damage during the operation of the vehicle. Foam padding is placed inside the safety cage to minimize vibration from the vehicle. A thin cloth dust cover is placed over the safety cage to prevent dust from entering the main unit of the Montana. A reflective sun cover is placed on top of the safety cage to help prevent the Montana from overheating.

The Montana is placed inside the safety cage and securely mounted to the roof of the vehicle. Figure 2 shows the Montana system and the external battery mounted on a motor grader. There are two reasons for placing the Montana on the roof of the vehicle. The first is so that the Montana will not interfere with the operation of the vehicle and the second is so that the research team members can have access to the Montana to check its status. The external battery is also located in an area that will not interfere with the operation of the vehicle. Although the vehicle's battery may be used to power the Montana, the research team always used a separate battery to minimize the number of connections to the vehicle's systems. The location of the Montana and the battery varied among different types of vehicles.

After installation on the vehicle, the Montana system must be warmed up for 45 minutes before data collection can begin. If the Montana has been installed properly, it will collect emissions data automatically and autonomously as the construction vehicle operates.

2.3.2.2 Laptop Computer

A second computer that is not part of the Montana system is used to collect and record modes of activity for each construction vehicle. Although the laptop computer is not directly connected to the Montana, it is coordinated with it via the laptop computer's internal clock. Therefore, the modes of activity of the vehicle can be directly correlated to its air pollutant emissions. The clock of the laptop computer is synchronized with the clock of the Montana to provide a second-by-second analysis of the emissions, based on the vehicle's mode of activity. The laptop computer is then ready to record modal activity of the construction vehicle that can now readily be linked to emissions as well as to engine performance.

During the data collection process, the research team follows the construction vehicle at a safe distance without interfering with the vehicle's operation. The objective is to collect modal activity data without interrupting the productivity of the vehicle.

Recording modal activity is accomplished by using the numeric keypad of the laptop computer. Each activity mode of the construction vehicle is linked to a keypad number. For example, the activity modes and their corresponding number for a motor grader are as follows:

1. Idling
2. Moving
3. Blade

Each time the motor grader begins one of these activity modes, the corresponding number is pressed on the numeric keypad. For example, when the motor grader begins to idle, the 1 key is pressed on the keypad; when the motor grader begins to move forward without using the blade, the 2 key is pressed on the keypad; when the motor grader moves while using the blade, the 3 key is pressed on the keypad. Since the time is recorded for each keystroke, the duration of each recorded activity mode can be determined. Both the Montana system and the laptop computer are synchronized to the current time before data collection begins. Furthermore, the emissions data from the Montana system are compared to the modal data from the laptop computer to provide a detailed timeline of emissions activity for the construction vehicle.

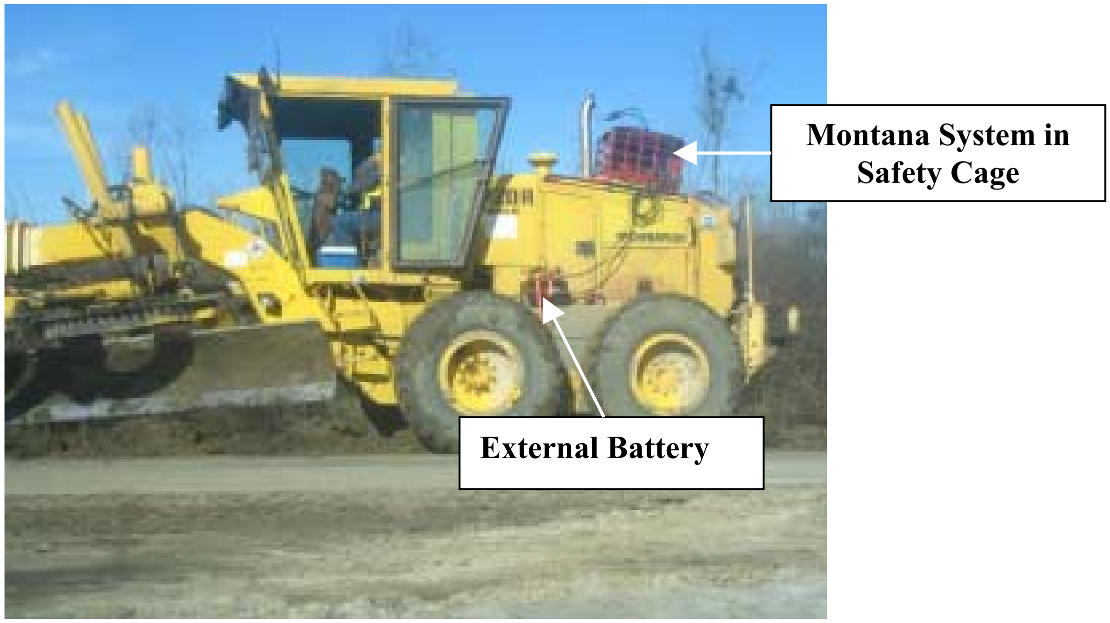


Figure 2. Montana System and External Battery Mounted on a Motor Grader

2.3.2.3 Video Camera

A video camera (camcorder) is used to record the activity pattern of the construction vehicle at the construction site. The camcorder is set up in a location that enables it to observe all activities of the construction vehicle, but without interfering with the work of the construction vehicle. Figure 3 shows a research team member using the camcorder to record activity of a vehicle at a construction site.

The camcorder records the following:

- The typical activity mode of operation
- The type of work being done at the site
- The project site characteristics, including terrain and weather

Enough video data is obtained to document the typical work activities and patterns being measured and the activity modes of the construction vehicle. This can usually be done with approximately 15 to 30 minutes of video. It is not necessary to record everything that the vehicle does, but only those activities that represent the typical activity modes for which data is collected. In addition, a general panoramic view of the job site is recorded to show the working conditions of the vehicle. Essentially, the video enables the data collection team to gather another form of data (visual) regarding the site, the vehicle, and the work performed by the vehicle. This is done to allow a visual analysis in case anomalies arise in the data that might be explained by an unusual or unanticipated duty cycle or operator activity.

Figure 3. Recording Work Activities Using the Camcorder

2.3.3 Data Collection

Data collection begins after the preliminary activities of pre-installation and installation have been completed. A part of the data collection process itself has already been described in the previous section titled “Installation”. The following activities are related to data collection:

- Assess and record field conditions
- Collect and record vehicle data
- Managing field data

2.3.3.1 Assess and Record Field Conditions

A necessary part of the data collection process is to assess and record the field conditions at the site where the vehicle is working and to record the nature of that work. This is done by completing the Construction Site and Activity Information field sheet. This sheet enables information such as location, weather conditions, and terrain to be gathered. The sheet also contains information about the work activity being performed by the vehicle, as well as a brief description of the modes that are recorded during the work activity.

Table 3. Sample Construction Site and Activity Sheet for a Motor Grader

		Motor Grader
General	**Project ID**	NCDOT MG4 PD
	Project	Dirt Road Maintenance
	Location	Gralyn Road, Raleigh, NC
	Date	4/03/07
	Time	8:40 AM - 12:00 PM
	Weather	73 F, 44% Humidity
	Terrain	Level
	Soils	Sandy Topsoil
Work Activity	**Activity**	Scraping Dirt Road
	Unit	Miles of road scraped
	Quantity	3.5
	Procedure	1. Lowers blade
		2. Moves forward, scraping top surface of road
		3. Continues until entire road is scraped
Modal Description	**Modes**	1. Idling
		2. Moving
		3. Blade
	Description	All three modes observed

Table 3 shows a sample Construction Site and Activity Information field sheet for a motor grader. The table illustrates a data collection activity for a motor grader performing dirt road maintenance in Raleigh, North Carolina. The motor grader was using the blade to remove ruts from the dirt road. Knowing and recording this was significant because emissions data associated with this activity may be compared to emissions data collected from similar motor grader activities performed at a different site. A copy of all Construction Site and Activity Information field sheets for all the backhoes, front-end loaders, and motor graders that were tested are shown in Appendix B.

2.3.3.2 Collect and Record Vehicle Data

During the data collection process, it is necessary to collect and record information about the vehicle being monitored. This information is recorded in the field on the Vehicle Information field sheet. This sheet includes information about how to identify the vehicle, the characteristics of its chassis and engine, and who is in charge of the use of and access to the vehicle. Information about the owner of the vehicle is also recorded on this sheet. Table 4 shows a sample Vehicle Information field sheet for three Hyundai front-end loaders and one Case front-end loader.

Table 4. Sample Vehicle Information Field Sheet for Front-End Loaders

		Front-End Loader			
Identification	**Project ID**	NCDOT FL01	NCDOT FL02	NCDOT FL03	NCDOT FL04
	Owner ID	010-0249	010-0301	010-5074	010-0388
	VIN	L702EJ10028	L70410264	JFF0060753	LF0210145
Chassis	**Manufacturer**	Hyundai	Hyundai	Case	Hyundai
	Model	HL 740 TM-3	HL 740 TM-3	621B XT	HL740TM-7
	Year	2002	2002	2002	2005
	GVW (lbs)	29,000	29,000	28,000	29,000
	Bucket (cy)	2.5	2.5	2.5	2.5
Engine	**Manufacturer**	Cummins	Cummins	Cummins	Cummins
	Model	B 5.9C	B 5.9C	6T 590	QSB 5.9-C
	Year	2002	2002	2002	2005
	Aspiration	Turbocharged	Turbocharged	Turbo-charged	Turbocharged
	Displacement (L)	5.9	5.9	5.9	5.9
	Cylinders	6	6	6	6
	Horsepower	130	130	126	133
	RPM	2200	2200	2200	2200
	Hours	3,645	9,345	3,569	446
	Fuel	Diesel	Diesel	Diesel	Diesel
User	**Company**	Div 4-Nash Co.	Div 4-Nash Co.	Div 5-Wake Co.	Div. 5-Wake
	Contact	Terry Ellis	Terry Ellis	Jason Holmes	Jason Holmes
Owner	**Name**	Div 4-Nash Co.	Div 4-Nash Co.	Div 5-Wake Co.	Div 5-Wake Co.

Three of these front-end loaders have a chassis and engine with the model year 2002 and one of these front-end loaders has a chassis and engine with the model year 2005. Two of the front-end loaders were assigned to Nash County in Division 4 and two of the front-end loaders were assigned to Wake County in Division 5. Entries in the table that are left blank indicate that this particular information was not collected, either because the information was not able to be determined in the field or because the information was not needed for analysis. All Vehicle Information field sheets are provided in Appendix A.

2.3.3.3 Managing Field Data

Another task was collecting accurate and quantifiable data for emissions from the vehicles that were being monitored. Furthermore, the data were stored and managed in a practical manner so that it was readily available when needed.

Raw data are gathered from the monitoring emissions activities of the vehicles at the job site. Processed data is the data that has later completed the data quality assurance process and is usable for analysis. This data was stored and updated periodically using the Data Collection Summary sheet.

The format of Data Collection Summary sheet is shown in Table 5. The purpose of this table is to enable the research team to monitor the progress of their work. The table shows the number of vehicles that are scheduled to be tested for both biodiesel and petroleum diesel and the number of vehicles that have already been tested for each type of fuel. The table also summarizes the amount of both raw data (hours) and processed data (hours) that has been collected for each activity mode for each type of vehicle.

2.3.4 Decommissioning

When the data collection process has been completed, the research team removes the Montana system and all of its connections from the vehicle. This decommissioning process typically takes approximately thirty minutes to complete, after which all of the equipment is returned to the laboratory to be cleaned and prepared for the next data collection session.

When a data collection session has ended, the data is saved and the laptop computer is turned off. The data is backed up on a compact disc (CD), as well as another computer. The engine emissions data and activity data are later reviewed and screened for quality assurance by the researchers. If there are no errors found in the emissions data, then the emissions data is acceptable for use in emissions analysis. However, there is nearly always a data quality deficiency detected, such as a missing value or an invalid value. Some of these deficiencies can be corrected but some cannot. Only those data that cannot be corrected are excluded from the final database that is used for analysis.

After the video has been recorded for a data collection session, the data collection team returns to the laboratory. The video data is archived on both a digital video disc (DVD) and another computer for future use.

Table 5. Format of the Data Collection Summary Sheet

June 30, 2007

Test Goals							
Target		Completed				Raw Data (hours)	Processed Data (hours)
Bio	Petrol	Bio	Petrol	Vehicle	Mode		
				Backhoe	Idling		
					Moving		
					Bucket		
					Scp/Dmp		
				Front-End Loader	Idling		
					Moving		
					Scp/Dmp		
				Motor Grader	Idling		
					Moving		
					Blade		

2.4 Data Screening and Quality Assurance

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

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

In addition to the development of data screening and quality assurance procedures, a technique for evaluation of the data obtained from diesel engines was developed that involves comparison of the observed air-to-fuel ratio from the data with general expectations for the variability in air-to-fuel ratio for diesel engines as reported by others. This comparison can provide insight regarding whether air leakage might be a problem in the sampling line or gas analyzer of the Montana system. Figure 4 is an overview flow diagram of data quality assurance procedures. A complete description of the data screening and quality assurance process is given in Appendix D.

The mass emission rates of CO_2, NO as Equivalent NO_2, HC, and CO are calculated based on engine data and exhaust concentration. Based on the engine data, the exhaust air molar flow rates are estimated from equations in Appendix D.6.1 entitled “Air-to-Fuel Ratio.” The exhaust concentrations are converted to a mole fraction for each gaseous pollutant. The mass emission rates for each gaseous pollutant are estimated based on the mole fraction and the exhaust air molar flow rates. For PM, the emission rate is calculated based on a reported mass per volume concentration multiplied by the estimated exhaust gas flow rate.

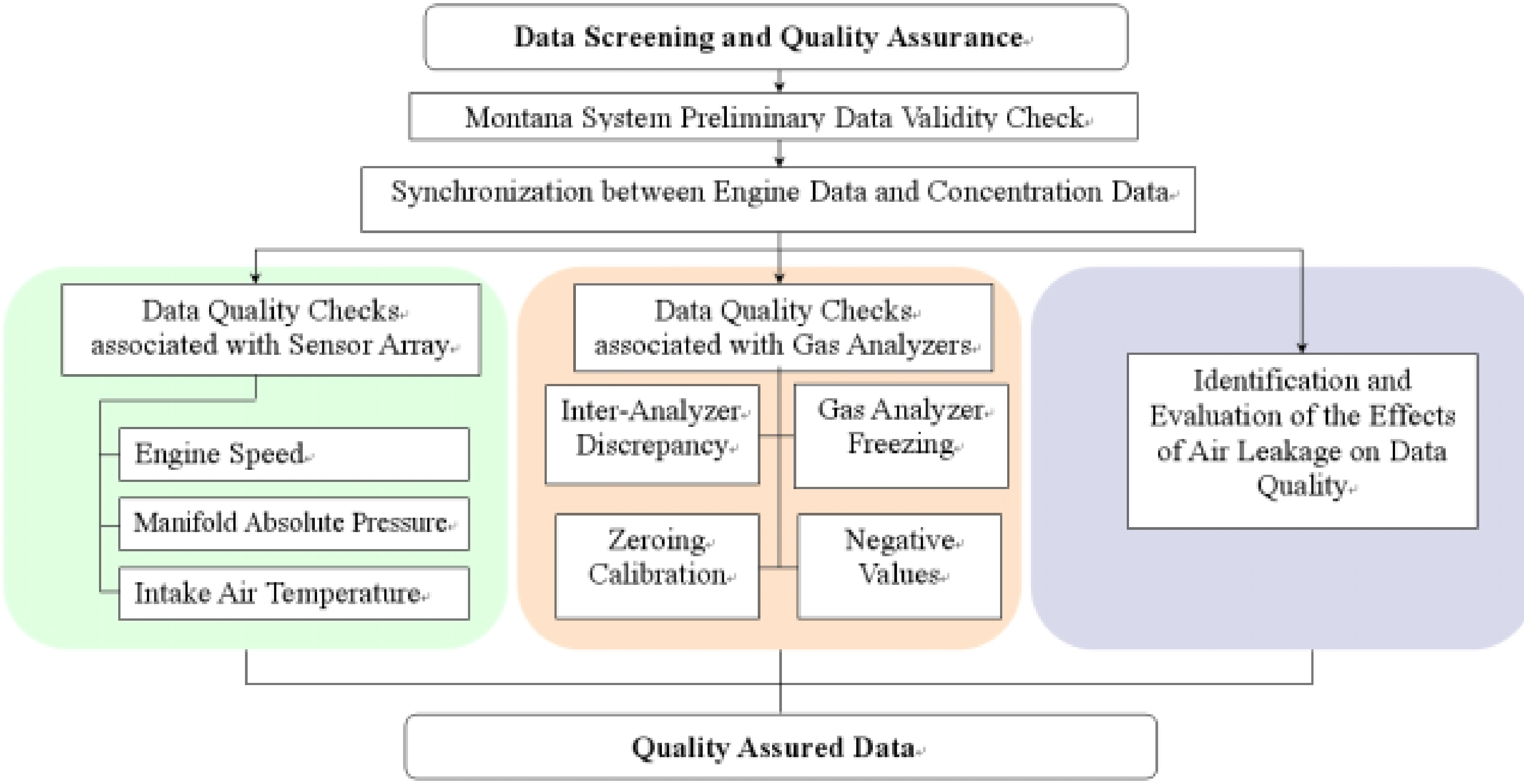


Figure 4. Overview Flow Diagram of Data Quality Assurance Procedures

2.5 Macros Developed for Data Screening and Quality Assurance of On-Board Data

The purpose of this section is to explain the algorithms and computer programs developed for quality checks and preliminary analyses of data. These items provide the user with an interface to communicate with inputs and outputs of the programs. All programs were written in Visual Basic. The programs can be used as macros incorporated with Microsoft Excel.

As shown in Figure 5, for a given set of raw data collected from a nonroad construction vehicle, a quality assured database is developed in 19 steps. Sixteen of these steps are performed running macros and 3 steps are performed manually. The details of these macros are given in Appendix E.

2.6 Exploratory Analysis of Data

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

2.7 Modal Analysis

Second-by-second data for engine data, fuel use, and emissions were analyzed to identify trends in the fuel use and emission rates. One purpose for this type of analysis is to determine whether there are consistent trends in the relationship between emissions and engine activity. Fuel use and emissions were found to be highly correlated with manifold absolute pressure (MAP) of the vehicle's engine. The data were grouped into bins based on specific ranges of normalized MAP and the average rate of fuel use and emissions of NO (nitric oxide), HC (hydrocarbons), carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM) was estimated on a mass per time and mass per fuel consumed basis. Based on the properties of B20 biodiesel (B20) versus petroleum diesel (PD), an average increase in mass-based fuel use rates of 2.2% was expected in order to supply the same amount of chemical energy to the engine. Emission factor units of mass per time are useful if one can estimate the total amount of time that a vehicle is operating in the field. Alternatively, an emission factor in units of mass per gallon of fuel consumed is useful if one can estimate or measure the total fuel use for a vehicle or a fleet of similar vehicles. The following sections explain the engine-based modes and task-oriented modes used in this project.

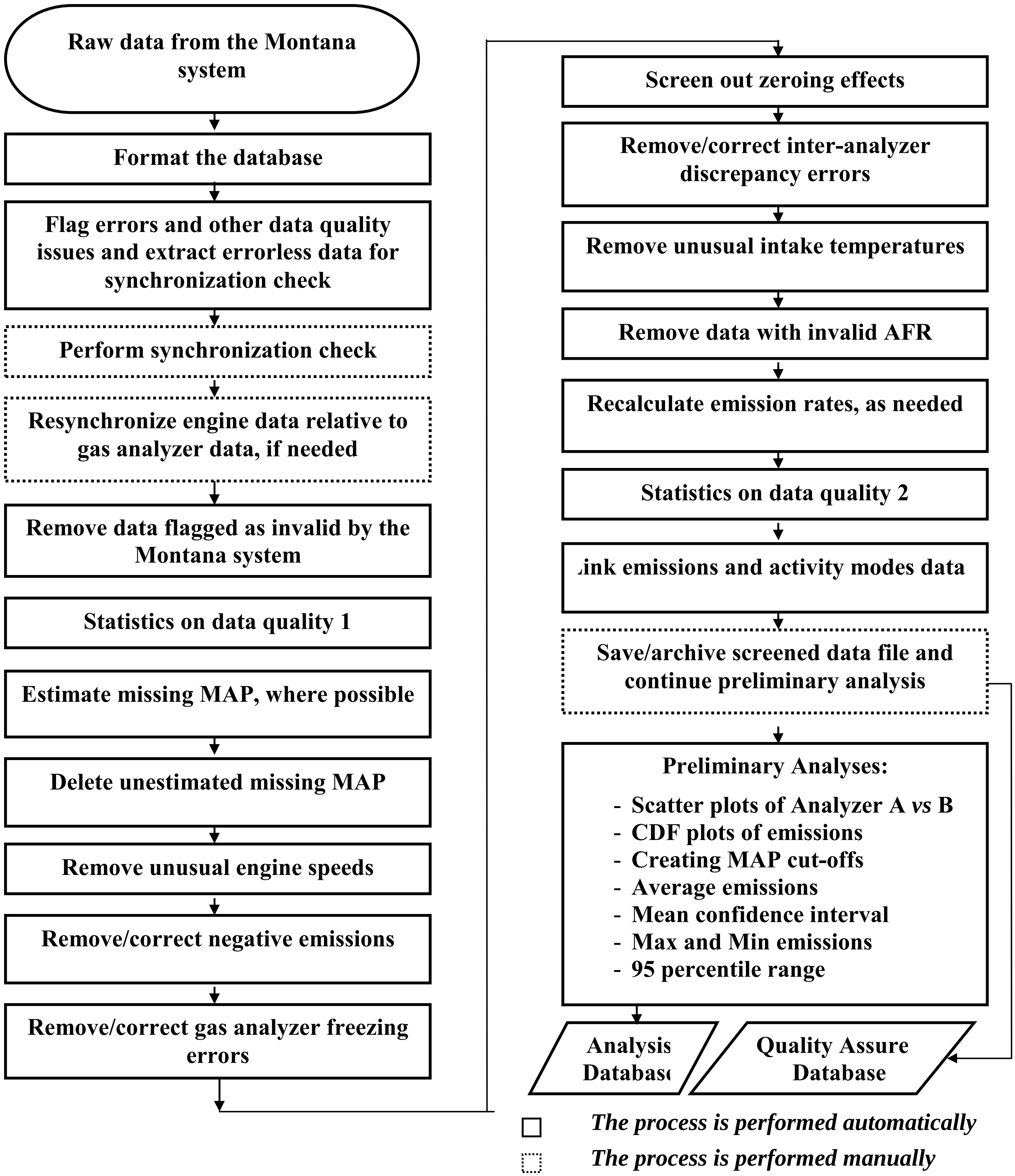


Figure 5. Flow Diagram of Data Quality Assurance and Preliminary Analysis

2.7.1 Engine-Based Modes

Based on the exploratory analysis of data as reported later in Section 3.4, manifold absolute pressure (MAP) has been consistently identified as the most highly correlated engine variable associated with variations in fuel use and emission rates. Therefore, a procedure for estimating modal emission rates based on ranges of normalized MAP has been developed. The normalized MAP was defined as:

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

Where,

MAP_{nor} = Normalized MAP for a measured MAP for a specific vehicle;
MAP_{max} = Maximum MAP for a specific vehicle;
MAP_{min} = Minimum MAP for a specific vehicle;
MAP = Measured MAP for a specific vehicle.

The normalized MAP bins are defined as 0 to 0.1, 0.1 to 0.2, 0.2 to 0.3, 0.3 to 0.4, 0.4 to 0.5, 0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, 0.8 to 0.9, and 0.9 to 1.0. The emission rates in mass per time and mass per gallon of fuel consumed were estimated for each normalized MAP bin. For the fuel based approach, results are not shown for fuel use since the mass of fuel consumed per gallon of fuel is a constant, regardless of engine activity. Similarly, since CO_2 emissions are highly correlated with fuel consumption, the CO_2 emissions on a per gallon basis are approximately constant and, therefore, are not shown.

2.7.2 Task-Oriented Modes

As an alternative to the "engine-based" modal analysis described above, a "task-oriented" modal analysis was also performed. In this analysis, the operations of the backhoes, front-end loaders, and motor graders were identified. During field data collection, a notation regarding the mode of activity was made using a laptop computer, as described in Section 2.3.2.2. The average fuel use and emission rates by task-oriented mode are shown, both on a mass per time and mass per gallon basis.

Activity modes are those activities that the vehicle routinely performs to accomplish a specific task. For a motor grader, examples of these include idling, moving, and blade. These activity modes are defined later in this section. The activity modes were monitored for each type of vehicle. The purpose of observing activity modes is to determine if there are varying level of emissions based on what the vehicle is doing rather than the task the vehicle is trying to accomplish, such as excavating or hauling. The following paragraphs define each activity mode for backhoes, front-end loaders, and motor graders.

One of the most versatile items of construction equipment is the backhoe. This vehicle combines the capabilities of a small front-end loader with those of a small excavator. The backhoe is wheel-mounted and has exceptional maneuverability around construction sites. The loader component may be used to move bulk material, excavate earth, and load trucks. The excavator component may be used for digging trenches, for digging shallow excavations below the surface of where the backhoe is located, and general grading. The following activity modes for backhoes were identified.

Idling
The engine is on but the vehicle is not moving and is not performing work.

Moving
The engine is on and the vehicle is moving in either a forward or reverse direction between locations but it is not performing work and neither bucket is loaded or being used.

Bucket (Using Rear Bucket)
The engine is on and the equipment is using the rear bucket to perform work. This mode encompasses any rear backhoe bucket use, including both dig/load and dig/dump operations.

Scoop/Dump Cycle (Using Front Bucket)
The engine is on and the vehicle is performing work beginning with scooping material with the front bucket, moving to another location while loaded, and ending with dumping the material. When the bucket is empty and the vehicle begins to move, the activity mode returns to *Moving*.

There are two basic types of front-end loaders, the crawler-tractor-mounted type and the wheel-tractor-mounted type, also known as a rubber tire loader. The rubber-tire loader was monitored and is simply referred to as a front-end loader in this report. These loaders can be economically and satisfactorily used in construction to handle and move bulk material such as rock and earth, to excavate earth, and to load trucks. Rubber tire loaders are more maneuverable, can travel faster on smooth surfaces, and typically have higher production rates than the crawler loaders. The following activity modes for front-end loaders were identified.

Idling
The engine is on but the vehicle is not moving and is not performing work.

Moving
The engine is on and the vehicle is moving in either a forward or reverse direction to another location, but no work is being performed and the bucket is not being used and is unloaded.

Scoop/Dump Cycle
The engine is on and the vehicle is performing work, beginning with scooping material with the loader bucket, moving to another location while loaded, and ending with dumping the material. When the bucket is empty and the equipment begins to move, the activity mode returns to *Moving*.

A motor grader is a rubber tire tractor with an undercarriage blade used for scraping and spreading material. It is primarily a fine grading machine, frequently used for removing a few inches of earth or spreading aggregate. Typical uses include fine grading for road beds or haul paths, excavating for small ditches, and snow and ice removal from roadways. The following activity modes for motor graders were identified.

Idling
The engine is on but the vehicle is not moving and is not performing work.

Moving
The engine is on and the vehicle is moving in either a forward or reverse direction between locations but it is not performing work because the blade is not in use.

Blade
The engine is on and the vehicle is moving in a forward direction and work is being performed by the blade by pushing or spreading material. When the equipment begins to move and the blade is not in use, the activity mode returns to *Moving*.

2.8 Determination of Representative Duty Cycles

A duty cycle may be defined as the sum of the task-related components that one specific vehicle can perform on a job site to complete a task such as mass excavation or material handling. For example, the duty cycle for a front-end loader performing material handling typically includes the components of load bucket, carry loaded, dump, and return empty; one complete cycle of these components comprises the duty cycle of material handling for a front-end loader.

In order to determine representative duty cycles for backhoes, front-end loaders, and motor graders, the data collection team went to the job site and observed the tasks for these vehicles prior to data collection. The following sections explain the typical duty cycles for backhoes, front-end loaders, and motor graders.

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

Compared to the other two observed duty cycles, “load truck” typically had higher engine loads because of the weight of the material in the bucket. The backhoes observed employed a front bucket with a 1.25 cubic yard capacity and a rear bucket with a 0.24 cubic yard capacity. Therefore, the front bucket is approximately five times larger than the rear bucket, meaning that “load truck” was usually the most power-demanding duty cycle for a backhoe. The other two duty cycles usually had lower engine loads compared to “load truck” because of the weight in the bucket and vehicle operation.

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

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

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

The cumulative frequency of normalized MAP was estimated for each duty cycle. The distribution of normalized MAP based on time and fuel use for each observed duty cycle is also estimated to calculate cycle-average emission factors for each vehicle. Section 3.7 provides the results for representative duty cycles.

2.9 Evaluation of Non-Detected Measurements of HC and CO Exhaust Gas Concentrations on Modal Average Emission Rates for Engine-Based Modes

For diesel engines, it is expected that the use of B20 should lead to lower HC and CO emission rates than for petroleum diesel, because B20 is an oxygenated fuel and, thus, should enhance combustion efficiency. For situations in which there is little vibration of the instrument, the detection limit for HC is 11 ppm (as reported in Appendix D). Likewise, the detection limit for CO is 0.003 volume percent. However, vibration can affect the precision and accuracy of the analyzer for HC and CO measurements. Hydrocarbons and carbon monoxide are measured at a lower wavelength of NDIR compared to CO_2. The measured concentration values can change with respect to vibration, particularly for the lower wavelengths of HC and CO detection (Norbeck *et al.*, 2001; Andros, 2003). Based on a comparison of the HC measurements made with gas analyzer B versus gas analyzer A, a detection limit can be inferred. The detection limit is selected such that concentrations below this value have a random pattern when comparing the two benches, and such that concentrations above this value are linearly proportional when comparing one bench to another.

Based on this approach, the detection limit for HC is 20 ppm for situations in which vibration is occurring during the test. Likewise, the detection limit for CO is 0.02 volume percent during vibration. An additional consideration is that diesel vehicles tend to have low HC and CO emissions. Thus, the sensitivity of HC and CO measurements to environmental factors, combined with low values of HC and CO, may lead to difficulty in obtaining measurements above the detection limit. The details of non-detected measurements of HC and CO are provided in Appendix G. Based on previous detailed statistical modeling using bootstrap simulation (Zhao and Frey, 2004), 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.

2.10 Emission Factors for B20 Biodiesel and Petroleum Diesel Based on Representative Duty Cycles

A key purpose of this work is to compare fuel use and emissions rates for B20 biodiesel (B20) versus petroleum diesel (PD) for each of five backhoes, four front-end loaders, and six motor graders. In order to compare fuel use and emissions rates for each of the two fuels, a standardized approach for comparing data from field tests on each of the two fuels was developed. This standardized approach is shown in Figure 6. The first step of data analysis is to estimate modal average fuel use and emission rates based on the quality assured data. Four different types of analyses are performed to show the engine-based and task-oriented modal analysis on mass per time and mass per gallon of fuel consumed basis. Depending on the distribution of normalized MAP bins based on time and fuel use, the weighted cycle fuel use and emission rates can be estimated. Each vehicle in this project was tested for both B20 biodiesel and petroleum diesel fuels. The last step is to compare cycle-average emission rate for B20 biodiesel and petroleum diesel. For each duty cycle, the ratio (B20/PD) is estimated for a given vehicle.

NO emission rates are sensitive to ambient temperature and humidity. Table 6 summarizes the ambient temperature and humidity for each of the tests. Because these ambient conditions vary from test-to-test, a "corrected" comparison was done in which the NO emissions were modified from actual conditions of a given test to standardized conditions of 77^{o}F and 54.5% relative humidity (EPA, 2003; 2004). The equation applied for the humidity correction is:

$$HF = \frac{1}{1 - 0.0182 (H - 10.71)}$$

Where,

HF = Humidity correction factor on NO_x formation for diesel engines

H = Absolute humidity (g/kg)

Table 6. Summary of Ambient Temperature and Humidity on Test Dates

Vehicle Type	Test ID	Vehicle ID ([a])	Petroleum Diesel			B20 Biodiesel		
			Test Date	Temp[b] (˚F)	Hum[c] (%)	Test Date	Temp[b] (˚F)	Hum[c] (%)
Backhoe	BH1	FDP20882 (5)	5/24/07	79	52	4/26/07	77	60
	BH2	803-0242 (5)	4/05/06	60	26	1/12/06	58	80
	BH3	803-0241 (4)	3/31/06	67	50	5/07/07	63	36
	BH4	808-0214(4)	4/13/07	54	42	5/01/07	83	38
	BH5	FDP22085 (5)	5/23/07	70	56	4/25/07	76	61
Front-End Loader	FL1	010-0249 (4)	3/08/06	50	40	5/08/07	49	74
	FL2	010-0301 (4)	4/07/06	71	44	4/10/07	50	46
	FL3	010-5074 (5)	5/18/07	64	63	7/21/06	85	64
	FL4	010-0388 (5)	5/22/07	50	40	5/17/07	49	74
Motor Grader	MG1	955-0515 (5)	2/01/06	48	43	2/14/06	48	38
	MG2	955-0606 (4)	3/23/06	47	42	4/20/07	64	44
	MG3	955-0516 (5)	5/25/07	74	54	8/04/06	87	63
	MG4	948-6647 (5)	4/03/07	73	44	12/05/06	45	37
	MG5	955-0277 (4)	1/17/07	35	39	2/21/07	60	72
	MG6	955-0633 (5)	6/22/07	88	56	6/28/07	83	42

[a] Division Number

[b] Ambient Temperature (˚F)

[c] Relative Humidity (%)

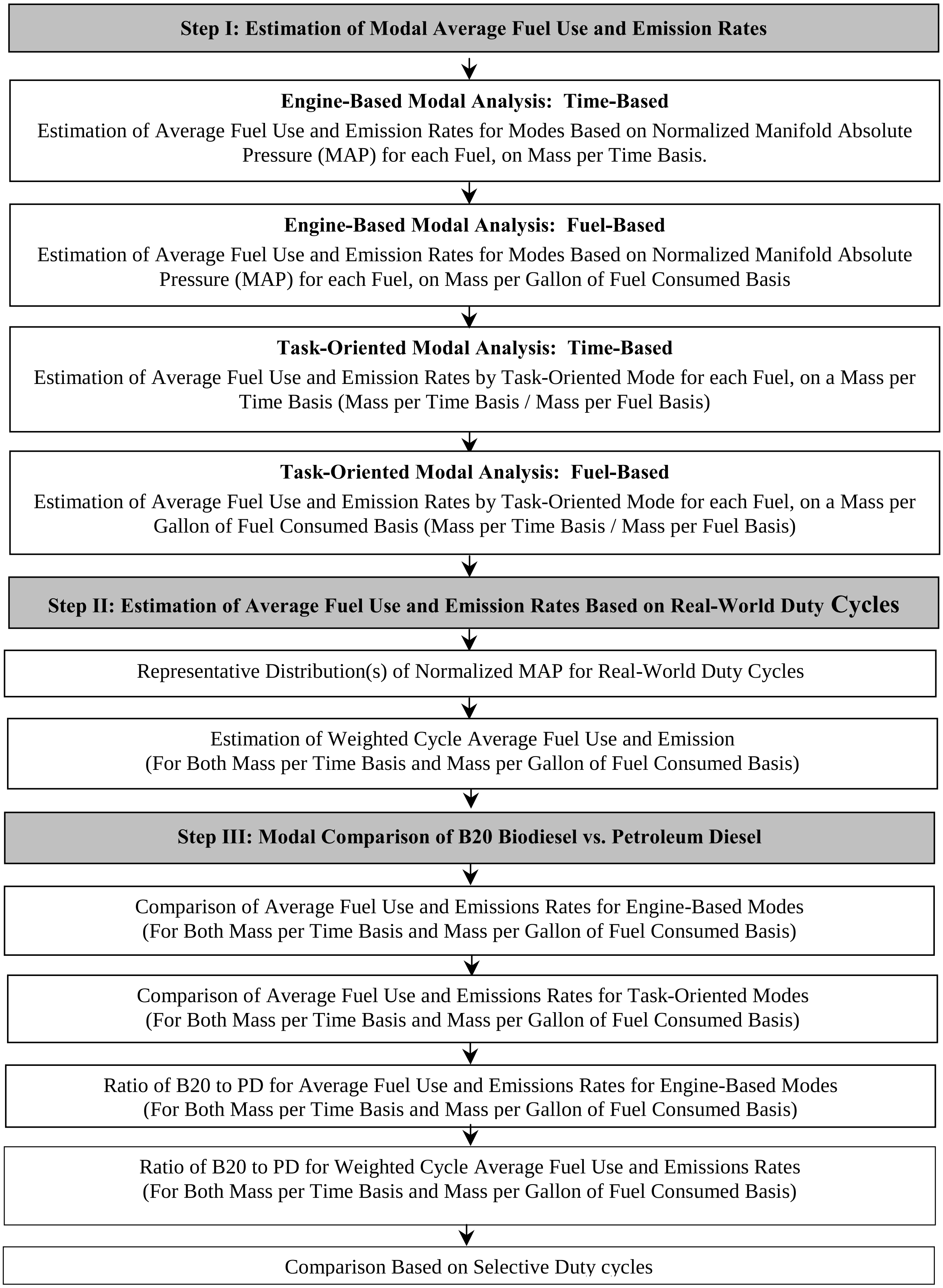


Figure 6. Procedure for Comparison of Fuel Use and Emission Rates for B20 Biodiesel vs. Petroleum Diesel for a Given Vehicle and Selected Duty Cycle

2.11 Benchmarks of Measured Emission Rates Based on the NONROAD Model

Fuel based emission factors from PEMS data were compared with fuel-based emission factors estimated using EPA's NONROAD model for the same model year, chassis type, and engine Tier. The NONROAD model produces fleet average emission estimates based on engine dynamometer data that are not representative of the real world duty cycles observed in the field data collection. Therefore, there are expected to be some differences in the absolute values of the emission factors when comparing both approaches. However, the purpose of the comparison is to determine whether the magnitudes of the emission factors are similar.

The EPA's NONROAD emission inventory model produces exhaust emission factors for nonroad diesel engines. This model includes pollutants of NO_x, HC, CO, and PM including the adjustments due to variations in fuel sulfur level. In addition, brake specific fuel consumption (BSFC) is given for fuel rate measurement (EPA, 2004).

For the deterioration of the engine and the variation of chassis, the NONROAD model uses two correction factors: the transient adjustment factors (TAF) and the deterioration factor (DF). TAF represents the variation of equipment type, and DF is for the representation of engine type and age. In addition, a few other correction factors are used such as median life, annual activity, and load factor for various types of nonroad engines (EPA, 2004).

The emission factors used in the NONROAD model were developed based on engine dynamometer measurements in the units of grams per brake horsepower-hour. However, in real-world measurements, the emission factors are obtained in the units of grams per second or grams per gallon of fuel consumed (Vojtisek-Lom, 2003). Thus, in order to enable comparisons with the PEMS data, the emission factors in the NONROAD model need to be converted to the units of grams per gallon of fuel using an assumed brake-specific fuel consumption rate.

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

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

where:

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

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

2.12 Benchmarks of Observed Fuel Use Rates vs. NCDOT Maintenance Data

The purpose of this section is to compare fuel consumption rates for selected construction vehicles obtained from field data collected using a PEMS with maintenance data for the same vehicles recorded by NCDOT. Fuel consumption rates are estimated from the PEMS data based on measured engine parameters (manifold absolute pressure, engine RPM, and intake air temperature) and exhaust concentration data for carbon dioxide. Thus, verification that the estimated mass consumption rates based on the PEMS are comparable to those from the NCDOT equipment records provides additional confidence regarding the accuracy of the PEMS data. Furthermore, since emission rates can be estimated from PEMS data on a per gallon of fuel consumed basis, the availability of annual fuel consumption data enables the development of fuel based inventories of total annual emissions by vehicle category.

NCDOT provided a vehicle maintenance database that included recorded annual hours of engine operation and gallons of fuel consumed for each vehicle. The fuel consumption is denoted as either B20 biodiesel or petroleum diesel. NCDOT provided this data for vehicles that were tested. From this recorded data, estimates were made of average fuel consumption in gallons per hour. It is possible that there could be errors in the fuel usage or engine hours of operation as recorded in the database and there were no additional quality assurance checks on this data. For vehicles for which NCDOT did not have fuel consumption records, industrial data were used to benchmark the fuel consumption rates.

2.13 Development of Emission Inventory

An emissions inventory was developed to determine the levels of air pollutants that are emitted by NCDOT backhoes, front-end loaders, and motor graders. Emissions inventory information for the following pollutants is provided:

- Nitrogen Oxides (NO_x)
- Opacity
- Hydrocarbons (HC)
- Carbon Monoxide (CO)

There were two primary components to developing the emissions inventory. The first component was to determine from field tests the appropriate emission factors for each vehicle type and each pollutant. These factors are based on grams of pollutant emitted per gallon of fuel used by the vehicle. Emission factors are discussed in detail in Section 2.9 and Section 3.9 of this report.

The second component was to apply the emission factors to the vehicle fleet inventory information that was provided by NCDOT. This information included an itemized list of all backhoes, front-end loaders, and motor graders that are on record for NCDOT. For example, the vehicle fleet inventory information provided fuel usage data for two years, as well as the model year and engine horsepower for each vehicle.

The fuel usage data included the amount (gallons) of petroleum diesel and B20 biodiesel that was used by each vehicle during the years of 2005 and 2006. This data was averaged over two years to determine the average annual fuel use (gallons per year) for both petroleum diesel and

B20 biodiesel. This average annual fuel use was used for calculations in the emissions inventory.

Since the vehicle model year and engine horsepower was provided in the NCDOT vehicle fleet inventory information, it was possible to stratify the vehicles based on the EPA engine tier classification (EPA, 2004). Table 7 summarizes the EPA engine tier classification. All of the backhoes, front-end loaders, and motor graders in the NCDOT vehicle fleet inventory are classified between Tier 0 and Tier 2. There were some Tier 3 motor graders placed into service during 2007 but there is no fuel usage history for these vehicles yet; therefore, they are not included in this emissions inventory. Emission factors were also determined for each engine tier for each type of vehicle, thus emission inventory values were computed for each engine tier for each type of vehicle.

To calculate average annual emissions, the average annual fuel use was multiplied by the appropriate emission factor. The average annual emissions were calculated for both petroleum diesel and B20 biodiesel and also for each engine tier classification for each type of vehicle. For example, the average annual fuel use (gallons) of petroleum diesel for all motor graders was multiplied by the emission factor (grams/gallon) for NO_x based on petroleum diesel usage to estimate the total number of grams per year of NO_x that was emitted by NCDOT motor graders using petroleum diesel. The number of grams per year of NO_x was converted to and reported as tons per year. The following is a sample calculation for estimating the average annual NO_x emissions (tons/yr) for all Tier 0 motor graders using petroleum diesel:

$$132{,}680\ \frac{\text{gallons}}{\text{year}} \times 134\ \frac{\text{g NO}_x}{\text{gallon}} \times \frac{1}{454}\frac{\text{lb}}{\text{g}} \times \frac{1}{2000}\frac{\text{ton}}{\text{lb}} = 19.6\ \frac{\text{tons NO}_x}{\text{year}}$$

When comparisons of emissions were made between petroleum diesel and B20 biodiesel, it was necessary to adjust the number of gallons of fuel that was used because of the difference in heating value for each fuel. The heating value for petroleum diesel is 128,500 BTU/gallon and the heating value for B20 biodiesel is 126,218 BTU/gallon. The ratio of heating values for petroleum diesel to B20 biodiesel is 1.02, or approximately a 2% increase. For example, 102 gallons of B20 biodiesel would need to be consumed to provide the same amount of vehicle work as 100 gallons of petroleum diesel would provide. Average annual emissions per vehicle (lbs/yr) for each pollutant and engine tier were calculated based on the current combined use of petroleum diesel and B20 biodiesel. The average annual emissions per vehicle were calculated by dividing the average annual emissions by the number of vehicles in a particular engine tier classification. For example, there were 119 backhoes with Tier 1 engines reported in the NCDOT fleet inventory data. The average annual emissions of NO_x for all of the Tier 1 backhoes were estimated to be 9.2 tons per year. Therefore, the estimated average annual emissions of NO_x per backhoe were 155 pounds per year. The average annual emissions per vehicle were converted to pounds per year (lbs/yr) for reporting purposes. The following is a sample calculation:

$$\left(9.2\ \frac{\text{tons NO}_x}{\text{year}} \div 119\ \text{Tier1 Backhoes}\right) \times \frac{2000}{1}\frac{lb}{ton} = 155\frac{\text{lb NO}_x\ \text{per year}}{\text{Tier1 Backhoe}}$$

The results of the emissions inventory are presented in Section 3.12 of this report.

Table 7. EPA Engine Tier Classification Based on EPA's NONROAD Model

Engine Power (Horsepower)	Model Years	Regulation
≥75 to < 100	Prior to 1998	Tier 0
	1998 – 2003	Tier 1
	2004 – 2007	Tier 2
	2008 – 2011	Tier 3
	2012 – 2013	Tier 4 Transitional
	2014 +	Tier 4 Final
≥100 to < 175	Prior to 1997	Tier 0
	1997 – 2002	Tier 1
	2003 – 2006	Tier 2
	2007 – 2011	Tier 3
	2012 – 2013	Tier 4 Transitional
	2014 +	Tier 4 Final
≥175 to < 300	Prior to 1996	Tier 0
	1996 – 2002	Tier 1
	2003 – 2005	Tier 2
	2006 – 2010	Tier 3
	2011 – 2013	Tier 4 Transitional
	2014 +	Tier 4 Final

3.0 RESULTS

This section summarizes the results of the data collection and the data analysis. The following sections are included:

- NCDOT Data Collection Summary
- Data Collection Problems and Solutions
- Error Analysis
- Non-detected Measurement of HC and CO
- Exploratory Analysis of Data
- Modal Analysis
- Representative Duty Cycles for Each Type of Vehicle
- Estimation of Cycle Average Fuel Use and Emission Rates for Selected Duty Cycles
- Emission Factors for NCDOT Backhoes, Front-End Loaders, and Motor Graders
- Benchmarks of Measured Emission Rates based on NONROAD Model
- Benchmarks of Observed Fuel Use Rate versus NCDOT Maintenance Data
- Emissions Inventory

3.1 NCDOT Data Collection Summary

The NCDOT Data Collection Summary is given in Table 8. The purpose of this table is to report the total number of hours of data collected and data processed as of a particular date for the specified vehicle and specified mode of activity. This information helped to determine where an emphasis needed to be placed with respect to gathering data and processing data and enabled the research team to quickly assess the project data collection schedule. Each column of the table is defined as follows:

Test Goals	The *Target* number of tests that are to be performed and the *Completed* number of tests that have been performed.
Fuel Type	The number of vehicles that have been tested for each type of fuel that is used by the vehicle, either *Biodiesel* or *Petroleum* diesel.
Vehicle	The type of vehicle that is being monitored.
Mode	The activity modes for each item of equipment (see Section 2.7.3 for definitions)
Raw Data	The total number of hours of data collected in the field to-date for a given item of equipment operating in a given mode.
Processed Data	The total number of hours of data that has been processed and is usable for analysis.

For example, the motor graders which were monitored as of June 30, 2007 had 18.1 hours of raw data collected while Idling, 12.7 hours of raw data while Moving, and 12.8 hours of raw data while it was using the Blade to do work. The processed data for the motor grader was 16.4 hours for Idling, 11.8 hours for Moving, and 12.3 hours for Blade, respectively. Table 9 summarizes all test vehicle information and the dates that the tests were completed. The test conditions (Actual Site condition or Maintenance Yard Condition) are also indicated in Table 9.

Table 8. NCDOT Data Collection Summary

June 30, 2007

Test Goals							
Target		Completed				Raw Data (hours)	Processed Data (hours)
Bio	Petrol	Bio	Petrol	Vehicle	Mode		
5	5	5	5	Backhoe	Idling	13.9	13.0
					Moving	4.9	4.4
					Bucket	8.7	8.1
					Scp/Dmp	5.1	4.4
4	4	4	4	Front-End Loader	Idling	12.9	12.5
					Moving	5.8	5.4
					Scp/Dmp	7.6	7.0
6	6	6	6	Motor Grader	Idling	18.1	16.4
					Moving	12.7	11.8
					Blade	12.8	12.3
15	**15**	**15**	**15**			**102.5**	**95.4**

Table 9. Summary of Test Vehicle Information and Test Dates

Vehicle Type	Test ID	Vehicle ID ([a])	Engine Type	Test Fuel Type	
				Petroleum Diesel	B20 Biodiesel
Backhoe	BH1	FDP20882 (5)	Tier 2	5/24/07 [c]	4/26/07 [c]
	BH2	803-0242 (5)	Tier 0	4/05/06 [b]	1/12/06 [b]
	BH3	803-0241 (4)	Tier 1	3/31/06 [b]	5/07/07 [c]
	BH4	808-0214(4)	Tier 1	4/13/07 [c]	5/01/07 [b]
	BH5	FDP22085 (5)	Tier 2	5/23/07 [c]	4/25/07 [c]
Front-End Loader	FL1	010-0249 (4)	Tier 1	3/08/06 [b]	5/08/07 [b]
	FL2	010-0301 (4)	Tier 1	4/07/06 [b]	4/10/07 [b]
	FL3	010-5074 (5)	Tier 1	5/18/07 [c]	7/21/06 [b]
	FL4	010-0388 (5)	Tier 2	5/22/07 [c]	5/17/07 [c]
Motor Grader	MG1	955-0515 (5)	Tier 1	2/01/06	2/14/06
	MG2	955-0606 (4)	Tier 2	3/23/06	4/20/07
	MG3	955-0516 (5)	Tier 1	5/25/07	8/04/06
	MG4	948-6647 (5)	Tier 0	4/03/07	12/05/06
	MG5	955-0277 (4)	Tier 0	1/17/07	2/21/07
	MG6	955-0633 (5)	Tier 3	6/22/07	6/28/07

[a] Division Number
[b] Actual Site Condition
[c] Maintenance Yard Condition

3.2 Data Collection Problems

There were several problems that were encountered with regard to the collection of emissions, engine, and site data. These problems included:

- Suitable weather
- Difficult operating conditions
- Scheduling
- Correlating emissions data with construction vehicle productivity data

3.2.1 Suitable Weather

The Montana is a sensitive electro-mechanical instrument that was designed for use in a controlled and moderate environment; it is not a "ruggedized" instrument. Thus, construction sites pose significant challenges when using the Montana, particularly with regard to temperature and moisture.

Due to the sensitivity of the electronics of the Montana, data collection cannot occur during a rain or snow event. Often it must be installed on an external surface of the vehicle. However, it can be used under these conditions if it is installed in a space conditioned cab, such as an off-road truck. Additionally, if the temperature drops below freezing (32ºF), data collection cannot occur because moisture in the sample line freezes. Likewise, if the ambient temperature exceeds 90ºF and if the Montana is installed externally on the vehicle, data collection cannot occur because the Montana is susceptible to overheating and will shut down at high temperatures. Therefore, the research team only collected data for nonroad vehicles on non-precipitation days and only when the temperature was between 32ºF and 90ºF.

3.2.2 Difficult Operating Conditions

The Montana is also sensitive to vibration transmitted from the construction vehicle as well as to dust and mud that are typically found on construction sites. Vibration, dust, and mud were frequently responsible for causing the Montana to malfunction. When these demanding conditions caused a malfunction, it was necessary to return the instrument to the manufacturer for repairs. These repairs required from several weeks to several months to complete, resulting in critical and substantial lost time for data collection.

These problems were solved by various methods. For instance, to minimize the effects of vibration on the Montana, three layers of one inch foam padding were placed between the surface of the Montana and the surface of the construction vehicle. To prevent dust from entering the Montana, a dust cover was fabricated using a fine mesh material. The cover acted as a filter that prevented dust from entering the Montana but allowed adequate air to flow to it. Also, the research team checked the Montana at approximately 30 minute intervals during the data collection process to ensure that it was still functioning properly.

3.2.3 Scheduling

For data collection to occur, it was necessary to find NCDOT maintenance yards that would cooperate. When the maintenance yards allowed their vehicles to be tested, data collection had to be scheduled to accommodate the production schedule. This was difficult because the maintenance yard would sometimes change their work schedule without notifying the research team ahead of time and a data collection day would be lost. Also, the data collection schedule sometimes changed due to the weather as well as to other unforeseeable events, such as a vehicle malfunction or operator absence. Ultimately, the data collection schedule was dependent upon a combination of the construction schedule, vehicle availability, and site conditions.

3.2.4 Correlating Emissions Data with Construction Vehicle Productivity Data

Since it is difficult to match activity modes with emissions, there presently is not a significant direct link between emissions data and construction productivity. The research team observed the activities as they occurred, gathering emissions data based on observed activity modes rather than duty cycle operations or units of productivity. Still, it would be very useful to have an estimate of the grams of NO_x emitted by a front-end loader per cubic yard of material moved (g/cy). Having this knowledge would actually allow construction emissions to be estimated from a construction schedule coupled with project plans.

3.3 Results of Quality Assurance

Emission tests were performed 30 times: twice each for 15 individual vehicles. Each raw data set was processed using the quality assurance procedures and macros shown in Appendix D and Appendix E, respectively. These procedures were used to identify problems in the data, correct the data where possible, or remove data that could not be corrected.

In addition to performing data screening and quality assurance procedures, there is a need to determine what errors might be high frequency errors in data collection. This section describes the results of error rates after applying data quality assurance procedures to the raw data. Table 10 reports information about the loss of data on each day of data collection. The column “Data Loss” shows the number of seconds of data removed for each specific identified error. For instance, column (3) shows that 635 seconds of data were removed because of analyzer freezing on 5/01/07.

Figure 7 shows a bar chart illustrating how many errors occurred on each day of data collection. On average, the total error rate leading to loss of data is approximately 7%. In 2006, only four tests (Tests 6, 7, 11, and 12) have error rates above 7%. However, due to intensive data collection that occurred in April and May 2007, higher error rates were observed. One possible reason is vibrations from the vehicle (the detailed effects of vibration are discussed in Appendix D). To avoid vibration associated with sites that have uneven terrain, many of the later data collection activities occurred at the vehicle maintenance yard on and after April 13, 2007. The tests at the maintenance yard included similar ranges of engine load and similar duty cycles, but less vibration. On April 13, 2007, the error rate of the test was only 3.4%, which is significantly lower than the previous two tests. However, the data collection team observed high error rates again during Tests 17-21. The manufacturer suggested replacing the NO_x and O_2 sensor in the PEMS because intensive data collection resulted in the deterioration of the sensors. Thus, the data collection team replaced the NO_x and O_2 sensor on May 7, 2007. Afterwards, the error rate decreased significantly. Only one test had a higher error rate due to the vibration of the vehicle itself.

Figure 8 shows the distribution of the different types of errors. This figure identifies which errors have a high probability of occurring during data collection. Analyzer freezing has the highest frequency among the seven identified types of errors. Negative emission value was the least frequent error among the seven identified types of errors.

In Table 11, the average error rates for backhoes, front-end loaders, and motor graders are 9.0%, 5.0%, and 6.5%, respectively. The backhoes have the highest average error rate because of vibration effects on the PEMS. The comparisons between the actual condition test and vibration controlled condition test (maintenance yard condition) are shown in Table 12. On average, errors decreased by approximately 1.1 percentage points after changing test conditions from the actual condition to the maintenance condition.

Table 10. Rate of Loss of Data Because of Data Quality Errors

Test No.	Date	Vehicle[a]	Fuel[b]	Total Raw Data (sec)	Amount of Data Lost for Specific Type of Error [c]							Average Error Rate (%)	Processed Data (sec)
					1	2	3	4	5	6	7		
1 [d.]	01/12/06	BH2	B20	21,535	0	2	176	102	69	0	0	1.6%	21,186
2 [d.]	02/01/06	MG1	PD	16,348	10	83	166	284	78	0	0	3.8%	15,727
3 [d.]	02/14/06	MG1	B20	19,532	0	92	397	126	317	153	0	5.6%	18,447
4 [d.]	03/08/06	FL1	PD	20,217	0	54	844	187	68	0	0	5.7%	19,064
5 [d.]	03/23/06	MG2	PD	12,205	0	52	150	201	92	0	6	4.1%	11,704
6 [d.]	03/31/06	BH3	PD	18,237	0	48	542	688	552	0	0	10%	16,407
7 [d.]	04/05/06	BH2	PD	11,567	16	0	428	326	213	0	33	8.8%	10,551
8 [d.]	04/07/06	FL2	PD	12,974	0	0	25	57	16	0	0	0.76%	12,876
9 [d.]	07/21/06	FL3	B20	8,798	22	25	271	222	101	0	0	2.0%	8,157
10 [d.]	08/04/06	MG3	B20	13,415	0	35	229	389	19	8	2	5.1%	12,733
11 [d.]	12/05/06	MG4	B20	14,304	0	48	541	418	156	0	3	8.2%	13,138
12 [d.]	01/17/07	MG5	PD	10,602	20	16	404	349	24	0	0	7.7%	9,789
13 [d.]	02/21/07	MG5	B20	14,606	0	22	283	106	38	0	9	3.1%	14,148
14 [d.]	04/03/07	MG4	PD	11,500	0	60	641	469	238	52	0	13%	10,040
15 [d.]	04/10/07	FL2	B20	9,171	8	81	551	557	332	0	0	17%	7,642
16 [e]	04/13/07	BH4	PD	8,647	35	0	109	63	12	74	0	3.4%	8,354
17 [d.]	04/20/07	MG2	B20	17,713	13	11	493	2135	62	0	0	15%	14,999
18 [e]	04/25/07	BH5	B20	8,681	54	15	497	374	48	21	0	12%	7,672
19 [e]	04/26/07	BH1	B20	8,951	6	2	421	328	86	5	0	9.5%	8,103
20 [d.]	05/01/07	BH4	B20	9,561	26	68	635	522	372	0	24	17%	7,914
21 [e]	05/07/07	BH3	B20	11,723	31	0	606	453	246	0	11	11%	10,376
22 [e]	05/08/07	FL1	B20	8,823	10	3	214	92	72	12	0	4.6%	8,420
23 [e]	05/17/07	FL4	B20	13,067	6	54	360	145	75	0	0	4.9%	12,427
24 [e]	05/18/07	FL3	PD	10,950	0	5	163	103	12	0	0	2.6%	10,667
25 [e]	05/22/07	FL4	PD	10,774	0	0	202	93	43	2	0	3.2%	10,434
26 [e]	05/23/07	BH5	PD	9,105	21	25	296	170	30	3	5	6.0%	8,555
27 [e]	05/24/07	BH1	PD	9,226	17	12	407	325	152	0	16	10%	8,297
28 [d]	05/25/07	MG3	PD	7,860	0	37	42	64	54	0	0	2.5%	7,663
29 [d]	06/22/07	MG6	PD	9,262	0	0	293	188	94	0	0	6.2%	8,687
30 [d]	06/28/07	MG6	B20	9,500	0	0	203	167	38	0	0	4.3%	9,092

Overall

Total Seconds	368,854	295	850	10,589	9,703	3,709	330	109	25,585	343,269
Percentage of raw data		0.08%	0.23%	2.9%	2.6%	1.0%	0.09%	0.03%	6.9%	93.1 %

(Continued)

Table 10. Continued

[a] Vehicle: BH=Backhoe, FL= Front-End Loader, and MG= Motor Grader

[b] Fuel: PD=Petroleum Diesel and B20= B20 Biodiesel

[c] Description of Errors (see Appendix D for detailed definitions)

1: Missing Manifold Absolute Pressure (MAP)
2: Unusual Engine Speed (engine RPM)
3: Analyzer Freezing
4: Inter-analyzer Discrepancy (IAD)
5: Air Leakage
6: Unusual Intake Air Temperature (IAT)
7: Negative Emission Value

[d] Actual site condition
[e] Maintenance yard condition

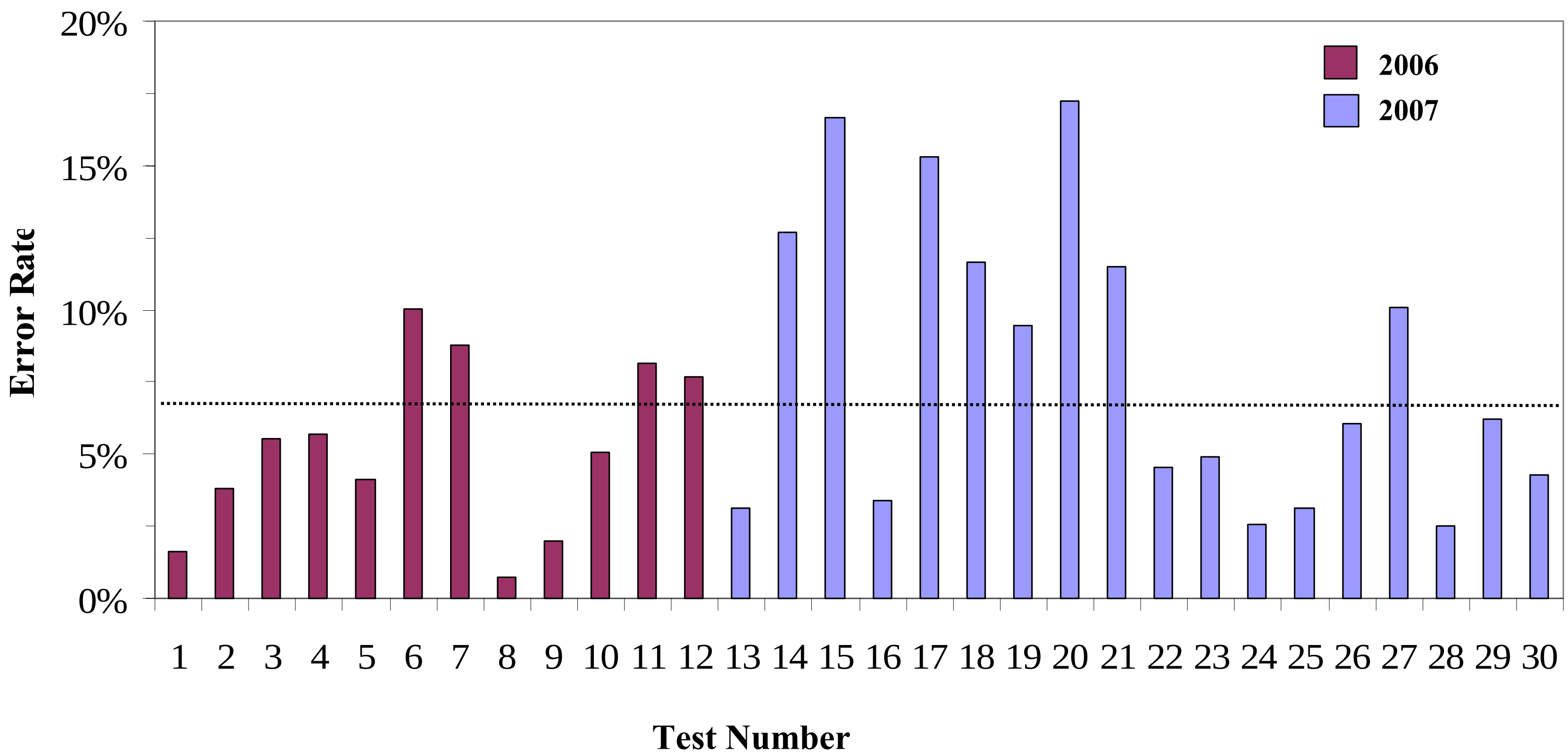


Figure 7. Error Rate for Each Day of Data Collection

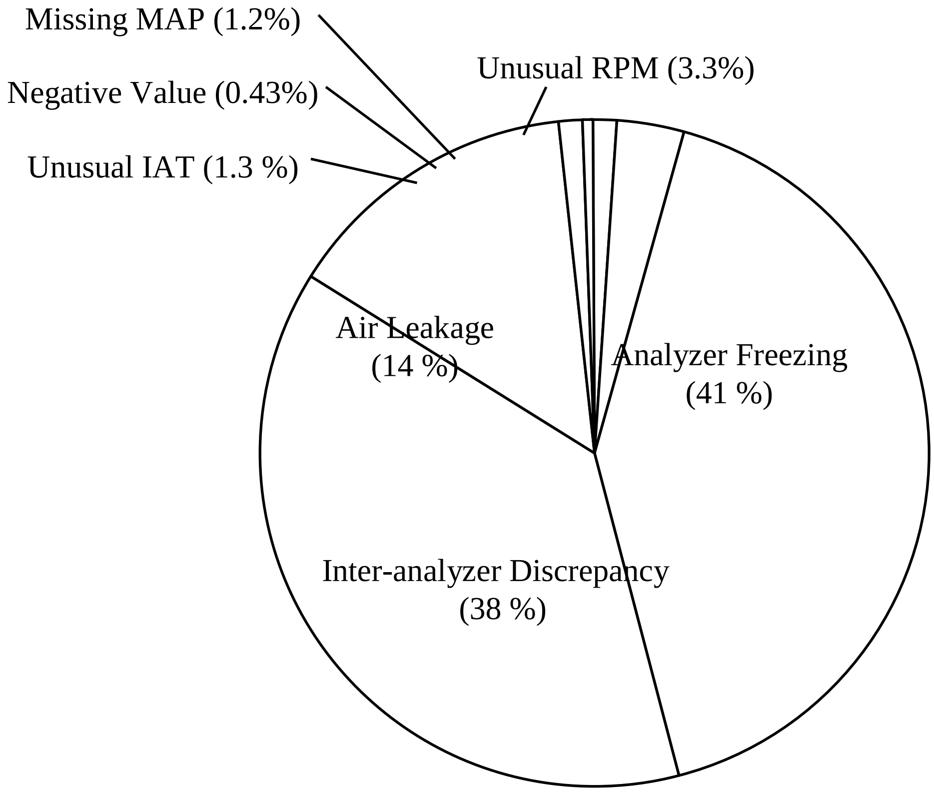


Figure 8. Distribution of Error Rates for Seven Identified Types of Errors

Table 11. Average Error Rates for Backhoes, Front-End Loaders, and Motor Graders

Vehicle	Average Error Rate
Backhoes	9.0%
Front-End Loaders	5.0%
Motor Graders	6.5%

Table 12. Average Error Rates for testing in Actual Site Condition and Maintenance Yard Condition

Condition	Average Error Rate
Actual Site Condition	7.8%
Maintenance Yard Condition	6.7%

3.4 Exploratory Analysis of Data

The raw data were analyzed in terms of the effect of engine activity on fuel use and emissions. A rank correlation analysis was performed to identify which engine variable is highly correlated with variations in fuel use and emission rates. Table 13 is an exploratory analysis of data from a selected front-end loader. Based on an example of this as well as other vehicles, manifold absolute pressure (MAP) has been consistently identified as the engine variable most highly correlated with variations in fuel use and emission rates.

The data were also analyzed in terms of the fuel use and average emission rate for activity modes. An activity mode can include idling, movement of the equipment for repositioning purposes, use of a blade or bucket, etc. These modes can vary depending on the type of vehicle. In Figure 9, an example is shown based on a front-end loader to represent time-series fuel use and emissions in terms of different activity modes. The lowest MAP, fuel use and NO emission rates are associated with the idling mode. The peak in MAP corresponds to the peak in fuel use and NO emission rates during moving and bucket modes. Activity modes are useful to explain the variations of fuel use and emissions among different work activities.

3.5 Modal Analysis

The quality assured data were analyzed in terms of the fuel use and average emission rate for engine-based and task-oriented modes. Manifold absolute pressure (MAP) has been consistently identified as the most highly correlated engine variable associated with variations in fuel use and emission rates. Therefore, engine-based modal emission rates were estimated based on ranges of normalized MAP. Based on Backhoe 1 data, the comparison of engine-based modal average emission rates for B20 versus PD is shown in Figure 10 for a time basis and Figure 11 for a fuel consumed basis, respectively. The engine-based and time-based modal average fuel use and emission rates of CO_2,, NO_x, HC, CO, and PM for all 15 NCDOT construction vehicles fueled with both B20 and PD are shown in Appendix F.

Table 13. Rank Correlation of Fuel Use and Emissions With Respect to Engine Data Based on Front-End Loader 1

	MAP [a]	RPM [b]	IAT [c]	AFR [d]
Fuel Use	0.99	0.93	0.48	-0.94
CO_2	0.98	0.93	0.48	-0.93
NO as Equivalent NO_2	0.77	0.73	0.44	-0.73
Opacity	0.85	0.81	0.44	-0.82
HC	0.99	0.93	0.48	-0.94
CO	0.96	0.90	0.48	-0.92

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

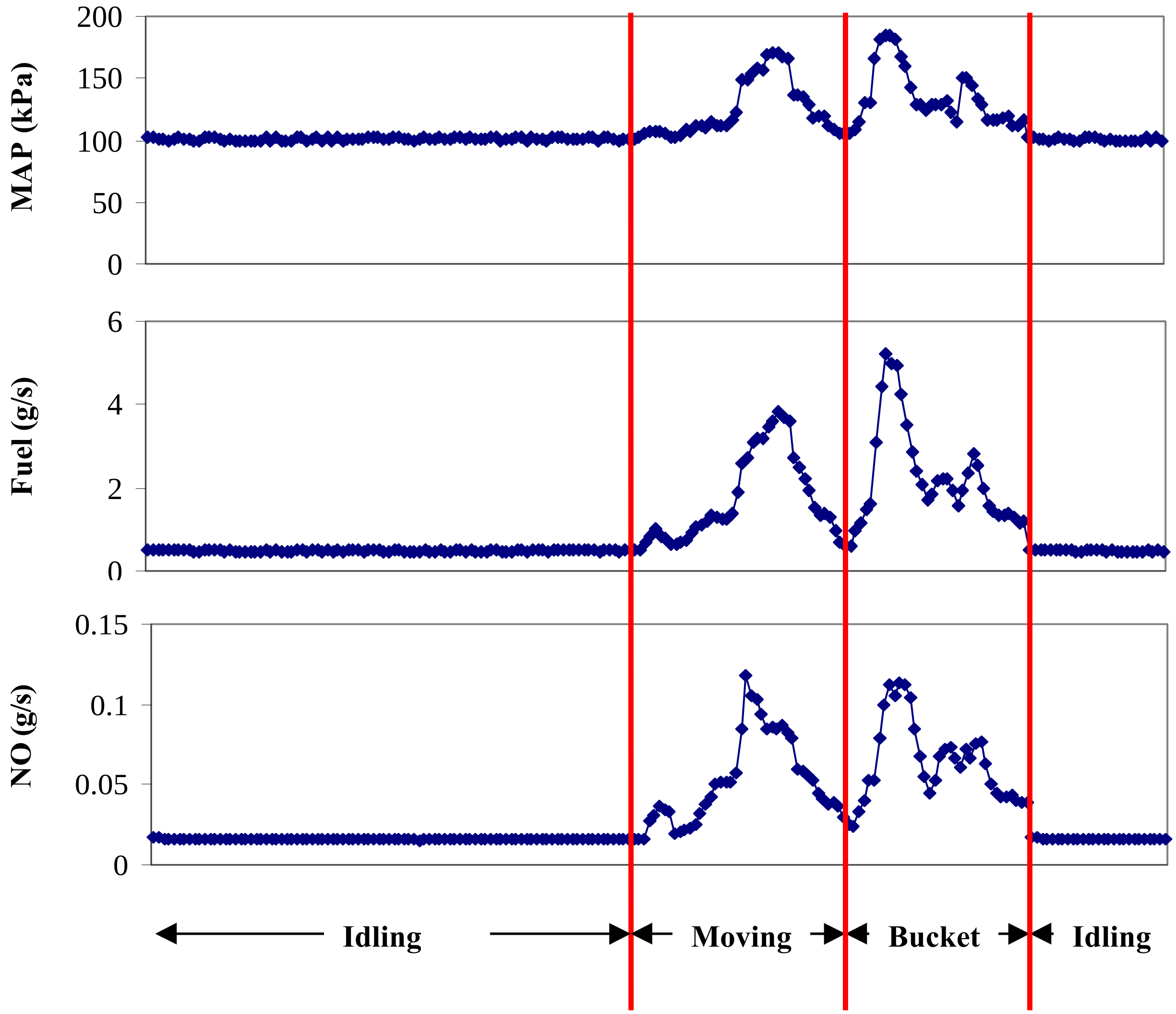


Figure 9. Example of a Time Series Plot of Manifold Absolute Pressure, Fuel Use, and NO as Equivalent NO_2 Emission Rate for a Front-End Loader

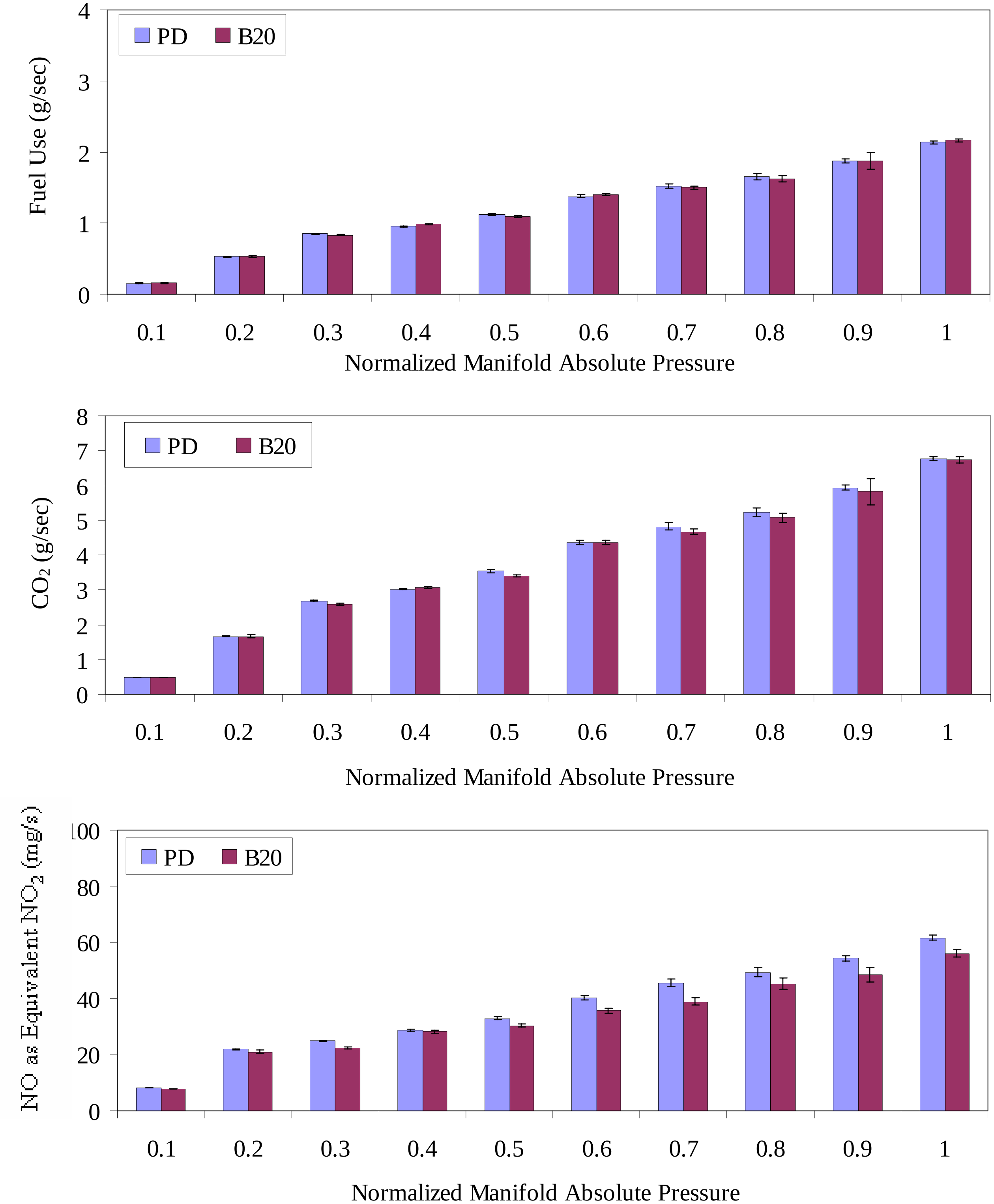
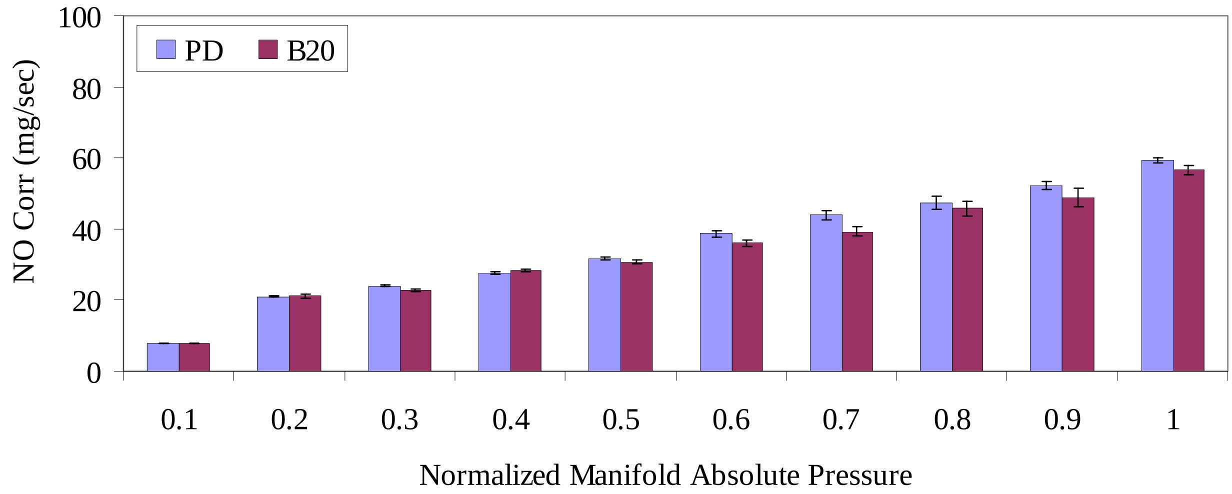
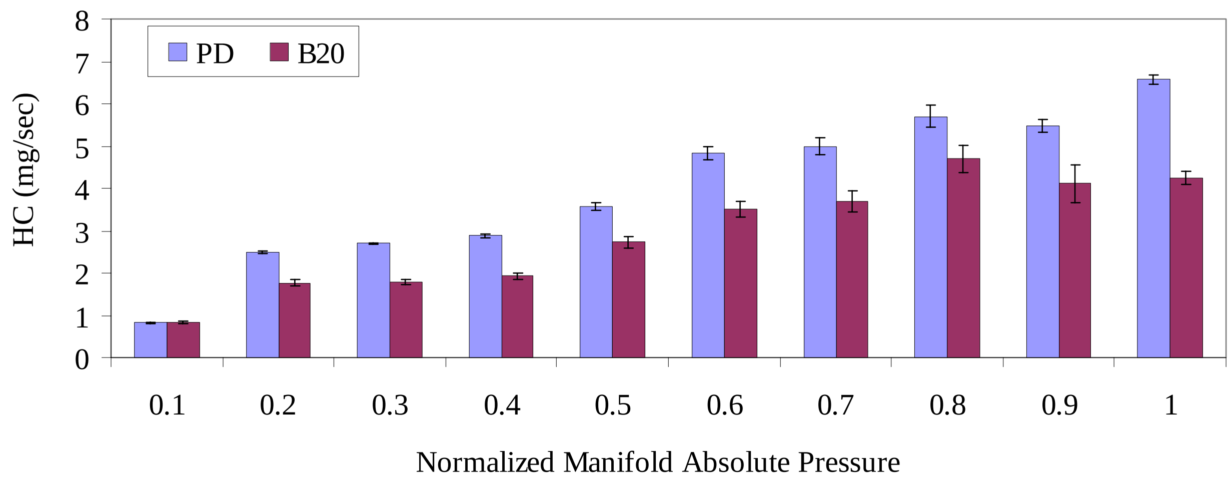


Figure 10. Comparison between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Emission Based Modes for Backhoe 1





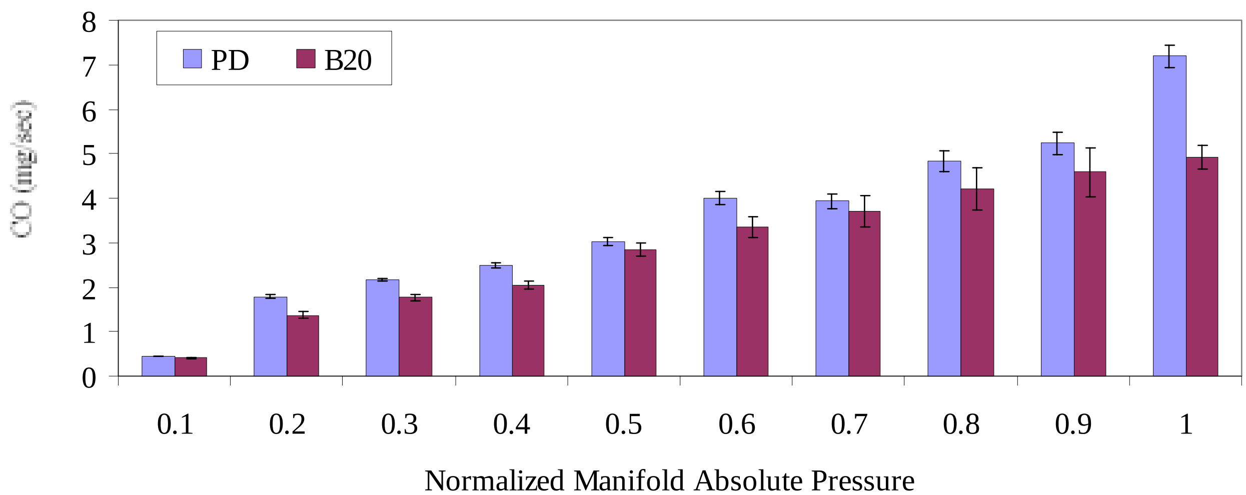


Figure 10. Continued

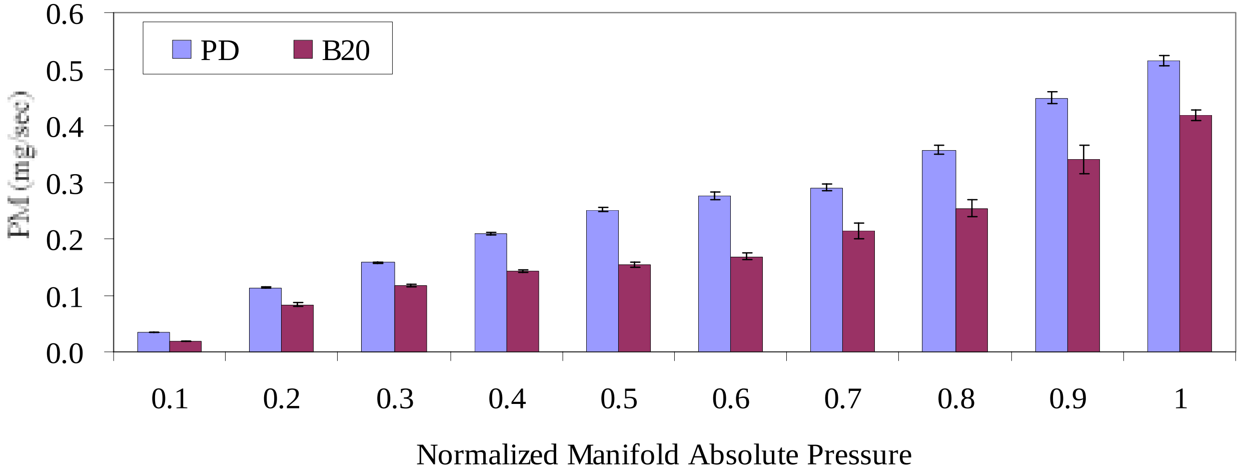


Figure 10. Continued

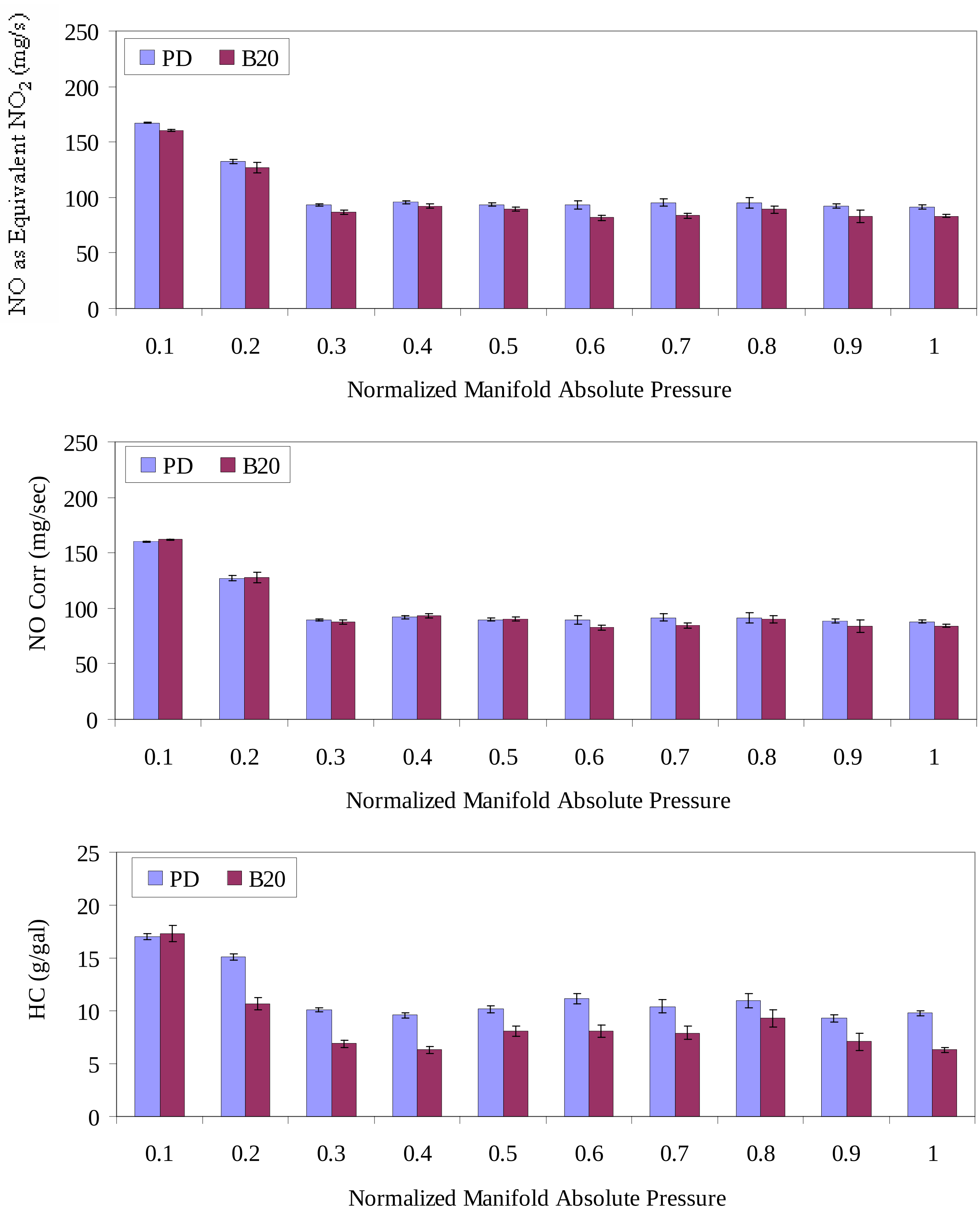


Figure 11. Comparison between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Engine-Emission Based Modes for Backhoe 1

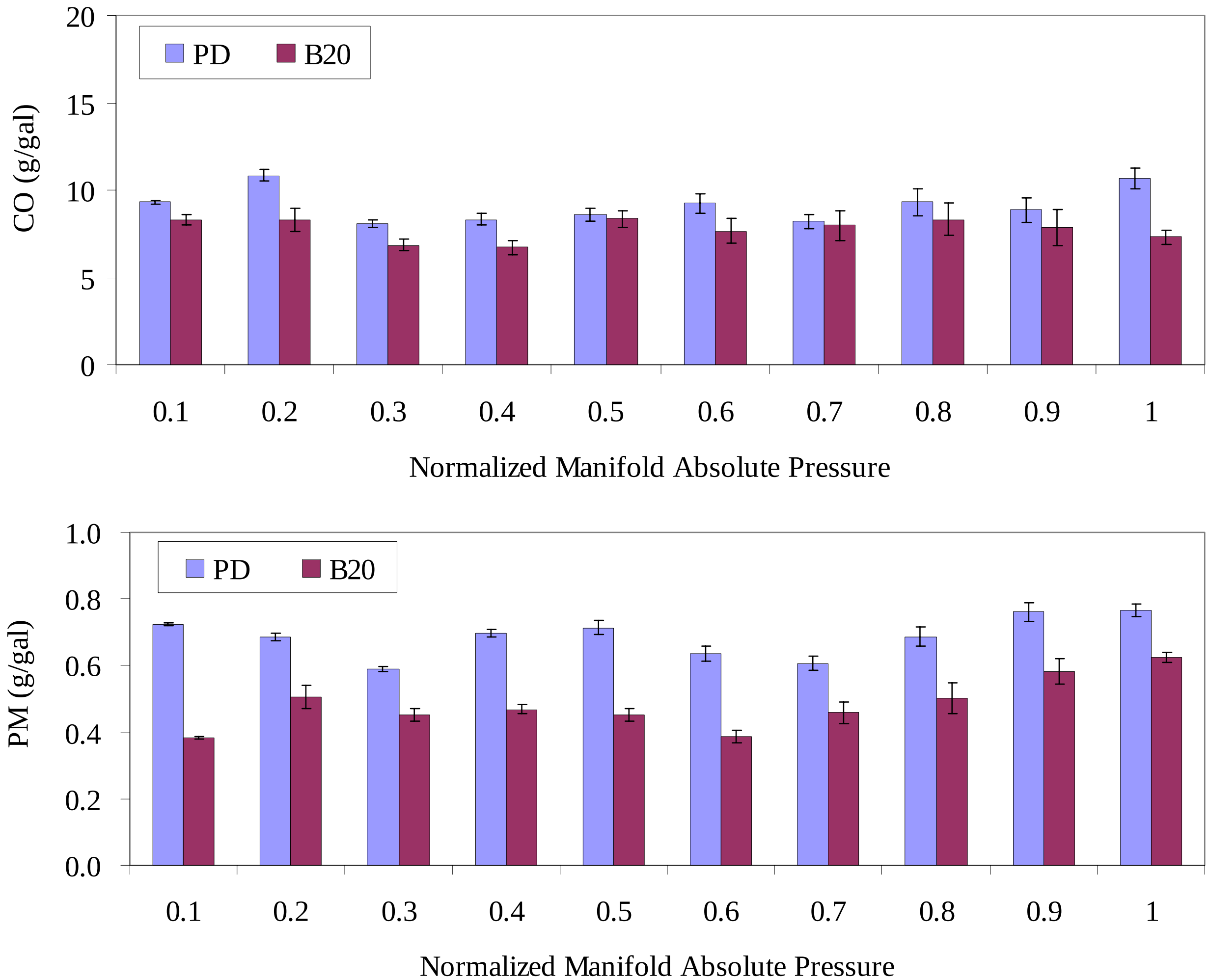


Figure 11. Continued

The results shown in Figure 10 indicate that fuel use and emissions of CO_2, NO, HC, CO, and PM increase monotonically with an increase in MAP. An increase in MAP generally indicates an increase in engine load. The lowest normalized MAP range included idling of the engine. Of course, CO_2 emissions are highly correlated with fuel use because the majority of carbon in the fuel is emitted as CO_2. Figure 10 provides a comparison of engine-based average modal emission rates for the two fuels on a per time basis. As expected, B20 biodiesel shows an overall reduction in engine-based modes for NO, HC, CO, and PM.

Emission factor units of mass per time are useful if one can estimate the total amount of time that a vehicle is operating in the field. Alternatively, an emission factor in units of mass per gallon of fuel consumed is useful if one can estimate or measure the total fuel use for a vehicle or a fleet of similar vehicles. Therefore, the emission rates in mass per gallon were estimated for each normalized MAP bin and are shown in Figure 11. Results are not shown for fuel use since the mass of fuel consumed per gallon of fuel is a constant, regardless of engine activity. Similarly, since CO_2 emissions are highly correlated with fuel consumption, the CO_2 emissions on a per gallon basis are approximately constant and, therefore, are not shown. For NO and HC, the emission rates on a per gallon basis generally decrease as MAP increases. For NO, the emission rate is highest for the lowest MAP range (idling). For the eight highest MAP ranges, the NO emission rates are approximately similar to each other. At the second highest MAP range, the NO emission rate per gallon of fuel consumed is approximately two-thirds of the fuel-based emission rate at engine idle. Of course, the rate of fuel consumption at high values of MAP is much higher than at low MAP values, as shown in Figure 10. Thus, the mass emission rate per unit time for NO increases with MAP because fuel flow increases significantly, despite the decrease in NO emissions when normalized to a gallon of fuel. Figure 11 provides a comparison of engine-based average modal emission rates for the two fuels on a per unit of fuel consumed basis. These results are typically qualitatively similar to those for the time-based results. B20 biodiesel shows an overall reduction for NO, HC, CO, and PM.

A similar trend is shown for the fuel-based HC emission rate. For CO, the average concentrations of CO measurements are below the detection limit of the PEMS. There was no significant trend of CO emission rates from the lowest MAP mode to the highest MAP modes. The non-detected measurements of CO are explained in Section 3.4. For HC and CO, it was expected that the use of B20 should lead to lower emission rates than for PD, because B20 is an oxygenated fuel and, thus, should enhance combustion efficiency. For HC, a reduction in average emission rates was observed for most engine-based modes. For CO, there appears to be consistently lower average emission rates for B20 compared to PD. However, a key factor in this comparison is that substantial portions of the measured exhaust gas concentrations of CO are below the reliable detection capabilities of the measurement instrument.

For PM, there was also no significant trend from the lowest MAP mode to the highest MAP modes. However, the comparison of modal average opacity for B20 versus PD, as a surrogate for PM emissions, indicates lower rates for B20 than for PD for all modes. These results are consistent with a previous study on dump trucks (Frey and Kim, 2005).

Activity modes can include idling, movement of the equipment for repositioning purpose, use of a bucket, etc. These modes can vary depending on the type of vehicle. A comparison of the two fuels with respect to fuel use and emission rates for the task-oriented modal analysis is given in Figures 12 and 13 for Backhoe 1. In Figure 12, the idling mode was associated with the lowest mass per time rates of fuel use and emissions in all cases. The fuel consumption rate and the emission rates of CO_2 NO, HC, CO and PM was approximately the same for the moving, scoop, and bucket modes. NO, HC, CO, and PM emission rates were slightly higher for the scoop mode than for the moving and the bucket modes. However, an important factor that affects fuel use and emissions is whether the vehicle is idling, since the fuel use and emission rates for the three non-idling modes are approximately similar in most cases. The task-oriented modal analysis does not explain as much of the variability in fuel use and emission rates as the engine-based data, but it does provide some indication of how fuel use and emission rates change for task-oriented modes of activity. Figure 12 provides a comparison of task-oriented average modal emission rates for the two fuels on a per time basis. As expected, B20 biodiesel shows an overall reduction in task-oriented modes for NO, HC, CO, and PM.

The task-oriented modes of activity were also analyzed on the basis of gallons of fuel consumed, as shown in Figure 13. These results generally indicate that the emission rate per gallon of fuel consumed is highest for idling, and in many cases is approximately similar when comparing the scoop, moving, and bucket modes. Similarly, there appears to be consistently lower average task-oriented emission rates for B20 compared to PD.

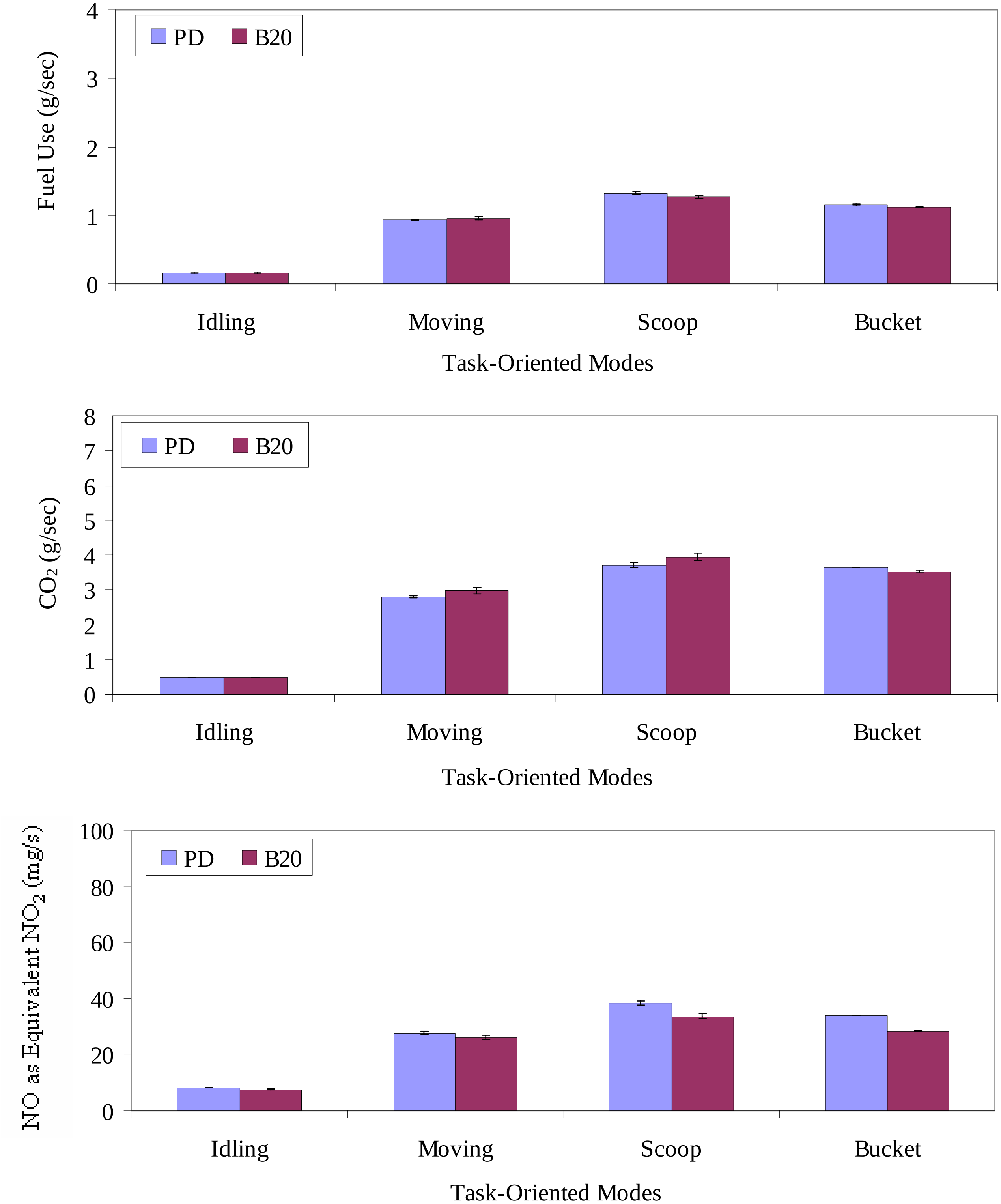
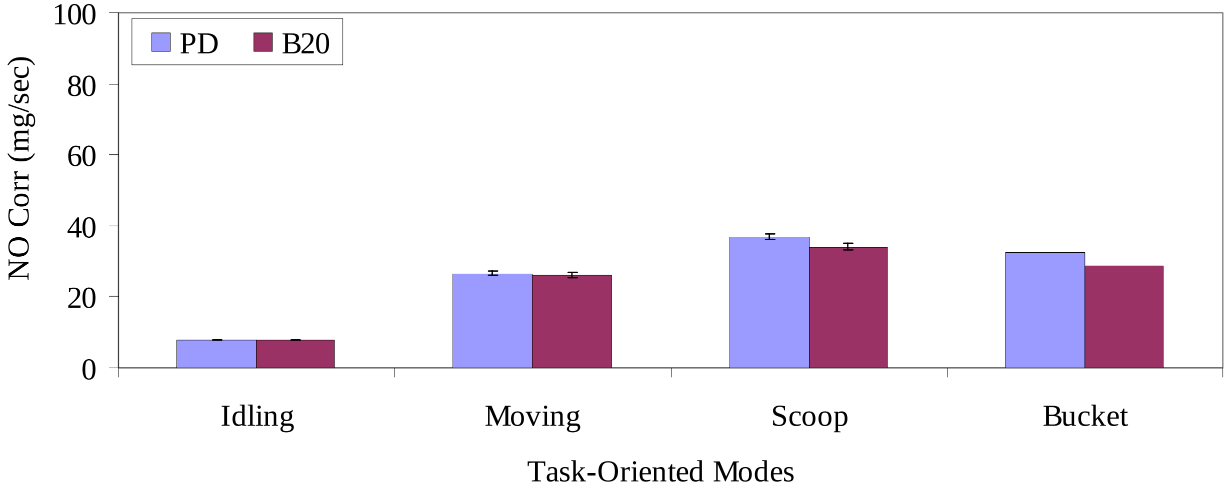
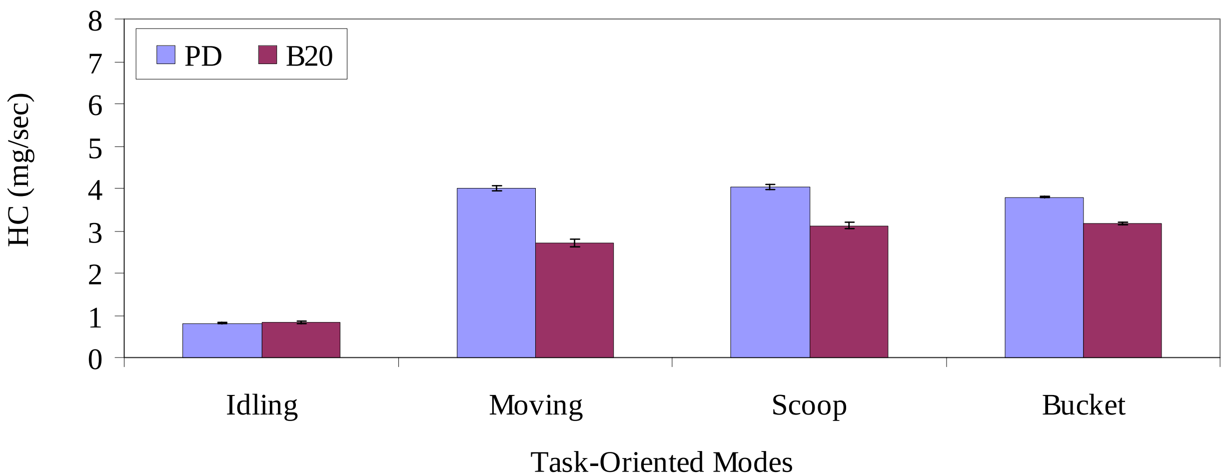


Figure 12. Comparison between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Task-Oriented Based Modes for Backhoe 1





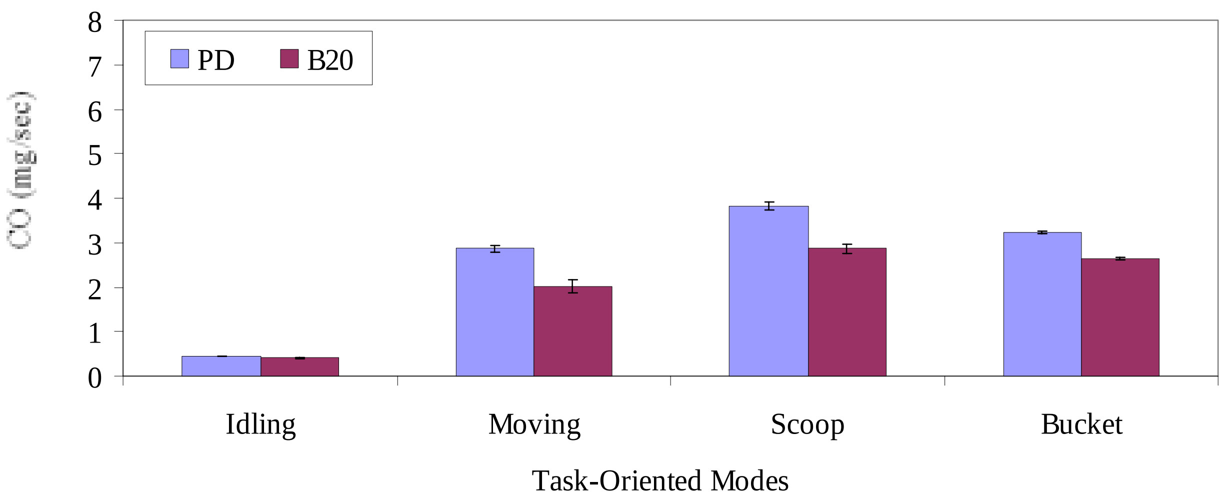
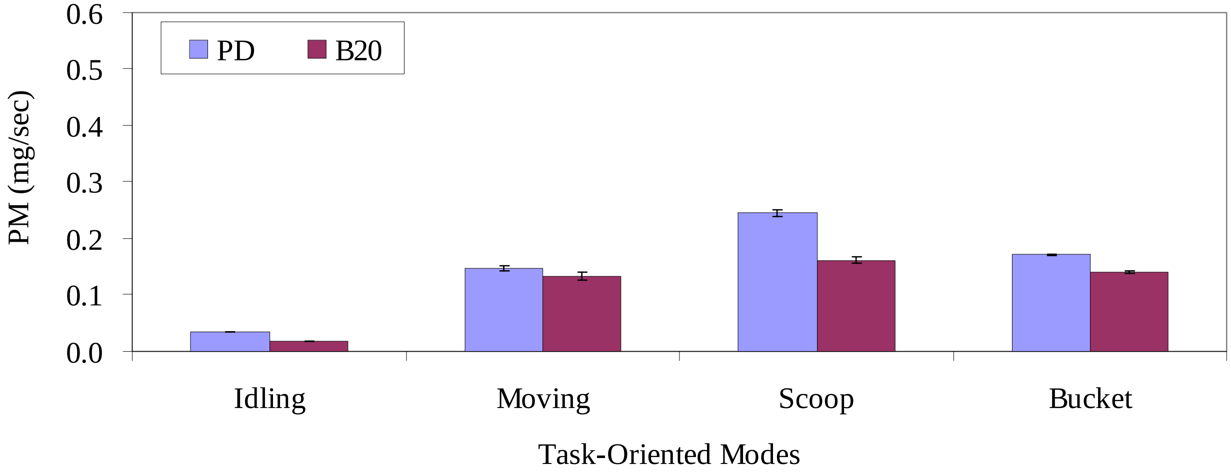


Figure 12. Continued



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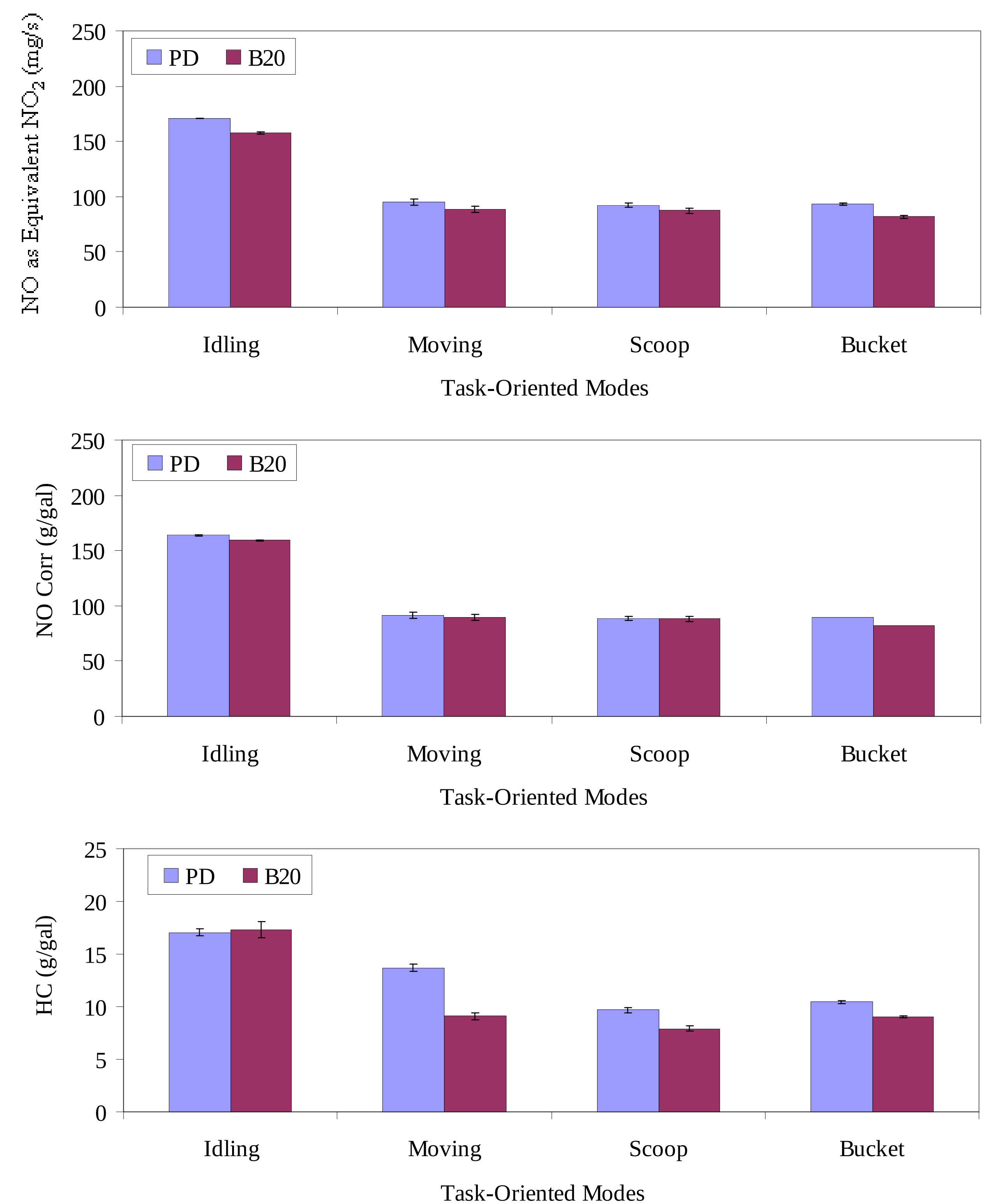

Figure 13. Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and Emission Rates of Each Pollutant on a Per Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Backhoe 1

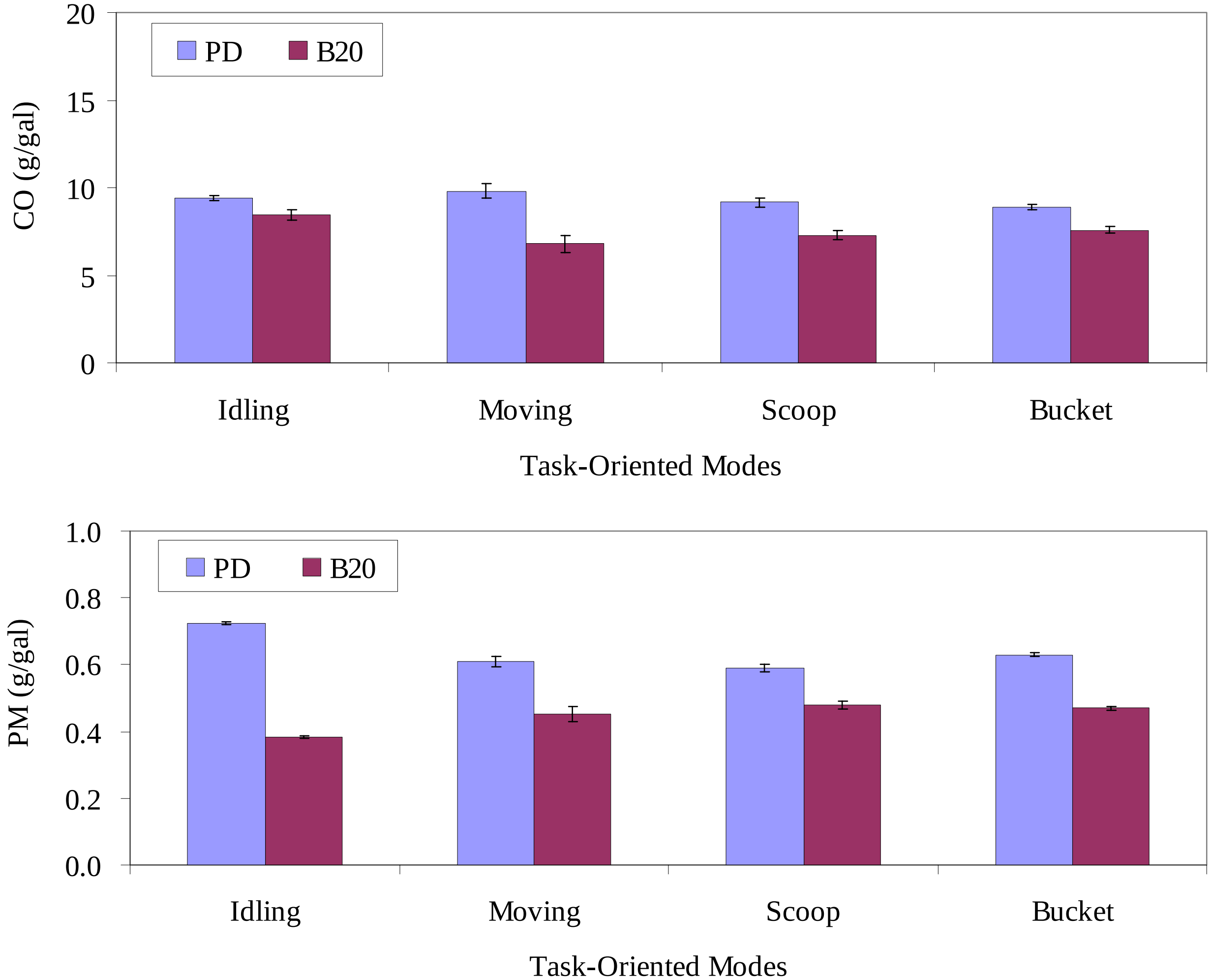

Figure 13. Continued

3.6 Representative Duty Cycles

Vehicle duty cycles are described in Section 2.8. In order to compare fuel use and emission rates, cycle-average emission rates are estimated based on selected duty cycles. In this section, the distributions of normalized MAP based on time and fuel use for each representative duty cycle are presented.

For backhoes, there were three observed real-world duty cycles including “mass excavation,” “material handling,” and “load truck.” The cumulative frequency of normalized MAP for the three representative duty cycles for a backhoe is shown in Figure 14. For the “load truck” cycle, a backhoe uses the front bucket, which is 5 times larger than the rear bucket, to place soil or rock into a dump truck. Each duty cycle must be completed in a short amount of time. The operator usually moves the soil or rock with the full capacity of front bucket. Thus, among the three duty cycles, the average engine load for “load truck” is relatively higher than the other duty cycles.

The observed duty cycles for a front-end loader include “rock handling,” “soil handling,” and “load truck.” The cumulative frequency of normalized MAP for the three representative duty cycles for a front-end loader is shown in Figure 15. The average engine loads for these three duty cycles are similar.

In Figure 16, two representative duty cycles for a motor grader are characterized by a frequency distribution of normalized MAP. The two cycles observed, “resurfacing” and “shouldering,” have substantially different average engine loads. The “resurfacing” cycle has a higher average engine load compared to the “shouldering” cycle because of the resistance of the blade on the ground surface while a motor grader works.

The distribution of normalized MAP based on time and fuel use for each observed duty cycle for a backhoe is shown in Figure 17. The left panel of the figure is the distribution of time for each duty cycle, and right panel of the figure is the distribution of fuel consumption. Similar figures for a front-end loader and a motor grader are shown in Figure 18 and Figure 19, respectively.

For the “load truck” cycle of backhoes shown in Figure 17, the lowest five MAP modes contribute to about 60% of time but only contribute to less than 50% of fuel consumption. High MAP modes consume more fuel, resulting in high emission rates of NO, opacity, HC, and CO. The lowest five MAP modes for the “mass excavation” cycle contribute to more than 90% of time and fuel consumption because the “mass excavation” cycle has the lowest average engine load among these duty cycles. The lowest five MAP modes for “material handling” contribute to about 90% of time and 80% of fuel consumption. In general, lower MAP modes contribute to more time but less fuel consumption and higher MAP modes contribute to more fuel consumption but less time.

The lowest MAP mode of the “load truck cycle” for front-end loaders contributes to 25% of time but only contributes to less than 10% of fuel consumption shown in Figure 18. For the motor grader cycles shown in Figure 19, the highest five MAP modes of the “resurfacing” cycle contribute to 60% of time and 80% of fuel consumption compared to 15% of time and 35% of fuel consumption for the “shouldering” cycle.

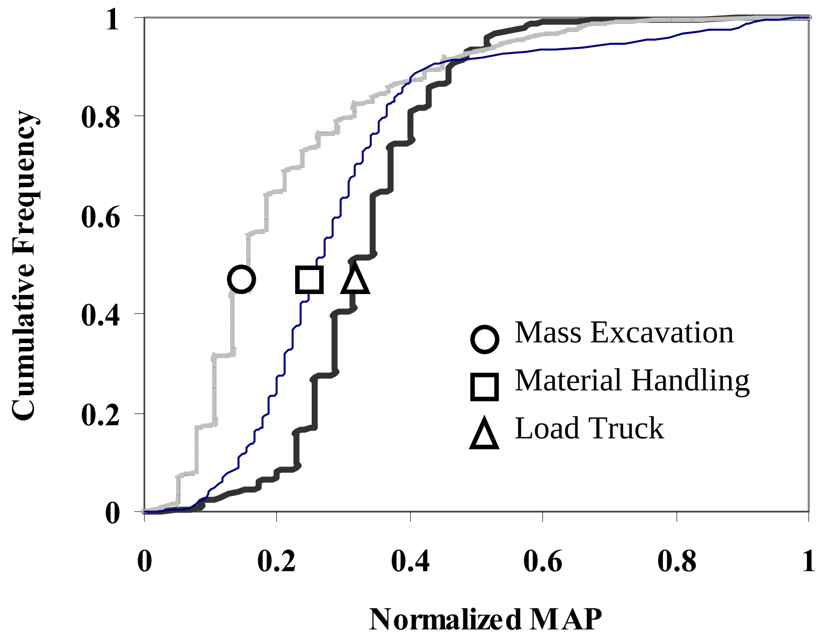

Figure 14. Cumulative Frequency of Normalized MAP for Three Representative Duty Cycles for a Backhoe

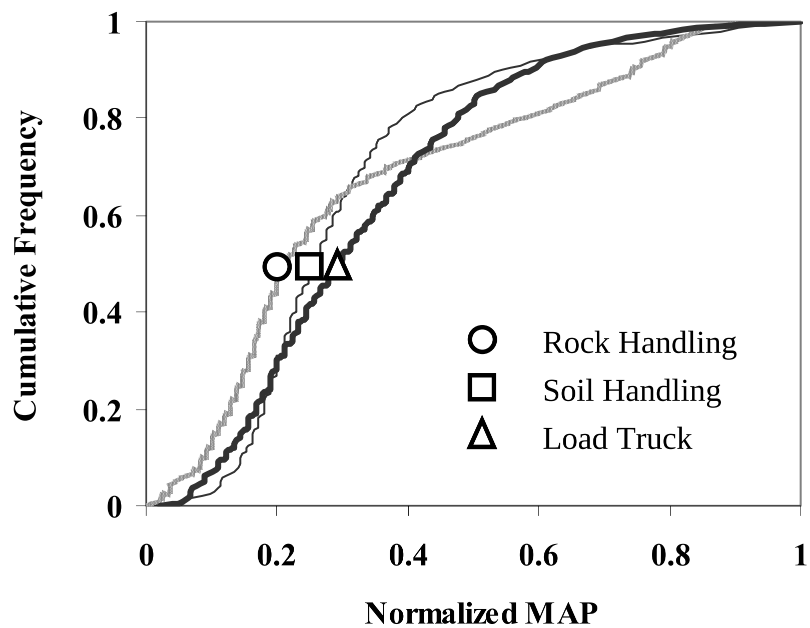

Figure 15. Cumulative Frequency of Normalized MAP for Three Representative Duty Cycles for a Front-End Loader

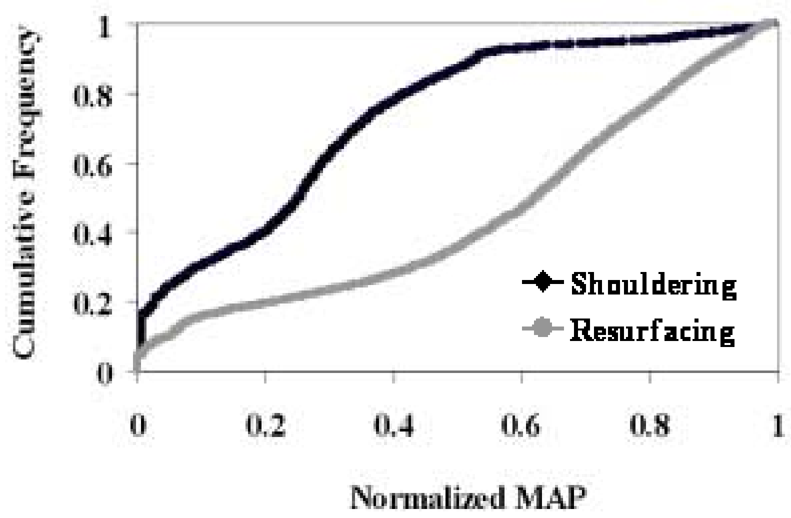

Figure 16. Cumulative Frequency of Normalized MAP for Two Representative Duty Cycles for a Motor Grader

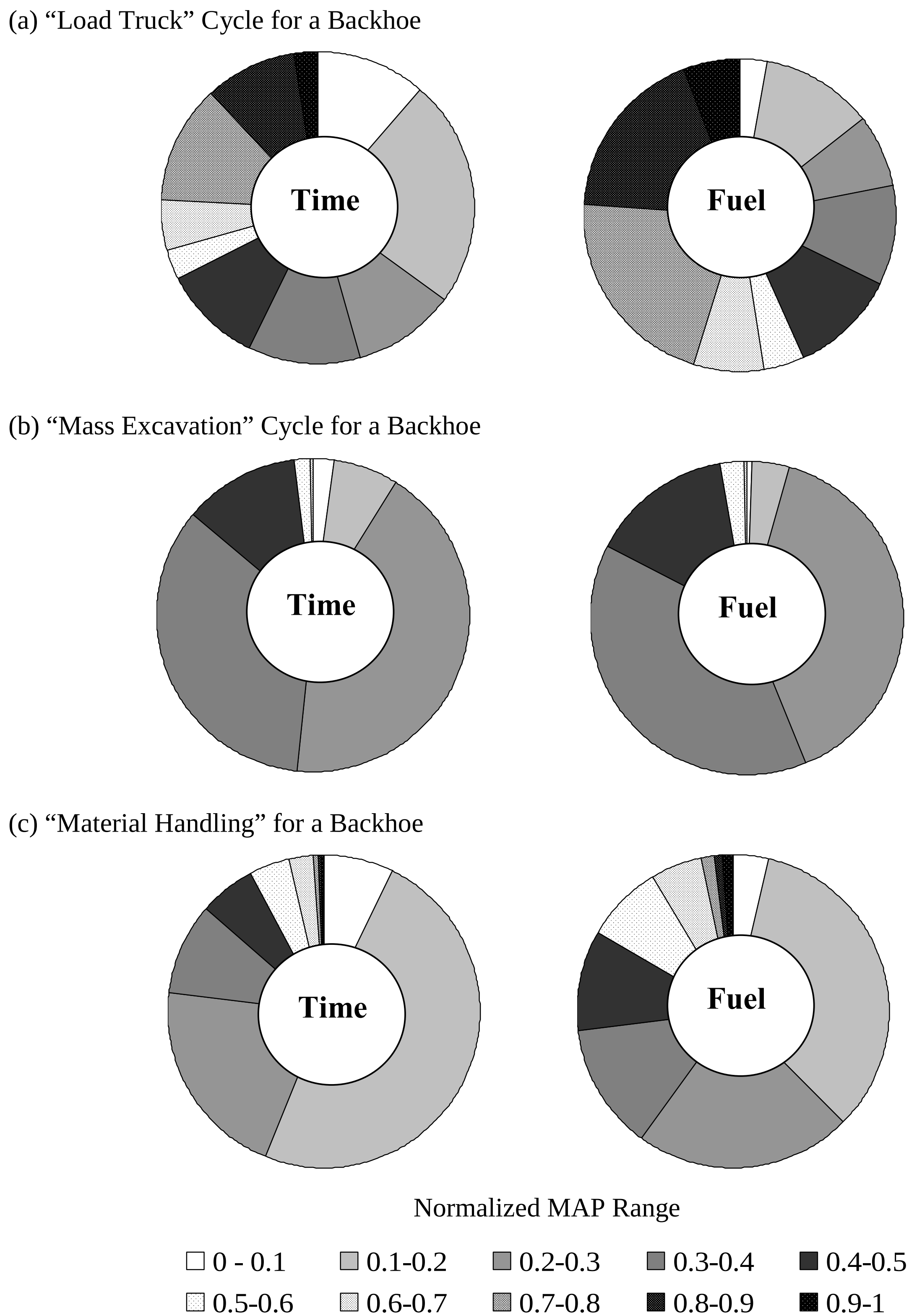

Figure 17. Distribution of Normalized MAP Based on Time and Fuel Use for Each Observed Duty Cycle

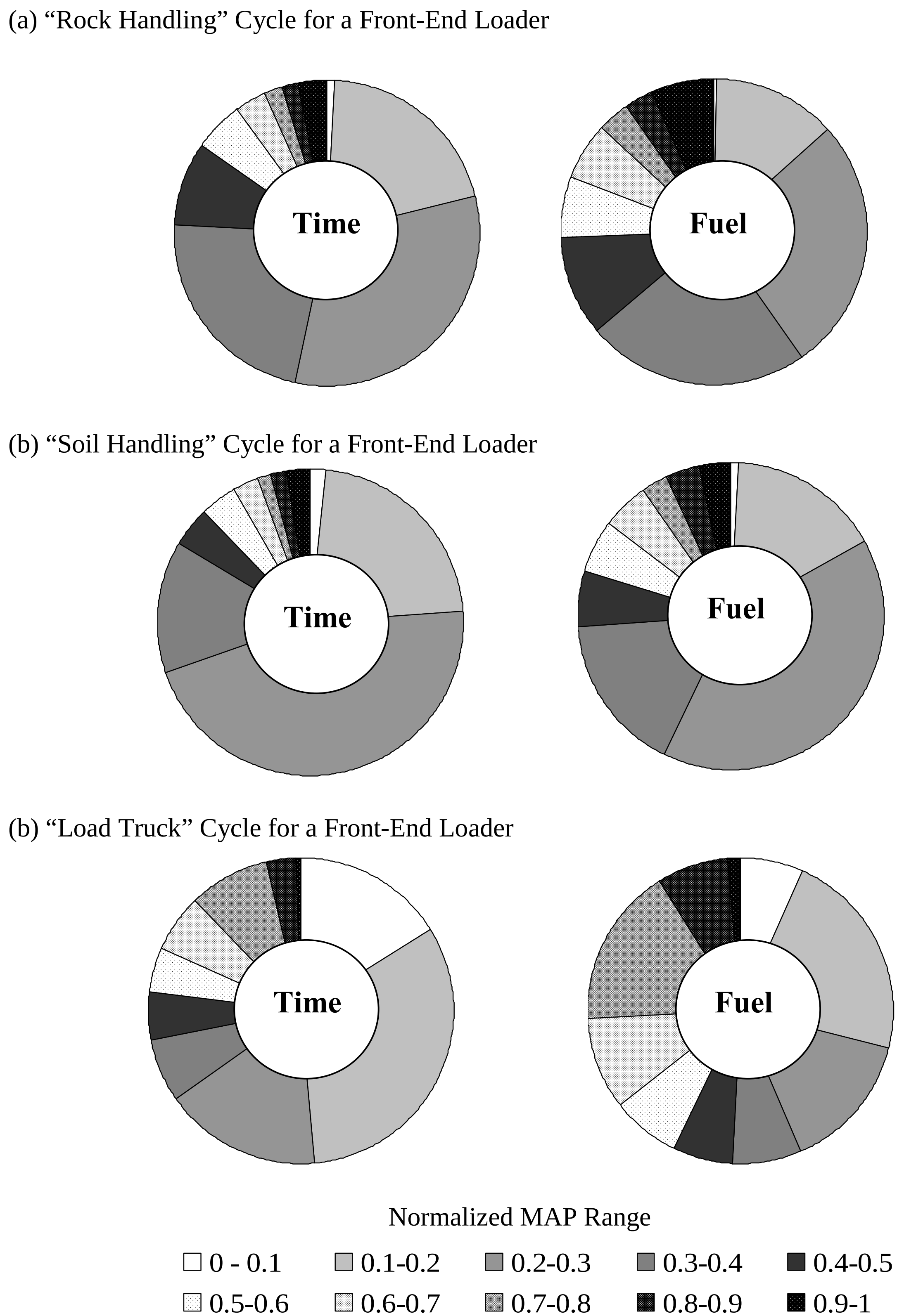

Figure 18. Distribution of Fuel Use and Time for Each Observed Duty Cycle for a Front-End Loader

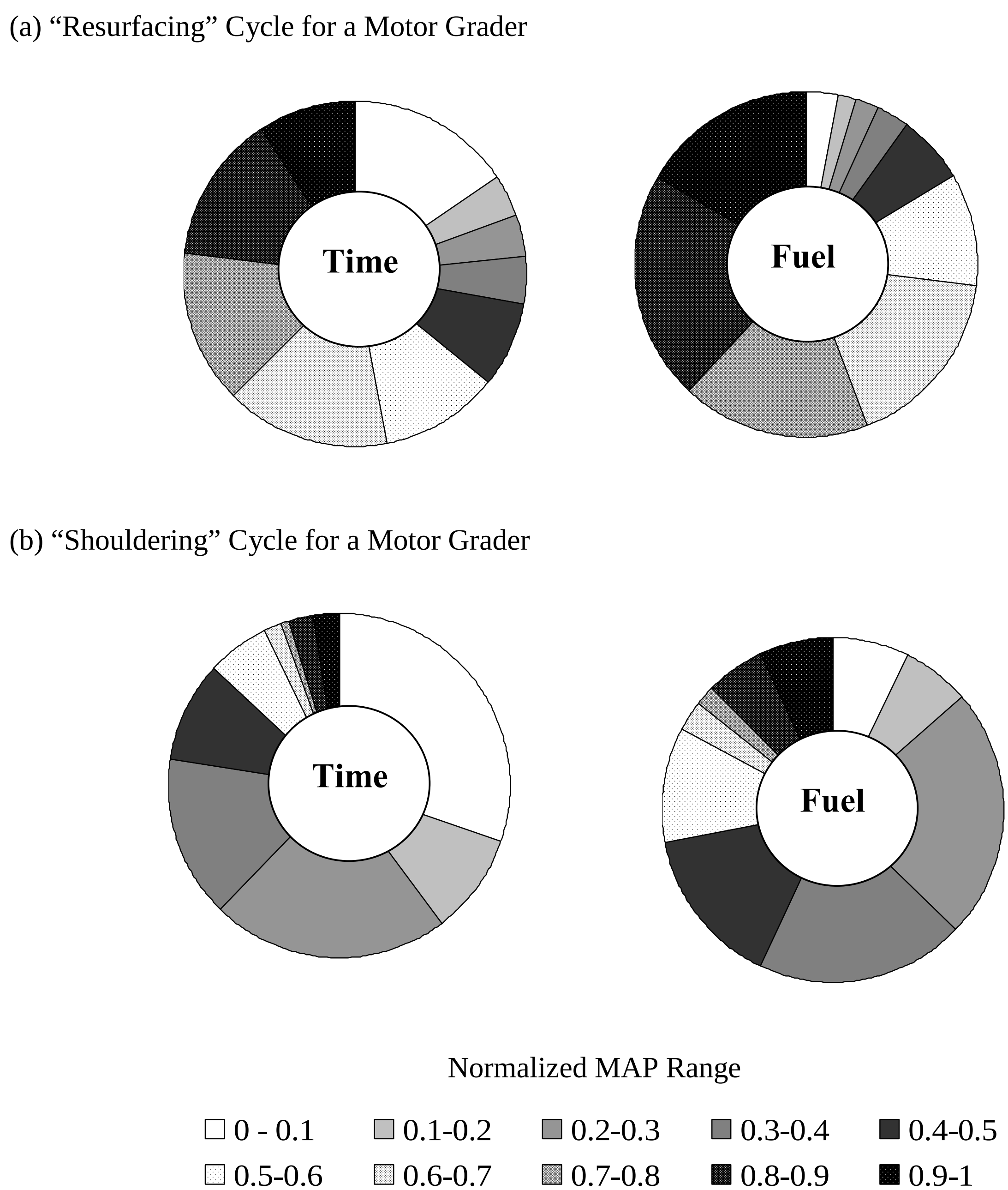

Figure 19. Distribution of Normalized MAP Based on Time and Fuel Use for Each Observed Duty Cycle for a Motor Grader

3.7 Evaluation of Non-Detected Measurements of HC and CO Exhaust Gas Concentrations and Modal Average Emission Rates for Engine-Based Modes

In some cases, HC and CO concentrations from diesel engines are below the detection limit of the gas analyzers. Thus, the robustness of comparisons of emission rates among modes or between fuels may be limited when substantial proportions of the measured exhaust gas concentrations of HC and CO are below the detection limit. Based on previous work, mean values of a data set are often robust if the mean of the data is larger than the detection limit. In order to identify the uncertainty associated with modal emission rates, the detection limit of the PEMS needs to be carefully determined. In order to determine the detection limit for HC and CO, a scatter plot was used to compare the HC and CO concentration for both analyzers as shown in Appendix G. Based on the scatter plots, the detection limits for HC and CO are approximately 20 ppm and 0.02 vol%, respectively. If a mean modal emission rate in a MAP bin is below these detection limits, there is less confidence in the stability of the mean value. Table 14 summarizes the number of engine-based modes for which the mean concentration was below the detection limit for a given test vehicle. Detailed information is provided in Appendix G.

In Table 14, 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 non-detects on both fuels.

Table 14. Frequency With Which Mean Exhaust Gas Concentration was Below Detection Limit for HC and CO Engine-Based Modal Emission Rates

Test Vehicle	Vehicle ID	Engine Type (Tier)	HC		CO	
			B20 Biodiesel	Petroleum Diesel	B20 Biodiesel	Petroleum Diesel
Backhoe	803-0242	0	O	O	X (1)	O
	803-0241	1	O	O	O	O
	808-0214	1	X (8)	X (8)	X (1)	O
	FDP22085	2	X (10)	X (8)	X (5)	X (10)
	FDP20882	2	X (10)	X (5)	X (10)	X (10)
Front-End Loader	010-0249	1	X (10)	O	X (9)	X (9)
	010-0301	1	X (10)	O	X (10)	X (10)
	010-5074	1	X (9)	O	X (10)	X (10)
	010-0388	2	X (10)	X (10)	X (7)	X (10)
Motor Grader	948-6647	0	O	O	O	O
	955-0277	0	O	O	O	O
	955-0515	1	O	O	O	O
	955-0516	1	O	O	O	O
	955-0606	2	X (8)	X (5)	X (7)	X (6)
	955-0633	3	X (10)	X (10)	X (10)	X (9)

O: The average modal concentrations are over detection limit

X: Number of engine-based modes for which the mean concentration was below the detection limit for a given tested vehicle

3.8 Estimation of Cycle Average Fuel Use and Emission Rates for Selected Duty Cycles

In order to compare the effects of substitution of B20 versus PD, average fuel use and emission rates were estimated for each tested vehicle for representative duty cycles. The time-based and fuel-based results are given in Table 15 and Table 16 for backhoes, Table 17 and Table 18 for front-end loaders, and Table 19 and Table 20 for motor graders, respectively. Each duty cycle is characterized by a frequency distribution of normalized MAP (see Section 3.6). The time-based, engine-based average fuel use and modal emission rates are weighted by these duty cycle distributions of normalized MAP in order to estimate cycle average fuel use and emission rates. These results enable a consistent comparison of emissions and fuel use between petroleum diesel and B20 biodiesel based on different representative duty cycles. There are variations among cycle-average emission rates when comparing different duty cycles.

In Table 15, the time-based cycle average fuel use and emission rates are shown for both B20 biodiesel and petroleum diesel. For each backhoe, the cycle average fuel use and emission rates are estimated based on "Load Truck Cycle (LTC)," "Mass Excavation Cycle (MEC)," and "Material Handling Cycle (MHC)." When the ratio (B20/PD) for the emission rates is greater than 1.0, biodiesel has higher emissions than petroleum diesel. As expected, the fuel use rates and CO_2 emission rates for both fuels are similar. However, there are significant variations among different duty cycles. For example, the fuel use rates for Backhoe 1 range from 0.72 g/sec to 1.01 g/sec among the duty cycles. This is a 40% difference between the high versus low values.

For NO emissions, both NO uncorrected and corrected emission rates are shown in Table 15. Although Backhoe 2 shows a small increase of NO for uncorrected (2% to 4%) and corrected emission rates (4%-5%) when using B20 biodiesel, the overall average ratios (B20/PD) are 0.90 for NO uncorrected and 0.93 for NO corrected emission rates. Backhoes 1, 3, 4, and 5 show an overall reduction for all duty cycles when using B20 biodiesel. The inter-cycle variations are significant for NO emission rates. There is an average 40% difference between the high versus low emission factor values among all of the vehicles.

For opacity, Backhoes 1, 4, and 5 show a significant reduction when using B20 biodiesel, but Backhoes 2 and 3 show equal or only slight reductions. The overall average ratio (B20/PD) for all vehicles is 0.81. The inter-cycle variations are significant for opacity rates. There is an average 79% difference in opacity between the high versus low values among all vehicles

Table 15. Estimate of Time-Based Cycle Average Fuel Use and Emission Rates for Selected Backhoe Cycles When Comparing B20 Biodiesel vs. Petroleum Diesel for All Five Backhoes

	Vehicle	B20 Biodiesel			Petroleum Diesel			Ratio (B20/PD)		
		LTC[a]	MEC[b]	MHC[c]	LTC[a]	MEC[b]	MHC[c]	LTC[a]	MEC[b]	MHC[c]
Fuel Use (g/sec)	BH 1	1.01	0.89	0.72	1.01	0.89	0.72	1.00	1.00	1.00
	BH 2	1.93	1.52	1.28	1.91	1.51	1.27	1.01	1.01	1.01
	BH 3	1.83	1.41	1.19	1.93	1.54	1.29	0.95	0.92	0.92
	BH 4	1.75	1.48	1.06	1.72	1.45	1.08	1.02	1.02	0.98
	BH 5	0.99	0.89	0.68	0.98	0.86	0.68	1.01	1.03	1.00
CO_2 (g/sec)	BH 1	3.14	2.77	2.23	3.20	2.82	2.26	0.98	0.98	0.99
	BH 2	5.99	4.72	3.97	5.93	4.69	3.94	1.01	1.01	1.01
	BH 3	5.74	4.40	3.70	6.05	4.80	4.01	0.95	0.92	0.92
	BH 4	5.44	4.59	3.30	5.40	4.54	3.39	1.01	1.01	0.97
	BH 5	3.08	2.77	2.12	3.11	2.72	2.16	0.99	1.01	0.98
NO as Equivalent NO_2 (mg/sec)	BH 1	29.3	25.2	22.9	31.8	27.0	24.5	0.92	0.93	0.93
	BH 2	75.3	52.4	43.1	73.5	50.7	41.6	1.02	1.03	1.04
	BH 3	52.7	36.2	36.4	63.7	51.5	44.4	0.83	0.70	0.82
	BH 4	46.4	48.3	38.2	55.4	55.2	45.6	0.84	0.88	0.84
	BH 5	28.6	24.6	21.9	31.5	26.6	24.0	0.91	0.92	0.91
NO Corr (mg/sec)	BH 1	29.6	25.5	23.2	30.6	25.9	23.5	0.97	0.98	0.99
	BH 2	72.3	50.3	41.4	69.8	48.2	39.5	1.04	1.04	1.05
	BH 3	47.4	32.6	32.7	59.9	48.4	41.8	0.79	0.67	0.78
	BH 4	45.0	46.8	37.0	49.3	49.1	40.6	0.91	0.95	0.91
	BH 5	29.1	25.1	22.3	30.8	26.1	23.5	0.94	0.96	0.95
Opacity (mg/sec)	BH 1	0.16	0.13	0.10	0.22	0.18	0.15	0.73	0.72	0.67
	BH 2	0.72	0.51	0.47	0.73	0.51	0.48	0.99	1.00	0.98
	BH 3	0.72	0.44	0.38	0.74	0.44	0.46	0.97	1.00	0.83
	BH 4	0.71	0.32	0.31	0.88	0.76	0.46	0.81	0.42	0.67
	BH 5	0.21	0.14	0.13	0.24	0.19	0.16	0.88	0.74	0.81
HC (mg/sec)	BH 1[d]	2.58	1.96	1.92	3.46	2.85	2.71	0.75	0.69	0.71
	BH 2	7.10	6.76	6.02	7.76	7.53	6.53	0.91	0.90	0.92
	BH 3	8.42	3.97	4.03	9.19	5.43	5.09	0.92	0.73	0.79
	BH 4[f]	2.24	2.63	1.89	2.62	2.93	2.38	0.85	0.90	0.79
	BH 5[g]	1.00	0.89	0.80	2.65	2.84	2.17	0.38	0.31	0.37
CO (mg/sec)	BH 1[d]	2.5	2.0	1.7	2.9	2.4	2.1	0.86	0.83	0.81
	BH 2[e]	52.3	30.3	26.9	65.5	38.5	33.1	0.80	0.79	0.81
	BH 3	18.2	16.3	12.0	21.1	18.4	14.2	0.86	0.89	0.85
	BH 4	22.8	16.5	14.4	28.7	20.7	17.8	0.79	0.79	0.81
	BH 5[g]	3.8	2.7	2.9	4.8	4.4	3.6	0.79	0.61	0.81

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

[d] For Backhoe 1, modal average HC concentrations were below the detection limit for B20 for all 10 modes and were below the detection limit for petroleum diesel for 5 out of 10 modes; modal average CO concentrations were below the detection limit for both fuels.

[e] For Backhoe 2, only modal average CO concentration was below the detection limit for only B20 for 1 out of 10 modes.

[f] For Backhoe 4, modal average HC concentrations were below the detection limit for both fuels for 8 out of 10 modes; modal average CO concentration was below the detection limit for only B20 for 1 out of 10 modes

[g] For Backhoe 5, modal average HC concentrations were below the detection limit for B20 for all 10 modes and were below the detection limit for petroleum diesel for 8 out of 10 modes; modal average CO concentrations were below the detection limit for B20 for 5 of 10 modes and were below the detection limit for petroleum diesel for all 10 modes.

Table 16. Estimate of Fuel-Based Cycle Average Emission Rates for Selected Backhoe Cycles When Comparing B20 Biodiesel vs. Petroleum Diesel for All Five Backhoes

	Vehicle	B20 Biodiesel			Petroleum Diesel			Ratio (B20/PD)		
		LTC[a]	MEC[b]	MHC[c]	LTC[a]	MEC[b]	MHC[c]	LTC[a]	MEC[b]	MHC[c]
NO as Equivalent NO_2 (g/gallon)	BH 1	94	91	103	101	96	109	0.93	0.95	0.95
	BH 2	124	109	107	121	106	103	1.02	1.03	1.04
	BH 3	93	94	98	105	106	109	0.89	0.89	0.90
	BH 4	89	107	123	105	123	138	0.85	0.87	0.89
	BH 5	94	90	106	102	98	112	0.92	0.92	0.95
NO Corr (g/gallon)	BH 1	94	92	104	96	92	105	0.98	1.00	0.99
	BH 2	118	104	102	115	101	98	1.03	1.03	1.04
	BH 3	83	84	88	99	100	103	0.84	0.84	0.85
	BH 4	87	104	119	93	109	120	0.94	0.95	0.99
	BH 5	96	92	108	100	96	110	0.96	0.96	0.98
Opacity (g/gallon)	BH 1	0.50	0.46	0.47	0.70	0.66	0.66	0.71	0.70	0.71
	BH 2	1.20	1.08	1.20	1.25	1.09	1.26	0.96	0.99	0.95
	BH 3	1.28	0.99	1.07	1.23	0.91	1.16	1.04	1.09	0.92
	BH 4	1.31	0.71	0.98	1.61	1.66	1.31	0.81	0.43	0.75
	BH 5	0.70	0.51	0.62	0.79	0.69	0.74	0.87	0.74	0.84
HC (g/gallon)	BH 1[d]	8.3	7.1	8.8	10.9	10.2	12.1	0.76	0.70	0.73
	BH 2	12.0	14.3	15.4	13.3	16.0	17.0	0.90	0.89	0.91
	BH 3	14.8	9.0	11.0	15.2	11.1	12.8	0.97	0.81	0.86
	BH 4[f]	4.3	5.9	6.0	5.6	6.7	9.1	0.77	0.88	0.66
	BH 5[g]	3.3	3.2	3.9	8.6	10.5	10.3	0.38	0.31	0.38
CO (g/gallon)	BH 1[d]	7.9	7.1	7.7	9.1	8.4	9.3	0.87	0.85	0.83
	BH 2[e]	86	62	67	106	77	82	0.81	0.80	0.82
	BH 3	32	36	32	36	39	36	0.89	0.92	0.89
	BH 4	43	36	46	54	45	53	0.79	0.81	0.87
	BH 5[g]	13	10	14	16	16	17	0.81	0.63	0.82

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

[d] For Backhoe 1, modal average HC concentrations were below the detection limit for B20 for all 10 modes and were below the detection limit for petroleum diesel for 5 out of 10 modes; modal average CO concentrations were below the detection limit for both fuels.

[e] For Backhoe 2, only modal average CO concentration was below the detection limit for only B20 for 1 out of 10 modes.

[f] For Backhoe 4, modal average HC concentrations were below the detection limit for both fuels for 8 out of 10 modes; modal average CO concentration was below the detection limit for only B20 for 1 out of 10 modes

[g] For Backhoe 5, modal average HC concentrations were below the detection limit for B20 for all 10 modes and were below the detection limit for petroleum diesel for 8 out of 10 modes; modal average CO concentrations were below the detection limit for B20 for 5 of 10 modes and were below the detection limit for petroleum diesel for all 10 modes.

Table 17. Estimate of Time-Based Cycle Average Fuel Use and Emission Rates for Selected Front-End Loader Cycles When Comparing B20 Biodiesel vs. Petroleum Diesel for All Four Front-End Loaders

	Vehicle	B20 Biodiesel			Petroleum Diesel			Ratio (B20/PD)		
		RHC[a]	SDHC[b]	LTC[c]	RHC[a]	SDHC[b]	LTC[c]	RHC[a]	SDHC[b]	LTC[c]
Fuel Use (g/sec)	FL1	2.24	2.08	2.04	2.15	1.97	1.93	1.04	1.06	1.06
	FL2	1.80	1.68	1.62	1.87	1.71	1.70	0.96	0.98	0.95
	FL3	2.75	2.55	2.48	2.74	2.53	2.46	1.00	1.01	1.01
	FL4	2.02	1.87	1.81	2.01	1.85	1.79	1.00	1.01	1.01
CO_2 (g/sec)	FL1	6.91	6.41	6.29	6.75	6.19	6.07	1.03	1.04	1.04
	FL2	5.56	5.19	4.98	5.88	5.39	5.34	0.95	0.96	0.93
	FL3	8.47	7.84	7.63	8.62	7.98	7.76	0.98	0.98	0.98
	FL4	6.21	5.77	5.57	6.34	5.81	5.65	0.98	0.99	0.99
NO as Equivalent NO_2 (mg/sec)	FL1	83.3	78.6	76.7	82.7	78.0	73.3	1.01	1.01	1.05
	FL2	76.0	73.1	66.2	79.3	73.8	71.3	0.96	0.99	0.93
	FL3	99.7	94.4	91.1	114	108	101	0.87	0.87	0.90
	FL4	58.1	55.4	51.7	58.0	54.3	52.1	1.00	1.02	0.99
NO Corr (mg/sec)	FL1	75.8	71.6	69.8	72.8	68.7	64.5	1.04	1.04	1.08
	FL2	66.9	64.3	58.3	74.5	69.4	67.1	0.90	0.93	0.87
	FL3	111	105	102	109	102	95.8	1.02	1.03	1.06
	FL4	56.3	54.3	50.7	58.6	54.8	52.6	0.96	0.99	0.96
Opacity (mg/sec)	FL1	0.45	0.42	0.41	0.68	0.63	0.63	0.66	0.67	0.65
	FL2	0.24	0.22	0.22	0.29	0.27	0.26	0.83	0.82	0.85
	FL3	0.64	0.60	0.59	0.78	0.71	0.73	0.82	0.85	0.81
	FL4	0.36	0.32	0.34	0.40	0.37	0.37	0.90	0.86	0.92
HC (mg/sec)	FL1[d]	5.00	4.70	4.70	11.2	10.6	10.7	0.45	0.44	0.44
	FL2[e]	4.52	4.24	4.32	9.10	8.65	8.62	0.50	0.49	0.50
	FL3[f]	8.04	7.57	7.73	10.7	10.2	9.61	0.75	0.74	0.80
	FL4[g]	3.02	2.88	2.81	3.38	3.17	3.08	0.89	0.91	0.91
CO (mg/sec)	FL1[d]	8.58	8.17	8.75	9.53	9.12	10.14	0.90	0.90	0.86
	FL2[e]	5.38	5.16	5.34	7.10	6.89	7.08	0.76	0.75	0.75
	FL3[f]	7.27	6.79	6.79	12.5	11.8	11.8	0.58	0.58	0.58
	FL4[g]	5.55	5.19	4.98	6.69	6.23	6.32	0.83	0.83	0.79

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

[d] For Front-End Loader 1, modal average HC concentrations were below the detection limit only for B20 for all 10 modes; modal average CO concentrations were below the detection limit for both fuels for 9 out of 10 modes.

[e] For Front-End Loader 2, modal average HC concentrations were below the detection limit only for B20 for all 10 modes; modal average CO concentrations were below the detection limit for both fuels for all 10 modes.

[f] For Front-End Loader 3, modal average HC concentrations were below the detection limit only for B20 for 9 out of 10 modes; modal average CO concentrations were below the detection limit for both fuels for all 10 modes.

[g] For Front-End Loader 4, modal average HC concentrations were below the detection limit for both fuels for all 10 modes; modal average CO concentrations were below the detection limit for B20 for 7 out of 10 modes and were below the detection limit for petroleum diesel for all 10 modes.

Table 18. Estimate of Fuel-Based Cycle Average Emission Rates for Selected Front-End Loader Cycles When Comparing B20 Biodiesel vs. Petroleum Diesel for All Four Front-End Loaders

	Vehicle	B20 Biodiesel			Petroleum Diesel			Ratio (B20/PD)		
		RHC[a]	SDHC[b]	LTC[c]	RHC[a]	SDHC[b]	LTC[c]	RHC[a]	SDHC[b]	LTC[c]
NO as Equivalent NO_2 (g/gallon)	FL1	120	123	123	124	128	123	0.97	0.96	1.00
	FL2	137	141	134	136	139	136	1.01	1.01	0.99
	FL3	116	119	118	133	136	131	0.87	0.88	0.90
	FL4	93	96	93	93	95	94	1.00	1.01	0.99
NO Corr (g/gallon)	FL1	109	112	112	109	113	108	1.00	0.99	1.04
	FL2	120	124	118	128	131	127	0.94	0.95	0.93
	FL3	130	133	132	127	129	125	1.02	1.03	1.06
	FL4	92	95	91	94	96	95	0.98	0.99	0.96
Opacity (g/gallon)	FL1	0.65	0.66	0.64	1.00	1.00	1.02	0.65	0.66	0.63
	FL2	0.42	0.42	0.43	0.49	0.51	0.49	0.86	0.82	0.88
	FL3	0.74	0.76	0.75	0.91	0.89	0.94	0.81	0.85	0.80
	FL4	0.57	0.54	0.60	0.62	0.62	0.66	0.92	0.87	0.91
HC (g/gallon)	FL1[d]	7.20	7.33	7.61	16.9	17.6	18.7	0.43	0.42	0.41
	FL2[e]	8.17	8.31	8.93	15.8	16.5	16.7	0.52	0.50	0.53
	FL3[f]	9.50	9.79	10.5	12.7	13.2	13.1	0.75	0.74	0.80
	FL4[g]	4.87	5.06	5.13	5.4	5.6	5.8	0.90	0.90	0.88
CO (g/gallon)	FL1[d]	12.4	12.9	14.9	14.5	15.5	18.4	0.86	0.83	0.81
	FL2[e]	9.8	10.3	11.4	12.4	13.3	14.1	0.79	0.77	0.81
	FL3[f]	8.54	8.7	9.13	14.8	15.4	16.1	0.58	0.56	0.57
	FL4[g]	8.94	9.07	8.93	10.7	11.0	11.3	0.84	0.82	0.79

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

[d] For Front-End Loader 1, modal average HC concentrations were below the detection limit only for B20 for all 10 modes; modal average CO concentrations were below the detection limit for both fuels for 9 out of 10 modes.

[e] For Front-End Loader 2, modal average HC concentrations were below the detection limit only for B20 for all 10 modes; modal average CO concentrations were below the detection limit for both fuels for all 10 modes.

[f] For Front-End Loader 3, modal average HC concentrations were below the detection limit only for B20 for 9 out of 10 modes; modal average CO concentrations were below the detection limit for both fuels for all 10 modes.

[g] For Front-End Loader 4, modal average HC concentrations were below the detection limit for both fuels for all 10 modes; modal average CO concentrations were below the detection limit for B20 for 7 out of 10 modes and were below the detection limit for petroleum diesel for all 10 modes.

Table 19. Estimate of Time-Based Cycle Average Fuel Use and Emission Rates for Two Selected Motor Grader Cycles (Resurfacing and Shouldering) When Comparing B20 Biodiesel vs. Petroleum Diesel for All Six Motor Graders

	Vehicle	B20 Biodiesel		Petroleum Diesel		Ratio (B20/PD)	
		RC[a]	SC[b]	RC[a]	SC[b]	RC[a]	SC[b]
Fuel Use (g/sec)	MG 1	5.30	2.94	5.33	3.06	1.00	0.96
	MG 2	5.03	2.89	5.02	2.87	1.00	1.01
	MG 3	5.43	2.94	5.38	2.86	1.01	1.03
	MG 4	5.41	3.02	5.75	3.13	0.94	0.97
	MG 5	5.48	2.91	5.56	2.98	0.99	0.98
	MG 6	3.98	1.98	4.03	2.01	0.99	0.99
CO_2 (g/sec)	MG 1	16.3	9.06	16.8	9.63	0.97	0.94
	MG 2	15.5	8.88	15.8	8.98	0.98	0.99
	MG 3	16.7	9.05	16.8	8.90	1.00	1.02
	MG 4	16.5	9.15	18.0	9.73	0.92	0.94
	MG 5	16.9	8.91	17.5	9.33	0.96	0.96
	MG 6	12.2	6.08	12.7	6.33	0.96	0.96
NO as Equivalent NO_2 (mg/sec)	MG 1	187	114	197	125	0.95	0.91
	MG 2	160	108	159	108	1.01	1.01
	MG 3	179	100	178	105	1.01	0.96
	MG 4	241	129	255	132	0.94	0.98
	MG 5	250	130	254	140	0.99	0.93
	MG 6	63.6	45.7	70.1	46.7	0.91	0.98
NO Corr (mg/sec)	MG 1	163	100	174	110	0.94	0.90
	MG 2	145	98.4	141	95.7	1.03	1.03
	MG 3	185	103	175	103	1.06	1.01
	MG 4	209	112	242	125	0.86	0.90
	MG 5	238	123	236	130	1.01	0.95
	MG 6	68.1	48.9	72.2	48.1	0.94	1.02
Opacity (mg/sec)	MG 1	1.19	0.707	1.43	0.864	0.83	0.82
	MG 2	0.695	0.499	0.971	0.585	0.72	0.85
	MG 3	1.12	0.517	1.36	0.723	0.83	0.72
	MG 4	1.37	0.641	1.68	0.754	0.82	0.85
	MG 5	1.41	0.775	1.82	1.03	0.77	0.75
	MG 6	0.529	0.311	0.665	0.382	0.80	0.81
HC (mg/sec)	MG 1	19.0	10.5	22.2	15.9	0.86	0.66
	MG 2[c]	11.9	8.80	14.4	13.1	0.82	0.67
	MG 3	19.6	14.7	27.5	16.8	0.71	0.88
	MG 4	21.9	16.2	27.8	21.0	0.79	0.77
	MG 5	20.0	15.0	21.3	16.0	0.94	0.94
	MG 6[d]	4.72	3.58	5.47	4.76	0.86	0.75
CO (mg/sec)	MG 1	19.5	13.9	20.4	14.8	0.95	0.94
	MG 2[c]	12.9	12.1	13.3	13.9	0.97	0.87
	MG 3	18.7	14.2	25.2	14.1	0.74	1.01
	MG 4	37.4	33.6	47.4	34.2	0.79	0.98
	MG 5	28.0	26.5	42.1	41.8	0.67	0.63
	MG 6[d]	6.11	3.42	11.7	5.58	0.52	0.61

(Continued)

Table 19. Continued.

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

[c] For Motor Grader 2, modal average HC concentrations were below the detection limit for B20 for 8 out of 10 modes and were below detection limit for petroleum diesel for 5 out of 10 modes; modal average CO concentrations were below the detection limit for B20 for 7 out of 10 modes and were below the detection limit for petroleum diesel for 6 out of 10 modes.

[d] For Motor Grader 6, modal average HC concentrations were below the detection limit for both fuels for all 10 modes; modal average CO concentrations were below the detection limit for B20 for all 10 modes and were below the detection limit for petroleum diesel for 9 out of 10 modes.

Table 20. Estimate of Fuel-Based Cycle Average Emission Rates for Two Selected Motor Grader Cycles (Resurfacing and Shouldering) When Comparing B20 Biodiesel vs. Petroleum Diesel for All Six Motor Graders

	Vehicle	B20 Biodiesel		Petroleum Diesel		Ratio (B20/PD)	
		RC[a]	SC[b]	RC[a]	SC[b]	RC[a]	SC[b]
NO as Equivalent NO_2 (g/gallon)	MG 1	114	125	118	129	0.97	0.97
	MG 2	103	120	101	119	1.02	1.01
	MG 3	108	111	107	117	1.01	0.95
	MG 4	143	139	141	133	1.01	1.05
	MG 5	148	143	146	150	1.01	0.95
	MG 6	53.3	76.3	56.9	75.2	0.94	1.01
NO Corr (g/gallon)	MG 1	99.0	109	104	113	0.96	0.96
	MG 2	93.9	110	90.0	106	1.04	1.03
	MG 3	111	114	105	115	1.06	0.99
	MG 4	125	121	134	126	0.93	0.96
	MG 5	140	136	136	139	1.03	0.97
	MG 6	57.1	81.6	58.6	77.4	0.97	1.05
Opacity (g/gallon)	MG 1	0.724	0.775	0.855	0.897	0.85	0.86
	MG 2	0.444	0.552	0.615	0.650	0.72	0.85
	MG 3	0.660	0.557	0.804	0.803	0.82	0.69
	MG 4	0.805	0.685	0.928	0.765	0.87	0.90
	MG 5	0.882	0.863	1.04	1.10	0.79	0.78
	MG 6	0.431	0.516	0.528	0.614	0.82	0.84
HC (g/gallon)	MG 1	11.6	11.3	13.2	16.5	0.88	0.69
	MG 2[c]	7.63	9.71	9.15	14.5	0.83	0.67
	MG 3	11.9	16.5	16.6	19.1	0.72	0.86
	MG 4	12.9	16.8	15.6	21.1	0.83	0.80
	MG 5	12.2	16.6	12.4	17.4	0.99	0.95
	MG 6[d]	3.96	6.04	4.51	7.90	0.88	0.76
CO (g/gallon)	MG 1	12.0	15.0	12.2	14.9	0.98	1.00
	MG 2[c]	8.11	13.5	8.46	15.4	0.96	0.88
	MG 3	11.5	16.0	15.2	16.0	0.75	1.00
	MG 4	22.5	33.0	26.6	33.9	0.85	0.97
	MG 5	17.2	29.8	25.7	46.1	0.67	0.65
	MG 6[d]	4.94	5.75	9.26	8.73	0.53	0.66

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

[c] For Motor Grader 2, modal average HC concentrations were below the detection limit for B20 for 8 out of 10 modes and were below detection limit for petroleum diesel for 5 out of 10 modes; modal average CO concentrations were below the detection limit for B20 for 7 out of 10 modes and were below the detection limit for petroleum diesel for 6 out of 10 modes.

[d] For Motor Grader 6, modal average HC concentrations were below the detection limit for both fuels for all 10 modes; modal average CO concentrations were below the detection limit for B20 for all 10 modes and were below the detection limit for petroleum diesel for 9 out of 10 modes

For HC, all backhoes show an overall reduction when using B20 biodiesel instead of petroleum diesel. However, the HC measurements for Backhoes 1, 4, and 5 are below the detection limit of the PEMS. The results from Backhoe 2 and 3 are more reliable than for Backhoes 1, 4, and 5. The overall average ratio (B20/PD) is 0.86 based on Backhoes 2 and 3. There is an average 46% difference in HC between the high versus low values among all vehicles.

For CO, all backhoes show an overall reduction when using B20 biodiesel. However, the CO measurements for Backhoes 1, 2, and 5 are below the detection limit of the PEMS. The results from Backhoes 3 and 4 are more reliable than Backhoes 1, 2, and 5. Thus, the overall average ratio (B20/PD) is 0.83 based on Backhoes 3 and 4. There is an average 58% difference in CO between the high versus low values among all vehicles.

In Table 16, the fuel-based cycle average fuel use and emission rates are shown for both B20 biodiesel and petroleum diesel. For each backhoe, the cycle average fuel use and emission rates are also estimated based on "Load Truck Cycle (LTC)," "Mass Excavation Cycle (MEC)," and "Material Handling Cycle (MHC)." For NO emissions, both NO uncorrected and corrected emission rates are shown in Table 16. Although Backhoe 2 shows a small increase of NO for uncorrected (2% to 4%) and corrected emission rates (3%-4%) when using B20 biodiesel, the overall average ratios (B20/PD) are 0.93 for NO uncorrected and 0.96 for NO corrected emission rates. Backhoes 1, 3, 4, and 5 show an overall reduction of NO for all duty cycles when using B20 biodiesel. The inter-cycle variations for fuel-based emission rates are not as significant as time-based emission rates. There is an average 18% difference in fuel-based NO emission rates between the high versus low values among all vehicles, as compared to 40% for time-based emission rates.

For opacity, Backhoes 1, 2, 4, and 5 show a reduction when using B20 biodiesel, but two duty cycles (LTC and MEC) of Backhoe 2 show a slight increase in the opacity rate. The overall average ratio (B20/PD) of the opacity rate for all vehicles is 0.83. The inter-cycle variations of fuel-based opacity rates are not significant. There is an average 34% difference in fuel-based opacity rates between the high versus low values among all vehicles, as compared to 79% for time-based emission rates.

For fuel-based HC emission rates, all backhoes show an overall reduction when using B20 biodiesel. However, the HC measurements for Backhoes 1, 4, and 5 are below the detection limit of the PEMS. The results from Backhoes 2 and 3 are more reliable than Backhoes 1, 4, and 5. Thus, the overall average ratio (B20/PD) based on Backhoes 2 and 3 are 0.89. The inter-cycle variations of fuel-based HC emission rates are not as significant as time-based emission rates. There is an average 36% difference in fuel-based HC emission rates between the high versus low values among all vehicles, as compared to 79% for time-based emission rates.

Table 21. Number of Tested Vehicles by Engine Tier and Vehicle Type

Vehicle Type	Tier 0	Tier 1	Tier 2	Tier 3	Total
Backhoe	1	2	2	NA	5
Front-End Loader	NA	3	1	NA	4
Motor Grader	2	2	1	1	6

NA: Not Available

For CO, all backhoes show an overall reduction when using B20 biodiesel. However, the CO measurements for Backhoes 1, 2, and 5 are below the detection limit of the PEMS. The results from Backhoes 3 and 4 are more reliable than Backhoes 1, 2, and 5. Thus, the overall average fuel-based ratio (B20/PD) is 0.86 based on Backhoes 3 and 4. The inter-cycle variations of fuel-based CO emission rates are not as significant as time-based emission rates. There is an average 26% difference in fuel-based CO emission rates between the high versus low values among all vehicles, as compared to 58% for time-based emission rates.

The time-based and fuel-based results for front-end loaders are shown in Tables 17 and 18, respectively. The time-based and fuel-based results for motor graders are shown in Tables 19 and 20, respectively. Similar to the other two types of vehicles, the overall average ratios show a reduction for corrected NO, opacity, HC, and CO emission rates.

The fuel-based emission rates are recommended in order to develop an emissions inventory for the NCDOT fleet inventory because of less inter-cycle and inter-vehicle variations. In some cases, fuel-based emission factors for HC and CO have larger inter-cycle variations than time-based emission factors due to the non-detected measurement of the PEMS. However, overall, fuel-based emission factors provide a more robust basis for the emissions inventory development.

3.9 Emission Factors for NCDOT Backhoes, Front-End Loaders, and Motor Graders

Based on the results in Section 3.8, time-based and fuel-based emission factors were developed for each type of vehicle. Each type of vehicle was classified into three categories: engine tiers, test fuel, and duty cycles. In this section, overall time-based and fuel-based emission factors and average fuel use are indicated for backhoes, front-end loaders, and motor graders respectively. Table 21 summarizes the numbers of tested vehicles by engine tiers and vehicle types.

For each engine tier, fuel type, and duty cycle, overall time-based emission factors and average fuel use for backhoes are indicated in Table 22. The "load truck" cycle (LTC) has the highest emission factors among the three cycles: For average fuel use and CO_2 emission factors, there was an approximate 33% increase between the lowest cycle (MHC) and the highest cycle (LTC) for both B20 biodiesel and petroleum diesel on average.

Time-based NO emission factors for backhoes given in Table 22 were corrected based on ambient conditions, such as ambient temperature and relative humidity. After switching fuel from petroleum diesel to B20 biodiesel, an approximate 6% reduction was observed on average for NO emission rates from backhoes

Table 22. Measured Time-Based Emission Factors for NCDOT Backhoes: Comparison of Tiers, Fuels and Duty Cycles

Pollutant	Engine Type	Test ID	Vehicle ID	B20 LTC[a]	B20 MEC[b]	B20 MHC[c]	Petroleum Diesel LTC[a]	Petroleum Diesel MEC[b]	Petroleum Diesel MHC[c]
Fuel (g/sec)	Tier 0	BH2	803-0242	1.9	1.5	1.3	1.9	1.5	1.3
		Average			**1.6**			**1.6**	
	Tier 1	BH3	803-0241	1.8	1.4	1.2	1.9	1.5	1.3
		BH4	808-0214	1.8	1.5	1.1	1.7	1.5	1.1
		Average			**1.5**			**1.5**	
	Tier 2	BH5	FDP22085	1.0	0.89	0.68	1.0	0.86	0.68
		BH1	FDP20882	1.0	0.89	0.72	1.0	0.89	0.72
		Average			**0.86**			**0.86**	
CO_2 (g/sec)	Tier 0	BH2	803-0242	6.0	4.7	4.0	5.9	4.7	3.9
		Average			**4.9**			**4.9**	
	Tier 1	BH3	803-0241	5.7	4.4	3.7	6.1	4.8	4.0
		BH4	808-0214	5.4	4.6	3.3	5.4	4.5	3.4
		Average			**4.5**			**4.7**	
	Tier 2	BH5	FDP22085	3.1	2.8	2.1	3.1	2.7	2.2
		BH1	FDP20882	3.1	2.8	2.2	3.2	2.8	2.3
		Average			**2.7**			**2.7**	
NO as Equivalent NO_2 (mg/sec)	Tier 0	BH2	803-0242	72	50	41	70	48	40
		Average			**55**			**53**	
	Tier 1	BH3	803-0241	47	33	33	60	48	42
		BH4[d]	808-0214	45	47	37	49	49	41
		Average			**40**			**48**	
	Tier 2	BH5[e]	FDP22085	29	25	22	31	26	24
		BH1[f]	FDP20882	30	26	23	31	26	24
		Average			**26**			**27**	
Opacity (mg/sec)	Tier 0	BH2	803-0242	0.72	0.51	0.47	0.73	0.51	0.48
		Average			**0.57**			**0.57**	
	Tier 1	BH3	803-0241	0.72	0.44	0.38	0.74	0.44	0.46
		BH4	808-0214	0.71	0.32	0.31	0.88	0.76	0.46
		Average			**0.48**			**0.62**	
	Tier 2	BH5[e]	FDP22085	0.21	0.14	0.13	0.24	0.19	0.16
		BH1[f]	FDP20882	0.16	0.13	0.10	0.22	0.18	0.15
		Average			**0.15**			**0.19**	

[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

(Continued on the next page)

Table 22. Continued

Pollutant	Engine Type	Test ID	Vehicle ID	B20			Petroleum Diesel		
				LTC[a]	MEC[b]	MHC[c]	LTC[a]	MEC[b]	MHC[c]
HC (mg/sec)	Tier 0	BH2	803-0242	7.1	6.8	6.0	7.8	7.5	6.5
		Average		**6.6**			**7.3**		
	Tier 1	BH3	803-0241	8.4	4.0	4.0	9.2	5.4	5.1
		BH4[d]	808-0214	2.2	2.6	1.9	2.6	2.9	2.4
		Average		**3.9**			**4.6**		
	Tier 2	BH5[e]	FDP22085	1.0	0.89	0.8	2.7	2.8	2.2
		BH1[f]	FDP20882	2.6	2.0	1.9	3.5	2.9	2.7
		Average		**1.5**			**2.8**		
CO (mg/sec)	Tier 0	BH2	803-0242	52	30	27	66	39	33
		Average		**37**			**46**		
	Tier 1	BH3	803-0241	18	16	12	21	18	14
		BH4	808-0214	23	17	14	29	21	18
		Average		**17**			**20**		
	Tier 2	BH5[e]	FDP22085	3.8	2.7	2.9	4.8	4.4	3.6
		BH1[f]	FDP20882	2.5	2.0	1.7	2.9	2.4	2.1
		Average		**2.6**			**3.4**		

[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

For opacity, an average 15% reduction was observed for backhoes after switching fuel from petroleum diesel to B20 biodiesel. This reduction rate is significant in Tier 1 and Tier 2 engines. In Tier 0 engines, there is 0% to 2% reduction in opacity.

The shaded cells in Tables 22 show the non-detect average concentrations for HC and CO emissions. This implies that some average HC concentrations were measured below the detection limits of the PEMS. Detailed information of non-detects for HC and CO is provided in Sections 2.9 and 3.7.

In Table 23, the fuel-based emission factors for backhoes are shown. For NO, the emission rates are approximately similar for the two fuels. The NO emission rates do not vary significantly by engine tier. For opacity, the emission rates are significantly lower for B20 biodiesel versus petroleum diesel, especially for the higher tiers. 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 biodiesel versus petroleum diesel but substantially with respect to engine tier.

Table 23. Measured Fuel-Based Emission Factors for NCDOT 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 as Equivalent NO_2 (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

For front-end loaders, the rates of reduction of fuel use and emissions with respect to fuel and engine tiers are slightly different compared to those for backhoes given in Table 22. However, the trends are similar to those of backhoes. Table 24 shows the time-based emission factors for front-end loaders, and Table 25 shows the corresponding fuel-based emission factors. The average time-based rates of fuel use, CO_2, and NO are similar for the two fuels but are lower for the higher tier vehicle. For opacity, HC, and CO, the emission factors are significantly lower for B20 biodiesel versus petroleum diesel and are lower for the Tier 2 engine versus the Tier 1 engines.

Time-based fuel use and emissions rates for motor graders are shown in Table 26. The average fuel use and CO_2 emission rates decrease as the engine tier increases. The NO emission rates are comparable for the two fuels, but decrease with an increase in 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 biodiesel versus petroleum diesel for all tiers, and the emission rates decrease monotonically as the tiers increase. This trend can be seen in the fuel-based emission factors for motor graders, as well, in Table 27.

Based on the PEMS data, the observed differences in fuel usage rates when comparing engine tiers illustrated a general tendency for increases in fuel efficiency as the tier increases. This trend is likely a result of optimization of engine design and operation even in the face of more demanding emissions constraints. Examples of the reduction in fuel consumption include:

- Six percent reduction for Tier 1 vs. Tier 0 (Backhoe);
- Ten percent reduction for Tier 2 vs. Tier 1 (Front-End Loader);
- Two percent reduction for Tier 1 vs. Tier 0 (Motor Grader); and
- Eight percent reduction for Tier 2 vs. Tier 0 (Motor Grader).

However, for the newer tier engines, such as Tier 2 Backhoes and Tier 3 Motor Graders, there are larger reductions in average fuel use compared to the corresponding Tier 0 engines. Approximately 30% to 46% reductions are indicated for both B20 biodiesel and petroleum diesel. These comparisons are based on only two Tier 2 Backhoes and one Tier 3 Motor Grader, and thus may not represent reliable average differences. In addition, each tested vehicle had a different engine model and manufacturer, and thus the comparisons may include some inter-manufacturer variability..

The large decrease in time-based fuel consumption rate for the Tier 3 motor grader compared to lower tiers, and for the Tier 2 backhoe compared to lower tiers, was difficult to benchmark given the absence of comparative field data. The only readily available data for comparison was from the Caterpillar Performance Handbook (CAT, 2006), which shows fuel consumption rates based on load factors and chassis models for all Caterpillar backhoes. Load factors are classified as high, medium, or low and are based on the type of task being performed by the vehicle. When comparing older model to newer model backhoes with similar engine displacement, there is an approximate 33 to 44% decrease in fuel consumption rates for a given load factor. Thus, the observed large decreases in fuel usage rate for the higher tier backhoes and motor graders may be reasonable.

Table 24. Measured Time-Based Emission Factors for NCDOT Front-End Loaders: Comparison of Tiers, Fuels and Duty Cycles

Vehicle Type	Engine Type	Test ID	Vehicle ID	B20			Petroleum Diesel		
				RHC[a]	SHC[b]	LTC[c]	RHC[a]	SHC[b]	LTC[c]
Fuel (g/sec)	Tier 1	FL1	010-0249	2.2	2.1	2.0	2.2	2.0	1.9
		FL2	010-0301	1.8	1.7	1.6	1.9	1.7	1.7
		FL3	010-5074	2.8	2.6	2.5	2.7	2.5	2.5
		Average		**2.1**			**2.1**		
	Tier 2	FL4	010-0388	2.0	1.9	1.8	2.0	1.9	1.8
		Average		**1.9**			**1.9**		
CO_2 (g/sec)	Tier 1	FL1	010-0249	6.9	6.4	6.3	6.8	6.2	6.1
		FL2	010-0301	5.6	5.2	5.0	5.9	5.4	5.3
		FL3	010-5074	8.5	7.8	7.6	8.6	8.0	7.8
		Average		**6.6**			**6.7**		
	Tier 2	FL4	010-0388	6.2	5.8	5.6	6.3	5.8	5.7
		Average		**5.9**			**5.9**		
NO as Equivalent NO_2 (mg/sec)	Tier 1	FL1[d]	010-0249	76	72	70	73	69	65
		FL2[e]	010-0301	67	64	58	75	69	67
		FL3[f]	010-5074	111	105	102	109	102	96
		Average		**81**			**80**		
	Tier 2	FL4[g]	010-0388	56	54	51	59	55	53
		Average		**54**			**55**		
Opacity (mg/sec)	Tier 1	FL1[d]	010-0249	0.45	0.42	0.41	0.68	0.63	0.63
		FL2[e]	010-0301	0.24	0.22	0.22	0.29	0.27	0.26
		FL3[f]	010-5074	0.64	0.60	0.59	0.78	0.71	0.73
		Average		**0.42**			**0.55**		
	Tier 2	FL4[g]	010-0388	0.36	0.32	0.34	0.40	0.37	0.37
		Average		**0.34**			**0.38**		
HC (mg/sec)	Tier 1	FL1[d]	010-0249	5.0	4.7	4.7	11	11	11
		FL2[e]	010-0301	4.5	4.2	4.3	9.1	8.7	8.6
		FL3[f]	010-5074	8.0	7.6	7.7	11	10	9.6
		Average		**5.6**			**9.9**		
	Tier 2	FL4[g]	010-0388	3.0	2.9	2.8	3.4	3.2	3.1
		Average		**2.9**			**3.2**		
CO (mg/sec)	Tier 1	FL1[d]	010-0249	8.6	8.2	8.8	9.5	9.1	10
		FL2[e]	010-0301	5.4	5.2	5.3	7.1	6.9	7.1
		FL3[f]	010-5074	7.3	6.8	6.8	13	12	12
		Average		**6.9**			**9.6**		
	Tier 2	FL4[g]	010-0388	5.6	5.2	5.0	6.7	6.2	6.3
		Average		**5.2**			**6.4**		

[a] RHC: Rock Handling Cycle; [b] SHC: Soil 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 25. Measured Fuel-Based Emission Factors for NCDOT Front-End Loaders: Comparison of Tiers, Fuels and Duty Cycles

Vehicle Type	Engine Type	Test ID	Vehicle ID	B20			Petroleum Diesel		
				RHC[a]	SHC[b]	LTC[c]	RHC[a]	SHC[b]	LTC[c]
NO as Equivalent NO_2 (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 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 26. Measured Time-Based Emission Factors for NCDOT Motor Graders: Comparison of Tiers, Fuels and Duty Cycles

Vehicle Type	Engine Type	Test ID	Vehicle ID	B20 Biodiesel		Petroleum Diesel	
				RC[a]	SC[b]	RC[a]	SC[b]
Fuel (g/sec)	Tier 0	MG 4	948-6647	5.4	3.0	5.8	3.1
		MG 5	955-0277	5.5	2.9	5.6	3.0
		Average		**4.2**		**4.4**	
	Tier 1	MG 1	955-0515	5.3	2.9	5.3	3.1
		MG 3	955-0516	5.4	2.9	5.4	2.9
		Average		**4.2**		**4.2**	
	Tier 2	MG 2	955-0606	5.0	2.9	5.0	2.9
		Average		**4.0**		**3.9**	
	Tier 3	MG 6	955-0633	4.0	2.0	4.0	2.0
		Average		**3.0**		**3.0**	
CO_2 (g/sec)	Tier 0	MG 4	948-6647	17	9.2	18	9.7
		MG 5	955-0277	17	8.9	18	9.3
		Average		**13**		**14**	
	Tier 1	MG 1	955-0515	16	9.1	17	9.6
		MG 3	955-0516	17	9.1	17	8.9
		Average		**13**		**13**	
	Tier 2	MG 2	955-0606	16	8.9	16	9.0
		Average		**12**		**12**	
	Tier 3	MG 6	955-0633	12	6.1	13	6.3
		Average		**9.1**		**9.5**	
NO as Equivalent NO_2 (mg/sec)	Tier 0	MG 4	948-6647	209	112	242	125
		MG 5	955-0277	238	123	236	130
		Average		**171**		**183**	
	Tier 1	MG 1	955-0515	163	100	174	110
		MG 3	955-0516	185	103	175	103
		Average		**138**		**141**	
	Tier 2	MG 2[c]	955-0606	145	98	141	96
		Average		**122**		**118**	
	Tier 3	MG 6[d]	955-0633	68	49	72	48
		Average		**59**		**60**	
Opacity (mg/sec)	Tier 0	MG 4	948-6647	1.4	0.64	1.7	0.75
		MG 5	955-0277	1.4	0.78	1.8	1.0
		Average		**1.0**		**1.3**	
	Tier 1	MG 1	955-0515	1.2	0.71	1.4	0.86
		MG 3	955-0516	1.1	0.52	1.4	0.72
		Average		**0.88**		**1.1**	
	Tier 2	MG 2[c]	955-0606	0.70	0.50	0.97	0.59
		Average		**0.60**		**0.78**	
	Tier 3	MG 6[d]	955-0633	0.53	0.31	0.67	0.38
		Average		**0.42**		**0.52**	

[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

(Continued on the next page)

Table 26. Continued

Vehicle Type	Engine Type	Test ID	Vehicle ID	B20 Biodiesel		Petroleum Diesel	
				RC[a]	SC[b]	RC[a]	SC[b]
HC (mg/sec)	Tier 0	MG 4	948-6647	22	16	28	21
		MG 5	955-0277	20	15	21	16
		Average		**18**		**22**	
	Tier 1	MG 1	955-0515	19	11	22	16
		MG 3	955-0516	20	15	28	17
		Average		**16**		**21**	
	Tier 2	MG 2[c]	955-0606	12	8.8	14	13
		Average		**10**		**14**	
	Tier 3	MG 6[d]	955-0633	4.7	3.6	5.5	4.8
		Average		**4.2**		**5.1**	
CO (mg/sec)	Tier 0	MG 4	948-6647	37	34	47	34
		MG 5	955-0277	28	27	42	42
		Average		**31**		**41**	
	Tier 1	MG 1	955-0515	20	14	20	15
		MG 3	955-0516	19	14	25	14
		Average		**17**		**19**	
	Tier 2	MG 2[c]	955-0606	13	12	13	14
		Average		**13**		**14**	
	Tier 3	MG 6[d]	955-0633	6.1	3.4	12	5.6
		Average		**4.8**		**8.6**	

[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

Table 27. Measured Fuel-Based Emission Factors for NCDOT 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 as Equivalent NO_2 (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

3.10 Benchmarks of Measured Emission Rates Based on the NONROAD Model

This section describes benchmarking the PEMS data based on comparisons to emission factors that were estimated using the NONROAD model. Pollutants included NO_x, HC, CO, and PM. These emission factors are used for comparison purposes in order to obtain insight regarding validity of the field data. The expectation is that the field data and the nonroad data should be similar in magnitude. Because the NONROAD model is based on fleet average emission rates and on engine dynamometer measurements that have to be converted using an assumed brake-specific fuel consumption rate, it is not expected to have an exact agreement with the field data. The EPA's NONROAD model utilizes the unit of grams per brake horsepower hour instead of grams per unit of time. Using brake specific fuel consumption (BSFC) factors from the EPA's NONROAD model, units of grams per brake horsepower hour were converted into units of grams per gallon of fuel in order to enable comparisons with the PEMS data (EPA, 2004).

Table 28 shows the emission factors estimated from the NONROAD model that are for the same vehicle types, model years and engine horsepower as the tested vehicles in NCDOT's inventory.

For backhoes, the estimated NO emission rates based on the model decrease significantly for higher tiers by 33 percent from Tier 0 to Tier 2. The PM, HC, and CO emission rates also decrease substantially with respect to engine tier. Approximately, 75%, 65%, and 38% decreases for the estimated emission rates of PM, HC, and CO were observed for Tier 2 vs. Tier 0 respectively.

For front-end loaders, the estimated NO emission rates are similar for the three Tier 1 vehicles, but are lower for the higher tier vehicle. For PM, the emission rates are significantly lower for the Tier 2 engine versus the Tier 1 engines. For HC and CO, there is little variation in emission rates between tiers. On average, the differences are in the range of 1.4% to 60 %, depending on the pollutant.

The estimated NO emission rates for motor graders decrease significantly compared to those for backhoes and front-end loaders. For example, the Tier 3 vehicle has emission rates of NO approximately 72% lower than the Tier 0 vehicles. For PM, HC, and CO, the emission rates decrease monotonically as the tiers increase. On average, an approximate 45% reduction is observed as the tiers increase.

The ranges of the emission rates from the three types of vehicles based on the field data was compared with similar estimates from the NONROAD model. These comparisons are summarized in Table 29. The ranges of data shown in Table 29 are influenced by different engine tiers.

Table 28. Emission Factors Estimated Using the NONROAD Model for Benchmark Comparison to Field Measurements

Vehicle	Vehicle ID	Vehicle Year	Engine			NO_x (g/gal)	HC (g/gal)	CO (g/gal)	PM (g/gal)
			Tier	Size (*l*)	HP[a]				
Backhoe	803-0242	1997	0	4.0	86	112	34	144	25
	808-0245	1999	I	3.9	99	91	18	93	15
	803-0241	2001	I	4.0	86	90	18	92	14
	FDP22065	2004	II	4.0	97	75	12	90	6.2
	FDP20882	2004	II	4.0	97	75	12	90	6.2
Front-End Loader	010-5074	1997	I	5.9	136	104	7.0	28	8.4
	010-0249	2002	I	5.9	133	103	6.9	27	6.9
	010-0301	2002	I	5.9	133	103	6.9	27	6.9
	010-0388	2005	II	5.9	133	74	6.8	26	3.4
Motor Grader	948-6647	1990	0	8.3	167	159	15	110	18
	955-0277	1993	0	8.3	160	157	15	105	16
	955-1515	2001	I	8.3	195	102	6.3	23	6.8
	955-0513	2001	I	8.3	195	102	6.3	23	6.8
	955-0606	2004	II	7.1	195	75	6.2	23	2.9
	955-0633	2007	III	7.2	198	45	3.7	22	1.8

[a] HP: Engine Horse Power

Table 29. Ranges of Emission Rates from Three Types of NCDOT Construction Vehicles based on Real-World Tests and EPA's NONROAD Model

Vehicle	NO as Equivalent NO_2 (g/gallon)		HC (g/gallon)		CO (g/gallon)		PM (g/gallon)	
	PEMS[a]	EPA[b]	PEMS[a]	EPA[b]	PEMS[a]	EPA[b]	PEMS[a]	EPA[b]
Backhoe	92–120	75–112	5.6–17	12–34	8.4–106	90–144	0.66–1.7	6.2–25
Front-End Loader	94–131	74–104	5.4–19	6.8–7.0	11–18	26–28	0.49–1.0	3.4–8.4
Motor Grader	59–139	45–159	4.5–21	3.7–15	8.7–46	22–110	0.53–1.1	1.8–18

[a]: PEMS Field Measurement Data
[b]: Estimations from the EPA's NONROAD model

In general, the average emission rates from the PEMS field measurement data are of similar magnitude to those based on the NONROAD model for NO, HC, and CO. For example, based on the NONROAD model, the average emission rate for NO varies from approximately 45 to 159 g/gallon, compared to ranges of approximately 59 to 139 g/gallon from the PEMS data. The two sources of data are not expected to agree because the PEMS data are for individual vehicles, whereas NONROAD is intended to predict average emissions for a fleet of vehicles. Also, the real-world duty cycles and ambient conditions of the PEMS data differ from the standardized engine dynamometer test conditions that are the basis of the NONROAD model.

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

3.11 Benchmarks of Observed Fuel Use Rates versus NCDOT Maintenance Data

The purpose of this section is to compare fuel consumption rates for selected vehicles obtained from field data collected using the PEMS with maintenance data for the same vehicles recorded by NCDOT. NCDOT provided these data for vehicles that were tested. These data are shown in Table 30. From these recorded data, estimates of average fuel consumption in gallons per hour are provided. These data are available for only 12 of the tested vehicles. Two of the tested backhoes were rental vehicles for which NCDOT does not have historical fuel use data. One of the tested motor graders was acquired by NCDOT in April 2007 and was tested as soon as it was placed in service.

For a given type of vehicle, there is substantial variability in the average fuel consumption rates reported in Table 30. For example, for backhoes, the average fuel use rates range from 1.41 to 2.75 gallons per hour among three vehicles. These differences are most likely because of differences in the duty cycles performed by these vehicles. However, the duty cycles performed by each vehicle are not recorded in the NCDOT database.

Table 31 provides a comparison of estimated fuel use rates based on PEMS data versus the NCDOT data for 12 vehicles that were tested and for which there are NCDOT fuel use data. The observed fuel use data for the other 3 tested vehicles are also shown. There is variation in fuel consumption rates among the vehicles within a given vehicle group. For the backhoes, the observed fuel consumption rate (based on the PEMS) ranges from 1.12 to 2.18 gallons per hour. Each backhoe was tested by the research team for one day.

Table 30. Summary of Fuel Usage from NCDOT Maintenance Database

Vehicle	Test ID	Vehicle ID	Operation Period		Fuel Type	Fuel Usage (gallon)	Operation Hours (hr)	Fuel Usage Rate (gal/hr)
			From	To				
Backhoe [a]	BH2	803-0242	01/05/04	12/18/06	B20	1589	1125	1.41
	BH3	803-0241	01/14/04	12/22/06	PD	3293	1196	2.75
	BH4	808-0214	01/13/04	12/19/06	PD	3151	1420	2.22
Front-End Loader	FL1	010-0249	01/05/04	12/18/06	PD	4538	1654	2.74
	FL2	010-0301	01/08/04	11/17/06	PD	3257	1150	2.83
	FL3	010-5074	01/08/04	11/06/06	B20	2144	1120	1.91
	FL4	010-0388	06/23/05	11/21/06	B20	1042	357	2.92
Motor Grader [b]	MG1	955-0515	01/05/04	11/07/06	B20	7997	1737	4.60
	MG2	955-0606	11/18/04	12/12/06	PD	4925	865	5.69
	MG3	655-0516	01/27/04	12/12/06	B20	6006	1387	4.33
	MG4	948-6647	09/27/04	12/14/06	B20	228	142	1.61
	MG5	955-0277	01/16/04	12/14/06	PD	2092	494	4.23

a. Two additional tested Tier 2 backhoes were rental vehicles for which no historical fuel use data were available.

b. A Tier 3 motor grader was tested on June 22, 2007. There are no historical fuel records for this vehicle.

Table 31. Comparison of Measured Fuel Use Rates versus NCDOT Maintenance Data for Selected Vehicles

Vehicle	Test ID	Fuel Type	HP	Disp.	Fuel Consumption Rate (gal/hr)		
			(*hp*)	(*l*)	NCDOT	NCSU	Diff. (%)
Backhoe	BH1	B20	97	4	(rental)	*1.13*	-
	BH2	B20	86	4.2	1.41	1.70	20.6
	BH3	PD	86	4.2	2.75	2.18	-20.7
	BH4	PD	99	3.9	2.20	1.95	-11.4
	BH5	B20	97	4	(rental)	*1.12*	-
Front-End Loader	FL1	PD	140	5.9	2.74	2.28	-16.8
	FL2	PD	140	5.9	2.83	2.45	-13.4
	FL3	B20	136	5.9	1.91	2.16	13.1
	FL4	B20	133	5.9	2.92	2.45	-16.1
Motor Grader	MG1	B20	195	8.3	4.60	4.61	0.2
	MG2	PD	198	7.1	5.69	4.43	-22.1
	MG3	B20	195	8.3	4.33	4.68	8.1
	MG4	B20	167	8.3	1.61	1.93	19.9
	MG5	PD	160	8.3	4.23	4.83	14.2
	MG6	B20	198	7.2	(new)	*3.33*	-
Average[a]					3.10	2.97	-4.2

a. Average fuel use rate for the 12 vehicles for which NCDOT owner historical data are available.

Backhoes 2 and 3 had substantially different fuel consumption rates (1.7 versus 2.2 gal/hr) during the field tests. However, these two backhoes are similar with respect to gross vehicle weight (GVW) and engine horsepower. The differences in average fuel consumption rate are most likely because of differences in the duty cycles. During the field testing, Backhoe 2 was performing “mass excavation,” whereas Backhoe 3 was performing “load truck,” which has a higher average engine power demand. Therefore, the average fuel consumption rate of Backhoe 3 is higher than Backhoe 2. The NCDOT database indicates that Backhoe 3 has a higher average fuel consumption rate (over a three year period) than Backhoe 2 (also over a three year period). Because the NCDOT data are for a long-term average, and the PEMS data are for a one-day average, it is not expected that they will agree exactly. In this case, the results agree qualitatively as to which backhoe has the higher fuel consumption rate and they agree to approximately plus-or-minus 21% for these two vehicles.

For Backhoe 4, the fuel consumption rates are higher than Backhoe 2 but less than Backhoe 3 based on both NCDOT and NCSU data. The difference between NCDOT and NCSU data is only 11%. The difference may result from different duty cycles performed at the job site during the one day test versus over the longer time period represented by NCDOT data. Backhoes 1 and 5 have Tier 2 engines and NCDOT does not have historical fuel consumption data for these two backhoes. These two backhoes have an average 42 percent reduction in fuel consumption rate compared to other backhoes. As described in Section 3.9, improvements in fuel economy of this magnitude have been reported by nonroad vehicle vendors. Thus, these numbers may be plausible but as yet there are not reliable field data via which to conduct a benchmark.

For the four front-end loaders (including Tier 1 and 2), the average fuel consumption rates from one day of field tests agree to within plus-or-minus 20% with the maintenance record data.

For five of the tested motor graders (Tiers 0, 1, and 2), the average fuel consumption rates from the PEMS agree to within approximately plus-or-minus 22% for each of the five vehicles. For Motor Grader 6 (Tier 3), NCDOT does not have historical records of fuel consumption rate. Compared to Motor Graders 1, 2, 3, and 5, Motor Grader 6 has an average 28 percent reduction in fuel consumption rate. The reduction in fuel use for the more recent engine might be plausible, based on industry trends as described in Section 3.9; however, there is an absence of empirical benchmark data at this time for verification of the low observed fuel consumption rate of this particular vehicle. Motor Grader 4 was found to have systematically lower fuel consumption than the others based on both the NCDOT and PEMS data. This motor grader is the oldest among the five tested, being a 1990 model year vehicle. It has one of the lower horsepower ratings among the vehicles tested and operated with a relatively low range of manifold absolute pressure (MAP) during the field tests compared to the other motor graders.

On average, over all 12 vehicles for which comparisons were possible, the observed fuel usage rates were 4.2% 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 a multi-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 1.1 to 4.8 gallons per hour based on the PEMS data.

The main conclusions from the comparison of fuel consumption rates based on the PEMS data versus the NCDOT data are:

- The estimated fuel consumption rates based on the NCSU PEMS data are similar in magnitude to those from the NCDOT maintenance data, even though the PEMS data are based on one day of observations and the NCDOT data are based on up to a three year average per vehicle.
- In most cases, the NCSU estimates of average fuel consumption agree with the NCDOT estimates to within plus-or-minus 20%.
- The duty cycles performed by the vehicles over the course of the data recorded by NCDOT are not known. It is possible that differences in average fuel consumption rates between the NCSU and NCDOT data are mostly attributable to differences in duty cycles. As shown in other work, differences in duty cycles can lead to large differences in average fuel consumption rate for a given vehicle.

- The range of inter-vehicle variability in fuel consumption rates was very similar for both the NCSU and NCDOT data, indicating agreement between the two data sets.
- Although it is possible that there could be some data quality issues within the NCDOT database, the substantial amount of agreement of the NCDOT data with an independent estimate of average fuel consumption based on PEMS measurements suggests that the NCDOT may be of good quality.

3.12 Emissions Inventory

Emission inventory results for NO_x, Opacity, HC, and CO were determined based on fuel type and engine tier classification for backhoes, front-end loaders, and motor graders. Comparisons were made between the existing fleet inventory use and a set of "what-if" scenarios.

For fuel use, the average annual emissions for each pollutant and each type of vehicle were computed based on the following scenarios:

- Current fuel use for both petroleum diesel and B20 biodiesel;
- "What if" only petroleum diesel were used and no B20 biodiesel were used; and
- "What if" only B20 biodiesel were used and no petroleum diesel were used.

Tables 32, 33, and 34 compare the results of these scenarios for backhoes, front-end loaders, and motor graders, respectively. Results are given in tons per year for each pollutant. The current fuel use is considered to be the base case. The percent difference between the base case and both the petroleum diesel only and B20 biodiesel only scenarios are computed. The differences in heating values for each fuel were accounted for, as described in Section 2.11, when determining the average annual fuel use for each scenario. Supplementary tables showing the intermediate calculations are provided in Appendix H.

Table 32 shows the average annual emissions for each pollutant for all backhoes in the NCDOT fleet inventory based on the current combined use of petroleum diesel and B20 biodiesel. Results are also provided for the scenarios of using petroleum diesel only and B20 biodiesel only. For example, based on the current combined use of petroleum diesel and B20 biodiesel, all backhoes produced an estimated total of 22.6 tons per year of NO_x. If all backhoes were fueled only with petroleum diesel, then NO_x emissions would increase to an estimated total of 22.8 tons per year which is an approximate 0.9% increase from the current combined fuel use emissions. This is also an approximate 0.9% reduction in NO_x emissions from backhoes when the the current mix of B20 biodiesel and petroleum diesel is used as opposed to using petroleum diesel only. If all backhoes were fueled only with B20 biodiesel, then NO_x emissions would decrease to an estimated total of 21.5 tons per year which is an approximate 4.7% decrease from the current combined fuel use emissions. If petroleum diesel only were to be used to fuel all of the backhoes, then emissions of each pollutant would increase slightly (0.9% - 4.4%). If B20 biodiesel only were to be used to fuel all of the backhoes, then emissions of each pollutant would decrease significantly (4.7% – 15.4%).

Table 32. Estimated Average Annual Emissions Comparisons Based on Fuel Type for All Backhoes

Pollutant	Current Fuel Use (tons/yr)	Petroleum Only (tons/yr)	% Difference from Current	B20 Only (tons/yr)	% Difference from Current
NO as Equivalent NO_2	22.6	22.8	0.9	21.5	-4.7
Opacity	0.25	0.26	4.4	0.22	-11.1
HC	2.61	2.7	3.2	2.2	-15.0
CO	12.2	12.6	3.6	10.3	-15.4

Table 33 shows the average annual emissions for each pollutant for all front-end loaders in the NCDOT fleet inventory based on the current combined use of petroleum diesel and B20 biodiesel. Results are also provided for the scenarios of using petroleum diesel only and B20 biodiesel only. For example, based on the current combined use of petroleum diesel and B20 biodiesel, all front-end loaders produced an estimated total of 22.1 tons per year of NO_x. If all front-end loaders were fueled only with petroleum diesel, then NO_x emissions would increase to an estimated total of 22.2 tons per year which is an approximate 0.4% increase from the current combined fuel use emissions. This is also an approximate 0.5% decrease in NO_x emissions from front-end loaders when the current mix of B20 biodiesel and petroleum diesel is used as opposed to using petroleum diesel only. If all front-end loaders were fueled only with B20 biodiesel, then NO_x emissions would decrease to an estimated total of 21.5 tons per year which is an approximate 2.7% decrease from the current combined fuel use emissions. If petroleum diesel only were to be used to fuel all of the front-end loaders, then emissions of each pollutant would increase slightly (0.4% - 6.8%). If B20 biodiesel only were to be used to fuel all of the front-end loaders, then emissions of each pollutant would decrease significantly (2.7% – 36.9%).

Table 34 shows the average annual emissions for each pollutant for all motor graders in the NCDOT fleet inventory based on the current combined use of petroleum diesel and B20 biodiesel. Results are also provided for the scenarios of using petroleum diesel only and B20 biodiesel only. For example, based on the current combined use of petroleum diesel and B20 biodiesel, all motor graders produced an estimated total of 95.9 tons per year of NO_x. If all motor graders were fueled only with petroleum diesel, then NO_x emissions would increase to an estimated total of 96.4 tons per year which is an approximate 0.5% increase from the current combined fuel use emissions. This is also an approximate 0.5% reduction in NO_x emissions from motor graders when the current use of B20 biodiesel and petroleum diesel is used as opposed to using petroleum diesel only. If all motor graders were fueled only with B20 biodiesel, then NO_x emissions would decrease to an estimated total of 94.1 tons per year which is an approximate 2.0% decrease from the current combined fuel use emissions. If petroleum diesel only were to be used to fuel all of the motor graders, then emissions of each pollutant would increase slightly (0.5% - 3.6%). If B20 biodiesel only were to be used to fuel all of the motor graders, then emissions of each pollutant would decrease significantly (2.0% – 19.2%).

Table 33. Estimated Average Annual Emissions Comparisons Based on Fuel Type for All Front-End Loaders

Pollutant	Current Fuel Use (tons/yr)	Petroleum Only (tons/yr)	% Difference from Current	B20 Only (tons/yr)	% Difference from Current
NO as Equivalent NO_2	22.1	22.2	0.4	21.5	-2.7
Opacity	0.14	0.15	3.4	0.115	-19.2
HC	2.3	2.4	6.8	1.4	-36.9
CO	2.6	2.7	3.9	2.0	-23.0

Table 34. Estimated Average Annual Emissions Comparisons Based on Fuel Type for All Motor Graders

Pollutant	Current Fuel Use (tons/yr)	Petroleum Only (tons/yr)	% Difference from Current	B20 Only (tons/yr)	% Difference from Current
NO as Equivalent NO_2	95.9	96.4	0.5	94.1	-2.0
Opacity	0.69	0.71	3.3	0.57	-17.4
HC	12.9	13.4	3.6	10.5	-19.2
CO	15.0	15.4	2.5	13.1	-12.8

For engine tier classifications, the average annual emissions for each pollutant and each type of vehicle were computed based on the following scenarios:

- Current engine tier classifications of the existing NCDOT fleet inventory
- "What if" all Tier 0 engines were replaced with Tier 1 engines
- "What if" all Tier 0 and Tier 1 engines were replaced with Tier 2 engines
- "What if" all Tier 0, Tier 1. and Tier 2 motor grader engines were replaced with Tier 3 motor grader engines

Tables 35, 36, and 37 compare the results of these scenarios for backhoes, front-end loaders, and motor graders. Results are given in tons per year for each pollutant. The current engine tier classification is considered to be the base case. The percent difference between the base case and both the Tier 1 replacement and Tier 2 replacement scenarios are computed. For the motor graders, a Tier 3 replacement scenario is computed as well. These estimates assume similar utilization of each vehicle regardless of engine tier classification. Supplementary tables showing the intermediate calculations are provided in Appendix H.

Table 35 shows the average annual emissions for each pollutant for all backhoes in the NCDOT fleet inventory based on the current engine tier classifications. Results are also provided for the scenarios of replacing all Tier 0 backhoes with Tier 1 backhoes and replacing all Tier 0 and Tier 1 backhoes with Tier 2 backhoes. For example, based on the current engine tier classifications, all backhoes produced an estimated total of 22.6 tons per year of NO_x.

Table 35. Estimated Average Annual Emissions Comparisons Based on Engine Tier Classifications for All Backhoes

Pollutant	Current Engine Tiers (tons/yr)	Replace All Tier 0 with Tier 1 (tons/yr)	% Difference from Current	Replace All Tier 0 & Tier 1 with Tier 2 (tons/yr)	% Difference from Current
NO as Equivalent NO_2	22.6	22.3	-1.4	21.6	-4.3
Opacity	0.254	0.260	2.3	0.149	-41.5
HC	2.6	2.1	-17.8	2.1	-19.9
CO	12.2	8.5	-30.1	2.7	-77.6

If all Tier 0 backhoes were replaced with Tier 1 backhoes, then NO_x emissions would decrease to an estimated total of 22.3 tons per year which is an approximate 1.4% decrease from the current engine tier classifications emissions. If all Tier 0 and Tier 1 backhoes were replaced with Tier 2 backhoes, then NO_x emissions would decrease to an estimated total of 21.6 tons per year which is an approximate 4.3% decrease from the current engine tier classifications emissions. Replacing all Tier 0 backhoes with Tier 1 backhoes would provide a slight decrease in NO_x, a slight increase in opacity, and a significant decrease in HC and CO. Replacing all Tier 0 and Tier 1 backhoes with Tier 2 backhoes would provide a slight decrease in NO_x but significant decreases in opacity, HC, and CO (19.9% - 77.6%).

Table 36 shows the average annual emissions for each pollutant for all front-end loaders in the NCDOT fleet inventory based on the current engine tier classifications. There were no Tier 0 front-end loaders tested so there are no estimated emission factors for Tier 0 front-end loaders. To provide an estimate of total emissions for each pollutant, Tier 1 emission factors were used for all Tier 0 front-end loaders. Thus, it is reasonable to believe that estimated average annual emissions based on the current engine tier classifications may actually be underestimated.

Table 36 also provides results for the scenario of replacing all Tier 0 and Tier 1 front-end loaders with Tier 2 front-end loaders. For example, based on the current engine tier classifications, all front-end loaders produced an estimated total of 22.1 tons per year of NO_x. If all Tier 0 and Tier 1 front-end loaders were replaced with Tier 2 front-end loaders, then NO_x emissions would decrease to an estimated total of 18.7 tons per year which is an approximate 15.7% decrease from the current engine tier classifications emissions. Replacing all Tier 0 and Tier 1 front-end loaders with Tier 2 front-end loaders would provide a significant decrease in each pollutant (14.2% - 51.8%).

Table 36. Estimated Average Annual Emissions Comparisons Based on Engine Tier Classifications for All Front-End Loaders

Pollutant	Current Engine Tiers (tons/yr)	Replace All Tier 0 with Tier 1 (tons/yr)[1]	% Difference from Current	Replace All Tier 0 & Tier 1 with Tier 2 (tons/yr)	% Difference from Current
NO as Equivalent NO_2	22.1	22.1	NA	18.7	-15.7
Opacity	0.143	0.143	NA	0.122	-14.2
HC	2.3	2.3	NA	1.1	-51.8
CO	2.6	2.6	NA	2.1	-17.9

[1] There were no Tier 0 front-end loaders tested , therefore there are no emission factors for Tier 0 front-end loaders. Thus, Tier 1 emission factors were used for all Tier 0 front-end loaders.

Table 37 shows the average annual emissions for each pollutant for all motor graders in the NCDOT fleet inventory based on the current engine tier classifications. Results are also provided for the scenarios of replacing all Tier 0 motor graders with Tier 1 motor graders, replacing all Tier 0 and Tier 1 motor graders with Tier 2 motor graders, and replacing all Tier 0, Tier 1, and Tier 2 motor graders with Tier 3 motor graders. For example, based on the current engine tier classifications, all motor graders produced an estimated total of 95.9 tons per year of NO_x. If all Tier 0 motor graders were replaced with Tier 1 backhoes, then NO_x emissions would decrease to an estimated total of 91.6 tons per year which is an approximate 4.5% decrease from the current engine tier classifications emissions. If all Tier 0 and Tier 1 motor graders were replaced with Tier 2 motor graders, then NO_x emissions would decrease to an estimated total of 84.5 tons per year which is an approximate 11.9% decrease from the current engine tier classifications emissions. Furthermore, if all Tier 0, Tier 1, and Tier 2 motor graders were replaced with Tier 3 motor graders, then NO_x emissions would decrease to 58.4 tons per year which is an approximate 39.1% decrease from the current engine tier classifications. Replacing all Tier 0 and Tier 1 motor graders with either Tier 2 or Tier 3 motor graders would significantly decrease emissions for each pollutant.

Average annual emissions per vehicle (lbs/yr) for each pollutant and engine tier were also calculated based on the current combined use of petroleum diesel and B20 biodiesel. The results for each type of vehicle are shown in Tables 38, 39, and 40. These tables also show the average annual fuel use for each vehicle; the average annual fuel use is based on the combined total of petroleum diesel and B20 biodiesel that was used for each vehicle type. The average annual fuel use per vehicle in each engine tier classification indicates the level of usage for the vehicles in that particular engine tier classification. The difference in heating value for each type of fuel has been taken into account.

Table 37. Estimated Average Annual Emissions Comparisons Based on Engine Tier Classifications for All Motor Graders

Pollutant	Current Engine Tiers (tons/yr)	Replace All Tier 0 with Tier 1 (tons/yr)[1]	% Difference from Current	Replace All Tier 0 & Tier 1 with Tier 2 (tons/yr)	% Difference from Current	Replace All Tier 0, Tier 1, & Tier 2 with Tier 3 (tons/yr)	% Difference from Current
NO as Equivalent NO_2	95.9	91.6	-4.5	84.5	-11.9	58.4	-39.1
Opacity	0.687	0.666	-3.1	0.523	-23.9	0.476	-30.8
HC	12.9	12.9	-0.6	9.7	-24.9	5.2	-60.1
CO	15.0	12.0	-20.4	10.1	-33.0	7.2	-51.7

For example, Table 38 shows the average annual emissions per backhoe based on the current combined fuel use of petroleum diesel and B20 biodiesel. There were 119 backhoes with Tier 1 engines reported in the NCDOT fleet inventory data Each Tier 1 backhoe used an estimated combined total of 670 gallons per year of petroleum diesel and B20 biodiesel. The average annual emissions of NO_x for all of the Tier 1 backhoes were estimated to be 9.2 tons per year. Therefore, the estimated average annual emissions of NO_x per backhoe were 155 pounds per year. A sample calculation is provided in Section 2.11 of this report. Similar results are reported for front-end loaders in Table 39 and for motor graders in Table 40.

The reader should note that in many cases the average annual emissions per vehicle increased as engine tier increased. This was because the vehicles with the higher tier engines typically were used more frequently than vehicles with lower tier engines, as indicated by the increased average annual fuel use for higher tier engines. Although the emission rate of each pollutant (grams per gallon of fuel use) decreased as engine tier increased, total emissions could actually increase because the higher tier vehicle was used more and thus consumed more fuel. Therefore, the average annual emissions per vehicle could be higher for vehicles with higher tier engines than vehicles with lower tier engines; however, this was also dependent on the emission rate for a particular pollutant and a particular type of vehicle. This also assumes that each vehicle was utilized for a similar number of hours, regardless of engine tier classification, throughout the years of 2005 and 2006 for which fuel use data was given in the NCDOT fleet inventory information.

For example, Table 38 shows an increase in average annual emissions per backhoe for NO_x from Tier 0 (155 lbs/yr) to Tier 1 (181 lbs/yr) but a decrease in average annual emissions per backhoe from Tier 1 (181 lbs/yr) to Tier 2 (110 lbs/yr). There is also an increase in average annual fuel use per backhoe from Tier 0 (670 gallons/yr) to Tier 1 (806 gallons/yr) but a decrease in average annual fuel use per backhoe from Tier 1 (806 gallons/yr) to Tier 2 (507 gallons/yr). This decrease in average annual emissions per backhoe and average annual fuel use per backhoe may be due to when the Tier 2 backhoes were introduced into the NCDOT fleet inventory. The fleet inventory data provided by NCDOT showed fuel use (gallons) and hours of operation (hours) for the years of 2005 and 2006; this data was used to compute average annual fuel use. Further inspection of the data revealed that 28 of the 52 (54%) Tier 2 backhoes were model year 2006 and the most hours of operation for any of these backhoes were 68 hours. Therefore, there was no fuel use data for 54% of the Tier 2 backhoes for 2005 since they were not used at all that year and very little fuel use data for 2006 since they were used for only a partial year. This resulted in lower average annual fuel use per backhoe and lower average annual emissions per backhoe for Tier 2 backhoes because 54% of the Tier 2 backhoes were not used at all during 2005 and only for a portion of 2006. Thus, the assumption of similar utilization of vehicles regardless of engine tier classification does not apply in this case.

Table 39 shows an increase in average annual emissions per front-end loader for NO_x from Tier 0 (124 lbs/yr) to Tier 1 (236 lbs/yr) but no change in average annual emissions per front-end loader from Tier 1 (236 lbs/yr) to Tier 2 (236 lbs/yr). There was also an increase in average annual fuel use per front-end loader from Tier 0 (465 gallons/yr) to Tier 1 (883 gallon/yr) to Tier 2 (1,135 gallons/yr). Although there was an increase in average annual fuel use per front-end loader from Tier 1 to Tier 2, there was no change in average annual emissions per front-end loader. Again, this may be due to when the Tier 2 front-end loaders were introduced into the NCDOT fleet inventory. Further inspection of the data revealed that 17 of the 55 (31%) Tier 2 front-end loaders were model year 2005. Although there was complete fuel use data for the year 2006, there was only partial fuel use data for the year 2005 for 31% of the Tier 2 front-end loaders. This would result in lower average annual fuel use per front-end loader and lower average annual emissions per front-end loader. Thus, the assumption of similar utilization of vehicles regardless of engine tier classification does not apply in this case either.

Table 40 shows an increase in average annual emissions per motor grader for NOx from Tier 0 (253 lbs/yr) to Tier 1 (445 lbs/yr) to Tier 2 (524 lbs/yr). There was also an increase in average annual fuel use per motor grader from Tier 0 (864 gallons/yr) to Tier 1 (1,865 gallons/yr) to Tier 2 (2,426 gallons/yr). All of the motor graders reported in the NCDOT fleet inventory data were model year 2004 or older. Therefore, all of these motor graders had fuel use data for the complete years of 2005 and 2006. Thus, the assumption of similar utilization of vehicles regardless of engine tier classification does apply in this case. There were some Tier 3 motor graders introduced into the NCDOT fleet inventory during 2007 but there was no fuel use data available for these motor graders. These motor graders were not included in the analysis of average annual emissions per motor grader.

Although the estimates of average annual emissions per vehicle were calculated assuming that all the vehicles in a specific engine tier classification were used similarly throughout the years of 2005 and 2006, this was not always the case. Only partial fuel use data for 2005 and 2006 was available for some backhoes and some front-end loaders because of when they were introduced into the NCDOT fleet; therefore, the average annual fuel use for these vehicles may be underestimated. However, complete fuel use data was available for 2005 and 2006 for motor graders which indicates that each motor grader was available for use for the entirety of 2005 and 2006.

In summary, the emissions inventory showed that the current fuel mix of B20 biodiesel and petroleum diesel that was used in the tested vehicle types produced slightly lower levels of emissions, by approximately 0.4% to 6.4% depending on the pollutant and the vehicle type, than the use of 100% petroleum diesel. However, if NCDOT were to use 100% B20 biodiesel in the same vehicle types instead of the current fuel mix, then emissions reductions would be significant, approximately 2.0% to 36.9% lower than emissions from the current fuel mix of B20 biodiesel and petroleum diesel.

Replacing older tier engines with newer tier engines will reduce the estimated total annual emissions significantly. For backhoes, replacing all Tier 0 and Tier 1 engines with Tier 2 engines will reduce the estimated total annual emissions by 4.3% to 77.6% depending on the pollutant. For front-end loaders, replacing all Tier 0 and Tier 1 engines with Tier 2 engines will reduce the estimated total annual emissions by 14.2% to 51.8% depending on the pollutant. For motor graders, replacing all Tier 0, Tier 1, and Tier 2 engines with Tier 3 engines will reduce the estimated total annual emissions by 30.8% to 60.1% depending on the pollutant.

Table 38. Estimated Average Annual Emissions per Backhoe Based on Current Fuel Use

Engine Tier	# Vehicles (Each)	Avg. Annual Fuel Use per Backhoe[1] (gallons/yr)	Avg. Annual Emissions (tons/yr)	Avg. Annual Emissions per Backhoe (lbs/yr)
NO as Equivalent NO_2				
Tier 0	119	670	9.2	155
Tier 1	116	806	10.5	181
Tier 2	52	507	2.9	110
Total	287	696	22.6	157
OPACITY				
Tier 0	119	670	0.10	1.8
Tier 1	116	806	0.13	2.2
Tier 2	52	507	0.02	0.8
Total	287	696	0.25	1.8
HC				
Tier 0	119	670	1.3	22
Tier 1	116	806	1.0	17
Tier 2	52	507	0.3	11
Total	287	696	2.6	18
CO				
Tier 0	119	670	7.4	125
Tier 1	116	806	4.4	76
Tier 2	52	507	0.4	14
Total	287	696	12.2	85

[1] Based on the combined average annual use of petroleum diesel and B20 biodiesel for each vehicle type and engine tier. The difference in heating value for each fuel has been taken into account.

Table 39. Estimated Average Annual Emissions per Front-End Loader Based on Current Fuel Use

Engine Tier	# Vehicles (Each)	Avg. Annual Fuel Use per Front-End Loader[1] (gallons/yr)	Avg. Annual Emissions (tons/yr)	Avg. Annual Emissions per Front-End Loader (lbs/yr)
NO as Equivalent NO_2				
Tier 0	107	465	6.7	124
Tier 1	76	883	9.0	236
Tier 2	55	1135	6.5	236
Total	238	753	22.1	186
OPACITY				
Tier 0	107	465	0.04	0.8
Tier 1	76	883	0.06	1.5
Tier 2	55	1135	0.04	1.6
Total	238	753	0.14	1.2
HC				
Tier 0	107	465	0.8	15
Tier 1	76	883	1.1	28
Tier 2	55	1135	0.4	14
Total	238	753	2.3	19
CO				
Tier 0	107	465	0.8	15
Tier 1	76	883	1.1	28
Tier 2	55	1135	0.7	27
Total	238	753	2.6	22

[1] Based on the combined average annual use of petroleum diesel and B20 biodiesel for each vehicle type and engine tier. The difference in heating value for each fuel has been taken into account.

Table 40. Estimated Average Annual Emissions per Motor Grader Based on Current Fuel Use

Engine Tier	# Vehicles (Each)	Avg. Annual Fuel Use per Motor Grader[1] (gallons/yr)	Avg. Annual Emissions (tons/yr)	Avg. Annual Emissions per Motor Grader (lbs/yr)
NO as Equivalent NO_2				
Tier 0	185	864	23.4	253
Tier 1	255	1865	56.8	445
Tier 2	60	2426	15.7	524
Total	500	1562	95.9	384
OPACITY				
Tier 0	185	864	0.16	1.8
Tier 1	255	1865	0.42	3.3
Tier 2	60	2426	0.10	3.3
Total	500	1562	0.69	2.7
HC				
Tier 0	185	864	2.9	31
Tier 1	255	1865	8.2	64
Tier 2	60	2426	1.9	62
Total	500	1562	12.9	52
CO				
Tier 0	185	864	5.6	60
Tier 1	255	1865	7.5	59
Tier 2	60	2426	1.9	63
Total	500	1562	15.0	60

[1] Based on the combined average annual use of petroleum diesel and B20 biodiesel for each vehicle type and engine tier. The difference in heating value for each fuel has been taken into account.

4.0 FINDINGS

This study provides many valuable insights, particularly for recruiting test vehicles, installation of the PEMS, field measurement, data quality assurance, analysis of data, development and comparisons of emission factors, and emissions inventories. The key findings from this study are summarized in this section.

4.1 Recruiting Test Vehicles

One of the first steps was to identify the vehicles to be tested, including the type of vehicle, engine size, and engine tier. The research team cooperated with NCDOT maintenance yards in Division 4 and Division 5 to have access to the vehicles. This cooperation was critical to the success of the study.

4.2 Installation of the PEMS

The PEMS must be protected from damage that might be encountered at a job site. The PEMS is vulnerable to damage from impact with trees and other obstacles since it is often located on top of a vehicle. A safety cage was designed to secure the PEMS and to protect it from damage.

Vibration from the vehicle and dust from the job site are other key considerations that can potentially damage the PEMS. Rubber and foam pads were used to reduce vibrations that were transferred from the chassis of the test vehicle to the cage and to the PEMS. A porous cloth protective cover was used to protect the PEMS from large particles and dust.

4.3 Field Measurement

Ambient conditions, such as temperature, can significantly affect data collection. In hot weather, the PEMS was found to overheat when the ambient temperature was above 90 °F, and thus data collection under such ambient temperatures must be avoided. In cold weather, residual water in the sampling hoses may freeze. Therefore, the sampling hoses should not be installed during pre-installation but during installation. Furthermore, data collection should not occur when the ambient temperature is below 32°F.

4.4 Data Quality Assurance

After applying the data screening and quality assurance procedures to the raw data, several errors and problems were corrected or removed (see Appendix B). Results were obtained for 30 total tests of 15 vehicles; a total of 103 hours of raw data were collected. These results show that approximately 7% of the data were deleted due to quality assurance checks. The most significant sources of the QA errors were gas analyzer freezing and inter-analyzer discrepancies. Gas analyzer freezing required re-initialization of the PEMS and thus needed to be corrected in the field when the problem was identified. Inter-analyzer discrepancies were identified based on the initial processing of the data and indicated that one or both analyzers may be producing inaccurate data. The calibration and performance of each analyzer was reviewed and a judgment made as to whether additional maintenance or repair was needed for one or both analyzers, as well as to whether data from one or both analyzers should be excluded for one or more pollutants and for which time periods.

4.5 Analysis of Data

Engine-based and task-oriented modal analyses of emission rates were used to analyze the second-by-second tail-pipe emissions data from nonroad construction vehicles using two different fuels. The lowest average emission rate occurred for the lowest values of MAP, which were associated with idling of the engine and low engine load. MAP is a surrogate indicator of engine load. As MAP increased, the average time-based, engine-based modal emission rate increased. The average emission rate for an entire duty cycle depended on the proportion of time spent in each mode.

For the task-oriented mode, the idle emission rate was similar to that for the lowest MAP engine-based mode. The average emission rates in non-idle modes (moving, using bucket, scoop, etc.) were higher than those in idle mode. This rate corresponded to a value between the minimum and maximum engine-based modes and implied that the engine was, on average, at a partial load. Since the non-idle task-oriented modes typically do not discriminate substantial differences in average emission rates, alternative definitions of task-oriented modes could be more useful, which are idle versus non-idle modes.

4.6 Developing Emission Factors

In addition to the engine-based and task-oriented modes results, emission factors based on observed real-world duty cycles for each vehicle type were developed. Characterized by a frequency distribution of normalized MAP, the time-based engine-based average fuel use and modal emission rates were weighted by the duty cycle distributions of normalized MAP to estimate a cycle average fuel use and emission rates. This approach was the better comparison of emissions and fuel use between petroleum diesel and B20 biodiesel. There were approximately 33% variations between cycles for the NCDOT fleet.

4.7 Comparison of B20 vs. PD Emission Factors and How This Comparison Differs by Pollutant, Vehicle Type, and Tier between B20 Biodiesel Vs Petroleum Diesel

In order to arrive at a “bottom line” comparison of the effects of substitution of B20 versus PD, average fuel use and emission rates were estimated for each tested vehicle for representative duty cycles. Based upon the fuel-based emission factors shown in Section 3.8, Table 41 represents the emission rate changes after switching fuel from PD to B20. In Table 35, the NO emission rate decreased by approximately 2% and the other pollutants showed a reduction as well (20% for opacity, 25% for HC and CO).

Engine and vehicle technologies have improved steadily in the past 20 years. Because of these new technologies, vehicles have become more efficient. Although the size of the engine is decreasing, the horsepower is increasing for the new engine tiers (see Appendix A). Table 42 shows the percent changes of emission rates by different engine tiers based on a fuel-consumed basis. Typically, the higher engine tiers have a decreasing trend in emissions and this trend is significant in Tier 2 and Tier 3 in Table 42. For example, using Tier 0 engines as the base line, there is a 25% reduction in NO for Tier 2 engines, and a 48% average reduction for Tier 3 engines. However, this result is based on the comparison of one or two vehicles for each vehicle type. Also, each tested vehicle has a different engine model and manufacturer. Thus, these reduction rates may not be statistically significant.

Table 41. Percent Changes in Fuel-Based Average Emission Rate after Switching Fuel from Petroleum Diesel to B20 Biodiesel

Vehicle	NO as Equivalent NO_2 [a]	Opacity	HC	CO
Backhoe	-4.1	-17	-27	-17
Front-end Loader	-1.0	-19	-35	-42
Motor Grader	-0.16	-18	-17	-17
Overall	-1.8	-18	-26	-25

[a] Ambient factors for the NO emission was applied

Table 42. Percent Changes (%) in Fuel-Based Average Emission Rates between Engine Tiers for Backhoes, Front-End Loaders, and Motor Graders

Vehicle	Engine Tiers	NO as Equivalent NO_2 [a]	Opacity	HC	CO
Backhoe	Tier 1 vs Tier 0	-7.0	0	-36	-49
	Tier 2 vs Tier 0	-8.0	-48	-46	-86
	Tier 2 vs Tier 1	-1.0	-48	-15	-72
Front-End Loader	Tier 2 vs Tier 1	-23	-15	-57	-23
Motor Grader	Tier 1 vs Tier 0	-18	-14	-9.4	-51
	Tier 2 vs Tier 0	-25	-36	-35	-61
	Tier 3 vs Tier 0	-48	-41	-65	-76
	Tier 2 vs Tier 1	-7.8	-26	-29	-21
	Tier 3 vs Tier 1	-37	-32	-61	-50
	Tier 3 vs Tier 2	-32	-8.0	-46	-37

[a] Ambient factors for the NO emission were applied

4.8 Comparison of Emission Factors from PEMS vs. NONROAD Model

In general, the average emission rates from the PEMS field measurement data were of similar magnitude to those based on the NONROAD model for NO, HC, and CO. For example, based on the NONROAD model, the average emission rate for NO varied from approximately 45 to 159 g/gallon, compared to ranges of approximately 59 to 139 g/gallon from the PEMS data. The two sources of data were not expected to agree because the PEMS data were for individual vehicles, whereas NONROAD is intended to predict average emissions for a fleet of vehicles. The real-world duty cycles and ambient conditions of the PEMS data differed from the standardized engine dynamometer test conditions that are the basis of the NONROAD model.

4.9 Emissions Inventory

Based on the results of the emissions inventory, using B20 biodiesel is estimated to produce lower air pollutant emissions than petroleum diesel. The current fuel mix of B20 biodiesel and petroleum diesel that was used in the tested vehicle types produced slightly lower levels of emissions, by approximately 0.4% to 6.4% depending on the pollutant and the vehicle type, than the use of 100% petroleum diesel. However, if NCDOT were to use 100% B20 biodiesel in the same vehicle types instead of the current fuel mix, then emissions reductions would be significant, approximately 2.0% to 36.9% lower than emissions from the current fuel mix of B20 biodiesel and petroleum diesel.

Based on the emission rates determined from field tests, lower tier engines produced a higher rate of air pollutant emissions than higher tier engines. For example, a Tier 0 engine in a given vehicle type produced a higher rate of emissions than a Tier 1 engine and a Tier 1 engine for a given vehicle type produced a higher rate of emissions than a Tier 2 engine.

Based on the results of the emissions inventory, replacing older tier engines with newer tier engines will reduce the estimated total annual emissions significantly. For backhoes, replacing all Tier 0 and Tier 1 engines with Tier 2 engines will reduce the estimated total annual emissions by 4.3% to 77.6% depending on the pollutant. For front-end loaders, replacing all Tier 0 and Tier 1 engines with Tier 2 engines will reduce the estimated total annual emissions by 14.2% to 51.8% depending on the pollutant. For motor graders, replacing all Tier 0, Tier 1, and Tier 2 engines with Tier 3 engines will reduce the estimated total annual emissions by 30.8% to 60.1% depending on the pollutant.

Based on the average annual fuel use per vehicle, newer vehicles with higher tier engines had higher average annual emissions per vehicle than older vehicles with lower tier engines. This is because the vehicles with higher tier engines were used more frequently, as indicated by the higher average annual fuel use for these vehicles.

5.0 CONCLUSIONS

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 activities that are influenced by extreme ambient conditions that affect 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 foam padding and protection for the PEMS.

A substantial amount of effort was spent in developing methods for data quality and assurance checks. The methods developed were aimed at producing an accurate emissions database. New programs were developed in Visual Basic that would allow a combination of emissions data collected from the PEMS and vehicle activity data collected from a laptop computer. Experience gained during field data collection and data processing has lead to the development of a rigorous quality assurance procedure involving several levels of screening. These levels include identification of known sources of possible errors in field data arising from potential problems with gas analyzer freezing, inter-analyzer discrepancy, air leakage, missing MAP, unusual engine speed, unusual IAT, and negative emission values. Knowledge of these sources of errors has lead to an improved database. Approximately 6.9 percent of measured raw data identified these errors. Overall, reliable data were obtained from the PEMS using these methods.

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 rates 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 sensitive 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 biodiesel 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 with lower tier engines 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.

Real-world duty cycles for backhoes, front-end loaders, and motor graders were observed for evaluating the inter-vehicle variability and inter-cycle variability. The vehicle duty cycle was one of the primary reasons for the emissions changes and engine loading between vehicles, especially for the time-based emission rates. For fuel-based emission rates, there is less variability between duty cycles compared to the time-based emission rates.

From the analysis of the engine and emissions data, the following conclusions were obtained:

- Measured time-based emission rates tend to increase with MAP.
- For the engine-based mode, measured emission rates on a gram per second basis are highest in the 10th normalized MAP bin, while the measured emission rates on a per gallon of fuel basis are highest in the 1st normalized MAP bin.
- For task-oriented modes, fuel-based emission rates in non-idle modes were high compared to those in idle mode.
- For emission factors, there was less variability for the fuel-based emission factors compared to time-based emission factors.
- There was a significant inter-cycle variation for each pollutant for time-based emission rates; however, non-idle fuel-based emission rates have relatively smaller inter-cycle variation among different duty cycles.
- Fuel-based emission factors are a more robust basis for emissions inventory development.
- Higher engine tiers produce lower emission rates with respect to NO, opacity, HC and CO
- Comparing B20 biodiesel versus petroleum diesel, an approximate 1.8% average reduction for NO emissions was shown in all three types of vehicles. For the other pollutants, an 18% reduction for opacity, 26% for HC, and 25% for CO emissions were shown respectively.

If NCDOT were to only use petroleum diesel in all backhoes, front-end loaders, and motor graders, then these vehicles would produce more emissions than the current combination of biodiesel and petroleum diesel fuel use. There would be slight increases in NO_x, opacity, HC, and CO emissions (0.4% - 6.8%).

If NCDOT were to only use B20 biodiesel in all backhoes, front-end loaders, and motor graders, then these vehicles would produce fewer emissions than the current combination of biodiesel and petroleum diesel fuel use. There would be slight decreases in NO_x emissions for each type of vehicle (2% - 4.7%) and significant decreases in opacity, HC, and CO emissions for each vehicle (11.1% - 36.9%).

Replacing lower tier engines with higher tier engines would reduce NO_x, opacity, HC, and CO emissions from NCDOT backhoes, front-end loaders, and motor graders. Replacing all lower tier engines with the highest tier engine available would significantly reduce emissions of each pollutant for each vehicle type.

In general, NCDOT equipment operators prefer to use newer vehicles with higher tier engines as opposed to older vehicles with lower tier engines, as evident by the higher amount of activity of the newer vehicles compared to older ones. Even though vehicles with higher tier engines have a lower emissions rate, these vehicles are used more frequently and thus may actually produce more average annual emissions than vehicles with lower engine tiers and higher emissions rates.

6.0 RECOMMENDATIONS

For nonroad construction vehicles, the data collection procedures and data analysis methodology described in this report are applicable to any construction site and any type of nonroad construction vehicle. Recommendations are made based on the experience gained in attempting to obtain valid fuel use and emissions data for nonroad construction vehicles.

For the data collection procedure, the following recommendations are made:

- Use a safety cage with padding for the PEMS to resist the vibration and shock from the test vehicle.
- Use a dust cover for the PEMS to reduce the damage from small particles or coarse aerosols in the field.
- Conduct data collection when the ambient temperature is above 32 ^oF or below 90 ^oF.

For the data analysis methodology, more sophisticated definitions of modes of activity are needed to link emissions to typical construction operations and quantities, thereby linking them to common construction project measures. Also, there is limited information for real-world duty cycles for the selected vehicles. Real-world duty cycles were observed for backhoes, front-end loaders, and motor graders. However, these are a limited subset of all types of nonroad vehicles.

For future study, the study approach can be extended to other commonly used vehicles in the NCDOT fleet inventory that have not been tested yet, such as bulldozers, compactor rollers, generator sets, pickup trucks, skid-steer loaders, and tractors. Emissions and vehicle activity results from these additional types of vehicles may help to develop more sophisticated emissions inventories and real-world duty cycles for the nonroad sector.

For future study, more statistically significant results can be determined if more vehicles are tested for each engine tier classification. For example, more accurate results can be determined from 10 to 20 tests for a given type of vehicle and tier instead of one or two tests. Also, comparisons of engine and chassis manufacturers for a given type of vehicle can be made rather than considering engine tiers only.

Tests should be conducted on newer tier engines as they become available. However, for Tier 4 vehicles, which are likely to use new types of emissions control systems, the ratio of NO and NO_2 in the exhaust is likely to be very different than for the lower tier vehicles tested to date. Thus, it will be important to characterize the total NO_x, not just NO. For this purpose, additional instrumentation will be needed in order to measure NO_2 or total NO_x, in addition to the current measurement capability for NO. Therefore, it is recommended that NCDOT support the procurement of instrumentation that provides this capability.

In addition to the current study of effects of B20 biodiesel, a more detailed assessment and comparison of fuel quality and emissions can be conducted for B20 biodiesel as an alternative fuel, including characterization of the fuel properties. Other biodiesel blends, such as B30 or B40, which can offer even larger tailpipe emission reductions, should be assessed and compared.

For future study, methodologies may be developed for controlled experiments in which vehicle activities are quantified in terms of typical maintenance or construction metrics, such as cubic yards of excavation. Such data would facilitate estimation of fuel use and emissions during project planning.

NCDOT should analyze the feasibility of using B20 biodiesel exclusively in all backhoes, front-end loaders, and motor graders to reduce emissions of NO_x, opacity, HC, and CO. This analysis should include fuel availability, fuel cost, and vehicle performance.

NCDOT should analyze the feasibility of replacing all lower tier engines with the highest available engine tier for each type of vehicle. Doing so would reduce emissions of NO_x, opacity, HC, and CO significantly for backhoes, front-end loaders, and motor graders. NCDOT can also investigate retrofitting existing vehicles with higher tier engines without replacing the entire vehicle.

NCDOT should analyze the feasibility of using B20 biodiesel in the highest engine tier available for all backhoes, front-end loaders, and motor graders to provide the most significant reductions of NO_x, opacity, HC, and CO emissions.

NCDOT should determine if older vehicles with lower tier engines are a necessary part of the fleet inventory. If these vehicles are not being used frequently, then perhaps they can be eliminated from the fleet inventory altogether. If it is necessary to replace these vehicles, then they should be replaced with vehicles of the highest engine tier available.

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